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EXPERIMENTAL
ELECTRONICS

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Preface

THIS BOOK has been written to supply definite practical information on the characteristics and non-communication applications of electron tubes. It is an outgrowth of the authors' experience in courses given for several years at New York University to students and industrial and academic research workers in chemistry, biology, and engineering. In these courses, students of widely different backgrounds and interests have found competence in handling electronic circuits most stimulating and helpful, revealing to them many unsuspected applications in their own fields.

Our confidence in the experimental approach to the subject has been warranted by the repeated observation that familiarity with electronic circuits is not to be gained by extensive reading alone. Sufficient explanation of the theory and underlying principles has been included to clarify each experiment. We have purposely avoided extensive proofs and rigorous derivations, most of which are to be found in standard textbooks. The instructor may wish to supplement the text, as we have done, with occasional lectures and discussions on electron physics and to point out additional applications and extensions of the subject. The inclusion of some very elementary principles in the earlier chapters will be welcomed by those readers who may have forgotten these fundamentals, or who may be encountering them for the first time.

For the general reader, an effort has been made to present a fairly complete and continuous picture. To this end, the results of each experiment are given in tables or graphs of original data. In practically all cases, idealized curves have been avoided, and the reader or experimenter can at once learn what may be expected from the prescribed equipment.

The radio engineer or communications expert may glean from the experiments a point of view or statement of problems, rarely encountered in his own specialty, which are peculiar to the requirements of other fields of science.

The authors' indebtedness to standard works on electronics and radio engineering is evident from the repeated references to these valuable sources, particularly to the treatises of Professor F. E. Terman and Professor H. J. Reich. References to selected articles in the literature on the subject have been chosen either to provide more detailed explanation of theoretical matters or to indicate further applications of a given principle.

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September, 1942.

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CHAPTER I

Introduction

This chapter presents a brief review or summary of some elementary electrical definitions which are essential for the understanding of electronic circuits. It is assumed that the reader is already familiar with elementary electrical theory and does not encounter these definitions for the first time.

A brief account is given of the characteristics and specifications of various circuit components, particularly those which are common to modern radio practice. These are rarely discussed in textbooks, although they are indispensable in electronic work. The reader will do well to acquire catalogs of the various manufacturers and dealers in radio parts, in order to keep abreast of the latest offerings in this class of equipment. The discussion in this chapter may be helpful in appraising the merits or particular functions of these devices.

A few methods of electrical measurement are discussed which are very common in the practice of electronics. In most cases, they represent tests or rough approximations of the more precise measurements so exhaustively treated in standard texts. It is important and useful to know when approximations will suffice for the purpose and when the more precise and conventional methods are required.

1-1. Ohm's law.

Direct current flows in circuits according to the well-known rule called Ohm's Law, which states that the current which flows through a resistance is inversely proportional to the resistance and directly proportional to the voltage. Further, since the unit of resistance is based on this law, no proportionality constant is required for the equation

$$I = \frac{E}{R},$$

if I is the current in amperes, E the electromotive force in volts, and R the resistance in ohms.

1-2. Resistances in series.

If several resistors are placed in series, as shown in Figure 1-1, then the current which flows in one must also be the same in all the others; fur-

ther, the total resistance of the circuit must be the sum of the individual resistances, and the formula becomes

$$I = \frac{E}{R_1 + R_2 + R_3};$$

transposing,

$$E = R_1I + R_2I + R_3I.$$

Accordingly, we see that the entire voltage is divided between the resistors R_1, R_2, and R_3 in proportion to the values of each, since the current I is the same throughout all of them. This relation is important, and may be better stated by writing

$$E_1 = R_1I, \qquad E_2 = R_2I, \qquad \text{and} \qquad E_3 = R_3I.$$

Thus the voltage E is divided into parts E_1, E_2, and E_3.

1–3. Resistance in parallel.

If several resistors are placed in parallel, as shown in Figure 1–2, the current is no longer the same in all resistors, since it divides between the various units. The current in each unit may be calculated from the relation

$$I = \frac{E}{R},$$

since the voltage across each of these resistors is the same. That is,

$$I_1 = \frac{E}{R_1}, \qquad I_2 = \frac{E}{R_2}, \qquad \text{and} \qquad I_3 = \frac{E}{R_3}.$$

The total current I must be equal to the sum of the individual currents, so that $I = I_1 + I_2 + I_3$. But I must be equal to $\frac{E}{R}$, where R represents the total equivalent resistance. Substituting the value I in $I = \frac{E}{R}$ gives us the following

$$I_1 + I_2 + I_3 = \frac{E}{R};$$

but $I_1 = \frac{E}{R_1}$, and so forth. Therefore,

$$\frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3} = \frac{E}{R}.$$
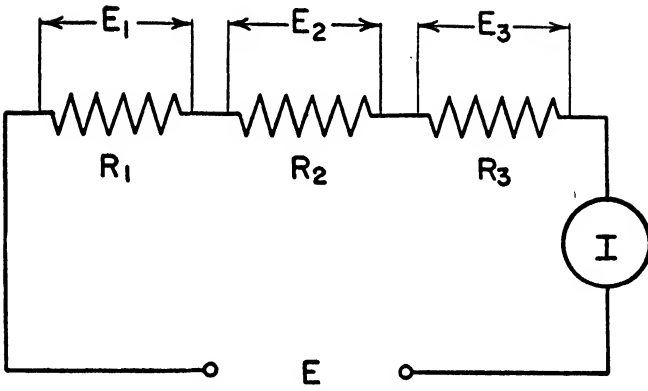
FIG. 1–1.   Resistors in Series.
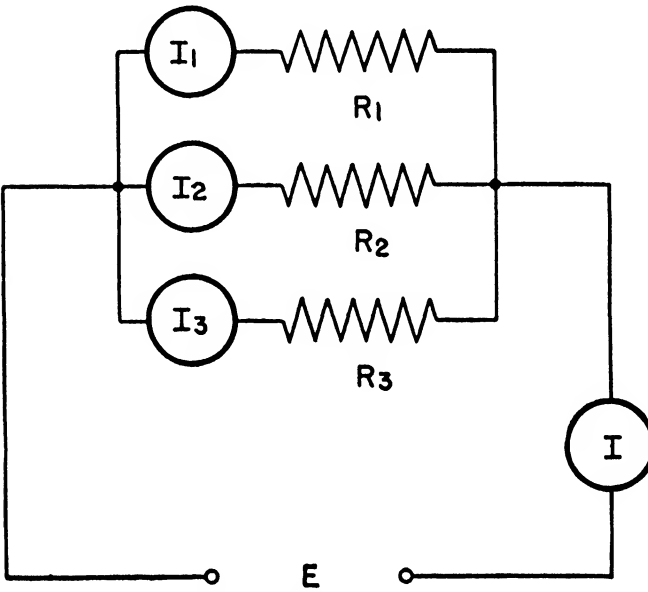
FIG. 1–2.   Resistors in Parallel.

Dividing both sides of this equation by E leaves us with

$$\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{R}.$$

It must be remembered that current flows according to the above formulation of Ohm's Law only if the value of R does not change with I or E. In the conduction of electricity through gases, for example, the value of the effective resistance is a function of the value of I and E, and the formula $E = RI$ is not applicable. Other forms of nonohmic resistors are known, and may be used whenever a nonlinear relationship is desired.

1–4. Power in electrical circuits.

When electrons travel through a conductor (wire), they collide frequently with the particles in the lattice of the metal. We say that the wire offers resistance to the passage of electricity. In these collisions, however, considerable energy is transferred to the lattice, that is, the thermal agitation of the particles in the metal is increased and the energy lost by the electrons appears in the form of heat. The heat energy developed in this way is proportional to the resistance and to the square of the current. The power correspondingly dissipated is given by $P = RI^2$ or $P = \dfrac{E^2}{R} = EI$, in watts if E is in volts and I in amperes. This heat energy is radiated to the surroundings. The temperature rise of a resistor is, therefore, proportional to the dissipated wattage and inversely proportional to the rate of heat radiation.

The temperature coefficient of resistance for most conductors is not zero, and if the resistor is to be used as a resistance standard its temperature must be held constant. If changes in resistance owing to changes in temperature are not greatly important, the temperature of the unit may be allowed to rise; but care must be exercised that the temperature does not rise to a point where the unit may be damaged. All resistors, therefore, are said to have a maximum wattage rating. The wattage rating depends upon the physical size, the rate of heat radiation, that is, the thermal conducting properties of the constituent materials, and the maximum temperature which may be tolerated, taking into account the resistance change and susceptibility to damage.

1–5. Analysis of alternating-current characteristics.

The current and voltage in an A.C. circuit is not constant, but varies periodically with time. If the circuit contains only resistance, the current variation follows the voltage variation, but in other circuits the two may not be in step at all times.

The manner in which a sinusoidal alternating current varies with time is shown in Figure 1-3. The time required for the current to go through one alternation and back to the starting point is called the period, during which the current is said to have progressed through one cycle. The number of these complete alternations per second is the frequency. It is expressed as cycles per second and abbreviated c.p.s.

Figure 1-4 shows another way of expressing the value of voltage or current at any instant, assuming for the moment that the vertical axis represents the value of voltage. Then the length of the radius represents the maximum value of the voltage in a given cycle. This radius is rotating constantly, making one complete revolution for each cycle. At any instant, the height of the end of this radius above or below the horizontal axis represents the value of the voltage.

It follows, therefore, that the instantaneous value of the voltage e is equal to the maximum value of the voltage times the sine of the angle through which the radius has moved. At 90° the sine is equal to 1 and therefore $e = E_{max}$, while at 0° and 180° the sine is 0 and the value of e is zero.

The value of θ at any instant can be calculated from the frequency and the time after $t = 0$. θ is equal to $2\pi ft$. The value of e will then be equal to $E_{max} \sin \omega t$, ω being equal to $2\pi f$.

1-6. Calculation of power in A.C. circuits containing resistance.

Since the current and voltage in an alternating-current circuit vary continually, the calculation of the amount of power dissipated in the circuit is not as apparent as it was in the D.C. circuit. Indeed, the average voltage and current are equal to zero. The thermal agitation and consequent heating effect produced by the electron migration is identical with similar effects caused by a direct current. In order to calculate the power, therefore, it is necessary only to determine the average effective heating current, which can be shown to be equal to $\dfrac{1}{\sqrt{2}}$ times the maximum current in the cycle; therefore $P = (.707 \times I_{max.})^2 R$, or simply,

$$P = I^2_{effective} R,$$

where

$$I_{eff.} = \frac{I_{max.}}{\sqrt{2}} = \frac{I_{max.}}{1.41}$$

In a similar manner, it may be shown that

$$E_{eff.} = \frac{E_{max.}}{\sqrt{2}} = \frac{E_{max.}}{1.41};$$

$$E_{eff.} = RI_{eff.}.$$

All measurements of sinusoidal voltage and current are based upon these effective values. $E_{effective}$, or the root mean square of the voltage as measured on an ordinary A.C. voltmeter, is equal to .707 of the maximum voltage in the cycle and conversely, the maximum voltage in the cycle is 1.41 times the measured value.
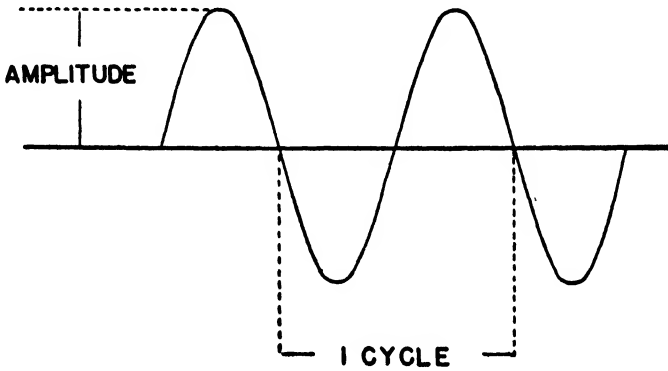
FIG. 1-3.   An Alternating-current Wave
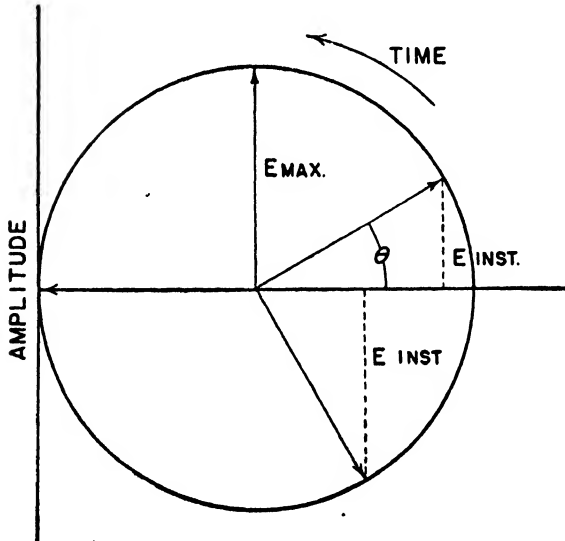
FIG. 1-4.   Projection of a Sine Wave.

The above discussions were based upon circuits composed entirely of resistances. If capacitors or inductors or both are present in the circuit, the variations of voltage and current may be quite different with respect to time. Before treating the exact relationships in detail let us consider the units themselves in more detail.

1-7. Capacitors.

A capacitor may consist of any two circuit elements separated by an insulator. Alternating currents may be said to flow through capacitors, since the unit is charged, then discharged, then charged in the opposite direction and discharged again during each cycle. This alternation represents a current, and the magnitude of such a current is determined by the voltage and the electrical size of the capacitor. A term similar in some respects to the term resistance may be used with reference to capacitors. This term is capacitative reactance. It is expressed in ohms and its value is a function of the frequency of alternation.

The capacitative reactance X_o is equal to $\dfrac{1}{2\pi f c}$ ohms, where c is the capacitance in farads and f the frequency in c.p.s. A reactance, although expressed in ohms, does not dissipate power.

1-8. The inductor.

An inductor may be any wire which is surrounded or linked by the magnetic field produced by the current passing through the wire. A wire in the form of a coil possesses a greater inductance than a straight wire, since each portion of the wire will be linked by the magnetic field of all the coils.

When an alternating voltage is impressed across a coil of wire (an inductor) the value of the current produced through the coil will depend upon the resistance and the inductance of the coil. The impeding effect of the inductance may be measured in terms of ohms and is called the inductive reactance. The value of the inductive reactance depends on the inductance and the frequency of the imposed voltage, and can be expressed as follows:

$$X_L = 2\pi f L,$$

where L is the inductance in henries and X_L is the inductive reactance in ohms.

1-9. Calculation of capacitance.

The capacitance of a condenser may be calculated if area, shape, and separation of the plates, together with the dielectric constant of the insulating material, are known. The capacitance in farads between two parallel plates is given by

$$C = 8.85 \frac{KA}{d \times 10^{14}},$$

where A is the area of the plate in square centimeters, d the distance between plates in centimeters, and K the dielectric constant of the insulating medium. Formulae for other types of capacitors may be found in standard handbooks of electrical engineering or physics.

1–10. Calculation of inductance.

The value of the inductance of a coil depends upon the number of turns of wire, the type of winding, and the size of the wire as well as the general shape of the unit. The inductance of a single-layer cylindrical coil is given by

$$L = \frac{2A^2n^2}{3A + 9B},$$

where L is in microhenries, A is the mean diameter of the coil in inches, n the number of turns, and B the length of the coil in inches. If the coil is closely wound, the value of B may be stated in terms of the pitch of the wire and the number of turns. Formulae for other types of windings may be found in standard handbooks.

1–11. Radio parts.

Mass production of radio parts has enabled manufacturers to produce resistors, capacitors, transformers, and other circuit components of fair quality at extremely low prices. In many cases, entirely new parts have been introduced to meet the radio demand. Developments have been so rapid that engineers in other fields as well as research workers in general have not had an opportunity to familiarize themselves with the general availability of these parts.

Resistors. Since the current in electronic circuits is usually of the order of milliamperes, we note, recalling that $P = RI^2$, that the power is of the order of watts even for R values of the order of 10^5 ohms. Thus, a resistor carrying a current of 1 ma. with a resistance of 10^6 ohms dissipates only 1 watt of energy and may, therefore, be of small size.

These small resistors, with ratings of $\frac{1}{2}$, 1, or 2 watts, are usually of the carbon type (fired) or of the sputtered filament type (metalized). Such resistors probably take care of 90 per cent of the resistor demand of the average radio receiver and are obtainable in sizes from 50 ohms to 20 megohms or higher.

Resistors of higher wattage are usually wire-wound. They are made by winding nichrome wire on vitreous forms, which are later fired so that a portion or all of the winding is covered with heat-resisting enamel. If the resistor is to be variable, a small portion or strip of the wire is left bare to permit the points of contact, which are made with metal bands, to be changed at will. Resistors of this type will withstand higher tem-

peratures than the carbon types, and are obtainable in wattages of 5, 10, 25, 50, 100, and 200, in resistance values from 1 to 100,000 ohms or even higher for the high-wattage types. Wire-wound resistors of lower rating are also obtainable in the form of molded resistors, some of them wound noninductively and guaranteed to 1 per cent accuracy. In many cases, a tolerance of 5 per cent or even 10 per cent is permissible in radio work; hence many of the units are guaranteed only to this accuracy.

I–12. Radio capacitors.

Condensers are usually classified in accordance with the type of dielectric employed. Many materials are suitable insulators (dielectrics), and it might appear that the higher the dielectric constant the more suitable the material. Other factors must, however, be considered. The capacitance of a perfect condenser should not change with impressed voltage, but this condition can exist only if the insulator or dielectric does not break down with the voltage or change in any way. Condensers are rated in farads f., in microfarads μf. (10^{-6} f.), or in micromicrofarads $\mu\mu$f. (10^{12} f.) and in accordance with the maximum voltage that the condenser will withstand. If an excessive A.C. voltage is impressed on a condenser, an imperfect dielectric will heat considerably and may finally break down. For this reason capacitors are often rated for A.C. and for D.C.

The usefulness of a capacitor across a D.C. circuit arises from the fact that it will not let direct current flow after the unit is fully charged, whereas alternating current is passed more freely.

I–13. Classification of radio capacitors.[1]

Air condensers. Air condensers are made in sizes from a few micromicrofarads to a few thousand micromicrofarads. They are easily made variable, since it is necessary only to move one plate or set of plates with respect to another to change the capacity. The voltage rating depends upon the shape, polish, and separation of the plates, as well as on the pressure of the air or other gaseous dielectric used and on the construction of the mountings. The useful rating is generally of the order of hundreds or thousands of volts, and may be as high as a few million volts, provided high dielectric pressures and wide separation of plates are employed.

Mica condensers. Mica is a suitable dielectric, since the dielectric constant is higher than air (approximately 6.0), and its strength against breakdown is satisfactory for many applications. Mica capacitors are

[1] Terman, F. S., "Radio Engineering." New York: McGraw-Hill Book Company, Inc., 1937; p. 23.

obtainable in capacitances from 10^{-10} to 10^{-8} f., and in ratings from a few hundred to 5,000 v. or more.

Paper condensers. These capacitors are made by separating alternate layers of metal foil with paper insulators. The paper may be impregnated with special materials to increase its dielectric constant and dielectric strength. Paper condensers are obtainable in sizes from 10^{-9} to 10^{-5} f. and in ratings from a few hundred to 1,000 v. For a given size, the high-capacitance condensers have smaller voltage ratings.

Oil-filled condensers. The capacitance of an air condenser may be increased by immersion in oil, which is an insulating material of higher dielectric constant. Various types of fixed condensers in which the dielectric is an oil of some type are available. In recent years, special liquid or semiliquid fillers have been developed with high values of K and high dielectric strength. Condensers of capacitances up to 4 μf., with ratings to 10,000 v. and even more, are used. Paper condensers with oil insulation are usually classified under this heading.

Electrolytic condensers. The development of radio receivers powered by alternating current brought a demand for low-cost condensers relatively high in capacitance and yet reasonably small in physical dimensions. This demand was met by the development of the electrolytic condenser. Electrolytic condensers are of low voltage ratings (6 to 600 or 800 v.), but a 16-μf. condenser with a 450-v. rating is no larger than a 5-μf. paper condenser or a .0001-μf. air condenser of the same rating. Dry electrolytic condensers may be obtained with capacitances ranging from 3,000 μf. or higher at 6 to 10 v. down to 4 to 32 μf. at 450 v. Because of the operational principle of these condensers, pure A.C. voltages should never be impressed on them. The voltage may vary, but the negative terminal (black) must never be allowed to become positive with respect to the positive (red) terminal of these capacitors. The chief usefulness of electrolytic condensers is in power supplies where a rectifier delivers a unidirectional or pulsating D.C. voltage and a combination of condensers and resistors or condensers and inductors (chokes) serves to smooth out the pulsations. (See Chapter 4.)

1–14. Classification of inductors.[2]

The size of an inductor for various purposes for a given reactance depends upon the frequency employed, and the form of the unit similarly depends upon the frequency. In practice, at high frequencies (10^7 to 10^8 c.p.s.), the inductor may consist of a few turns of wire made self-supporting (or even a single turn or fraction of a turn: 10^{-7} henries or less), while at low frequencies many thousands of turns may be used and soft iron may be placed in the coil to increase the value of the inductance.

[2] Terman, F. E., *op. cit.*, p. 35.

A coil wound on a low-loss insulator has an inductance which is independent of the current and only slightly dependent upon frequency, while a coil with an iron core has an inductance which is dependent upon current and frequency.

Until a few years ago, iron-cored inductors were used only at comparatively low frequencies (up to 20,000 c.p.s.), and the core consisted of laminated iron plates arranged in a manner to concentrate the iron in the coil field. Iron cores of this type do not work satisfactorily at high frequencies because of the losses resulting from large eddy currents in the core. The art of producing finely divided iron (small, almost microscopic particles, insulated from each other) has progressed sufficiently to permit the use of iron cores at frequencies as high as 50×10^6 c.p.s. A unit which contains only a single set of windings is called a choke, while a unit which consists of two or more windings coupled magnetically is called a transformer.

1–15. Transformers. Types.

Transformers may be divided into two classes: power transformers, used to supply power from A.C. mains to the electronic appartus; and so-called audio- or radiofrequency transformers, used to transfer power from one tube to another, from an aerial to a tube, or from a tube to a loudspeaker or meter.

1–16. Power transformers.

Power transformers are usually made to operate at 60 c.p.s., but may be made to operate at 25 c.p.s. or lower. A transformer designed for 25 c.p.s. may be used on 60 c.p.s., but the reverse is not usually possible. These transformers generally consist of a low-voltage winding (step-down) to supply the filaments and heaters of radio tubes (2.5, 5.0, and 6.3 v.) and a high-voltage winding (300 v. or higher) for the plate supply of these tubes. High-voltage transformers (1,000 to 10,000 v.) are usually made with only a single output winding, and separate units are used to supply filament and plate voltages. This simplification is necessitated by insulation difficulties encountered in multiple-purpose units for the higher voltages. In some cases, copper shields are placed between windings to minimize capacitative coupling.

1–17. Audio transformers.

An audio (strictly, audiofrequency) transformer is used to transfer energy from one circuit to another at audible frequencies, that is, from 20 to 20,000 c.p.s. It is designed along the same lines as the power transformer, except that particular attention must be given to core material and construction in order to minimize core losses. The distributed ca-

pacity must be kept low if the response of the transformer is to be maintained at higher frequencies. The frequency range of many of these units is, therefore, much smaller than that given above.

Audio transformers are available for matching microphones (100 ohms at 400 c.p.s) to the input of a tube (100,000 ohms or more) at the same frequency; for interstage coupling in which set-up ratios of 2 to 3 are used; for matching the output of a tube to a speaker coil; and for other purposes.

1-18. Transformers for radio frequencies.

Radiofrequency transformers are available to cover intermediate frequencies (100 to 500 kc.) and are most commonly tuned to a particular frequency by the use of a semivariable capacitor. Such transformers are usually band-pass filters in which both the primary and secondary are tuned. Transformers are available for the broadcast band (500 to 1,500 kc.) and for higher frequencies, the so-called short-wave bands. All of these transformers may be of the air-core or iron-core types. Tuning these coils to various frequencies is accomplished by variable air capacitors. Since the inductance of a coil varies with the amount of core material within the field, transformers are sometimes tuned by movable plugs of the core material, a fixed capacitor being used to supply the capacitative reactance.

1-19. Special types of power transformers.

In many types of electrical measurements, it becomes necessary to vary the voltage supply. This may be accomplished by the use of series resistors or potentiometers, with attendant losses, or by the use of transformers. A number of manufacturers are producing variable step-down transformers. Using them, the operator has at his command voltages from zero to line voltage or higher. Such transformers are manufactured under trade names such as Variac, Varitran, and so forth, and are available in a variety of power and voltage ratings.

1-20. Constant-voltage transformers.

Power mains fluctuate considerably in voltage from hour to hour and even from second to second. If the mains are used to supply apparatus, meters in these circuits may vary from one measurement to another and reduce the precision of the measurement. A number of transformers are available, designed to minimize these fluctuations. These are so-called constant-current or constant-voltage transformers. (See Chapter 4.)

1-21. Volume controls: radio potentiometers.

The ordinary radio volume control is a small potentiometer or voltage divider, arranged as shown in Figure 1-5. Volume can also be con-

trolled by variable cathode resistors and other devices. Frequently, a small change in resistance at one end of the potentiometer will have a large effect on the volume, while a comparable change at other values causes only an imperceptible effect. To avoid the resulting difficulties, radio potentiometers and variable resistors are available in which the
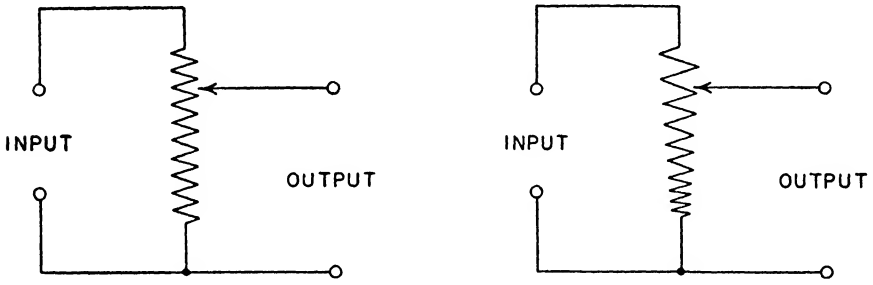
FIG. 1–5.   Radio Potentiometers.
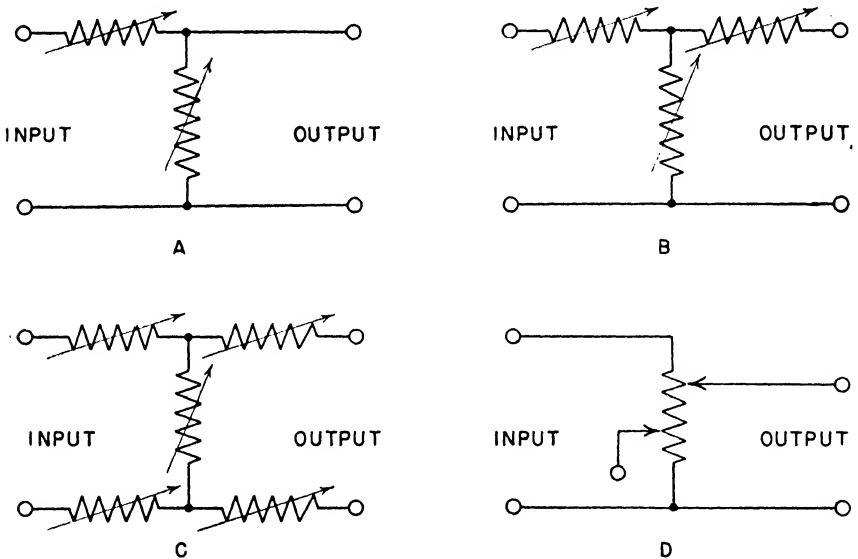
FIG. 1–6.   Radio Attenuators.   (A) L pad; (B) T pad; (C) H pad; (D) Tapped potentiometer.

change of resistance with angle of rotation is not uniform but varies in some predetermined way (taper). Taper resistors are usually of the carbon type, but may be wire-wound; in the latter case, the wire turns are reduced in length to obtain the proper relation between resistance and angle of rotation.

The ordinary potentiometer (Figure 1–5) presents a constant resistance to the voltage source, but the resistance between the output

posts is variable. This condition is satisfactory when the resistance of the device connected to the output posts is much higher than the total resistance of the potentiometer (grid circuit of tube), but is unsatisfactory in other cases (transformers). Various types of complex variable resistors are available, however, so constructed that when the resistance of one unit increases, another unit coupled to the same shaft reduces another resistance in the circuit to maintain the over-all resistance constant. These devices are called pads, and some available types are shown in Figure 1-6.

1-22. Relays: classifications.[3]

Whenever electronic devices are used for control purposes and are required to start motors, close heavy lamp loads, and so forth, a relay is used as an intermediate agent. This generalization is true for all electronic circuits other than those using gas triodes, because the currents passed by such tubes are relatively small.

In general, a relay consists of an electromagnet which is excited by a comparatively weak source. A moving armature, attracted by the magnet, carries contacts which will open or close the circuit and in so doing control relatively heavy loads. In some types, the armature translates its motion to a separate contact system. Relays have been designed to meet a great variety of problems and to handle loads of wide range. The present discussion (§§1-22 to 1-27) will be limited to a brief classification and a description of the more important specifications. Manufacturers can usually give helpful advice in choosing a relay if the nature of the problem is clearly stated.

1-23. Relay coil specifications.[4]

Specifications for the coil through which the actuating current is passed are usually in terms of volts and coil resistance. The first refers to the normal voltage which is to be applied to the coil for satisfactory operation; the significance of the second term is evident. Occasionally the current is also listed; if not, it is readily calculated from the other two ratings.

Double coil windings may be had for forward and inverse operation. Additional specifications which may be important include (1) temporary overload which can be tolerated, (2) normal temperature rise on continuous current flow, (3) special impregnation for humid conditions, (4) coil-to-frame insulation (in high-voltage circuits).

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[3] Beverly, Dudley, *Electronics*, May, 1938; p. 18.
[4] *Electronics*, Aug., 1940; p. 13.

1–24. Dynamic characteristics of relays.

Practically any motion-time function can be provided by proper design of a relay. A very slow pull-up and quick "drop-out" may be arranged, or vice versa. On the other hand, either event may be made to take place very rapidly or very slowly. Relays which are to be actuated by alternating current are usually fitted with a shading coil to prevent chattering. Time-delay relays can be designed for reasonably short delay intervals. Where long delay periods or elaborate cycling operations are required, a common relay is usually supplemented by such auxiliary devices as air or oil dashpots, thermal relays, clock-driven timers, or electronic circuits.

Stepping relays permit the selection of a desired circuit from a large choice of positions. They are really impulse-actuated selector switches. A common type used in automatic telephone exchanges will handle 100 circuit paths of one to six conductors each. They are usually provided with a homing release which automatically resets the selector. Countless circuit combinations are possible with elaborate selectors of this type.

1–25. Relay contacts.[5]

Contact troubles cause the majority of relay failures. A careful study of the problem in hand, however, permits the choice of a wholly dependable relay. This fact is exemplified by the very exacting requirements for railroad signals, for telephone exchange apparatus, and for many safety devices.

The load which can be handled by a given set of contacts is usually expressed in watts, or more specifically amperes and volts A.C. On D.C. or inductive loads, the rating is much lower.

Open contacts. Studs or buttons are made of pure silver, silver alloys, platinum, palladium, or tungsten. Careful alignment is essential and a slight wiping motion during contact is desirable, to exert some self-cleaning action.

In micro-switches, an ingenious snap-action blade of beryllium-copper alloy provides a very rapid motion of the contacts for an actuating motion of a few thousandths of an inch, with a capacity of 10 amps. at 250 v. A.C.

Mercury contacts. In one type, a sealed glass bulb containing a pool of mercury is tilted by the relay armature, making or breaking contact with the pool of mercury. In another type, the mercury contact is provided by an iron armature which floats in a column of mercury; the iron float is moved by a solenoid (relay). Mercury relays are free from most contact troubles; they are particularly suited, also, for installation where explosion hazards prevail.

[5] Clement, A. W., *Electronics*, Dec., 1938; p. 29.

Vacuum contacts. An evacuated glass tube has in it two contacts: one fixed, the other mounted on the end of a re-entrant stem. External flexure of the stem brings the two contacts together. A typical rating is 6 amps. noninductive load at 220 v. A.C. or D.C. This type shares all the advantages of the mercury type.

1-26. Special relays.

Polarized relays for differential operation; galvanometer relays in which a light D'Arsonval movement is fitted with light contacts; latch relays in which a closed or opened contact is mechanically locked after a single operation and must be released either manually or by another relay.

1-27. General operational hints.

A good relay of the proper characteristics is highly dependable. Nevertheless, periodic attention is advisable. Open contacts should be kept clean and properly aligned. They should be cleaned when necessary by pulling a strip of good hard paper between the contacts. Open contacts are a perpetual source of trouble in chemical laboratories, where some corrosive fumes are almost always present. Filing or treatment with abrasives is usually worse than outright neglect. Moving parts, such as bearings and limit studs, should not be oiled unless the entire relay is provided with a dust cover.

1-28. Simple electrical measurements.

Accurate measurements of resistance, capacitance, and inductance involve the use of various forms of the Wheatstone bridge. In electronic work, however, this precision is usually not justified, since the tolerance limit is usually more than 1 per cent. Meters may, therefore, be used for most measurements. Since the measurements may involve currents as low as 10^{-5} amp. or as high as a few amperes, and voltages from .1 to 1,000 v., a large number of meters must be available unless provision is made to convert the sensitive meters to ones of lower sensitivity.

1-29. Ammeters and shunts.

Ammeters scaled for low values may be converted to read higher values by the use of shunt resistances as in Figure 1-7. Consider a meter of 50 ohms resistance which gives a full-scale deflection with 1 ma. If this meter is to be read full scale, the voltage at the terminals must be .05 volts. If we wish to convert this meter into one which will indicate 10 ma. at full scale, then it will be necessary to place a resistance in parallel with the meter resistance, of such a value that $\frac{9}{10}$ of 10 ma. will flow through this resistance when the voltage is .05 v. The remain-

ing $\frac{1}{10}$, or 1 ma., flows through the meter. The result is derived from $R = \frac{E}{I}$, where $I = .009$ and $E = .05$. The value of R is 5.55 ohms.

This calculation may be checked by noting whether $\frac{1}{R_{total}} = \frac{1}{R_{meter}} + \frac{1}{R_{shunt}}$, where R_{total} must be equal to 5 ohms, since the total current we wish to measure is 10 ma. and with a voltage loss (RI drop $= .05$ volts). Shunt resistances for other values of meter conversion may be calculated
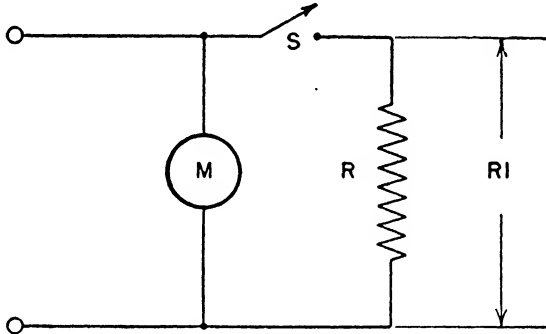
Fig. 1-7. A Meter Shunt.
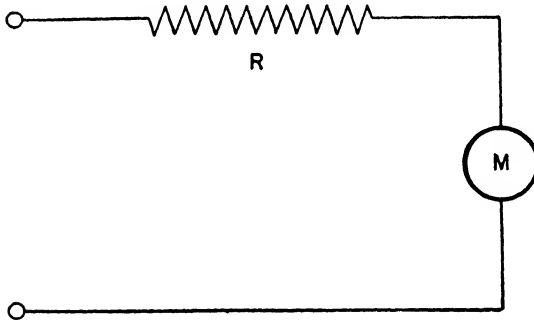
Fig. 1-8. A Meter Multiplier.

in a similar manner. It is possible, therefore, to use one meter and adapt it to the measurement of many values of current. In a practical apparatus, all the shunts are so arranged that they may be connected to the meter at will by means of rotary switches.

1-30. Voltmeters and multipliers.

The same meter which measures current may be used also to measure voltage, and it will measure 50 mv. or fractions thereof without any changes, as was noted from the foregoing calculations. If, however, the range of the meter is to be extended, a resistance in series with the meter, sufficient to limit the total current to 1 ma., must be used as

shown in Figure 1–8. If the meter, for example, is to read 1 volt at full
scale, then the total resistance would be equal to 1000 ohms; but since
the meter resistance is 50 ohms, only 950 ohms are necessary for this
conversion. A 9,950-ohm multiplier would be required to convert the
unit into a 0–10 voltmeter, and so on. D.C. voltmeters may be con-
verted for use with A.C. by inserting a copper oxide rectifier in the
circuit as shown in Figure 1–9. The scale of the meter will no longer be
uniform because of the loss in efficiency of rectification at low currents.
Scales are available, however, which include these correction factors.

1–31. Resistance measurements.

The value of a resistor may be calculated from Ohm's law, provid-
ing the voltage across the resistor and the current flowing are known.
This method suggests the use of two independent meters. Since we re-
member, however, that an ammeter may be converted to a voltmeter at
will, the circuit shown in Figure 1–10 may be used in the following
manner. The input terminals are shorted and resistor R is adjusted until
the meter reads full scale. Under these conditions, the milliammeter has
been converted to a voltmeter which reads the full battery value at this
position on the scale. This voltage is given by $E = RI_1$. If, now, an
unknown resistance R_u is connected to the posts, the meter will read a
current I_2. The impressed voltage E will still be the same, so

$$E = (R + R_u)I_2 = RI_1$$
$$\frac{I_2}{I_1} = \frac{R}{R + R_u}.$$

This relationship is exact and the precision of the measurement would
depend only upon the accuracy and readability of the meter and on a
constant voltage of the battery B from one measurement to the next.

In practice, a hyperbolic scale is made from the above equation and
placed in correct position above or below the milliampere scale. The
meter then becomes a direct-reading ohmmeter. Small changes in bat-
tery voltage may be compensated for by making a small portion of R
variable. A change of R should be accompanied by a corresponding
change in the calibration of the scale. However, small changes of E will
not reduce seriously the accuracy of the measurement. Several ranges
may be accommodated by changing the value of E and R, or by chang-
ing I_1 and R. Since provision is already made, usually, to change the
range of the milliammeter, the latter method may be employed most
conveniently. For the measurement of resistances of 1 megohm or
higher, voltages as high as a few hundred volts may be used with the
meter in its most sensitive position. Low resistances, of the order of 10
ohms or less, are measured more conveniently by using them as shunts,

rather than multipliers as outlined above. Ohm's law again applies, except that the resistor will now be in parallel with the meter resistance and hence the rule for parallel resistors applies. In this method, the
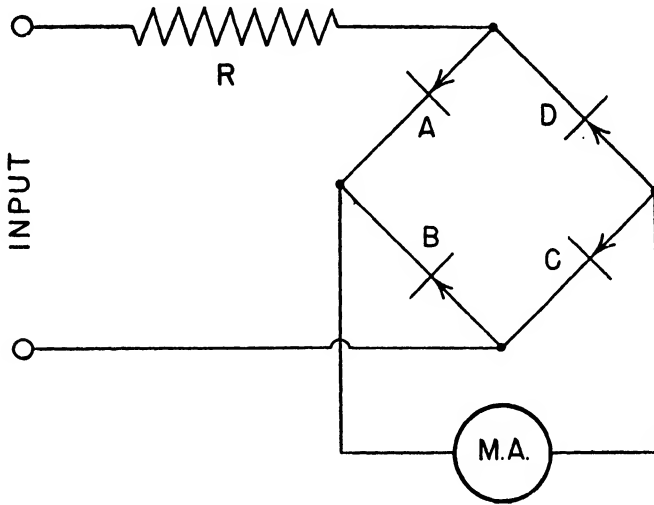
FIG. 1–9. A Full-wave Copper-Oxide Rectifier Circuit.
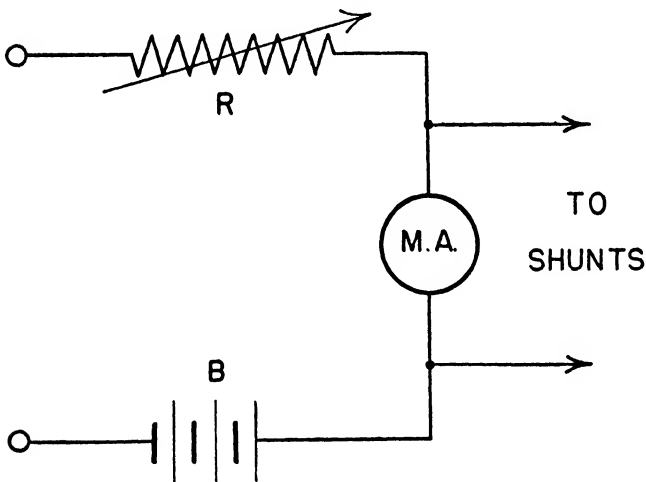
FIG. 1–10. An Ohmmeter Circuit.

changes in voltage of the battery with age are of less importance than in the former case. The methods outlined are not the only ones which may be used; for instance, the unknown resistor might be shunted across R of Figure 1–10.

I–32. Portable bridges.

Inexpensive bridges for the measurement of capacitance, inductance, and resistance are also available, and while the accuracy is not as high as for those used in the usual physical measurements, the units are worth while since they are completely portable and measurements may be made rapidly.

I–33. The calculation of impedances.

We have considered the methods of calculation for the reactance of a capacitor and inductor in §1–7 and §1–8, but have not attempted to calculate the combined effect of these in any circuit. In the discussion of these A.C. units, resistance was not taken into consideration. All circuits, of course, have resistance, but in a few cases its relative value may be neglected. The total reactance of two inductors in series may be obtained by adding them as in the case of resistors. The total reactance of two condensers in series is obtained in a similar way. The total capacitance of two condensers in series is, however, equal to the reciprocal sum of the reciprocal capacities. The reactance of an inductor and capacitor in series may be obtained by adding the two reactances algebraically, remembering that capacitative reactance X_c is negative while inductive reactance X_L is positive.

The resultant of parallel reactances is obtained as in the case of resistances, that is, from the reciprocal of the reciprocal sum.

When combinations of resistance and reactance exist together, the effect on current cannot be calculated by simple algebraic additions. Reactance and resistance are combined vectorially because each affects the current differently. When resultants are calculated in this fashion, they are known as impedances. The methods used may be demonstrated from a consideration of circuit in Figure 1–11. Let us calculate the impedance of the above circuit if

$$X_{L_1} = 10^4$$
$$X_{L_2} = 10^4$$

Since the inductors are in parallel, the effective value of the inductive reactance is equal to 5×10^3. If

$$X_{C_1} = 1000,$$
$$X_{C_2} = 10,000,$$

the total capacitative reactance is equal to 11,000 ohms. This is negative, and therefore the sum of the reactances is equal to $-11,000 + 5,000$ or $-6,000$ ohms capacitative reactance remaining. Combining
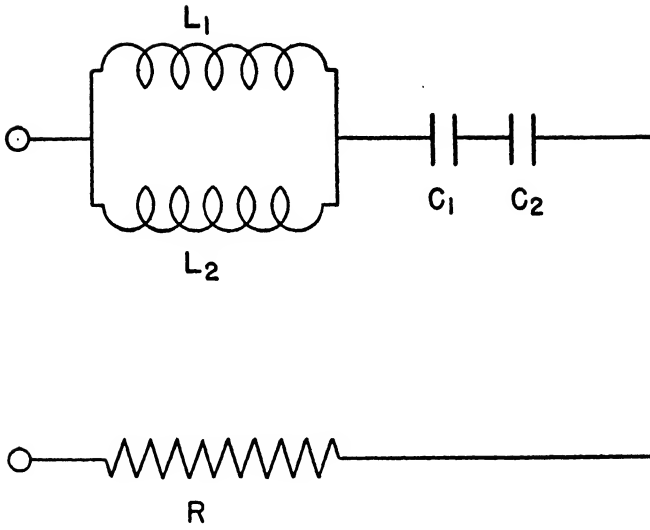
Fig. 1-11.   A Combination of Inductance, Capacitance, and
Resistance.
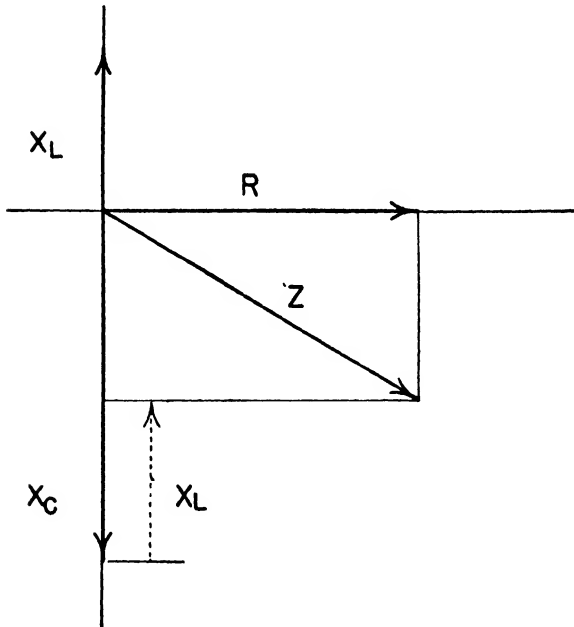
Fig. 1-12.   Vectoral Representation of Circuit Elements
of Figure 1-11.

this vectorially with 10,000 ohms of total resistance, we obtain the impedance

$$Z = \sqrt{(-6,000)^2 + (10,000)^2},$$

or

$$Z = \sqrt{1.36 \times 10^8} = 11,600 \text{ ohms}$$

The manner in which these calculations were made is shown in Figure 1-12.

1-34. Time constants of resistance-capacitance circuits.

A capacitor in combination with a resistor is of great importance in electronics. Let us consider the properties of this combination. If a condenser is connected across a battery, there will be a surge of current in which the initial current is limited only by the resistance of the condenser leads and by the current-delivering power of the battery (internal resistance). The current will decrease rapidly with time, however, since although at zero time the voltage across the condenser proper was zero, this voltage builds up rapidly and all current flow ceases after the condenser voltage is equal to the battery voltage. The charging rate may be decreased by adding resistance to the circuit. The product of RC is the time constant, and is equal numerically to the time in seconds required to charge the condenser to 63 per cent of its final value. If a condenser is discharged through a resistance, then RC expresses the time required for the condenser to lose 63 per cent of its charge, or the time at which only 37 per cent $\left(\dfrac{1}{e}\right)$ of the charge remains. This relation follows from the fact that the charge $Q = CE(1 - e^{-t/CR})$. If this equation is solved for RC the value turns out to be $.63\ Q_{max.}$ regardless of the value of E, except that the value of $Q_{max.}$ is a function of E. Applications of this principle will be shown in later chapters.

1-35. Phase angle of resistance-capacitance circuits.

If an A.C. voltage is impressed on a condenser, the maximum values of current and voltage will not occur at the same instant. The maximum value of voltage occurs one-fourth cycle or less after the maximum current. If a resistance is placed in the circuit, this time lag is reduced, provided one considers the voltage and current through the combination and not through the condenser alone. The relationship between this time lag and the values of reactance and resistance is

$$\tan \theta = \frac{X_c}{R},$$

where θ is the phase angle, that is, the angle through which the radius of Figure 1–4 has moved between the time of maximum value of current to the time for the maximum value of voltage. In a condenser the voltage lags behind the current. A condenser placed in a circuit tends to maintain voltage even if the current is decreasing. Inductors operate in the opposite fashion, that is, the value of maximum current may lag one-fourth cycle behind the maximum voltage, and this lag is again expressed by

$$\tan \theta = \frac{X_L}{R},$$

$$\cos \theta = \frac{R}{Z},$$

or

$$\sin \theta = \frac{X_L}{Z}.$$

An inductor, therefore, tends to keep current flowing when the voltage is decreasing. A combination of capacitative and inductive reactance is very useful in obtaining steady power supplies from A.C. mains, as will be demonstrated in Chapter IV.

1–36. Resonance.[6]

Since capacitative reactance is negative while inductive reactance is positive, it is apparent that at some frequency the values of X_L and X_c may be of equal magnitude and, since they are of opposite sign, the net value be zero. When this condition is secured the circuit is said to be at resonance. If an inductor and capacitor are connected in series, the current will be limited only by the resistance in the circuit at the point of resonance. The value of the voltage across each unit may be calculated by

$$E_L = X_L I,$$

and

$$E_c = X_c I.$$

The voltage is equal to the product of the impressed voltage and the ratio between the reactance and resistance. The ratio X_L/R at resonance is usually called the Q of the circuit.

If an inductor is in parallel with a capacitor, the voltage across the terminals at resonance will be a maximum. The current surges from the inductor to the capacitor, but the current to the two units in parallel is a minimum; that is, the impedance is a maximum.

[6] Terman, F. E., *op. cit.*, p. 51.

SUPPLEMENTARY LITERATURE

Everitt, W. L. (editor), "Fundamentals of Radio," Prentice-Hall, Inc., New York, 1942.

CHAPTER 2

Triodes

Introduction.

A triode consists of three tube elements: an electron source, a grid, and a plate.[1,2,3] The source is a hot filament, or a small metal sleeve coated with an electron-emitting material. The sleeve is indirectly heated by means of a helical wire imbedded in an insulating ceramic. As a rule, the tube elements are coaxially mounted in an evacuated envelope, with the source (cathode) in the center. The grid is usually in the form of a helix, surrounding the cathode. At some distance from this is the plate, usually in the form of a cylinder. The size and spacing of the grid wires and the relative spacing of all the elements determine the tube characteristics. Appropriate formulas have been derived and checked, from which design engineers can calculate tube specifications which will produce any desired values for these characteristics.

The envelope may be of glass or metal. It is highly evacuated, and residual traces of gas are removed by flashing a "getter" after the tube has been sealed off. The various electrodes are brought out through insulated leads to the appropriate terminals in the molded base. In some tubes, the grid connection is brought out at the top of the tube to a small metal cap. This arrangement may afford somewhat better insulation and a reduction in interelectrode capacitance.

2–1. Operation of a triode.[4]

A triode may be represented symbolically as in Figure 2–1. If the cathode K is brought to the appropriate temperature by passing a suitable current through the heater H, the cathode will emit electrons. These can be collected by applying a battery between the plate and cathode terminals, with the positive pole connected to the plate. An

[1] R.C.A. Tube Manual.
[2] Chaffe, E. L., "Theory of Thermionic Vacuum Tubes." New York: McGraw-Hill Book Co., 1933; ch. 5–7.
[3] Terman, F. E., "Radio Engineering." New York: McGraw-Hill Book Company, Inc., 1937; p. 122.
[4] Terman, F. E., *op. cit.*, p. 112.

electron current flows from the cathode through space to the plate, thence through the battery, returning to the cathode. In their flight from cathode to plate, the electrons must pass through the meshes of the grid. If the grid is made negative with respect to the cathode by means of another battery or any source of potential, the flow of electrons will be impeded and the current in the plate circuit will be diminished. If the grid is made positive with respect to the cathode, the plate current will be increased. This action may be understood by reference to Figure 2–2. The lines originating at the cathode may represent paths traveled
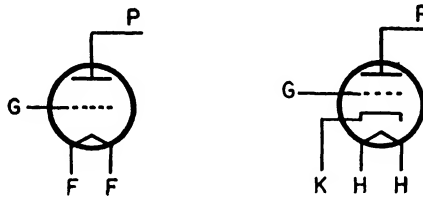
FIG. 2–1.   Triode Symbols
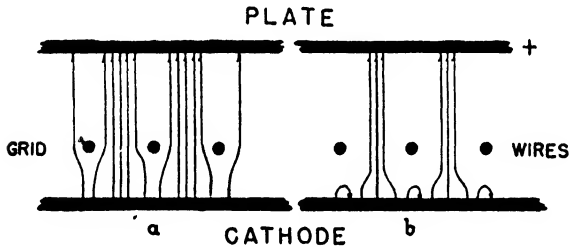
FIG. 2–2.   The Action of the Grid.

by electrons attracted towards the positive plate at various initial velocities. If the grid is only slightly negative with respect to the cathode, the electrons bend around the grid wires but most of them reach the plate, since the positive field of the plate is relatively stronger in this region than the corresponding negative field of the grid. This condition is shown in Figure 2–2a. If the grid is made more negative, as shown in Figure 2–2b, fewer electrons reach the plate, since a number of them do not possess sufficient energy to overcome the negative field of the grid. Electrons also repel each other in the tube; this effect is known as space charge. The plate current of any tube is thus determined by the positive field of the plate or other electrodes, the negative field of the grid, and the space charge of the emitted electrons. The field of the plate depends on the voltage applied to it, on its shape, and on its distance from the cathode. The field of the grid depends on the pitch and size of the grid coil and on its distance from the cathode. The space charge is influenced

by the plate and grid fields and by the temperature and nature of the cathode.[5]

2-2. Grid current.

An analysis of Figure 2-2 shows that there is no current flowing in the grid circuit, since the grid apparently serves only to make electrons deviate from their normal flow paths toward the plate. A closer analysis, however, reveals that in a practical tube there is some grid current. Some of the electrons emerge from the cathode space with considerable velocity and are not, therefore, deflected away from the grid wires. These electrons may be collected by the grid; the resulting current represents electron flow from the grid into the external circuit. The number of electrons so collected is quite small if the plate field is sufficiently strong in the vicinity of the grid. Positive ions within the tube envelope are definitely attracted to the grid, since this is the most negative electrode, and the current produced is equivalent to an electron current from the external circuit to the grid. These positive ions are produced by high-velocity electrons suffering collisions with the residual gas within the cathode-plate space. Some positive ions are also emitted directly by the cathode. The current produced by positive ions can be reduced by lowering the residual gas pressure and by selecting proper cathode material.

The grid may emit electrons if its temperature becomes sufficiently high; this emission also results in an electron flow from the external circuit into the grid. Illumination of the grid produces an emission of photoelectrons and causes a current in the same direction.[6] The illumination of the grid may come from the hot cathode or from external light. Electron emission from the grid may be minimized by the proper choice of grid material and by keeping the grid cool and unilluminated.

Another source of grid current is leakage over the external and internal grid-structure supports. Leakage over the interior surfaces is caused by a film of "getter" material which may have been sputtered over the supports during manufacture, while leakage on the outside may be caused by moisture or by inadequate insulation in the tube base and sockets.

Since electron collection by the grid results in a current which flows externally from the grid to the cathode, while the collection of positive ions and emission of electrons produce a current flow in the opposite direction, and since these currents vary individually with the grid voltage, a grid voltage may exist at which the net current is zero. This is actually the case, and the value of the grid voltage is almost equal to

[5] See Chaffe, E. L., *op. cit.*, p. 175, for an exact treatment.

[6] Hughes, A. L., and DuBridge, L. A., "Photoelectric Phenomena." New York, 1932, McGraw-Hill Book Co.

the potential which an unconnected grid assumes while plate current is flowing. This potential is the so-called free grid potential, and is determined in the following manner: The grid connection is opened at the socket or cap and the equilibrium value of plate current under these conditions is recorded. The grid is then reconnected, and a varying potential is imposed on the grid until the plate current again assumes the recorded value. This potential is the free grid or contact potential for the plate voltage used and for the particular cathode and grid temperatures existing at the time of measurement. At potentials more negative
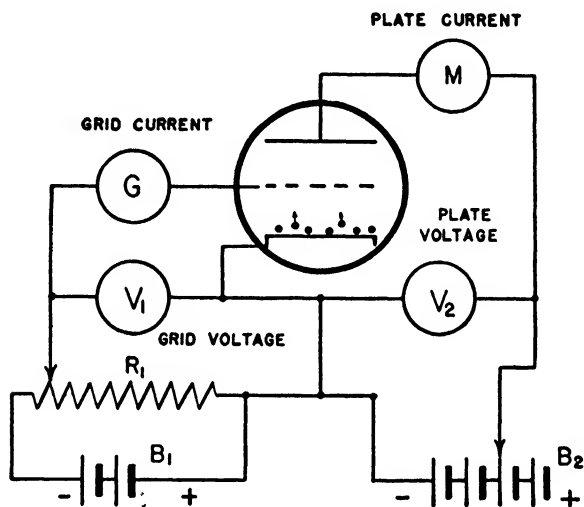
FIG. 2–3. A Circuit for the Measurement of Triode Characteristics.

than free grid, the grid current is quite small. On the other hand, it increases rapidly as the grid potential changes in the positive direction. Consequently, under appropriate conditions, grid control of the space current may be maintained almost purely electrostatically—that is, with no appreciable flow of current in the control-grid circuit. The ability of the triode to produce large changes in the anode or plate current with a very small expenditure of energy in the grid circuit constitutes its most important function. The magnitude of this "amplifying" property is best learned by actual measurement. From such measurements, we may then calculate the various tube constants.

2–3. Triode transfer characteristics.[7]

Several important characteristics of a triode may be obtained from the circuit shown in Figure 2–3. The plate potential e_p is measured by

[7] Hickman, R. W., and Hunt, F. V., *The Review of Scientific Instruments*, **6**, 268, 1935.

means of voltmeter V_2, and the plate current i_p with the milliammeter M. Various grid potentials e_g are determined by V_1 and changed by the potentiometer R_1. The grid voltage is measured negative with respect to the cathode, while the plate voltage is measured positive with respect to the cathode. The magnitude of the grid current is determined by the sensitive galvanometer G and is known as i_g. For 6.3-volt heater tubes, a 6-volt storage battery or a 6.3-volt transformer is used to heat the cathode, and its voltage must remain constant during the measurements. The relation between plate current and plate voltage is expressed in terms of Ohm's law, though this law is applicable only to the flow of current through a metallic or semimetallic conductor, where the resistance is independent of the applied voltage. The equivalent resistance of an electron tube may accordingly be compared with that of a conductor whose resistance is not independent of the applied voltage. Under these conditions, the voltages of both plate and grid of the electron tube, as well as the cathode temperature, must be specified whenever the resistance is evaluated. The actual plate resistance would be

$$\left(\frac{e_p}{i_p}\right)_{e_g},$$

but this has little significance in the use of electron tubes. Since changes in current corresponding to changes in the other variables are more important than the static values, the A.C. or dynamic resistances or conductances are usually measured and evaluated at various operating points. Thus, the equation

$$r_p = \left(\frac{\partial e_p}{\partial i_p}\right)_{e_g}$$

defines the dynamic plate resistance r_p for a small change of plate voltage resulting in a change of plate current ∂i_p at a fixed grid potential e_g. The reciprocals of the above plate-resistance formulas represent the corresponding conductances, expressed in reciprocal ohms as the resistances are expressed in ohms.

The effect of the grid voltage on the plate current is expressed in conductance units as

$$g_m = \left(\frac{\partial i_p}{\partial e_g}\right)_{e_p},$$

where g_m is the grid-plate transconductance and the other terms have the usual significance. The grid-cathode resistance is seldom evaluated as such, except in occasional instances, but instead the average grid current is given over the operating range. The value of this resistance may,

however, be calculated in a fashion similar to the calculation of the plate resistances.

Another constant, which is often used, expresses the ratio between the effects of the plate voltage and the grid voltage on the plate current. It is defined by

$$\mu = \frac{\left(\dfrac{\partial i_p}{\partial e_g}\right)_{e_p}}{\left(\dfrac{\partial i_p}{\partial e_p}\right)_{e_g}},$$

where μ is the amplification factor of the tube. It may be noted that the numerator is the grid-plate transconductance and the denominator is the reciprocal of the plate resistance. When common terms are cleared from the equation, the expression reduces to

$$\mu = -\left(\frac{\partial e_p}{\partial e_g}\right)_{i_p},$$

which, in words, means that μ expresses the ratio between (a) the change in plate voltage required to change the plate current by a certain amount, and (b) the grid voltage required to effect the same change. If g_m and r_p are substituted for their respective values, $\mu = g_m r_p$. Since μ is a ratio of two voltages, it has no dimensions. Note that ∂ has the meaning of small changes in the respective parameter.

EXPERIMENT 2–1

Purpose: To determine the characteristics of a triode.

Materials: Small triode tube, 76, 6C5, 6J5
Socket
6-v. storage battery
7.5-v. grid battery
4-45-v. B batteries
0-8 voltmeter
0-10 milliammeter
0-300 voltmeter
10^{-8}-amp. galvanometer
2,000-ohm potentiometer

Procedure. Connect the triode as shown in Figure 2–3. With the plate disconnected, reduce the grid voltage until the galvanometer indicates full scale. Record this grid voltage; then increase the plate voltage in steps of 22.5 volts and read and record the grid voltage e_g, the grid current i_g, the plate current i_p, and the plate voltage e_p. Make the grid more negative

by .5 volt, and repeat the above readings. If the plate current reaches values higher than 10 ma., record these values as >10 ma., and proceed to the next set of measurements. Repeat at .5-v. increments on the grid until this voltage is at least 7.5 v. Plot a family of curves, as shown in Figure 2–4. Label each curve with the proper value of the grid voltage. Deter-
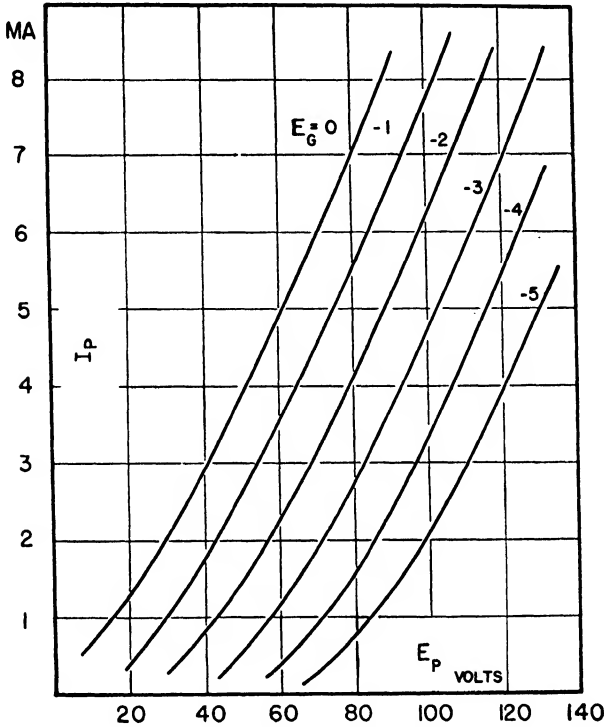
FIG. 2–4. i_p-e_p Curves for a Triode.

mine the value of r_p at several points on each curve by drawing a tangent to the curve at the desired point, and determining the slope

$$\frac{\Delta e_p}{\Delta i_p}$$

for this line. Tabulate these values and specify the grid and plate voltage at which the value r_p was calculated.

The data represented by Figure 2–4 may be plotted in another fashion. By extending vertical lines parallel to the y-axis at various values of the plate voltage, the point of intersection may be plotted, treating i_p as a function of e_g for constant plate voltage, as shown in Figure 2–5. Label each curve for the respective plate voltage at which it was drawn.

Draw tangents to the curve at various points and calculate the trans-conductance from the slope of these tangents. Remember that

$$g_m = \left(\frac{\partial i_p}{\partial e_g}\right)_{e_p}$$

and is usually expressed in micromhos, that is, reciprocal resistance times 10^6. In all calculations, remember that i_p is plotted as milliamperes and that amperes should be used in the calculations. Plot the
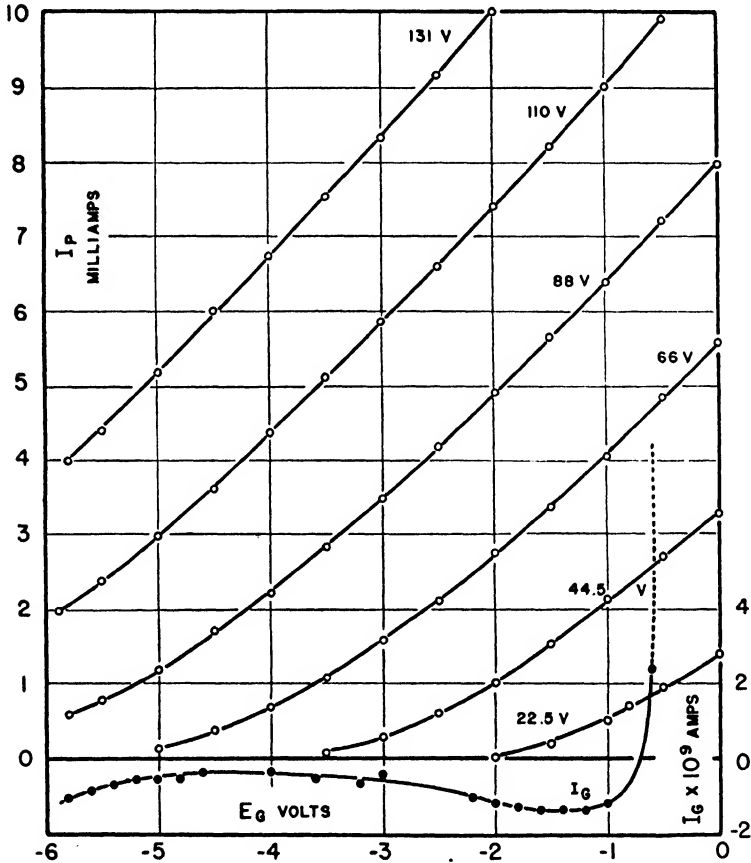
Fig. 2-5. i_p-e_g Curves for a Triode.

value of r_p, g_m, and μ as functions of negative grid voltage, as shown in Figure 2-6. Note that μ is almost a constant, but that g_m and r_p change rapidly at high grid voltages and in opposite directions. Note that this plot must be made for a definite plate voltage.

Plot grid current as a function of grid voltage for various plate voltages. Note that if the galvanometer sensitivity is too low, the lower part of the grid current curve of Figure 2-5 may not be measurable.

2–4. Characteristics of a triode with a plate load.

All of the characteristics evaluated in Experiment 2–1 were obtained with a negligible resistance in the plate circuit, since it was composed
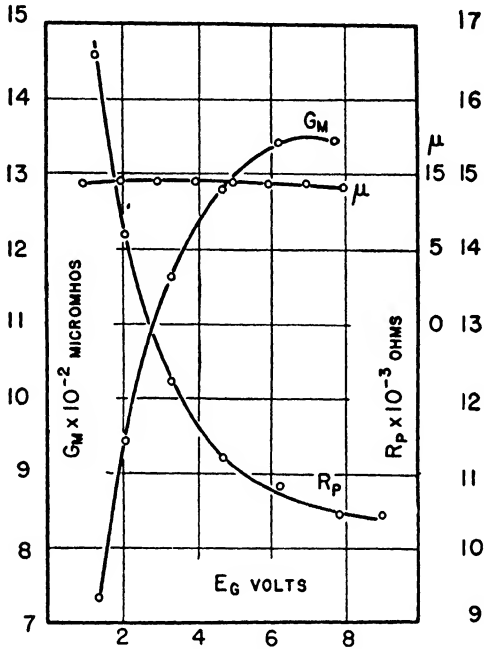
Fig. 2–6. g_m, μ, and r_p as a Function of e_g.
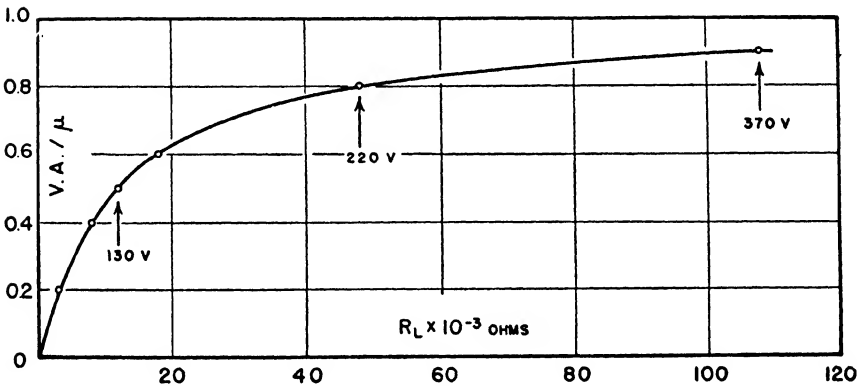
Fig. 2–7.   Voltage Amplification as a Function of R_L.

only of the plate milliammeter and the internal resistances of the batteries. Most practical circuits involve finite plate-load resistors, and it is necessary to see what effect these have on the values of the tube parameters. It is obvious, immediately, that the plate voltage will change

with plate current when a resistor is in the circuit, since part of the supply voltage will be represented by an RI drop in the plate-load resistor. If a series of i_p-e_g measurements are taken at various load values, the slopes of the resulting curves tend to drop as the plate load increases. The reason is that, theoretically, all the curves start from the same point at a grid voltage which represents zero plate current. At this point the plate voltage will be equal to the supply voltage at all values of the load resistor. At other points, however, the plate voltage is reduced in proportion to the value of the load resistor and the resultant plate current.

· The choice of appropriate load resistors depends upon the intended function of the triode circuit, that is, whether the load is to dissipate power or to convert changes in plate current into correspondingly large changes in voltage across its terminals. The power that can be obtained from a given grid voltage e_g can be shown to be equal to

$$P = \frac{(\mu e_g)^2 R_L}{2(r_p + R_L)^2},$$

where R_L is the value of the load resistance.[8] When this expression is differentiated with respect to R_L and solved for maximum, it will show a maximum when $R_L = r_p$, and the maximum power which can be obtained from an applied grid voltage e_g can be calculated from

$$P_{\text{max.}} = .25 \frac{\mu^2 e_g^2}{r_p}.$$

When voltage amplification is desired, that is, when the tube is required to amplify a small grid voltage e_g and pass it on to the next tube as a magnified potential, the load resistance is made as large as is compatible with other secondary effects. The relation between voltage amplification and load resistance is shown in the equation

$$\frac{E}{e} = \text{V.A.} = \frac{\mu R_L}{r_p + R_L},$$

where E is the output voltage, e the input voltage, and V.A. the voltage amplification achieved by the circuit. The expression shows that if μ is a constant, the amplification increases with R_L and is equal to $.5\mu$ when $R_L = r_p$, finally approaching μ at infinite values of R_L. In using this equation, it must be remembered, however, that as R_L increases the plate voltage decreases, owing to the RI drop in the load resistor, and that the value of r_p increases rapidly at low plate voltages. If R_L is large, the power-supply voltage must also be high in order to maintain a nominal plate voltage. This relation is shown in Figure 2–7, where the voltage amplification which can be realized from a given tube is

[8] Terman, F. E., *op. cit.*

plotted as a function of R_L under conditions where both μ and r_p are constant. The arrows indicate the corresponding power-supply voltages required to maintain a constant value of r_p. These voltages soon run to prohibitive figures, and indicate the nature of the limitation. If the load is an inductance with negligible resistance, this difficulty is avoided; but other difficulties are introduced, as shown in Chapter 10, and the inductive load will be useful only for A.C. signals.

EXPERIMENT 2–2

Purpose: To study the influence of plate resistors on the transfer characteristics of a triode.

Materials: Load resistors of 1,000, 2,000, 4,000, 8,000, 12,000, 16,000, 25,000, 50,000, and 100,000 ohms
Apparatus of Experiment 2–1

Procedure. Connect a 1,000-ohm load resistor in series with the meter of Figure 2–3, and with 180 to 270 v. as a plate supply (E_b) determine the plate current at various grid voltages. Repeat with other values of plate resistors, covering the range shown in the list of materials.

Plot the curves as shown in Figure 2–8 and note that the slope decreases with an increase of load resistance. Calculate the power developed in the plate load for a unit change in grid voltage at each plate load. This may be calculated from

$$P = R_L \Delta i_p{}^2,$$

where Δi_p represents the change in plate current produced by a unit change in e_g, all calculated at comparable plate voltages. Plot these calculated values as a function of load resistance and determine the maximum in the curve.

Calculate, graphically, the actual voltage amplification obtained for a unit change in grid voltage from the curves of Figure 2–8 by multiplying the slopes of the curves by R_L. Compare the values thus calculated with those obtained from the equation

$$\text{V.A.} = \frac{\mu R_L}{r_p + R_L}.$$

For each calculation, use the correct value of r_p as determined from the family of curves in Figure 2–4. Plot the voltage amplification so obtained as a function of load resistance. Note that a voltage amplifier must be operated at high negative grid voltage in order to retain a nominal voltage at the plate for high values of plate-load resistance, as is shown by the curves of Figure 2–8. Calculate the actual plate voltage at the points where the slope of the i_p-e_g curve decreases at high plate currents.

2–5. Load lines for triode power amplifiers.[9]

The maximum power developed for a definite grid signal, as shown in §2–4, is not the same as the maximum power that can be obtained for larger grid signals. The optimum power output is defined broadly as the greatest power output that can be obtained at a given supply voltage, subject to such limitations in operation as distortion, allowable grid and
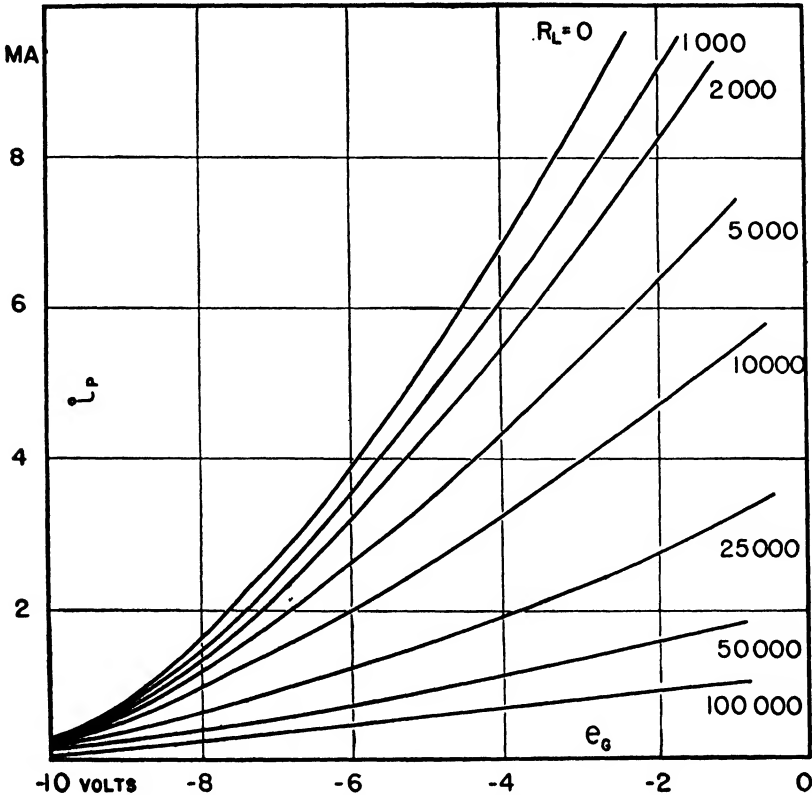
Fig. 2–8. i_p-e_g at Various Values of R_L.

plate currents, and so forth. The calculation of power output for a transformer (or other impedance load) and for A.C. signals may best be illustrated by an example. Figure 2–9 shows a family of i_p-e_p curves for a 2A3 triode and the graphical methods used in the calculation. The first step in the procedure consists in determining the static operating grid voltage at the available plate voltage. This grid voltage may be approximated graphically or may be calculated from

$$e_g = \frac{.68 \times E_b}{\mu},$$

[9] Reich H. J., "Theory and Application of Electron Tubes." New York: McGraw Hill Book Co., Inc., 1939; chap 4.

where e_g is the static grid voltage and E_b the plate voltage at the static operating point, that is, the supply voltage for a transformer or choke load. A line is now drawn as in Figure 2–9 through the static operating point to a point represented by zero grid volts and a plate current twice that flowing at the operating point. This line is extended in the lower direction to the intersection of a curve which represents a grid voltage of $2e_g$. Thus, the operating characteristics which have been determined by this line include the maximum plate current at zero grid volts at point
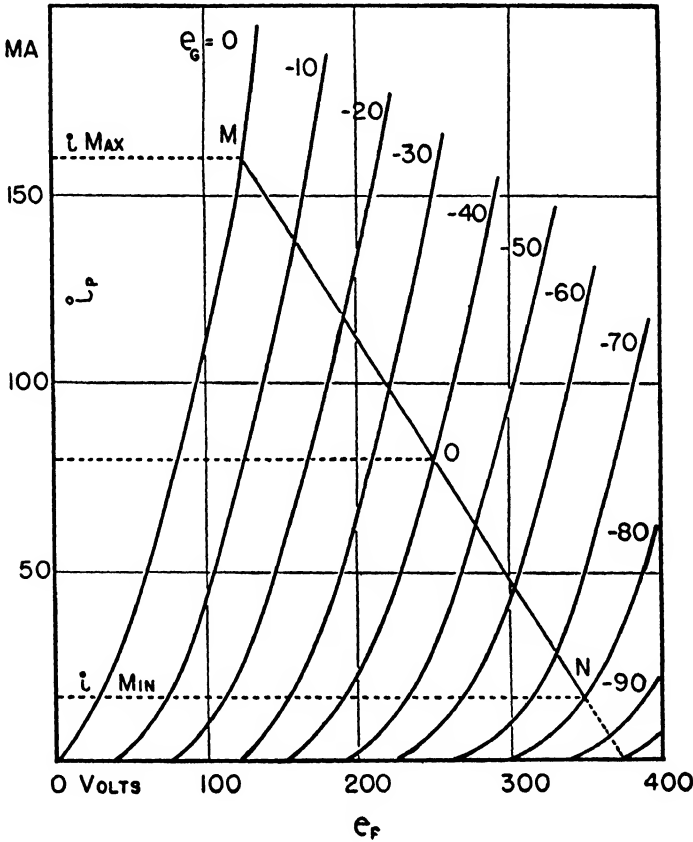
FIG. 2–9. A Load Line for a 2A3 Power Tube.

M, the $i_{min.}$ obtained at a grid voltage $2e_g$ at point N. The resistance represented by the line MON may be calculated from its slope, that is,

$$R_L = \frac{e_p \text{ at } N - e_p \text{ at } M}{i_{max.} - i_{min.}}$$

The actual value for the 2A3 tube as shown is given by

$$R_L = \frac{350 - 125}{.160 - .017} = 1580 \text{ ohms.}$$

The power output when the output is a sine wave is calculated from

$$P = \frac{(i_{max.} - i_{min.})}{2\sqrt{2}} \times \frac{(e_p \text{ at } N - e_p \text{ at } M)}{2\sqrt{2}}$$

and for this tube is equal to 4 watts.

The distortion due to nonlinear portions of the operating curves resulting in a second harmonic is given by

$$\text{Per cent of second harmonic} = \frac{\left(\dfrac{i_{max.} + i_{min.}}{2}\right) - i_0}{i_{max.} - i_{min.}} \times 100,$$

where i_0 is the plate current when no A.C. signal is impressed on the grid. Consequently, there will be no distortion if the average value of $i_{max.}$ and $i_{min.}$ is the same as the plate current at the operating point 0. For the 2A3 tube, as shown in Figure 2–10, the actual value is given by

$$\frac{\dfrac{.160 + .017}{2} - .080}{.143} \times 100 = 5.6\%$$

It will be noted that in order to develop this power output the grid voltage must be changed by the input grid signal from 0 to 80 volts, or a root mean square grid signal of $\dfrac{56.3}{2}$ volts for a sinusoidal voltage wave. The calculation of the power output for more complex tubes and for tubes in push-pull is beyond the scope of this book. Note, however, that if the grid current for a particular tube or application is too large at $e_g = 0$, this point must be changed to a more negative value. Note also that the load resistance calculated for this tube is 1580 ohms, while the plate resistance of the tube is only 800 ohms at comparable conditions.[10] In general, the load resistance for optimum power output for a triode is higher than the plate resistance.

2–6. The characteristics of a triode with a cathode resistor.

If a resistor R_c is placed in the cathode circuit as shown in Figure 2–10, the current flowing through this resistor causes an RI drop which forms part or all of the grid voltage. Since a voltage on the grid is μ times more effective than the same voltage on the plate, it becomes obvious that small resistors in the cathode circuit produce effects which, at a first approximation, are the same as those produced by large resistors in the plate circuit. The curves of Figure 2–8 showed that plate-load resistors decreased the slope of the i_p-e_g curve and tended to straighten out the curve. This effect was, however, achieved only at large values

[10] R.C.A. Tube Manual.

of plate-load resistance and with high-voltage power supplies at large values of plate swing (Δi_p). How these results may be achieved at low supply voltages with a cathode resistor is apparent from the graphical analysis illustrated in Figure 2–11.
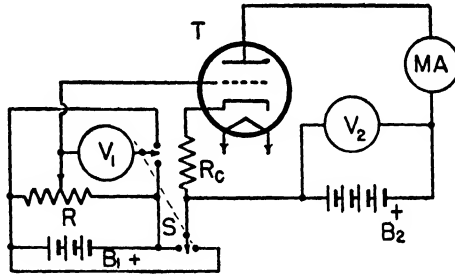
FIG. 2–10. A Simple Inverse-feedback Circuit.
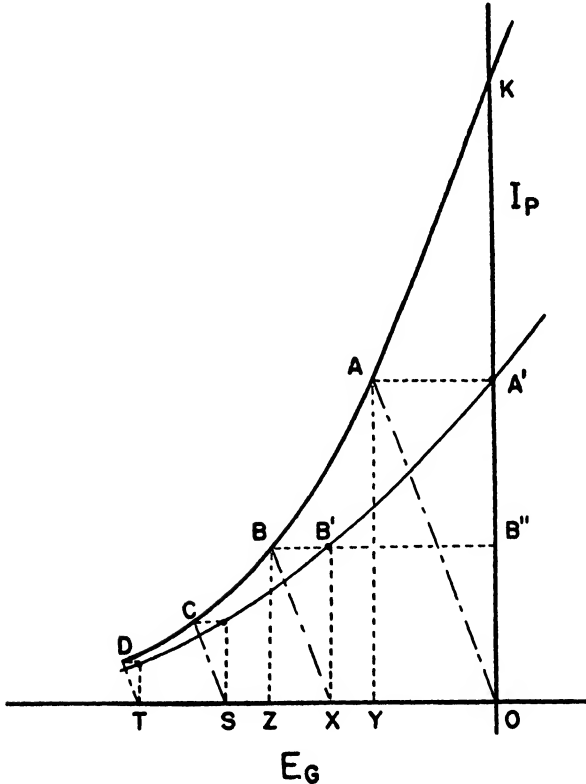
FIG. 2–11. Graphical Analysis of Inverse Feedback.

A line OA is drawn passing through the origin ($e_g = 0$) with a slope equal to the resistance of the cathode resistor and intersecting the i_p-e_g curve for the triode at point a. Current i_a passing through the resistor

will cause a voltage drop across the resistor equal to $R_c i_a$. If no other potential exists on the grid, then this must represent the total grid potential. A condition of equilibrium has been found, since the grid potential developed is such that the resulting plate current at a' in turn generates exactly the same grid voltage.

It will, therefore, be noticed that the effect of the cathode resistor has been to reduce the plate current from a value k to a value of a', assuming, of course, that plate currents are compared at equal values of signal grid voltages, in this case $e_g = 0$.

When an external signal voltage is impressed on the grid, for example, $e_g = \text{x}$, equilibrium conditions can be redetermined by passing line BX through X and parallel to OA. In this instance, current B″ passing through the cathode resistor develops a voltage drop equal to XZ. The total potential on the grid becomes the sum of the signal voltage OX plus the cathode drop XZ, that is, OZ. Equilibrium again exists, since a grid voltage equal to OZ will produce plate current B″, which in turn generates a total grid voltage equal to OZ.

Since plate current B″ is being produced with an external grid-voltage of X, point B of the i_p-e_g curve can be moved to point B′ in the same manner that A was moved to A′. If this procedure is repeated for other values of external grid voltages such as S and T, and a line drawn through the new points A′, B′, and so on, then the curve which is obtained will represent the i_p-e_g curve for the triode operated with a cathode resistor.

It should be noted that both the slope and the curvature of the i_p-e_g curve have been materially reduced by the use of a cathode resistor.

The graphical method just described can be used to determine the exact shape of the i_p-e_g curve. The general characteristics of this circuit are, however, obtained more readily in the following manner.

2–7. Feedback theory.

Assume that the triode has a value of transconductance of g_m. Let a small signal voltage de_s be impressed on the grid. The change in plate current di_p will cause a change in the voltage drop across the cathode resistor of $-R\,di_p$, where R is the resistance of the cathode resistor. Consequently, the actual change in grid voltage de_g is not de_s but $de_s - R\,di_p$. Since di_p must at all times be equal to $g_m de_g$, then in this particular case the following equation must hold:

$$di_p = g_m(de_s - R\,di_p).$$

Solving the equation for di_p, the following is obtained:

$$di_p = \frac{g_m de_s}{1 + g_m R},$$

or,

$$\frac{di_p}{de_s} = \frac{g_m}{1 + g_m R}.$$

But $\frac{di_p}{de_s}$ can be termed the effective transconductance of the circuit and given the symbol g' to differentiate it from

$$\left(\frac{\partial i_p}{\partial e_g}\right)_{e_p}$$

the transconductance of the triode itself. The results may, therefore, be written as follows:

$$g' = \frac{g_m}{1 + g_m R},$$

which is the fundamental equation for this type of circuit.

The first consequence of the use of a cathode resistor is to reduce the effective transconductance by a factor

$$\frac{1}{1 + g_m R}.$$

At first sight, this reduction would appear to represent a loss in sensitivity which might be obtained just as readily if desired by simply attenuating the input. However, the same degree of stability would not be obtained, because in the latter case the triode, while insensitive to signal voltages, would remain just as sensitive to fluctuations in circuit constants; that is, a change in grid bias would be just as effective as ever. With a cathode resistor, the effects of all circuit constants on the plate current are reduced by the factor

$$\frac{1}{1 + g_m R}.$$

The second consequence is a reduction in the curvature of the i_p-e_g curve. If the expression

$$g' = \frac{g_m}{1 + g_m R}$$

be differentiated with respect to g_m, the following expression is obtained:

$$dg' = \frac{dg_m}{(1 + g_m R)^2};$$

that is, the change in effective transconductance will only be

$$\frac{1}{(1 + g_m R)^2}$$

as great as the change in transconductance of the triode. The use of a cathode resistor consequently contributes to linearity of plate current with grid signal voltage.

A third consequence, which cannot always be realized, is complete independence from circuit constants. When $g_m R$ is very much larger than 1, the fundamental equation can be written

$$g' = \frac{g_m}{g_m R} = \frac{1}{R}.$$

Under these circumstances, the effective mutual conductance of the circuit becomes independent of the tube characteristics. Such a property is invaluable in the design of measuring instruments which are to possess a fixed sensitivity.

This last consequence cannot be realized with available triodes, because their transconductance in relation to the values of R which can be used is far too low to satisfy this requirement; that is, $g_m R$ large with respect to 1.

The theory as outlined is, however, not limited to a single triode, but can be extended directly to any amplifier system in which the output current is fed back to the grid circuit of the input tube. For this reason, all circuits of this type are referred to as feedback circuits. The only modification in point of view which must be made is that g_m becomes the transconductance of the system without feedback; that is,

$$\frac{di_p \text{ (output)}}{de_g \text{ (signal)}},$$

while g' becomes the effective transconductance for the over-all amplifier with feedback. Obviously, the value of g_m can be made as large as desired by the use of a sufficient number of stages, and the amplifier may thus be rendered independent of most circuit constants.

The importance of feedback theory to instrument design cannot be overemphasized. For this reason, it will be considered in greater detail in later chapters.

EXPERIMENT 2–3

Purpose: To determine the effect of cathode resistors on the transfer characteristics of a triode.

Materials: Cathode resistors of 100, 200, 500, 1,000 2,000, and 5,000 ohms

    Procedure. Wire the circuit shown in Figure 2–3 so that cathode resistors may be placed in the circuit as shown in Figure 2–10. Determine the relation between i_p and the grid potential (E_g) supplied by R at a fixed plate potential of approximately 180 volts and at 0 cathode-load resistance. Repeat the measurement at the various resistance values

shown above, and plot as shown in Figure 2–12. Note that, at large
values of the cathode resistor, the RI drop in this resistor is so large that
at zero voltage from the potentiometer R the plate current is still quite
small.

In order to obtain the entire i_p curve, reverse the polarity of the bat-
tery and voltmeter connected to the potentiometer R by means of S
and plot as shown in Figure 2–12. Note that the voltages represented by
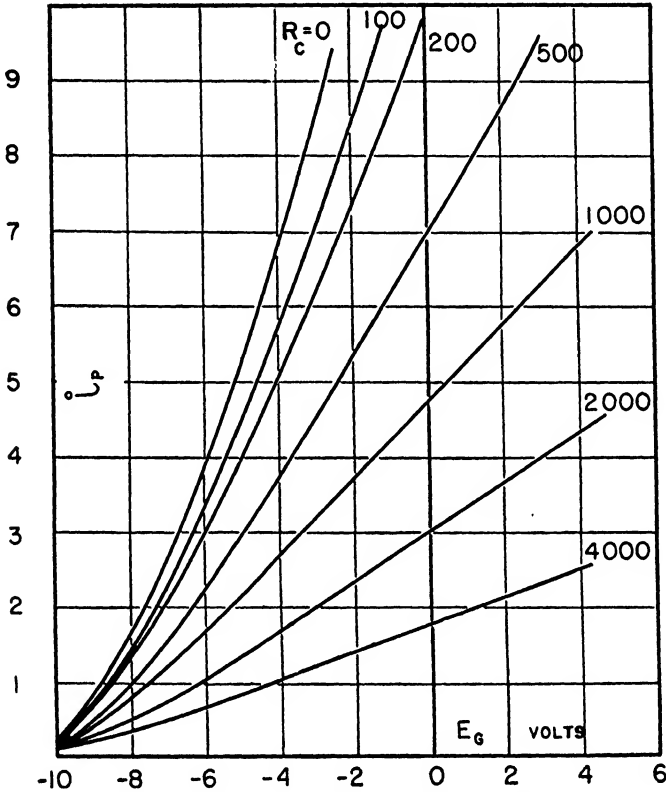
FIG. 2–12. i_p-E_g at Various Values of R_c.

the x axis of Figure 2–12 are not the actual grid voltages but the applied
potential from R of Figure 2–10. Calculate the actual grid voltage (e_g)
by subtracting the RI drop in the cathode resistor from the applied po-
tential. Remember that this RI drop is always negative with respect to
the grid.

Plot a few of these calculated grid voltages and note that the plate
currents superimpose on the curve for zero cathode resistance. Cal-
culate graphically the effective value of the transconductance at vari-
ous points on the family of curves shown in Figure 2–12. Compare these

effective values, which will hereafter be designated as g', with the calculated values from the equation

$$g' = \frac{g_m}{1 + g_m R}$$

Note that at large values of cathode resistance the reduction in plate potential contributes only a small reduction in the effective value of the transconductance, as in Experiment 2–2.
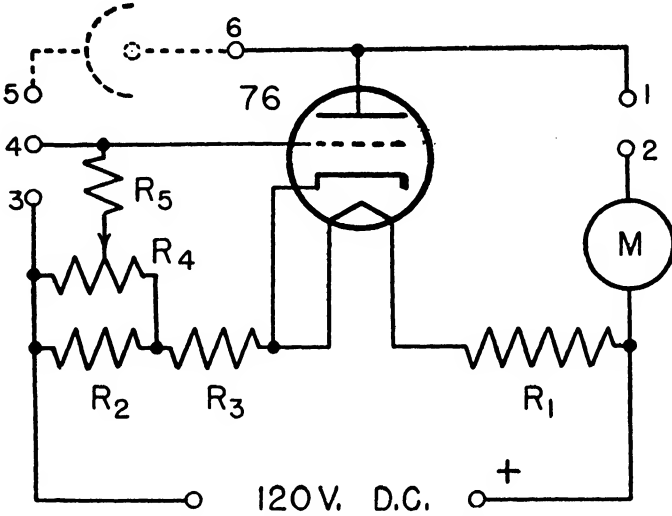
FIG. 2–13. A D.C. Line-operated Triode Circuit.
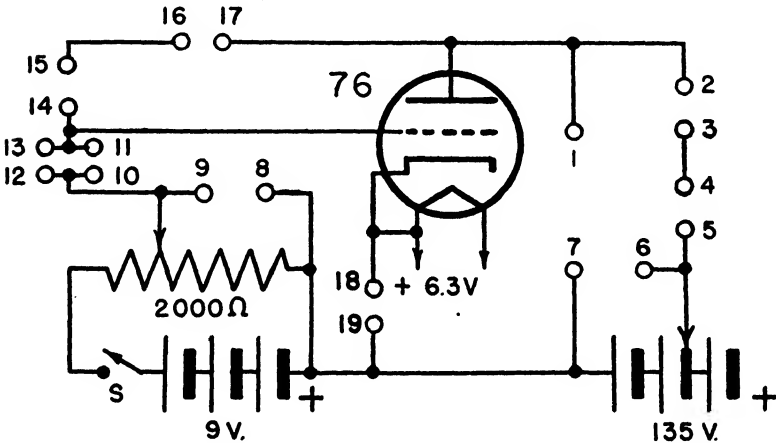
FIG. 2–14.

2–8. Line-operated triode for control purposes.

If a D.C. power line is available, the triode may be connected as shown in Figure 2–13. Operation on an A.C. line will be discussed in a

later chapter. The design of this circuit will be discussed in some detail
in order to illustrate the design principle which will be used throughout
the remaining sections.

The heater of the 76 tube is connected to the line in series with re-
sistors R_1, R_2, R_3, R_4, to limit the current to the normal rating. First, the
desired operating conditions must be decided upon. The heater requires
0.3 amp. at 6.3 v. The resistance of the heater at operating temperature
is, therefore,

$$R_h = \frac{6.3}{0.3} = 21 \text{ ohms.}$$

Let the plate voltage be 100 and the minimal grid bias be –1.5 v., with
provision for increasing this bias.

In order to limit the heating current to 0.3 amp., the total re-
sistance $(R_1 + R_2 + R_3 + R_h)$ must be $\frac{120}{0.3}$ = 400 ohms. The drop
across R_1 supplies the plate potential, and its value should be $R_1 = \frac{100}{0.3}$
= 333 ohms. The drop across R_3 supplies the normal grid bias of —1.5
v., and its value is $R_3 = \frac{1.5}{0.3}$ = 5 ohms. Since R_h is 21 ohms, this leaves
41 ohms for R_2, that is, 400 – (333 + 5 + 21), and the drop across R_2 is
12.3 v.

In addition, it is necessary to calculate the energy dissipation in each
resistor. This is given by RI^2 and has the values:

$$\text{In } R_1 = 333 \times .09 = 30.0 \text{ watts.}$$
$$\text{In } R_2 = 41 \times .09 = 3.69 \text{ watts.}$$
$$\text{In } R_3 = 5 \times .09 = 0.45 \text{ watts.}$$

Since the requirements are not too exacting, these specifications may
be modified slightly in order to utilize readily available parts.

For R_2 and R_3, 10-watt resistors of 40 and 5 ohms resistance may be
used. Both of these sizes are readily available, are close enough in value
to the required resistance, and have more than ample power rating. For
R_1, a 50-watt 400-ohm resistor with an adjustable tap is the best choice.
It can be set to provide the correct resistance by sliding the tap and
measuring the resistance with an ohmmeter.

To provide the variable bias, R_2 might be replaced by a 5-watt 40-
ohm potentiometer. However, the arrangement shown in Figure 2–13 is
somewhat more flexible and illustrates a generally useful principle. In
this case R_2 is shunted with a high resistance (10,000-ohm) potentiometer
R_4. The effect of this shunt on the resistance of R_2 is negligible (.3 per
cent) and it suffices for smooth dependable control of the grid bias volt-

age. The input resistor R_5 has a value of 20 megohms. Terminals 1, 2, 3, 4, and 5 are provided for convenience in connecting auxiliary devices to the circuit.

2–9. Triode-relay operation.[11]

The operation of the triode relay may be demonstrated by performing the following operations. Connect terminals 1 and 2 with a jumper or link. Move the slider on R_4 to the extreme right. The grid bias is now —1.5 v. Under these conditions, the meter M will indicate a plate current of about 8 ma. If terminals 3 and 4 are now connected, the plate current will be reduced nearly to zero. If a relay is introduced between 1 and 2, it may be operated by closing 3 and 4. Note that the current required in the input circuit is extremely small. It is $\frac{12.3}{2} \times 10^{-7} = 0.615$ μamp. at the most, and may be made considerably smaller. The current amplification is of the order of

$$\frac{8 \times 10^{-3}}{0.615 \times 10^{-6}} = 13,000.$$

The electron-tube relay will consequently control large amounts of power with the expenditure of a negligible amount of energy at the control contacts.[12–20] It is pre-eminently suited for thermostatic control, for closing contacts where extremely delicate or light contact is essential ("feeler gauges"), and so forth. If all material contact is out of the question, then optical control may be employed.

2–10. Photocell control of triode relay.

If a high-vacuum photocell is connected to terminals 5 and 6, as shown by the dotted lines in Fig. 2–13, the photocell will control the relay. The cathode or active surface is connected to terminal 5 and the anode or collector to terminal 6. To understand the operation better, a high-sensitivity galvanometer may be connected between terminals 4 and 5. The bias adjustment at R_4 is moved to the extreme left, thus reducing the plate current to a value near zero. If the photocell is now illuminated, the plate current will increase. The photocell current i flows through R_5

[11] George, E. E., *Electronics*, Aug. 1937; p. 19.
[12] Beaver and Beaver, *Ind. Eng. Chem. 15*, 359, 1923.
[13] Ferguson, Van Lente and Hitchens, *Ind. Eng. Chem. Anal. Ed., 4*, 218, 1932.
[14] Hawes, R. C., *Ind. Eng. Chem. 11*, 222, 1939.
[15] Heisig and Gernes, *Ind. Eng. Chem. 6*, 155, 1934.
[16] Huntress, E. H., and Hershberg, E. B., *Ind. Eng. Chem. 5*, 144, 1933.
[17] Parks, *Ind. Eng. Chem. 5*, 356, 1933.
[18] Serfass, E. J., *Ind. Eng. Chem. 13*, 262, 1941.
[19] Waddel, H. M., and Salman, W., *Ind. Eng. Chem. 12*, 225, 1941.
[20] Yee and Davis, *Ind. Eng. Chem. 8*, 477, 1933.

and the drop in potential across the latter is impressed on the grid of the triode. Hence, a photocurrent of 10^{-7} amp. will produce an input potential of 2 v. This will change the plate current by several milliamperes. Several values of the photocurrent may be read directly on the sensitive galvanometer, and their amplified value on the plate meter. The illumination on the cell may be changed in any convenient manner. The current amplification may be computed directly from the two values of current. By suitable adjustment of the relay, tube bias, and level of illumination, the optical control of any circuit may now be demonstrated. This simple arrangement may be used for counting objects, for controlling the illumination of a room, and in countless other applications where a beam of light may be modified or eclipsed.

2–11. Time delay in the triode relay.

In the above cases, the action of the tube is practically instantaneous. In many instances, it is desirable to introduce a definite delay in response. This delay may be brought about by shunting R_5 with a large condenser. If we use a 5-μf. condenser, the action is as follows: When the photocell is dark, the plate current will be nearly zero. If the cell is suddenly illuminated, the photocurrent flowing through R_5 will start to charge the condenser. During this period no change in plate current will occur. As the condenser charges to a higher potential, the plate current will rise and eventually reach the maximum value. The delay action in this case will be of the order of 5 to 10 seconds. At some time within this period, the relay will close (depending upon its adjustment). If the light is suddenly extinguished, the condenser will slowly discharge through R_5 and, after some time, the relay will open. Many variations of this general principle exist; some of them will be studied in detail later.

2–12. A universal triode unit.

Many measurements, both in the nature of the determination of tube characteristics and practical measurement, may be performed with a triode. In the authors' laboratory this multiplicity of functions is provided by the universal triode unit shown in Figure 2–14. Nineteen banana jacks are provided, so that the circuit may be connected in many ways and in such a manner that the actual circuit is always visible to the student, since the instrument panel contains a reproduction of the circuit shown in Figure 2–14. Thus, if the unit is to be used to determine tube characteristics, as in Experiment 2–1, the following adjustments are made: 14–15, 16–17, 1–7, 10–11 are left open, while jumpers are connected from 2–3 and from 18–19; e_p is measured between 6 and 7, i_p between 4 and 5, e_g between 8 and 9, and i_g between 12 and 13. The

6.3-v. heater battery or transformer is left permanently connected. The resulting circuit is that shown in Figure 2–3.

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PROBLEMS

1. Design a line-operated circuit which will detect a brief, transient flash of light and maintain a relay in the closed condition until it is manually reset. (Hint: The relay closes a circuit to a small lamp, which illuminates the detecting photocell, thus providing optical lock-in.)

2. Design a battery-operated circuit which will provide full-scale deflection on a plate milliammeter 0–1 ma. for an input potential of 1 v. The requirements are: small grid current, linear response, and a simple method for checking the zero setting.

3. Design a line-operated photocell relay which is to be illuminated by a constant light source. It is desired that any interruption of the light beam shall be recorded, but only if such interruption is of at least 2 seconds duration.

4. Design a simple triode circuit using inverse feedback, and calculate the effective values of g' for various cathode resistors.

5. Calculate the deviation from linearity for the circuit of Problem 4 at various plate currents.

6. Design a triode circuit with a 6J5 tube in which a 6-v. storage battery supplies heater current, a variable grid potential, and a bucking potential for a sensitive meter in the plate-cathode circuit.

7. Design a simple triode relay circuit for counting objects passing over a conveyor belt system.

8. Design a triode relay circuit for the control of an electric stop clock to determine small time intervals. (Note: These clocks are available with accuracies of the order of .005 second or better.)

9. Design a bridge circuit which could be used to measure the amplification factor of a tube by applying 1,000-cycle alternating current to the bridge terminals.

10. Show how g_m and r_p may be measured with an A.C. bridge, as in Problem 9.

CHAPTER 3
Characteristics of Photoelectric Cells

Introduction.

Photoelectric cells are selective detectors of radiant energy. Their range extends from the extreme ultraviolet to the near infrared; the particular range and the sensitivity for each spectral region depends upon the nature of the cell, its envelope (glass or quartz), and the chemical and physical factors involved in its construction. The relative importance of these factors is sufficiently well understood to permit the manufacture of photocells which respond to the desired spectral region[1] with a fairly reproducible degree of sensitivity. Photocells are among the most versatile and useful of all electron tubes and for that reason their principal electrical characteristics are to be studied in order to appreciate their utilization in other electronic circuits.

Two general classes of photocells will be studied: the high-vacuum emissive type (phototubes), and the barrier-layer or self-generative type.

3–1. Photoemissive cells.

The first type, the photoemissive cell, consists of a transparent, highly evacuated envelope containing two electrodes. One of these electrodes, the cathode, is in the form of a plate or hemicylinder which is made light-sensitive by condensing a film of alkali metal (usually caesium) on its surface. Appropriate chemical and physical treatment of this surface makes it very sensitive to light; that is, upon illumination photoelectrons are ejected from the surface. The second electrode, called the anode, serves to collect the photoelectrons. It is usually arranged in the form of a small plate or wire near the cathode, and so disposed that it offers the minimum obstruction to the light. To obtain maximum efficiency from a photoemissive cell, a potential must be maintained between the electrodes from some external source. The photoelectric current which flows under such conditions is quite small (of the order of microamperes or less), and very sensitive instruments or amplifier methods must be employed to measure this current or to utilize it for control purposes. Figure 3–1 shows how the voltage drop caused by the photocurrent is measured with an electron tube.

[1] Glover, A. M., *Proc. I.R.E.* *29*, 413, 1941.

3–2. Barrier-layer cells.

The barrier-layer or self-generating type, of which the selenium class (for example, the Weston photronic cell) is typical, consists of an iron disk upon which is placed a thin layer of selenium. The selenium layer in turn is covered with an extremely thin (transparent) layer of metal which serves as the collector. It may consist of lead, silver, or platinum. In operation, the composite disk is illuminated through the transparent collector. A galvanometer or microammeter is connected to the collector and the iron base plate. Under these conditions a spontaneous current flows in the external circuit as long as the cell is illuminated. No aux-
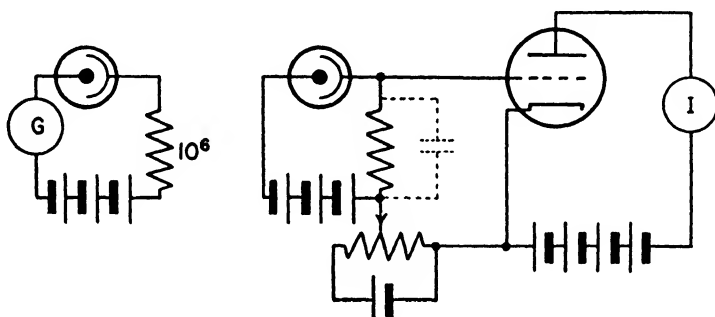
Fig. 3–1.   Phototube Measuring Circuits.

iliary source of potential is required. According to the theory of Lange, the cell generates an electromotive force owing to the difference in electron density between the semiconductor (selenium) and the boundary layer[2]; such differences in electron density are very nearly proportional to the light intensity.

The two classes of cells are entirely different in principle—especially so in their operational characteristics, although at first glance they both seem to perform the same function, that is, converting light into an electric current. They are by no means interchangeable, and the study of their characteristics will reveal their individual limitations.[3]

The principal electrical characteristics of photocells can be studied with little difficulty, but to secure very precise data, elaborate optical equipment is necessary. Since we shall be interested primarily in the electrical characteristics, it must be kept in mind that the simple optical arrangements which are suggested are the principal factors which limit the accuracy of the results.

[2] Lange, B., "Photoelements and their Application," New York: Reinhold Publishing Co., 1938.
[3] Müller, R. H., *Ind. Eng. Chem., Anal. Ed.*, 11, 1, 1939.

3–3. The construction of a simple illumination unit.

An illumination unit which may be used in most of the experiments consists of a large wooden box, in the center of which is mounted a long square metal rail. The lamp is mounted on a small carriage which slides along the rail. The carriage should slide easily but with a minimum of side-play. A simple system of pulleys, over which a tight loop of fishing line is stretched, moves the carriage along the bar. The shaft of one pulley is brought through the front of the box and terminates in a knob. The lamp is a 6-v. concentrated-filament type with a spherical bulb. (Automobile lamps with lens contours blown in the bulb are unsatisfactory.)

Leads are soldered directly to the bulb and are so arranged that they will trail the lamp carriage without obstructing the beam. Sockets for either type of photocell are mounted at one end of the box. The exact position of the lamp carriage can be determined by means of a pointer which moves over a meter stick mounted on the front of the box. A narrow slot in the case permits free motion of the pointer without admitting a significant amount of light. The entire interior of the box is painted dead black to minimize reflection. A still better method is to have the boards milled with " saw-tooth " slots pointing toward the light source. This furnishes a large number of optical traps and eliminates reflections almost completely. Adequate ventilation is necessary, and is best provided by holes in the base of the box and re-entrant louvres at the top. Such accessories as banana-plug connectors, voltage dividers, and so forth, can be mounted on the case.

The lamp must be operated from well-charged storage batteries or from a constant-voltage transformer. Direct operation from the mains, either with D.C. and a series resistor, or with A.C. and an ordinary step-down transformer, is unsatisfactory. A good voltage regulator, the operation of which is independent of the load, is less troublesome and will well repay the larger initial cost. The illumination at a certain distance from the photocell may be varied by selecting various-sized lamps or by connecting a fixed resistance in series with a given lamp.

With careful attention to these details, this piece of apparatus will enable the student to vary the light intensity uniformly, and the inverse-square law will apply over most of the useful range. It may be expected to fail for very small distances, since the source is not a true point source, but is of finite size.

3–4. A measuring circuit for a high-vacuum photocell.

At high levels of illumination, a galvanometer may be used to measure the current from a high-vacuum photocell; but since measuring may be done more conveniently with an electron tube connected as shown in

§ 2–6, both methods will be outlined. The circuit shown in Figure 3–2 may be used for this purpose. The photocurrent flows through resistor R_1, thus increasing the grid voltage, and the resultant increase in plate current is an index of the photocurrent. Since the negative grid voltage is obtained from the cathode resistor R_2, the output current will be almost linear with input voltage. The errors caused by the residual
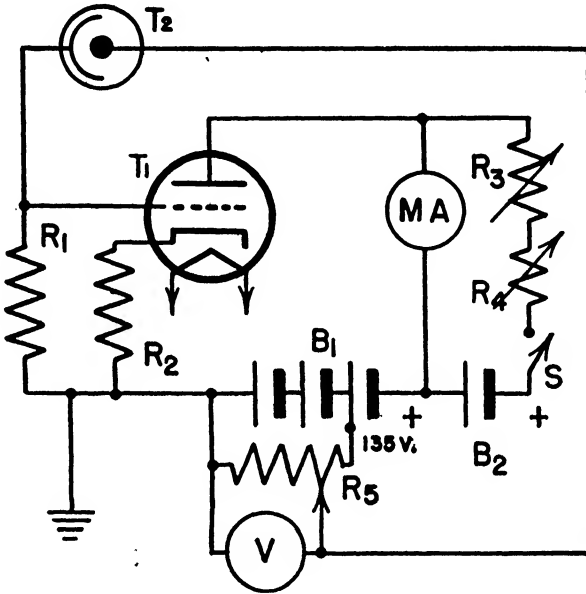
Fig. 3–2. Circuit for the Determination of Phototube Characteristics. R_1 = 20 megohms; R_2 = 1,000 ohms; R_3 = 1,000-ohm volume control; R_4 = 100-ohm volume control; R_5 = 10,000-ohm volume control.

curvature may be corrected by a previous calibration. The initial plate current with the photocell dark may be balanced out with R_3 and R_4. The sensitivity of the entire unit may be regulated by changing R_1.

EXPERIMENT 3–1

Purpose: To determine the saturation characteristics of a high-vacuum photocell.

Materials: Illumination unit of § 3–3

Photocell, such as R.C.A. types 917, 919, 922, 925 or 929, or equivalent

10^{-8} amp. wall galvanometer or 6J5 tube
Sockets
10,000-ohm volume control, 1,000-ohm volume control, and
    100-ohm volume control
20-megohm resistor, 1,000-ohm resistor
0–1.0 milliammeter
6-v. storage battery
4 45-v. B batteries
1.5-v. dry cell

Procedure. Connect the various units as outlined in § 3–3 and Figure 3–2, and make the following preliminary adjustments.
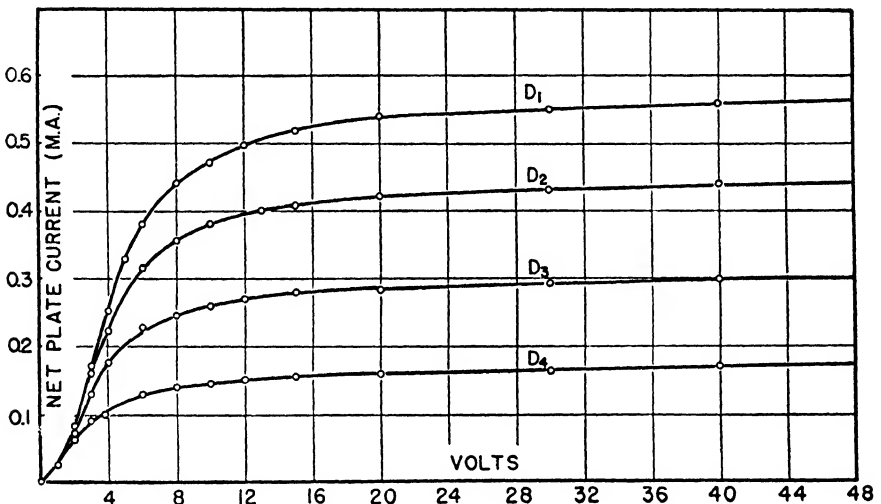
FIG. 3–3. i_p-e_p for a Phototube at Several Levels of Illumination.

Connect the 6-v. battery to the heater of the 6J5 tube, and after the meter begins to deflect connect B_2 with switch S and adjust R_3 and R_4 for zero meter reading with the photocell dark. Now, connect a potentiometer across the terminals of R_1 and determine meter readings as a function of input volts. Plot a curve from this data for later reference, and note that about 2 v. are required to produce full-scale deflection on the meter. Disconnect the potentiometer and illuminate the photocell. Set R_5 to about 50 v. and move the lamp carriage through its full range, starting from the maximum distance. If the output meter indicates full scale before the lamp is closer than 10 cm. from the phototube, the illuminating unit is properly adjusted. If the lamp is too weak or too bright, adjust it as indicated in § 3–3 until the output meter varies from

full scale to almost zero as the lamp carriage is moved from a position about 10 cm. from the photocell to its maximum distance.

Set the lamp at a distance such that the output meter reads about 100 μamps., then reduce the photocell voltage to zero, and with the photocell dark readjust R_4 until the meter reads zero. Illuminate the photocell and read the meter. Take additional readings of the output meter at photocell voltages increasing in 2-v. steps from 0 to 20 v. and in 5-v. steps from 20 to 50 v. Increase the illumination by decreasing the lamp-photocell distance until the meter reads 200 μamps. at 50 v.; then repeat the photocell measurement as before. Make the same measurements for lamp distances which produce 300, 400, 500, μamps., and so upward, in the output meter, and plot as shown in Figure 3–3. Subtract the voltage drop in R_1 from the reading of the voltmeter V across R_5 before plotting the values on the graph. This voltage is obtained from the calibration chart made at the beginning of the experiment. Calculate the actual photocurrent by noting the actual voltage across R_1 (refer to the calibration chart), and compute the actual value of output current by dividing this voltage by the value of R_1. Note that the photocurrent increases only slightly beyond a certain voltage. This is called the saturation voltage, and its value is a function of the light intensity.

If a galvanometer and shunts are used instead of the vacuum-tube amplifier, the galvanometer is connected in series with the photocell and the voltage from the potentiometer R_5. Use a shunt in conjunction with the galvanometer so that its sensitivity may be reduced when required. The procedure is the same in other respects, the photocurrent being given directly by the galvanometer.

Since considerable time will have elapsed between the beginning of the experiment and the last measurement, the intensity of the light source may have decreased appreciably, so that a plot of photocurrent as a function of light intensity may be made more advantageously by repeating part of the experiment. Select a photocell voltage from Figure 3–3 which is on the flat portion of the curve, even at the highest photocurrent. Set R_5 to this voltage and read the output meter as a function of lamp distances throughout the entire range.

For a point source of light, the intensity of illumniation at any point in space is inversely proportional to the square of the distance between the point and the source, as given by the equation $i = Kd^{-2}$, where K is a constant which depends on the intrinsic brightness of the source. Taking logarithms of both sides of the equation yields

$$\log i = \log K - 2 \log d.$$

Plot, therefore, the logarithm of i against the corresponding value of log d as shown in Figure 3–4. If the cell exhibits linear response, a straight

line with a slope of –2 will be obtained. This graph is obtained only when the illumination unit approximates an ideal inverse-square-law apparatus. Determine the slope of the line graphically from $\dfrac{\Delta \log i}{\Delta \log d}$. Note that a precise value of i must be obtained by correcting for variations in linear response of the electron tube from the chart made at the beginning of the experiment.

3–5. Color response of photocells.

Photocells are selective detectors of radiant energy only in the sense that their response varies with wave length. At long wave lengths, the
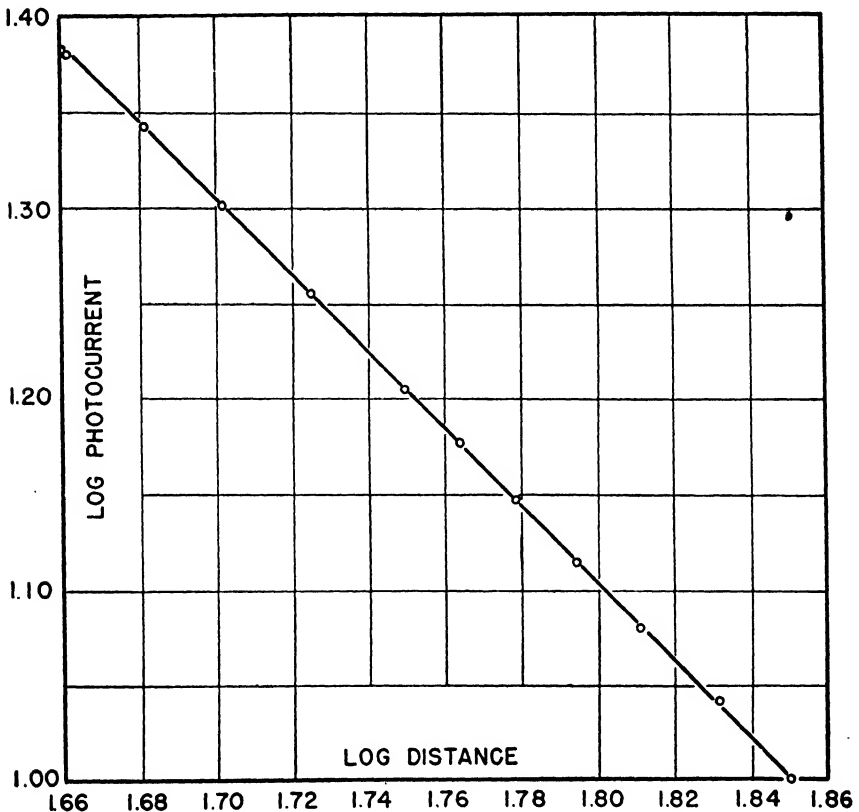
FIG. 3–4. Logarithmic Plot of i_r-D for a Phototube.

energy of the light quanta may be too low to expel an electron from the metal. The response of all cells, therefore, falls at long wave length, and the wave length at which the response is substantially zero is referred to as the long-wave limit of response. While the lack of long-wave response is essentially due to the work function of the photocathode ma-

terial employed, the relative response at shorter wave lengths is influenced by a large number of factors[4] residing in the history or treatment of the cathode. The envelope naturally contributes to the net response, and must be considered in evaluating the performance of a given photocathode.

The response curve of an assembled photocell is of importance to the user in that the intensity at some wave lengths will be unduly emphasized in the measurements at the expense of that at other wave lengths. In measurements of this type, the accompanying light source must also be considered in evaluating the net-response curve.

It is obvious, therefore, that if a photocell is to be used to measure light values comparable to those seen by the human eye, the color response of the photocell must first be adjusted with filters until it matches that of the eye. Similarly, the color-response curves of the photocell and photographic plate should be matched in exposure meters if a high order of accuracy is desirable.

3–6. Apparatus for the determination of the color response of a photocell.

To obtain the response of a photocell to various regions of the spectrum, it is necessary to resolve the radiation of a source into narrow regions of the spectrum by means of a monochromator. The absolute energy of each region is usually measured with a sensitive thermopile (a nonselective radiometric device) connected to a sensitive galvanometer. The response of the photocell is then measured for the same region. This is done over the entire spectrum range, and the response values are reduced to an equal-energy basis, that is, divided by the corresponding thermopile measurements. An exact comparison of this sort involves a rather costly array of instruments. It will be no less instructive to use the much simpler arrangement shown in Figure 3–5, correcting for the lamp response with curves given in a later section.

The wave-length drum of the monochromator is to be checked with spectral lines of known wave length. A small mercury arc will suffice for this test, using the yellow lines 5790 and 5770, the green line 5461, the blue lines at 4359, and the violet lines at 4047. After the necessary adjustments have been made to correct for any wave-length error, the image of the concentrated-filament lamp is focused on the entrance slit of the monochromator. The photocell is mounted in a lightproof housing located at the exit slit, the photocell being set at a distance from the slit such that the emergent light is distributed fairly uniformly over the entire photocell cathode. Particular attention must be given to the photo-

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[4] Hughes, A. L., and Du Bridge, L. A., "Photoelectric Phenomena." New York: McGraw-Hill Book Co., Inc., 1932.

cell anode to make sure that the cell is turned in such a position that the anode wire does not obstruct a very large fraction of the emergent beam. Otherwise, minute displacements of the cell (vibration, and other causes) will cause marked changes in the photocurrent. A blue-sensitive cell (Na, K, or R.C.A. S-4 cathode)[5] is recommended for this experiment. The photocurrents are measured with the vacuum-tube voltmeter shown in Figure 9–8, using a load resistor of 100 megohms. The entire optical train must be screened from any stray light, and to this end, any mechanical defects in the arrangement may be eliminated by covering them with several folds of black cloth. The circuit should be grounded as indicated in the diagram, and the components shielded as indicated by the dotted lines.

EXPERIMENT 3–2

Purpose: To determine the color response of a high-vacuum photocell.

Materials: Apparatus adjusted as in § 3–6
Voltmeter of Figure 9–8
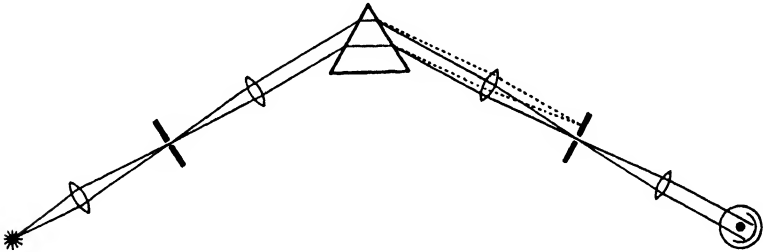
FIG. 3–5.   Optics for Determination of Color Response of a Photoelectric Cell.

Procedure. Measure the voltage and calculate photoelectric current for various settings of the wave-length drum at intervals of 20 to 30 angstrom units. These photocurrents can be reduced to an equal-energy basis by means of the factors given in Table 3–1 (page 83). These have been computed by assuming that the temperature of the source is 2870° K., and represent the energy distribution of a gray-body emitter at this temperature. This procedure is obviously not as precise as a direct measurement of the energy with a thermopile, but the resultant color-response curve will be in error by an amount no greater than the variation among individual cells of the same type. Figure 3–6 indicates the comparison of measurements of this kind with the average color curve exhibited by this class of cell. It is to be emphasized that each cell is highly individual with respect to its color response and total sensitivity. Furthermore, the

5 Glover, A. M., and James, R. B., *Electronics*, Aug. 1940; p. 26.

exact shape of the color-response curve is rarely of any importance. If for any reason it becomes necessary to know this, or to know the exact
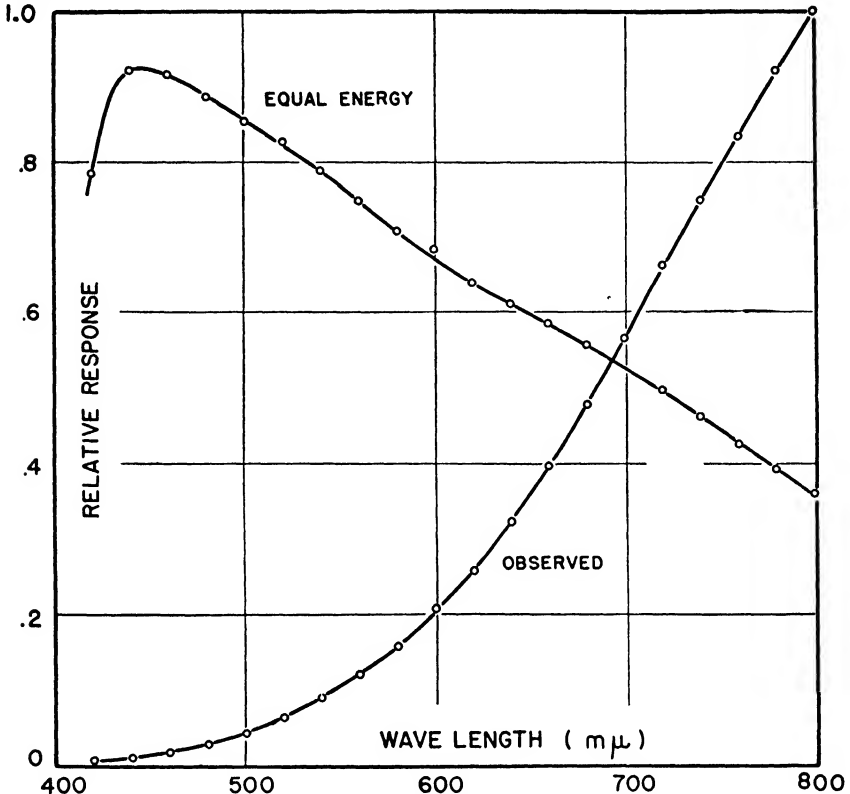
FIG. 3–6.   Color Response of a Blue-sensitive Cell.

response for several definite wave lengths, then the thermopile comparison method must be used.

3–7. Characteristics of barrier-layer cells.

The characteristics of barrier-layer cells differ from those of a high-vacuum photocell, as was indicated in §§ 3–1, 3–2. This cell generates its own driving voltage, which is quite small but which serves to produce considerable current, since the resistance of the cell is small. The resistance of the cell is, however, appreciable, and the resistance of the measuring unit is, therefore, important. The following experiments, carried out with the same illumination unit as used before, will serve to illustrate some of these properties.

EXPERIMENT 3–3

Purpose: To determine the relationships between light intensity and current for a barrier-layer cell.

Materials: Illumination unit of § 3–3
           Barrier-layer cell, such as a Weston photronic cell
           Low-resistance microammeter, such as Weston model No. 322
           2 resistance boxes

Procedure. Connect the apparatus as shown in Figure 3–7, and with R_1 set to zero and R_2 to the critical damping resistance of the meter, vary the lamp distance to determine the proper measuring range. If the meter does not register full scale before the lamp approaches to within 10 cm. of the cell, increase the intensity of the lamp; similarly, if the meter does not read near zero when the lamp is at its maximum distance, decrease the intensity of the light source. Calculate the equivalent resistance of the load circuit of the cell by applying Ohm's law to the parallel network composed of R_2 and the meter. Note this for future reference.

Set the decade resistance box R_1 to zero, and move the light source to a position which yields a photocurrent equal to full-scale deflection. Note that an appreciable period of time must elapse before a steady deflection sets in. The cell will tend to overshoot the equilibrium value. The cell is delivering the indicated current through a load equal to the net meter resistance. Now, introduce additional resistance from the decade box until the photocurrent is reduced to a small fraction of its original value, say 20 per cent. Note the value of resistance at this point, and find other values which will reduce the current to definite fractions of the original value (40, 60, 80 per cent). Five or six settings will suffice, and to simplify the subsequent plots it will be convenient to add resistance in such amount that the sum of this value and the net meter resistance will yield an even total value of the resistance. The corresponding currents are to be noted for each value of the total external resistance (decade box and net meter resistance). Repeat this procedure for various settings of lamp distance, the latter being chosen for more or less uniform increments of current rather than uniform increments of distance. In each case, the same values of external resistance should be introduced and the corresponding currents noted. The data obtained in this manner will show how the current varies with light intensity as a function of the external resistance.

Plot log i against log d as in Experiment 3–1, using only the data obtained with the decade box at zero, that is, the external resistance equal to the meter resistance. This curve should exhibit negligible deviation from a straight-line relationship; that is, the variation of individual points will be greater than systematic deviation from the best straight line drawn through the points.[6] As before, the slope should be very close to the value of –2.00. On the basis of this plot, the various distances

[6] Holmes, R. M., *Electronics*, April, 1937; p. 33.
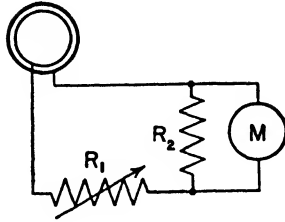
FIG. 3–7. A Measuring Circuit for a Barrier-layer Cell.
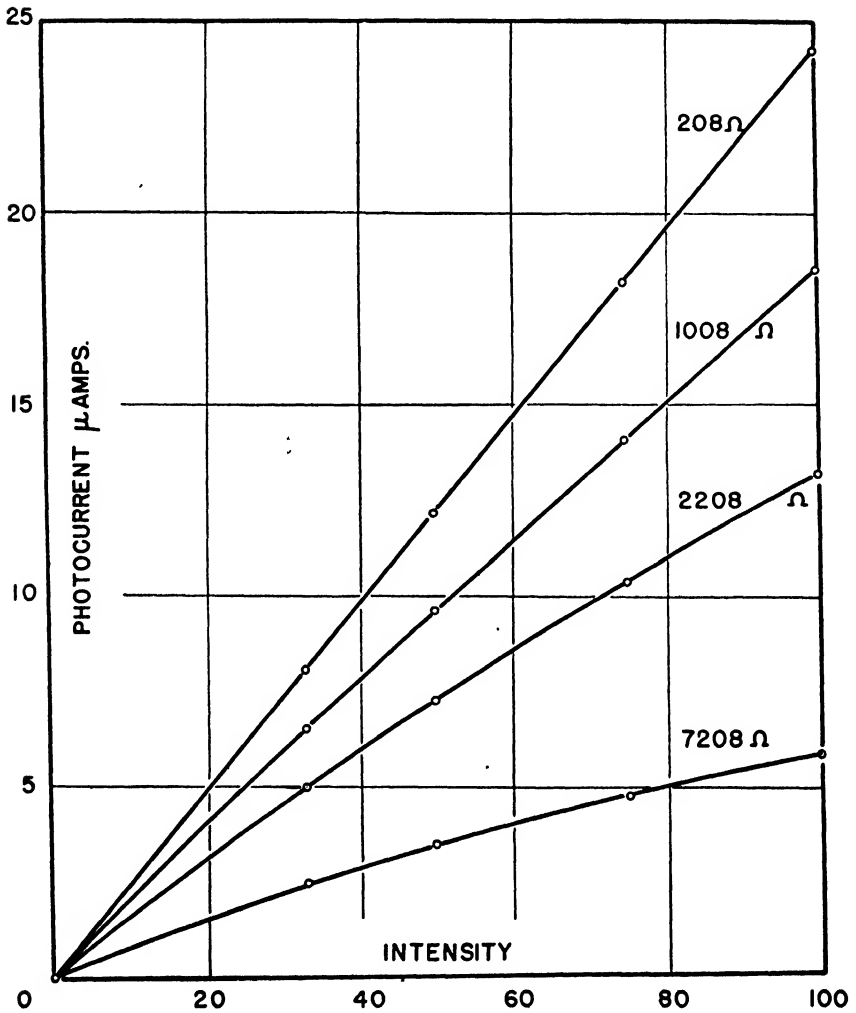
FIG. 3–8. External Resistance and Current from a Barrier-layer Cell.

which are common to the remaining data may be translated into their equivalent light intensities or into the equivalent photocurrents.

A family of curves showing the effect of external resistance can now be plotted with the photocurrents as ordinates and light intensities as abscissae. A typical plot is shown in Figure 3–8. It will be seen that as the external resistance decreases the photocurrent becomes more nearly directly proportional to the light intensity. Very precise measurements
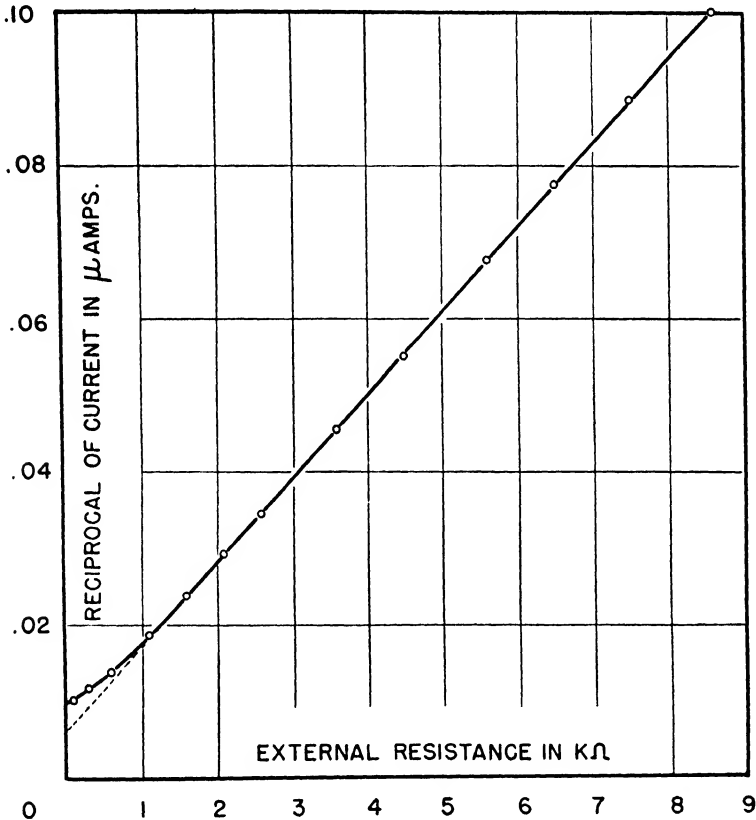
Fɪɢ. 3–9. Relation Between Current and External Resistance of a Barrier-layer Cell.

have shown that even for zero external resistance there is still a small deviation from linearity, but for most purposes the relation may be considered linear.

In the interest of some calculations which are to be made later, it is advisable to repeat the above measurements in the following manner. Set the lamp at a distance which yields a large photocurrent, and then introduce successive increments of resistance, reducing the current in small steps. Take about fifteen readings. Plot the total external resistance

against the reciprocal of the corresponding current. As shown in Figure 3–9, the relationship is linear at high values of the resistance. This illustrates the fact that the total photocurrent divides between the internal resistance of the cell and the external or load resistance according to the familiar rule for parallel resistances. The internal resistance of the cell is a very complex function of the operating conditions. Its value depends most certainly upon the current which flows through it. According to many investigators, its value also changes with illumination, although there is some evidence to indicate that this is not the case.

EXPERIMENT 3–4

Purpose: To determine the relationship between illumination and electromotive force in a barrier-layer cell.

Materials: Illumination unit
0-75-mv. potentiometer
Galvanometer
Galvanometer key
Barrier-layer cell

Procedure. The open-circuit electromotive force of the cell as a function of the light intensity can be measured with a potentiometer. If a standard potentiometer is not available, the simple arrangement shown in Figure 3–10 may be assembled. A simple network of fixed and variable resistors adjusts the current from the dry cell to a value such that the total voltage across R_1 is approximately .1 v. If the current is adjusted to .5 ma., the total drop in potential across the General Radio 200-ohm type 314A potentiometer R_1 will be 100 mv. Intermediate values can be read on the dial plate or from a 0-.1 voltmeter, as shown in Figure 3–10. This voltage divider is sufficiently uniform for such interpolation if the voltmeter is disconnected. If any difficulty is experienced in obtaining exact balance, due to the finite jumps from one turn of the resistor to the adjacent turn, the final balance may be made by a slight adjustment of the light intensity. In the interest of economy, banana-plug terminals may be provided for introducing a milliammeter, thus releasing this instrument for other uses in the laboratory.

The light source calibrated in the preceding experiment should be used for this experiment, and it may be assumed at this stage that the exact relationship between illumination on the cell and the corresponding distance is known. On the other hand, it may be checked during the e.m.f. measurements by alternately connecting the cell to the potentiometer and to a low-resistance microammeter by means of a double-pole double-throw switch. Experiment 3–3 will have shown to what extent the short-circuit current is a reliable measure of the light intensity.
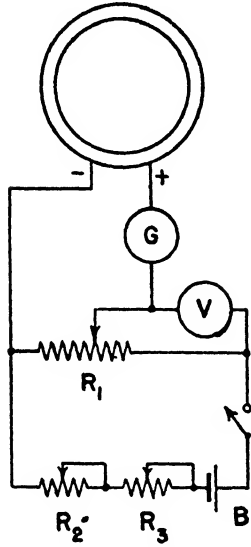
FIG. 3–10. A simple
Potentiometer Circuit.
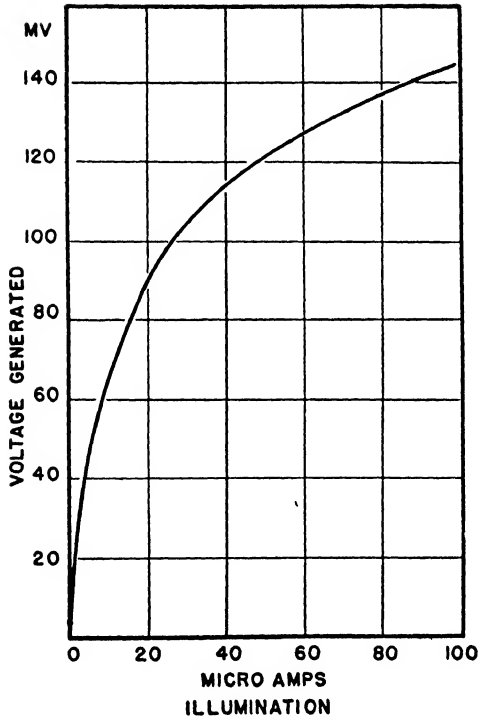
FIG. 3–11.   E.M.F. versus Light Intensity for
a Barrier-layer Cell.

Measure the e.m.f. produced and plot against the corresponding light intensities. As shown in Figure 3–11, the e.m.f. rises very rapidly with increasing intensity and then levels off. It is instructive to replot the e.m.f. against the logarithm of the light intensity. Monocyclic, semilogarithmic graph paper is convenient for this purpose. On the semilogarithmic plot, the e.m.f. rises in a gentle curve at low light intensities and soon assumes a linear behavior. It can be shown that at extremely high levels of illumination the plot is once more curved and approaches a limiting e.m.f.[7] The linear relationship between open-circuit e.m.f. and the logarithm of the light intensity does not seem to be widely known, but it is predicted by the theory of Lange and has a number of important possibilities in photometry. Considerable care must be exercised to avoid large temperature changes in the photocell. The temperature coefficient of e.m.f. is very much larger than that for the photocurrent. Neglect of this factor will account for an occasional lack of reproducibility in the measurements.

EXPERIMENT 3–5

Purpose: To determine the color-response curve of a barrier-layer cell.
Materials: Monochromator adjusted as in § 3–6
             Barrier-layer cell
             10^{-10}-amp. galvanometer with resistance 500 ohms or lower

Procedure. Use the same optical setup which was employed in Experiment 3–2. It will be found advantageous to place a short-focus lens at the exit slit of the monochromator in order to spread out the beam over the large surface of the photocell. A low-power microscope objective will do nicely. The photocell is connected directly with the terminals of a low-resistance, high-sensitivity galvanometer, and the latter carefully shunted for the critically damped condition. The deflections are read with the customary lamp and scale set at the greatest distance consistent with stability and reability. Complete screening from stray light is essential, and the best way to make sure the screening is complete is to cover the entrance slit of the monochromator; then the reading of the galvanometer should coincide with its mechanical zero. Read the galvanometer deflections at wave-length intervals of about 30 angstrom units, keeping the light source constant.

The deflections for each region of the spectrum should be corrected by the factors given in Table 3–1 (page 83). As we have indicated previously, the use of these factors for a general reduction to an equal-energy basis is very approximate, and inferior to the more refined comparison with thermopile readings. Figure 3–12 shows representative

[7] Wood, L. A., *R.S.I. 6*, 196, 1935.

curves obtained in this manner with a selenium-type barrier-layer cell. The effects of reduction to an equal-energy basis are strikingly illustrated by the two curves.

This experimental setup, as well as that of Experiment 3–2, can serve as a crude photoelectric spectrophotometer, that is to say, one can by these means determine the absorption or reflection spectrum of colored substances. To take a specific case, a dilute solution of potassium per-
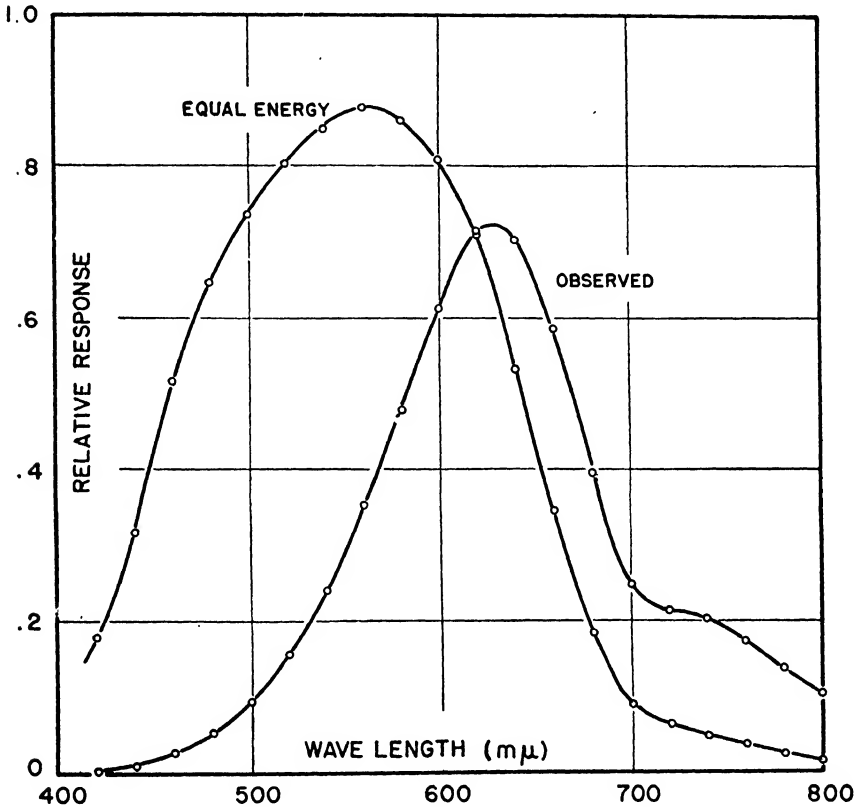
Fig. 3–12.   Color Response of a Photronic Cell.

manganate could be introduced in the optical path, preferably between the exit slit and the photocell, and the decrease in photocurrent noted. In each case, the reading would be compared with the reading obtained when the permanganate solution was replaced by an identical vessel filled with distilled water. If this were done at small intervals throughout the spectrum, the complete absorption spectrum would be mapped. In general, photoelectric spectrophotometers are provided with more refinements to permit rapid and precise comparisons, as indicated in Chapter 9.

3–8. Deflection-time characteristics ("fatigue").

In the strict sense of the term, barrier-layer cells do not exhibit fatigue; but they do display a behavior somewhat akin to fatigue, which should be understood and evaluated in any intended application. Upon sudden exposure to light, the photocurrent rapidly rises to a value several per cent higher than the apparent equilibrium value.[8] The deflection
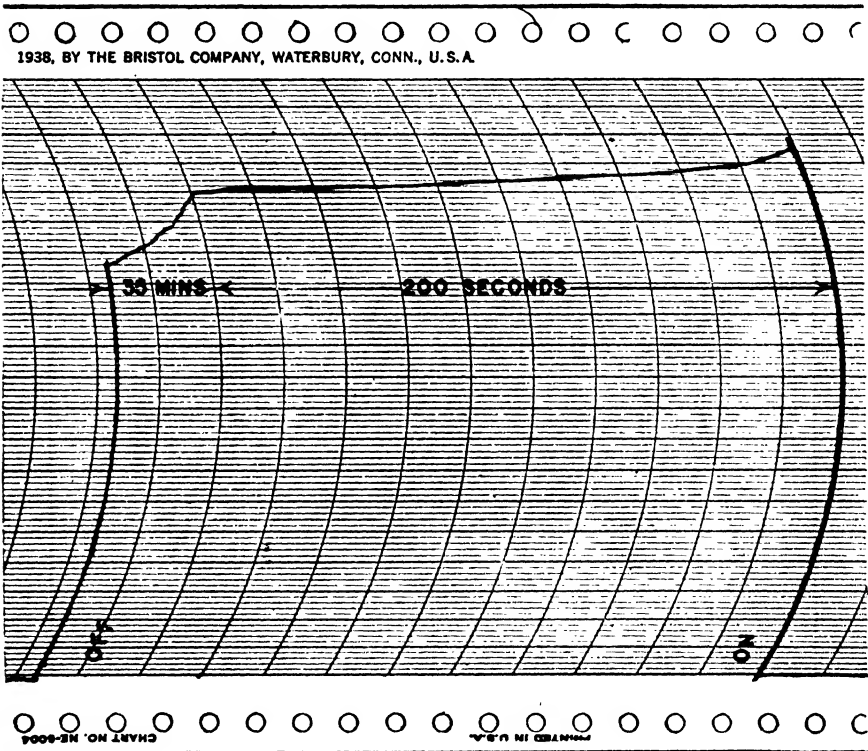
FIG. 3–13.   Current Time for a Photronic Cell.

then drops slowly at a steady rate. Figure 3–13 shows a recording of this phenomenon.

EXPERIMENT 3–6

Purpose: To determine the overshoot characteristics of a barrier-layer cell.

Materials: Illumination unit of § 3–3 or its equivalent
2 barrier-layer cells
2 meters
Shutter

[8] Wilson, E. D., *Electronics*, Jan., 1939; p. 15.

Procedure. Arrange two cells on opposite sides of the illumination unit so that the current from each cell produces almost maximum current in each meter. Shut off the light from one of the cells and keep the cell dark for a few minutes. Re-expose this cell to light, and read the meter as soon as the pointer stops oscillating. Start a stop watch at the time the exposure begins, and read the meter at 15-second intervals for the first minute. Continue the reading at 30-second intervals for about five minutes. Read the second meter from the monitoring cell to correct for any changes in light intensity. Plot the meter readings against time after correcting them. Repeat the experiments at several levels of illumination. The illumination level may be changed either by moving the cells away from the light source or by dimming the lamp. From these results, correction factors may be computed or an acceptable time schedule for taking readings may be set up. More or less elaborate precautions of this kind are necessary whenever a barrier-layer cell is used to obtain any but the crudest estimates of light intensity.

3–9. Light-source stability.

The importance of a stable light source must be apparent as a result of the foregoing experiments. Many ingenious schemes have been devised for furnishing light of constant intensity, and some of these will be considered in subsequent chapters. The following simple experiments will serve to define the problem and to illustrate the difficulties in finding a solution. Photoelectric methods will be used to study the problems: first, because of their importance; and secondly, because they provide a very convenient and sensitive criterion of stability.

In general, if a photocell is illuminated with the total radiation from an incandescent lamp, the photocurrent i can be expressed as a function of the lamp voltage by the empirical equation: $i = KV^n$.

The constant K includes, among other things, the ratio of the units in which i and V are expressed. The exponent n has a value usually between 3.5 and 4.0. It is apparent, then, that the photocurrent will be very sensitive to small changes in the lamp voltage, and therefore well suited to appraise any method which attempts to keep the lamp voltage constant.

EXPERIMENT 3–7

Purpose: To determine the illumination characteristics of a light source with a photocell.

Materials: Lamp
                   Transformer
                   Variac

Voltmeter

Photocell

Meter

Procedure. Illuminate a photocell with an incandescent lamp and adjust the distance between the lamp and the photocell to obtain a suitable meter reading. The lamp may be a 6-volt automobile headlight type operated from a step-down transformer, the voltage of which is measured with an A.C. 0-8 or 0-10 volt meter as shown in Figure 3–14; or the output of the Variac may be measured with an A.C. 0-150 voltmeter.

In either case, vary the illumination with a variable transformer and record the voltages of the lamp as measured with a voltmeter connected directly across the lamp terminals. Plot photocurrent as a function of voltage over a large range of lamp voltages, as shown in Figure 3–15a. The equation for this curve is $i = KV^n$. Replot the data, this time plotting the logarithm of the photocurrent as a function of the logarithm of the lamp voltage. The resulting curve is a straight line. The value of n is given by the slope of the straight line, since the equation for this line is

$$\log i = \log K + n \log V.$$

Repeat the experiment with a mercury-arc or neon lamp, and treat the results in a similar fashion. Plot, and note that the value of n is much smaller for these lamps.

3–10. Compensation for light-source variations with balanced photocells.

The difficulties encountered with fluctuating light sources may be eliminated either by stabilizing the light source or by using a measuring circuit which compensates for or rules out the effects of the fluctuating source.[9-12] Various methods of stabilization will be discussed in Chapter 4, and circuits for photoelectric measurements with variable light sources will be covered in Chapter 9. It is advisable at this point to show how two barrier-layer cells may be used to achieve the same end.

If two photocells are equally illuminated, and if the photocurrents from the two cells are equal, it is axiomatic to assume that, when these cells are connected to a common meter so that the currents from the cells oppose each other, the meter will read zero. If the light-source intensity is decreased until the photocurrent for one of the cells is halved, the meter will remain at zero only if the photocurrent from the other cell is also halved. This result is not necessarily attained in practice, and

⁹ Berry, J. K., *Ind. Eng. Chem. 13*, 396, 1941.

¹⁰ Brice, B. A., *R.S.I. 8*, 279, 1937.

¹¹ Müller, R. H., *Ind. Eng. Chem., Anal. Ed., 11*, 1, 1939.

¹² ~~Wilson~~ T. V. *Ind. Eng. Chem., Anal. Ed., 6*, 167, 1934.
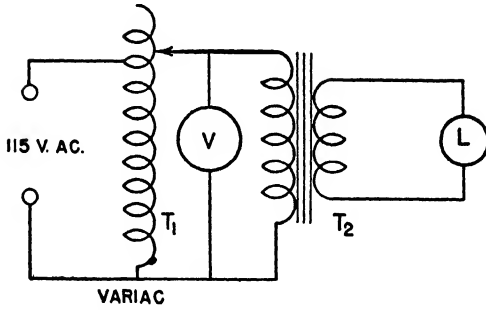
FIG. 3–14. Light-Source Characteristics Determined with a Photoelectric Cell.
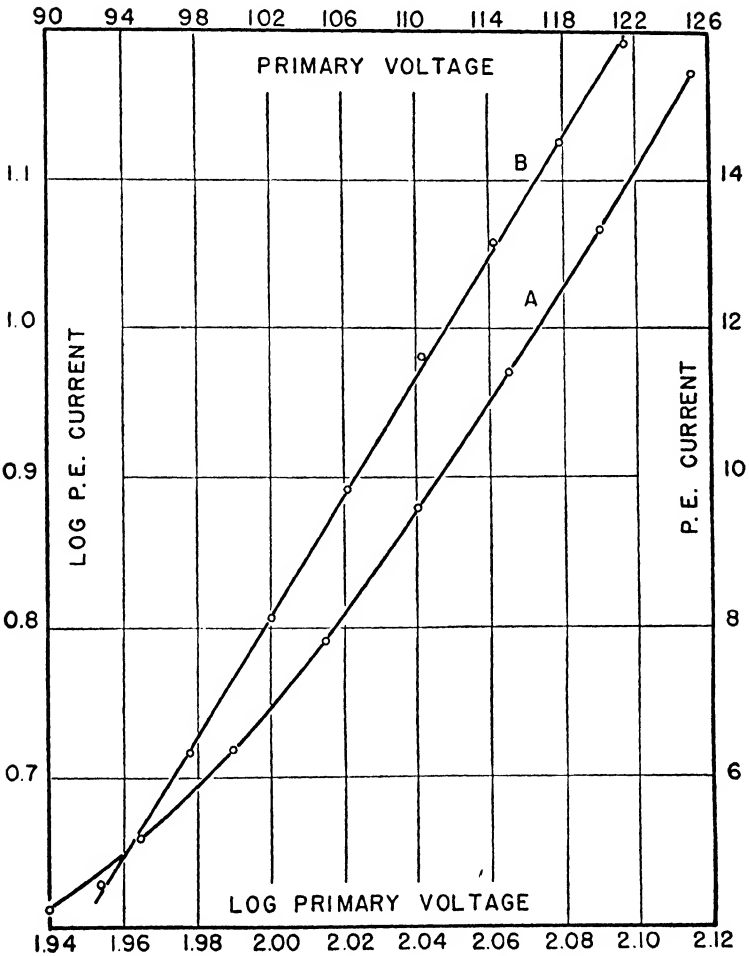
FIG. 3–15. Photocurrent-voltage of a Tungsten Lamp.

the statement is true only if the illumination-response curves and the spectral-response curves of the two cells are identical. It is also axiomatic to assume that, when the two cells are producing different photocurrents, the meter will change its deflection as the voltage of the light source is changed; thus, the two photocells do not fully stabilize the measuring instrument against the effects of light-source fluctuation.

EXPERIMENT 3–8

Purpose: To determine the extent of compensation obtained with balanced barrier-layer cells.

Materials: Illuminator unit
2 barrier-layer cells
Microammeter
Step-down transformer
Variac
A.C. voltmeter

Procedure A. Connect one of the cells to the microammeter and move the light source of the illumination unit described in §3–3 until the meter reads full scale. Now, place the other barrier-layer cell at the same distance from the light source as the first one but on the opposite side, and connect this cell to the meter so that the current from this cell flows in opposition to the current from the first cell, as shown in Figure 3–16. Change the position of the light source slowly until the meter reads exactly zero, then vary the voltage of the light source with the variable transformer. Read any changes in meter deflection and plot these readings as a function of lamp voltage. If the meter readings are less than zero, reverse the polarity of the meter, but do not change the polarity of the cells with respect to each other. A double-pole double-throw switch may be wired as a reversing switch to effect the change of meter polarity. If several barrier-layer cells are available, select various combinations and repeat the experiment.

Place a partially exposed photographic plate in the path of one of the light beams, or move the light source to increase the illumination on one of the cells, and repeat the measurement. Note that the compensation attained depends on the match obtained with the two-cell combination, and that the compensation becomes progressively poorer as the differences in the illumination of the two cells becomes greater.

Procedure B. Connect the two cells as shown in Figure 3–17. The galvanometer may be either a low-resistance unit with an internal resistance of 100 ohms or less or else a low-resistance 0–25 microammeter. Place the two cells one on each side of the lamp, as in Procedure A. Set R_1 and R_2 to 100 ohms, and vary the position of the light source
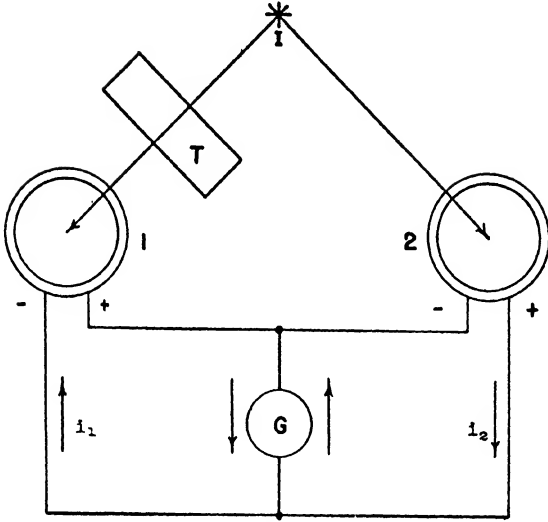
FIG. 3–16. Barrier-layer Cells in Opposition.
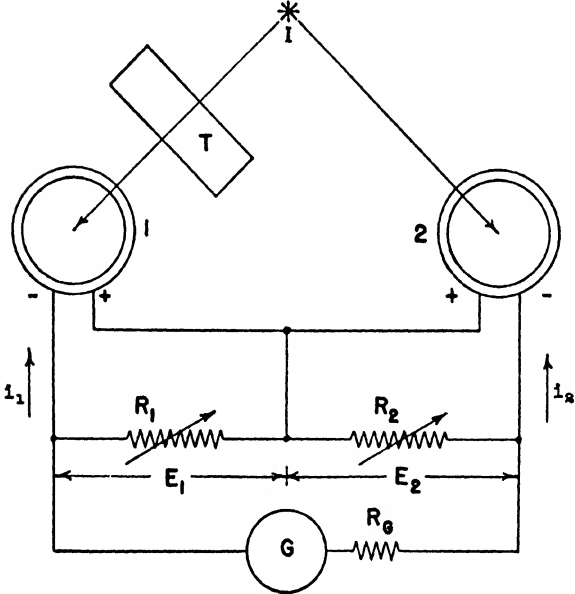
FIG. 3–17. Barrier-layer Cells in a Bridge Circuit.

until the galvanometer reads zero. Study the effect of lamp voltage as in Procedure A, and plot in a similar manner. Move the light source in order to increase the illumination of one of the cells, and change the value of R_1 or R_2 until the galvanometer again reads zero. Determine the effect of light-source voltage variation on the reading of the meter adjustment. Repeat for other values of unequal illumination after the ratio of R_1 to R_2 has been readjusted for zero galvanometer reading. Note that the cells now become compensating even when the illumination to the two cells is unequal.

Procedure C. Connect the two cells as shown in Figure 3–18, and set R_1 to the same resistance as R_2 and adjust the position of the light source for zero galvanometer deflection, with the slider on R_2 at the maximum (to the right). Repeat the light-source variation and plot as in Procedure A. Adjust the illumination so that the cell indicated on the right receives more light and compensate for this increase by decreasing the potentiometer R_2 (to the left) until the galvanometer reads zero. Determine the effect of light-source variations as before.

3–11. Double-cell photometers.

The circuits used in Procedures A, B, and C may be used for a practical measuring instrument in which light-source variations will be at least partially compensated for. The arrangement in Procedure A may be used in a photometer if a calibrated optical unit is used to reduce the light on the second photocell by a known amount to match the reduction effected by an unknown material placed in the light path of the first cell. Match is indicated by the microammeter. The circuit shown in Figure 3–17 may be used without the optical-compensation unit, and the ratio of the illumination may be read directly from the ratio of R_1 to R_2. The slide wire of the circuit in Figure 3–18 may be used to indicate the reduction of light intensity upon the cell on the left. The success and accuracy of these measurements depend on the constancy of photocurrent from the individual cells, the constancy of the internal resistance, as well as on the match obtained for the response curves of the two cells. A complete discussion of these problems is found in the extensive literature on this subject.

3–12. Multiplier photocells.[13, 14, 15]

An electron-multiplier tube is so constructed that use is made of the phenomena of secondary emission to produce current amplification. Photoelectrons emitted from the cathode of a photoemission cell are

[13] Farnsworth, P. T., *J. Franklin Inst. 218*, 411, 1934.
[14] Rajchman, J. A., and Snyder, R. L., *Electronics*, Dec., 1940; p. 20.
[15] Zworykin, V. K., Morton, G. A., and Malter, L., *Proc. I.R.E. 24*, 351, 1936.

accelerated, focused on a second electrode called the collector or target, where each of the original electrons (called primaries) may produce several secondary electrons as a consequence of the impact. The number of secondary electrons so produced depends on the properties of the collector or target and on the velocity of the primary electrons. At velocities corresponding to about 100 v., the number of secondary electrons produced from one primary may vary from two to ten, depending on the type of metal under bombardment. In the usual case, surfaces such
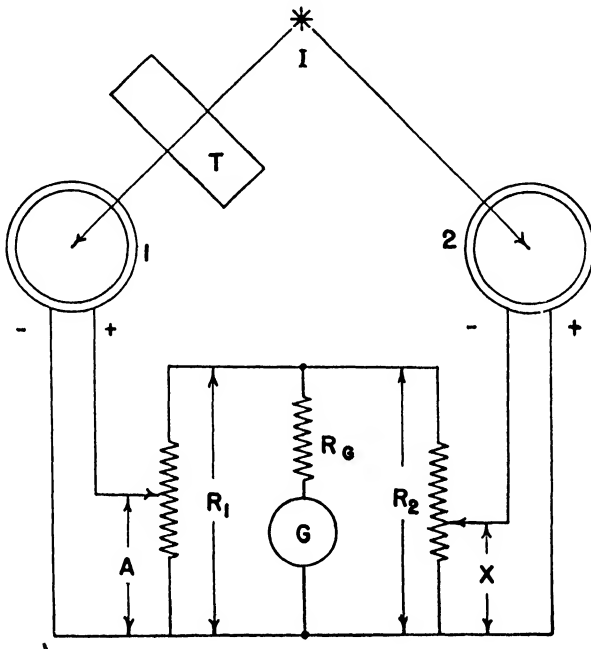
Fig. 3–18. Barrier-layer Cells in a Bridge-potentiometer Circuit.

as caesium-silver oxide produce two to five secondaries at voltages from 50 to 200. The gain for one stage of electron multiplication is quite small, but since the process may be repeated as many times as is desirable, enormous gains are possible. The gain of nine stages of electron multiplication using caesium-silver oxide surface is about two million, and may be achieved in a tube only slightly larger than the ordinary modern type of photocell. While the ordinary photocell may be rated at 10 μamps. per lumen, an electron-multiplier photocell may be rated at 10 amps. per lumen. It should be pointed out, however, that the multiplier phototube is not ordinarily capable of producing an output higher than several milliamperes; this output may, however, be produced at illumination levels of the order of 10^{-4} lumen.

In the design of efficient multipliers, the chief difficulty which must be overcome is the proper focusing of the electron beams. It is not necessary actually to focus the electrons in the optical sense, but rather to collect them in bundles and direct them from one electrode to the next electrode. Electrons may be focused in a variety of ways. Crossed electric and magnetic fields may be used, but the weight and bulk of the units producing the magnetic fields make such devices rather inconvenient to use. By proper shaping and positioning of electrodes it is possible to perform the desired functions with the use of electric fields alone.[16] One example of this type of construction is represented by the R.C.A. type 931 multiplier phototube. In this tube, the photoelectrons from the cathode are directed to the first collecting surface or dynode under the action of the field produced by the accelerating voltage on this dynode. The secondaries so produced are attracted to the next dynode by a similar field. The dynodes are so placed that alternate dynodes are on the outer circle and the other dynodes are on an inner circle, and the electrons progress from one dynode to the next one through apertures formed by the respective fields.

The electron multiplier possesses several distinctive characteristics, of which the most important from the standpoint of measurement is the variation in gain with applied voltage. The over-all sensitivity may vary from 10^{-2} amp. per lumen at 50 v. per stage to .4 amp. per lumen at 100 v. per stage; that is, doubling the voltage increases the sensitivity by a factor of 40. Under these conditions, where constant sensitivity is desired, voltage regulation must therefore be employed. Regulation may be accomplished by stabilizing the power supply as shown in Chapter 4, or by controlling the gain of the multiplier tube with an electron tube or photocell in a manner which will offset the variation in the gain of the electron multiplier. If the voltage on one dynode is changed by an amplified variation in line voltage this one dynode may compensate for the variations caused by the unregulated voltages on the remaining dynodes, providing the amplified variations in line voltage produce the same but opposite change in the over-all gain. An example of this method of stabilization is illustrated in Figure 3–19.

This method is possible only because the gain of a particular stage is not a linear function of the voltage. If a negative voltage is applied to dynode 4 and across the resistor R_1 of Figure 3–19, the voltage between dynodes 4 and 5 is increased, while the voltage between dynodes 4 and 3 is decreased. The resulting increase in gain at dynode 5 is not as large, however, as the decrease in gain at dynode 4, and thus the over-all gain is reduced. If a positive voltage is applied at this point, the same effect is obtained, except that the decrease in gain takes place at

[16] Zworykin, V. K., and Rajchman, J. A., *Proc. I.R.E.* **27**, 558, 1939.

dynode 5 and the increase at dynode 4. The total effect is again to re-
duce the total gain.

The change in over-all gain is not linear with the voltage across R_1,
but portions of the curve are sufficiently linear to reduce the fluctuations
caused by small line-voltage variations by a factor of 200 or more. The
fluctuations caused by line-voltage changes are in general less at high
power-supply voltages (saturation) than at low ones, and since the
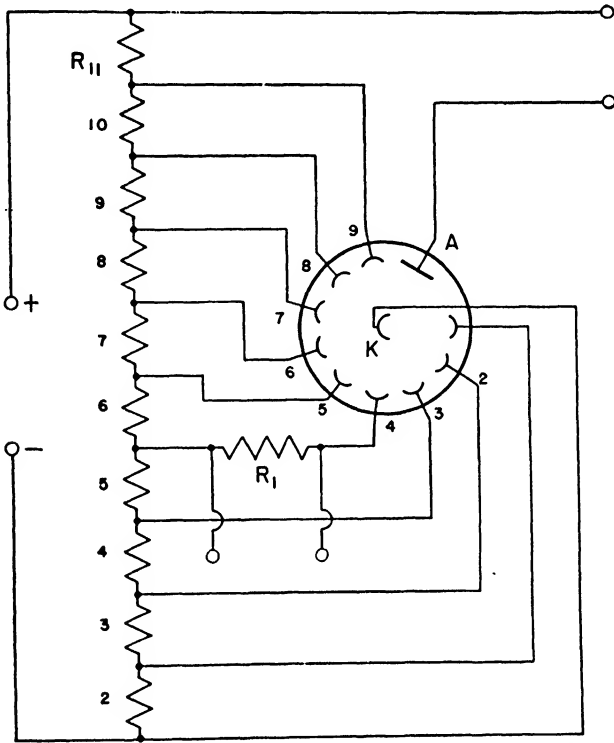
Fig. 3–19.   An Electrostatic Photomultiplier Circuit.
R_2 to R_{11} equal resistors, 10,000 to 50,000 ohms each; R_1,
see text.

final stabilization depends on the combination of two nonlinear curves it
cannot be regarded as perfect. One practical method for achieving a
measure of stability is shown in Figure 3–20, where part of the voltage
divider consists of a nonohmic element such as a glow lamp. In this cir-
cuit, variations in the supply voltage are concentrated across R_2, R_3,
and R_4; the variation in the voltage of dynode 7 is therefore larger than
for the other dynodes, and may be used to offset the changes caused by
the other dynodes.

Compensation for changes in the light intensity of the source may
be obtained by a combination of the circuits shown in Figures 3–19 and

3–20, a photocell connected across R_1 of Figure 3–19 being used to control the voltage of dynode 4 in such a manner as to reduce the voltage of this electrode and consequently reduce the gain of the multiplier with increasing light intensity. This compensation will be perfect if the gain of the photocell is so adjusted that the product of the gain of the multiplier times the light intensity is a constant. To exert control, the amount of photocurrent passing through R_1 must be several times that of the control dynode. If the photocell is to be operated at the same
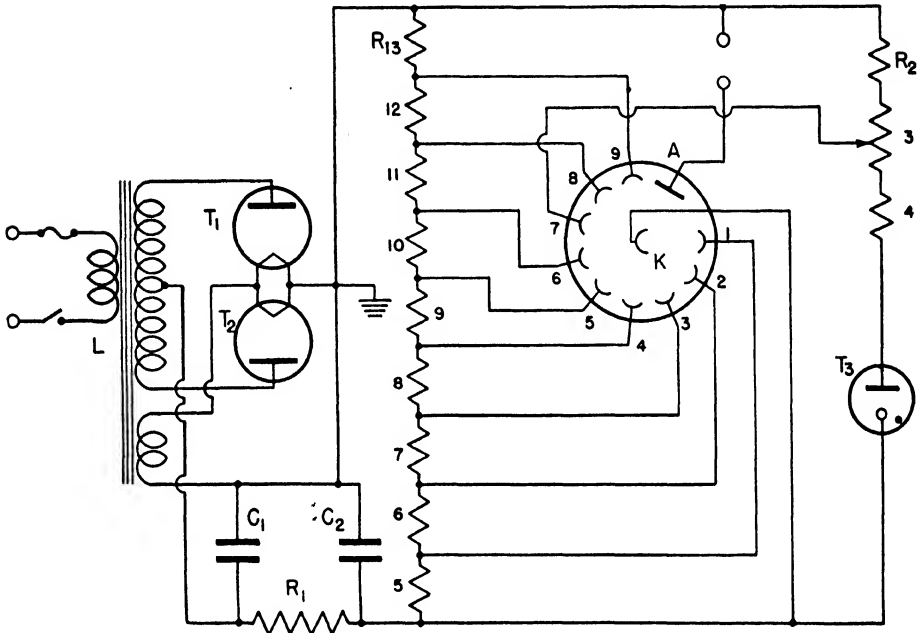
Fig. 3–20. A Self-compensating Photomultiplier Circuit. R_1 = 20,000-ohm resistor, 10 watts; R_5 to R_{13} = 10,000-ohm resistors, 1 watt; R_2 = 20,000-ohm resistor, 2 watts; R_3 = 20,000-ohm potentiometer, 2 watts; R_4 = 30,000-ohm resistor, 5 watts; C_1 and C_2 = 1-μf. 1,500-v. capacitors; T_1, T_2 = 2X2 tubes; T_3 = Two VR150 tubes.

light intensity as the multiplier, amplification of the photocurrent is imperative. In most cases, however, this is not necessary, since the photocell can in general be illuminated directly by the light source, and the multiplier can be used with only a small portion of the total light intensity, as in monochromators, photoelectric photometers, and so forth.

The multiplier photocell thus combines a photoemitter with an amplifier, and achieves a high current output within a single envelope. The limit to the amplification that can be obtained with a unit of this type depends on two factors, the noise level and the leakage current. In the ordinary photocell circuit, the load resistor produces considerable noise

or fluctuating voltages. The multiplier may be regarded as a photocell with a high load resistor which, however, contributes no noise or fluctuating voltage to the measuring instrument. The ratio of superiority of the multiplier photocell over the ordinary photocell thus depends on the level of illumination to be measured. The superiority increases as the illumination decreases.[17] In the limiting case, the multiplier is capable of detecting and measuring illumination about 200 times weaker than can be achieved with the ordinary photocell amplifier.[18] This ratio depends on other factors, and the reader is referred to the literature for the exact equations and calculations.

The leakage current of the present types of multiplier photocells correspond to about 10^{-7} lumens of radiant energy or about 10^{-12} amp. of photocurrent. This leakage current may arise from various sources, chief among which is the thermionic emission of the photocathode, and may be reduced by proper selection of cathode material, but usually at a loss in efficiency and amplification.

EXPERIMENT 3–9

Purpose: To study the characteristics of an electrically focused multiplier photocell.

Materials: 929 R.C.A. photocell
               931 R.C.A. multiplier photocell
               900-O-900-v. power transformer
               2 rectifier tubes, 2X2
               9 10,000-ohm 1-watt resistors
               2 VR-150 tubes
               20,000-ohm resistor
               2 1 μf 1500-volt capacitors
               Variac
               20,000-ohm, 10-watt resistor
               20,000-ohm, 2-watt potentiometer
               30,000-ohm, 15-watt resistor
               Illumination unit of Experiment 3–1
               0–.1 milliammeter
               1-megohm volume control

Procedure A. Render the illumination unit of Experiment 3–1 completely light-tight, either by mechanical construction as in §3–3 or by covering with several thicknesses of black cloth. Place a 931 multiplier phototube in a housing mounted on the optical axis of the unit, and provide the housing with a window composed of several layers of milky

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[17] Whitford and Kron, *R.S.I. 8*, 78, 1937.
[18] Zworykin, Morton, and Malter, *loc. cit.*

glass to cut down the illumination from the incandescent source of light as used in the former experiments. It is advisable to equip the window with a variable iris diaphragm so that the intensity of light may be conveniently varied.

Connect the multiplier phototube to its power supply as shown in Figure 3–20, and with the lamp at its maximum distance adjust the aperture in front of the multiplier until the 0-.1 milliammeter, connected as an output load, reads less than 5 μamps. (*Caution!* Do not allow any excessive amount of light from the room to energize the photocell without first disconnecting the power supply.) Now move the lamp carriage closer to the cell until the meter reads about half scale. Change the setting of R_3 until the output becomes a maximum, reducing the light intensity by narrowing the aperture should the meter go off scale. Change the line voltage with the Variac and note the changes in the output reading. If the output changes, adjust R_3 for lower gain until the output is practically independent of the input from 110 to 115 v. If this degree of adjustment cannot be attained, then use either dynode 8 or dynode 6 for control purposes; that is, if the previous adjustment overcontrolled the output at all settings of R_3, use dynode 8 for control by increasing R_4 to 40,000 ohms, decreasing R_2 by the same amount, and connecting R_3 to dynode 8.

On the other hand, if with the previous settings the output always increased with an increase in line voltage, increase R_2 by 10,000 ohms, decrease R_4 by the same amount, and connect R_3 to dynode 6.

After the line voltage fluctuations have been minimized in this fashion, determine the output current as a function of the lamp distance, as in Experiment 3–1, and plot as log i against log d and determine the slope as before. Repeat the experiment at lower values of light intensity, and measure the output with a more sensitive meter or with a D.C. vacuum-tube voltmeter, as described in Experiment 3–1 or in Chapter 7.

Procedure B. Replace R_8 of Figure 3–20 with a 10,000-ohm 1-watt potentiometer, and connect dynode 3 in series with a 1-megohm volume control to the arm of this potentiometer. Connect the anode of an R.C.A. 929 photocell to dynode 3 and the cathode to the photocathode of the multiplier. Place a lamp similar to the one used in the illumination unit about eight inches from the 929 photocell, and with the multiplier turned on adjust potentiometer R_8 until the output of the multiplier is a maximum. If this maximum is not reached before R_8 is at its maximum position, reduce either the value of the photocell load resistor, that is, the 1-megohm volume control, or the illumination, or both.

Connect both lamps to the same step-down transformer, and vary the voltage of both lamps with a Variac and note the changes in meter

readings. If the meter reading is not constant, change the setting of R_8 until the gain of the multiplier is lower than before, and again note the change in the output current as a function of line voltage. If the new condition is worse than the old one, change the setting of R_8 in the opposite direction until the gain is again reduced, and check the stability.

Make final adjustments of R_8 and the output voltage of the 929 phototube until the output current is practically independent of the lamp voltage. Change the lamp voltage over a large range and record the output current. Plot output current as a function of the lamp voltage, and compare with the double-photocell compensation achieved in Experiment 3–8.

3–13. The iconoscope.[19]

The iconoscope is a combination of multiple photocells and a cathode-ray tube, used in television transmission for picking up a scene and converting it into a series of electrical impulses. The tube contains a plate on which has been built up a mosaic consisting of millions of small photocell elements insulated from each other, upon which the scene to be transmitted is focused; an electron gun which provides an electron beam for scanning this image; and a signal plate which acquires a voltage in proportion to the brightness of that portion of the scene being scanned at that instant. This voltage variation with time constitutes the video signal for a television picture.

The process by which the iconoscope generates this voltage can be described by considering the various effects produced by the beam and the photoemission. When the mosaic is dark, secondary electrons are emitted in large numbers as the cathode-ray beam strikes individual globules. Some of these secondary electrons return to the globule; the rest escape and either go to the collector or to other parts of the tube, with the result that the globule acquires a positive charge in reference to other globules not under electron bombardment from the cathode beam. The potential developed is about $+3$ v. After the beam leaves this globule, some of the secondary electrons emitted by the remainder of the mosaic fall on the globule, and its potential changes to a less positive value, usually to about -1.5 v. If the globule under discussion remains dark, the potential remains at this value until the beam has completed its scanning cycle and returns to this portion of the mosaic, at which time the potential is again increased to about $+3$ v. If, however, this portion of the mosaic is illuminated, this globule emits photoelectrons and its potential will be at some point between -1.5 and $+3$ v., the value depending on the scene brightness at this point. When the beam strikes this globule, therefore, the change in voltage will be

[19] Zworykin, V. K., *R.C.A. Rev.* **1**, 60, 1936.

smaller than for an unilluminated globule. This voltage difference constitutes the television signal.

It may be pointed out that the light from the scene to be transmitted falls continually on the mosaic, thus allowing adequate time for charging the globular photocell units. Not so with mechanical scanning, where the light from a section of the picture falls on the photocell only during the scanning interval for that particular section of the picture. Thus, the iconoscope sensitivity is essentially independent of the number of picture elements, while the Nipkow-disk method produces a sensitivity which is inversely proportional to the number of picture elements. Since the modern television picture is effectively broken up into about 300,000 parts for transmission, a 100-per-cent efficient iconoscope is about 300,000 times more sensitive than the old mechanical photocell methods of transmission.

The disadvantage of the iconoscope is that the photoemissivity is quite inefficient, since the accelerating potential for the photoelectrons is so small and since the voltage assumed by a globule in the mosaic is not strictly proportional to the light intensity, even for small ranges of intensity.

3–14. The orthicon or orthiconoscope.[20, 21, 22]

The orthicon, as the name implies, is a form of iconoscope which produces a current in linear relation to the brightness of the image. This is achieved by operating the mosaic in a manner similar to the conventional photocell. Photoelectrons are given off by the globules in proportion to the intensity of illumination, and drawn off by a collector electrode, leaving the mosaic positive with respect to the source of the electron scanning beam. When this low-velocity scanning beam impinges on a certain globule, it returns to the globule the same number of electrons which were given off during the exposure period. Since the velocity of the scanning beam is low (25 v.), no secondary electrons are involved in the process. The current created by the returned electrons flowing through a resistance produces the television signal. The photoemissivity of the mosaic is normal, and the sensitivity of the orthicon is, therefore, about ten times greater than the corresponding iconoscope; the effects produced by secondary electron emission are eliminated; and the output voltage is a linear function of the illumination and time of charge. In order to achieve these results, the electrons from the scanning beam must strike the mosaic at normal incidence; special deflection systems must be used to preserve this incidence at all portions of the mosaic.

[20] Rose, H., and Iams, H., *Proc. I.R.E. 27*, 547, 1939.
[21] Rose, H., and Iams, H., *R.C.A. Rev. 4*, 186, 1939.
[22] *Electronics*, July, 1939; p. 11.

The iconoscope or orthicon tubes may be used advantageously for measurements where a large amount of data must be accumulated in a short time, the data being plotted on a cathode-ray tube. Since these tubes have been available for only a short time, only a small number of practical applications outside the television field have appeared in the literature.

TABLE 3–1

A λ mμ	B factor	A λ mμ	B factor
400	—	600	9.13
420	462	620	6.86
440	236	640	5.25
460	136	660	4.06
480	87.1	680	3.22
500	56.0	700	2.54
520	35.4	720	2.05
540	24.5	740	1.66
560	17.1	760	1.40
580	12.5	780	1.17
		800	1.00

Column B lists the weighted values of the appropriate factors with which all observed photocell current values are to be multiplied. They have been calculated to give a value of unity for a wave length of 800 mμ.

It will be observed that the factor rises very rapidly at short wave lengths. This rise is due in part to increasing absorption in the flint prism of the monochromator, and not entirely to ordinary spectral distribution.

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PROBLEMS

1. Compare the current sensitivity of a typical phototube with that of a typical barrier-layer cell.

2. Calculate the power which can be developed in matched load resistors for a phototube and for a barrier-layer cell at various levels of illumination.

3. The highest sensitivity normally attained with lamp-and-scale galvanometers is 10^{-10} amp. per millimeter deflection. On this basis, what is the lowest level of illumination (in lumens) which a photronic cell will detect? Calculate the voltage developed across a 10^{10}-ohm load resistor by a phototube with a sensitivity of 50 amps. per lumen at this same level of illumination.

4. If the phototube and load resistor of Problem 3 have an associated capacitance of 10^{-10} f., calculate the time required to develop 99 per cent of the final voltage.

5. Calculate the maximum resistance which can be used with a phototube having an associated circuit capacitance of 10^{-10} f. if 67 per cent of the full voltage must be developed in (a) 10^{-5} second, (b) 10^{-3} second, and (c) 10^{-1} second.

6. Show, by means of the e.m.f. data of Experiment 3–4, why an electron-tube amplifier should not be used with a barrier-layer cell.

7. Design a double-cell phototube circuit using an electron-tube amplifier, which will compensate for light source variation.

8. Show how the color-response curve of a photocell is changed by the use of color filters.

9. How does the absolute color-response curve of a photocell differ from that measured with a tungsten light source?

10. Calculate the gain of a ten-stage electron multiplier with a gain of three per stage.

11. Why does the gain of an electron multiplier increase approximately as the logarithm of the accelerating voltages?

12. Design an electron-multiplier photocell unit which compensates for the change in gain and for the light-source variation caused by line-voltage fluctuations.

13. Design an electron-multiplier photocell unit in which a triode tube is used as the measuring instrument. Indicate the over-all sensitivity of the instrument.

14. Show how an iconoscope or orthicon could be used to measure the velocity of certain types of rapid chemical reactions.

CHAPTER 4

Power Supplies

Introduction.

Power supplies are units which supply electrical power to operate other devices. In some cases the power supply is designed as an integral part of the complete equipment. The practicability of an integral power supply is largely dictated by such considerations as weight, portability, or convenience of operation. A separate power supply is always required if A.C. coupling between the operating unit and the power supply must be kept at a minimum. In addition, when cooling problems are encountered, they can generally best be solved by the use of an external power supply. The circuits shown in later sections were not necessarily drawn in conformance with the above requirements. Wherever common power supplies can be used the supply has been indicated but not included in the diagrams.

4-1. Power-supply requirements.

The main requirement of a power supply for electronic equipment is to furnish D.C. at several hundred volts to the plates of the tubes. The tubes must also be supplied with voltage for the grids and with sufficient power to heat the cathodes.

Although the required plate voltages are moderately large, the current demands are quite small and depend on the tube size and the number of tubes. When several tubes are used, each tube may be supplied individually, or the several tubes may be supplied in parallel from a single power supply. The screen grid or other grids of tetrodes and pentodes must be supplied with D.C. at voltages of the order of hundreds of volts. The demand may vary from several milliamperes for a small tube to half an ampere for two or three large receiving-type tubes. The screen current demands are smaller than those for the plate, and a voltage divider across the plate supply may be used in most cases to supply this electrode. The same method may be used to obtain grid voltages.

The heater may require currents as large as several amperes at low voltages. In heater-type tubes, fortunately, the electrical insulation and thermal lag between the heater and cathode is sufficiently high to per-

mit A.C. heater operation without introducing any modulation (hum) into the electron stream. Heater-type tubes are thus operated by step-down transformers of the proper voltage and current ratings.

The heater current remains constant during operation, but the plate and screen (Chapters 2 and 5) currents change in accordance with the grid signal voltage. It is important, therefore, that the power supply deliver plate and screen voltages which remain relatively constant and independent of these variable currents; that is, the equivalent internal resistance of these power supplies should be low in comparison to the resistance of the load (the cathode-plate resistance).

The problems encountered in the design of plate and screen power supplies are those of rectification, filtering, and internal resistance. Each of these problems will be discussed separately.

4–2. Rectification.

Rectification may be achieved by a number of different devices, of which the most commonly used is the high-vacuum diode tube.
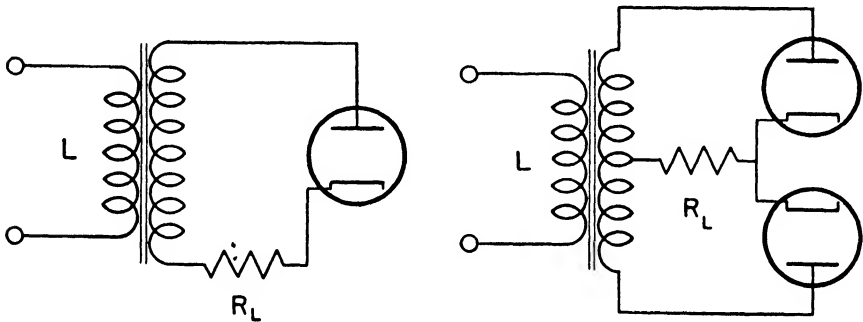
FIG. 4–1.   Half-wave and Full-wave Rectifiers.

A simple diode rectifier circuit is shown in Figure 4–1. Since only the cathode can emit electrons in appreciable quantities, an electron current can flow only in one direction (counterclockwise in Figure 4–1). When A.C. is rectified, the flow of current is not steady, but varies with time as indicated by the solid curve of Figure 4–2c. The diode prevents current from flowing during the period represented by the dotted curve, and the flow of current is, therefore, unidirectional in the load resistor R_L. This portion of the line-voltage wave may be included in the output by using another diode unit, as shown in Figure 4–1b. The second unit is duplicated in all details, and is connected to the same load resistor R_L. The operation of the two units is complementary, in that the transformer secondaries are so arranged that one diode is working while the other one is idle. This complementing is achieved simply, by poling the two secondaries so that when the upper

diode plate is negative the lower diode plate is positive, and is accomplished by using a continuous secondary winding tapped at its midpoint. Under these conditions, the current flowing through the load is shown in Figure 4–2b. The actual peak voltage is determined by the
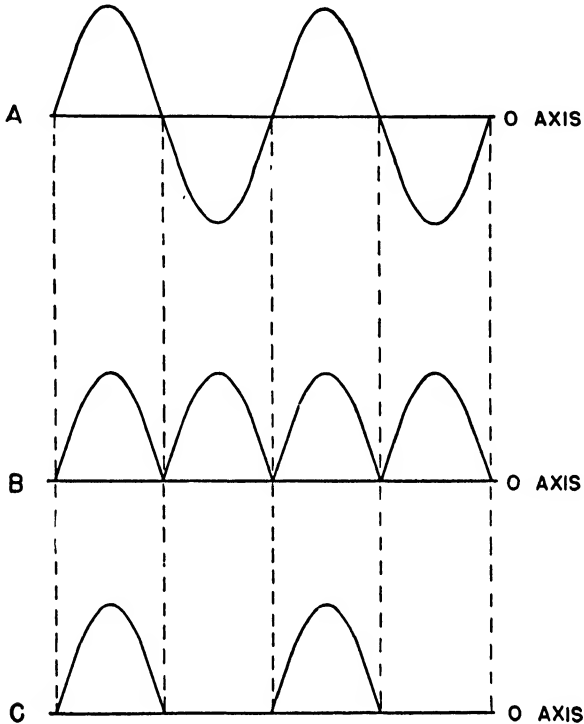
FIG. 4–2.   Sine Wave after Full-wave and Half-wave
Rectification.

step-up or step-down ratio of the transformer, and is equal to one-half of the peak voltage of the complete secondary if a tapped secondary is used. The value is calculated from

$$\frac{V_L \times R_s \times \sqrt{2}}{2}$$

where V_L is the line voltage and R_s the ratio of the secondary to primary turns. Secondaries are usually rated in root mean square voltages for normal line voltages and for each side of the secondary; for example, 300-0-300 indicates that the secondary produces 300 root mean square volts A.C. at each side of the secondary, referred to the mid-tap. This transformer will produce a maximum of 420 volts D.C. when used in the circuit at the right in Figure 4–1 followed by adequate filtering.

4–3. Filtering.

For many applications, the voltage across the load R_L must be maintained at a steady value despite changes in current flowing through the respective diodes. The conversion of this fluctuating D.C. voltage to a steady or uniform voltage is called filtering, and may be achieved in a number of ways.[1,2] When the load resistance is large, this filtering may be accomplished by connecting a capacitor C_L across the load resistor R_L of Figure 4–1. This capacitor will tend to charge to a voltage represented by the maximum of the peaks in Figure 4–2, and will discharge into the load when the voltage of the transformer secondary decreases, thus maintaining the voltage across the load resistor.
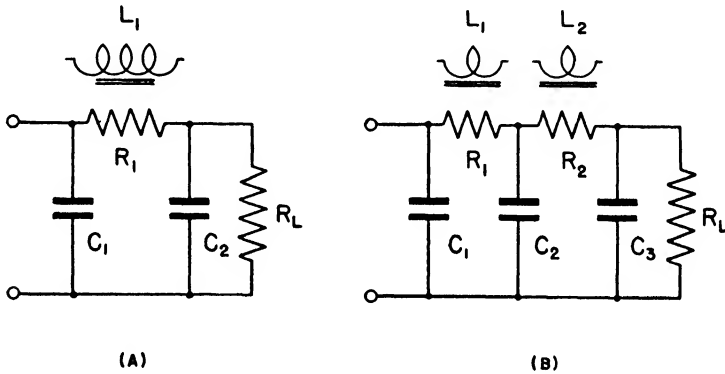
Fig. 4–3. Filter Circuits.

If the product $R_L C_L$ is large in comparison to the frequency of the wave of Figure 4–2 (where R_L is the resistance of the load and C_L the capacitance across the load), then the capacitor discharges only slightly during the decrease in the secondary voltage and the voltage across the load is substantially constant. If the load resistance is relatively small (1,000 ohms), the value of C must be very large in order to attain a large RC product. Owing to the high costs and the size of these large capacitors, more complicated circuits using smaller components are usually employed. Figure 4–3a shows a two-section filter composed of two capacitors and two resistors. If the $R_1 C_1$ product is such that the ripple voltage is reduced to 10 per cent of its initial value in the first stage, the second stage $C_2 R_L$ will reduce this voltage to 1 per cent if a similar time constant is used; and the combined size of $C_1 + C_2$ will be only one-fifth the size of C_1 if C_1 is used alone to achieve the desired filtering. If another stage is used, as shown in Figure 4–3b, the ripple voltage is reduced to only .1 per cent.

[1] Terman, F. E., "Radio Engineering." New York: McGraw-Hill Book Co., Inc., 1937; p. 488.

[2] Kellog, E. W., and Phelps, W. D., *Electronics*, Feb., 1938; p. 26.

Such reduction of the ripple voltage is, however, accompanied by a considerable loss in the net output voltage across the load R_L of Figure 4-3. The loss is represented by the voltage drop across the resistors R_1 and R_2, and becomes larger as the values of R_1 and R_2 increase with respect to R_L. The difficulty may be partially avoided if the resistors R_1 and R_2 are replaced by inductors with reactances equal to the resistance of the replaced resistors. Since the inductors have small D.C. resistance, the voltage loss is greatly reduced, although a residual loss of voltage still occurs. A 10-henry inductor offers a reactance equal to about 7,500 ohms at 120 c.p.s., and may have a D.C. resistance of only
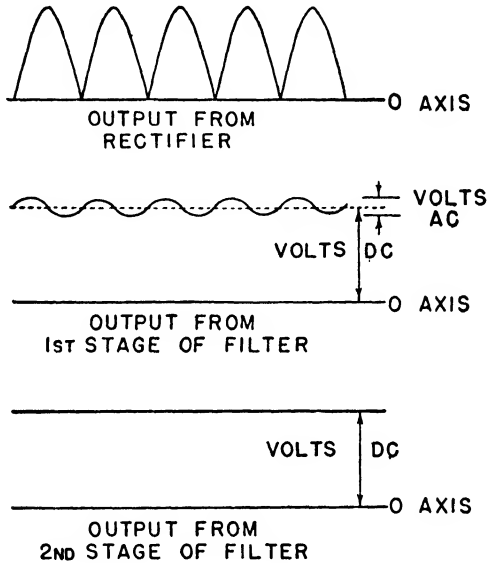
FIG. 4-4. The Effect of a Filter Circuit.

100 ohms. The various steps in the filtering process are indicated in Figure 4-4.

When the input capacitor C_1 of Figure 4-3b is omitted, C_2 becomes the input capacitor. This capacitor, however, is charged through R_1 or L_1, and will not charge to peak value. The output voltage is, therefore, lower; but the charging period is relatively longer. Changes in current demands of the load resistor will affect the voltage across the load to a smaller extent than they do in the circuit which includes an input capacitor C_1. It may be noted that the diode delivers current to the unit shown in Figure 4-3b only if the instantaneous voltage of the transformer is larger than the voltage across C_1. When current flows, it is limited only by the resistance of the transformer and the resistance of the diode. At high voltages, this large current may injure the tube if C_1 discharges appreciably between cycles. The voltage and current ratings

of rectifier tubes for inductor or resistor input are larger than for capacitor input.

From the foregoing, it is apparent that the output ripple voltage is inversely proportional to the size of the capacitors and inductors or resistors making up the various stages of the filter, and directly proportional to the current flowing through the load. For the actual calculations of filtering efficiencies, the reader is referred to standard texts on this subject. The relation between D.C. and A.C. voltages at various stages of filtering is shown in Figure 4–4.

4–4. Internal resistance.

An analysis of the circuits represented by Figure 4–1 and Figure 4–3 shows that the internal resistance of a power supply is influenced by many factors, as follows: the resistance of the transformer secondary; the resistance across the diode; the resistance of the inductors in the filter stage, as well as the loss of D.C. voltage caused by less than 100-per-cent filtering. This internal resistance is further complicated by the fact that the reactance of iron-core inductors is not constant but varies inversely with current. The variation in filtering action may best be demonstrated with an experiment on a conventional radio power supply.

EXPERIMENT 4–I

Purpose: To determine the characteristics of the high-voltage section of a common power supply.

Materials: Radio power transformer rated 300-0-300-v. at 75 ma.
2 20-henry chokes
3 8-μf. electrolytic capacitors
3,000 ohm 50-watt resistor
30,000 ohm 50-watt variable resistor
0-100 milliammeter
1.0 μf. paper capacitor (C_4)
Multirange voltmeter, A.C. and D.C.
80 or 5Y3 rectifier

Procedure. For the purpose of the experiment the load may be a variable resistor, although in practice this would be represented by the plate, screen, and grid circuits of an electron tube, as shown in a later experiment. A variable resistance of 30,000 to 40,000 ohms or higher may be used to measure the characteristics of the power supply at low currents. This resistance should be made up in two parts, a variable and a fixed section. The fixed section should be selected with a rating such that the current at no time exceeds a safe value. The values shown in the list of materials satisfactorily match the indicated transformer.
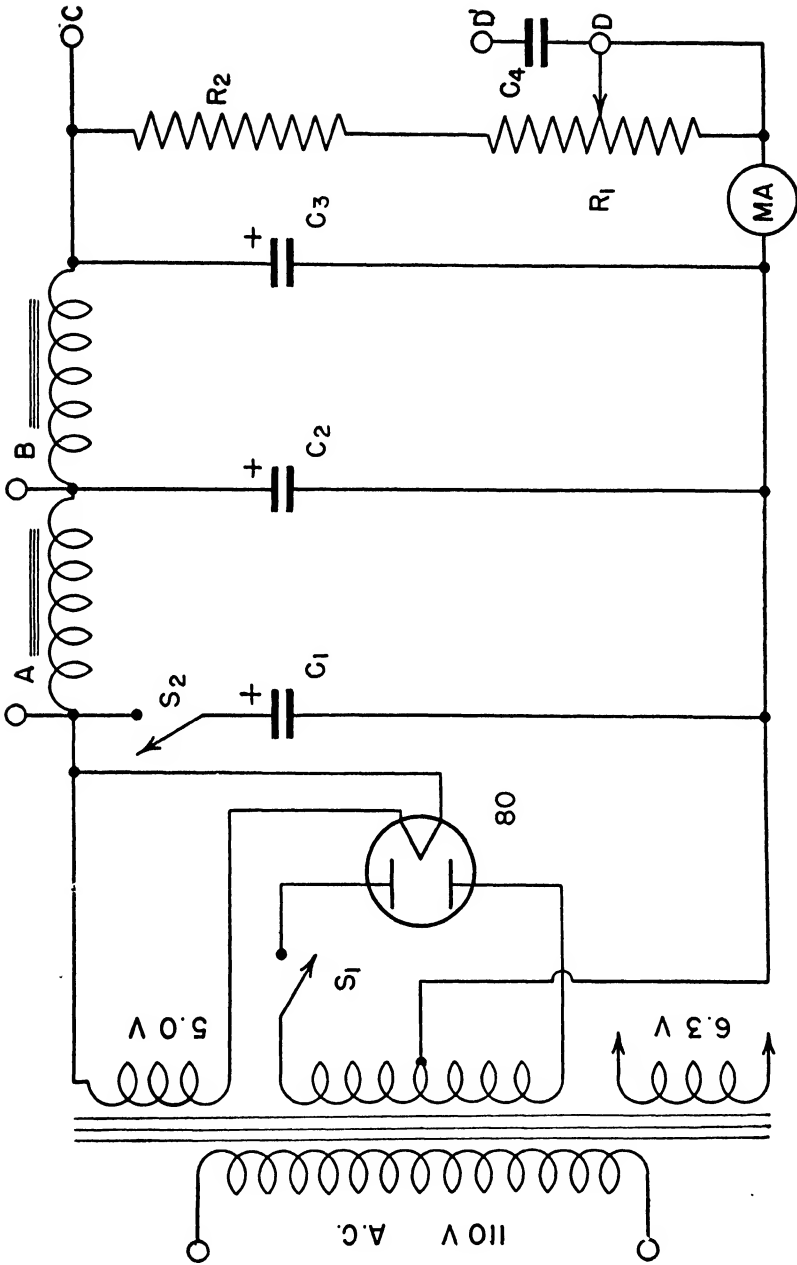
Fig. 4-5. A Conventional Power Supply.

(*Caution!* Voltages of the order of a few hundred are not dangerous, but the effects of shocks are distinctly unpleasant. Proceed, therefore, with care.)

Wire the apparatus as shown in Figure 4–5, and set R_1 to its maximum value.

Connect the A.C. line to the primary of the transformer, then slowly reduce the value of R_1 until the meter reads 10 ma. With a D.C. multi-
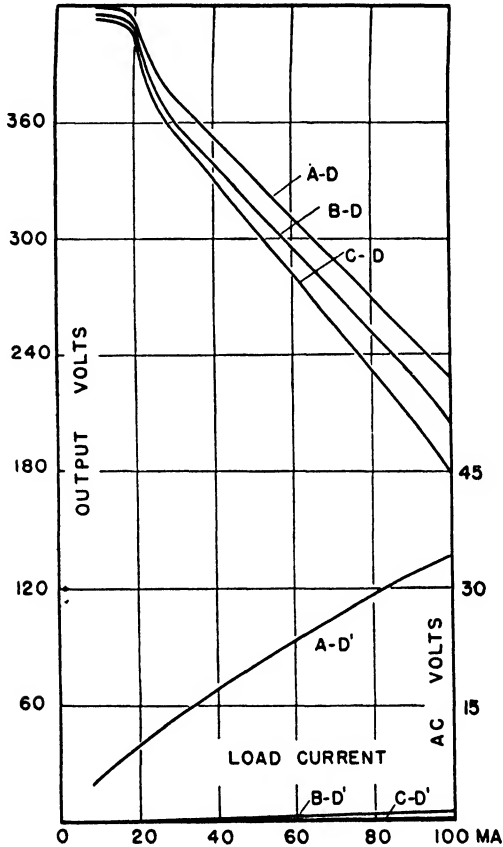
FIG. 4–6. Voltage-current Curves for a Full-wave Capacitor Input Power Supply.

voltmeter, or with a voltmeter of the proper range, measure the D.C. voltages from points A, B, and C to point D. (*Caution!* If a combined A.C.-D.C. multivoltmeter is used be sure to check the position of the range switch before each measurement.) Point D is the reference point, · and in some cases is connected to ground or to the metal supporting chassis and may be called ground potential. Also measure the A.C. voltages from points A, B, and C to point D′, and record both sets of read-

ings. Note that the capacitor C_4 between points D and D' blocks the D.C. from the A.C. voltmeter. The A.C. voltages are quite small at low currents through the load, but their values should be recorded in all cases either as a definite reading or as less than the smallest reading which can be read on the meter. Now, increase the current in steps of 10 ma. by decreasing R_1, and record both D.C. and A.C. voltages for each particular current setting. Plot the voltages at various points as a
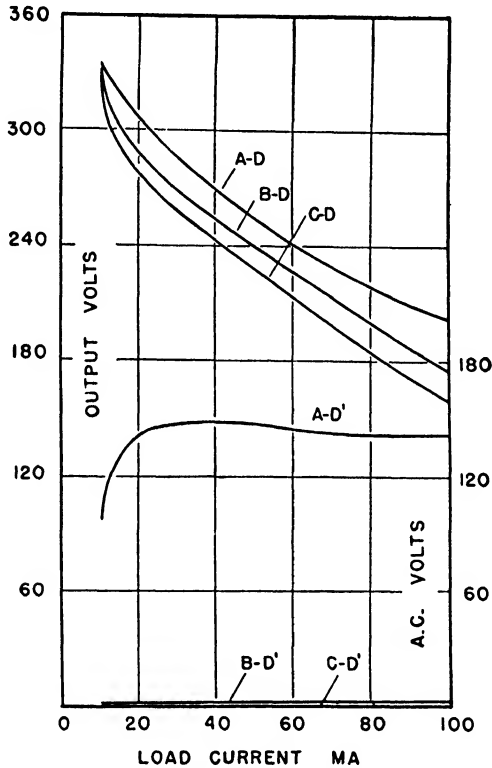
Fig. 4–7.   Voltage-current Curves for a Choke
Input Power Supply.

function of the current, as shown in Figure 4–6. Calculate the equivalent internal resistance from the slope of the curves in Figure 4–6.

Repeat the experiment after disconnecting the input capacitor C_1. This converts the power supply from a so-called capacitor input type to the choke input type. Plot the readings so obtained as shown in Figure 4–7, and compare the results with those obtained previously.

4–5. Half-wave rectifiers.

The rectifier illustrated in Figure 4–5 will operate even if one of the plates of the tube is disconnected. In this case, the input to the filter

will be represented by Figure 4–2c. It will be noticed that current flow is obtained only during half the time, corresponding to the periods when the connected plate is positive. The output across the load R_1 and R_2 is still direct current, since the current flows only in one direction. The ability of the filter network C_1, C_2, C_3, L_1, L_2 to hold the current constant is, however, greatly reduced, as might be expected from the fact
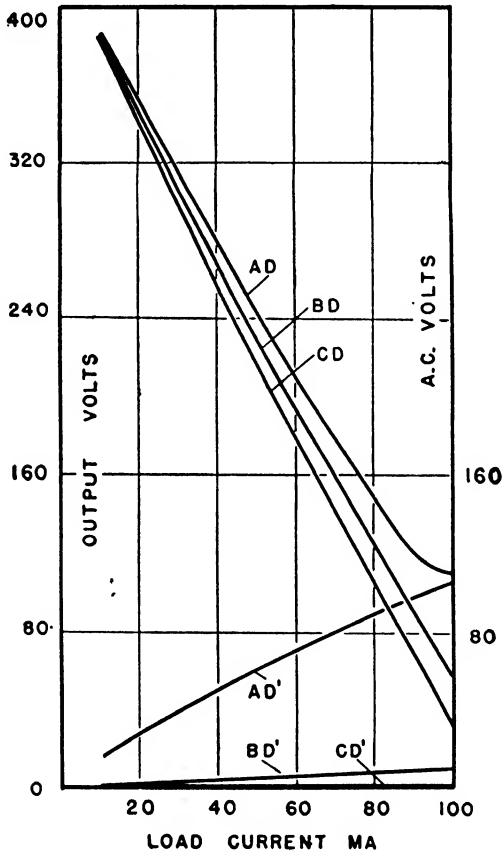
Fig. 4–8. Voltage-current Curves for a Half-wave Capacitor Input Power Supply.

that under half-wave conditions the capacitor has to maintain its peak voltage for a longer interval of time. Filter theory indicates that efficiency of filtering increases as X_C decreases and X_L increases. A change from full-wave to half-wave rectification represents a drop in frequency which results in a higher value for X_C and a lower value for X_L. The filtering efficiency is therefore decreased by this change in the circuit.

EXPERIMENT 4–2

Purpose: To determine the characteristics of a half-wave rectifier and filter.

Materials: Same as for Experiment 4–1.

Procedure. Repeat Experiment 4–1, using only one plate of the rectifier, but with input capacitor C_1 in place, and plot as in Figure 4–8.
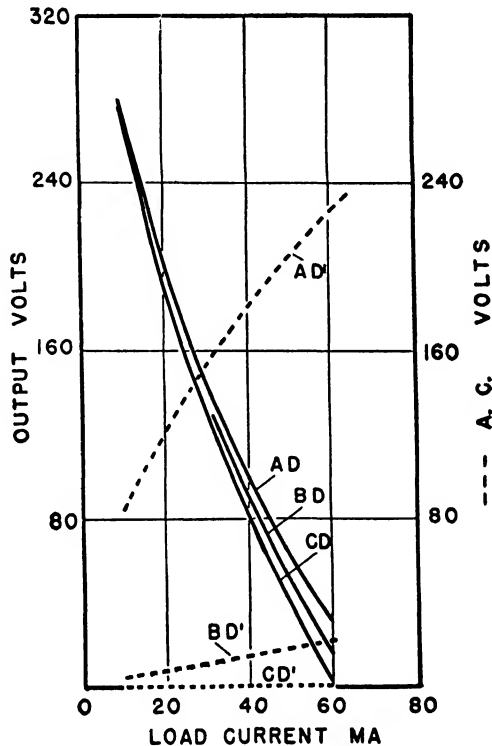
FIG. 4–9.   Voltage-current Curves for a Choke Input Half-wave Rectifier Power Supply.

Again repeat the experiment, disconnecting the input capacitor C_1, and plot as shown in Figure 4–9.

Compare all results and write up your conclusions

4–6. Summary.

Some of the conclusions may be summarized briefly as:

(1) The voltage output of a simple power supply is never constant but varies with the load.

(2) The A.C. voltage or ripple voltage is low when the power drain is low, but increases with an increase of load.

(3) The full-wave capacitor input power supply produces the highest voltage and the lowest ripple voltage for small currents, but the voltage decreases somewhat faster with increased load than for the choke-input type.

(4) The half-wave rectifier supply is less than half as good as the full-wave type, and the ripple voltage is much higher.

(5) The power supply is not the equivalent of a fully charged or new battery and must, therefore, be used with discretion.

EXPERIMENT 4–3. SUGGESTIONS FOR ADDITIONAL WORK

If a cathode-ray oscillograph is available, the wave form and value of peak voltage may be measured at each of the points A, B, and C with respect to D' for various loads. The oscillograph must be equipped with an amplifier, for it will be remembered that the A.C. voltages are usually quite small. If the peak voltages are to be measured by this means, the oscillograph must, of course, be calibrated with a known voltage. Compare the wave forms so obtained with the idealized curves for rectifier alone, as shown in Figures 4–2 and 4–4.

4–7. Rectifier power supply versus batteries.

From the foregoing, it may appear that power supplies as usually constituted are poor substitutes for batteries. This is not so, however, if the unit is used for its intended purpose. Most applications are to audio- or radiofrequency amplifiers, where the current output is changing rapidly about an equilibrium value. We have seen that a combination of inductance and capacitance will tend to maintain a steady voltage even though the rectifier delivers pulses. The output choke and condenser will maintain the output voltage, but only for short periods, that is, for variations below the time constant of the filter combination. If the supply is to be used for D.C. circuits, such as those described in Chapters 2 and 7, the supply must be designed for a heavier rating ("brute supply"), or special methods must be employed to keep the voltage constant.

4–8. Voltage dividers.

In order to obtain lower voltages from the ordinary power supply, a resistor is usually connected across the output, and voltages are tapped off from the correct points. The voltage obtained at one of these taps on the divider depends on the ratio of the resistance tapped in comparison to the resistance of the whole, and on the current flowing to the load connected to the divider, as may be demonstrated by Experiment 4–4.

EXPERIMENT 4–4

Purpose: To study the effect of power-supply characteristics on an electron tube used as a load.

Materials: Adjustable bleeder resistors, 20,000 ohms and 1,000 ohms
0-10 voltmeter
0-20 voltmeter
3 0-300 voltmeters
0-100 milliammeter
Power supply of Experiment 4–1
2,000-ohm potentiometer
7.5-v. battery

Procedure. This experiment is designed to demonstrate how voltage dividers should or should not be used. It may be considered an extension of Experiment 4–1, with an electron tube substituted for the load
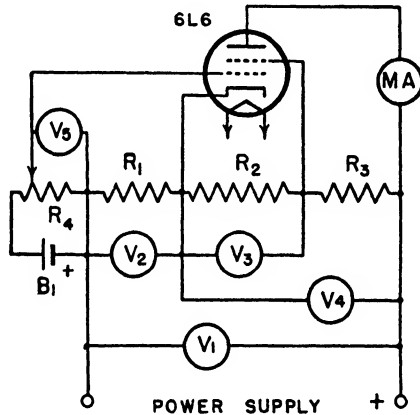
Fig. 4–10. A Power Supply and Voltage Divider Applied to an Electron-tube Load. R_1 = 1,000 ohms, 10 watts; R_2 + R_3 = 20,000 ohms, 50 watts; R_4 = 2,000-ohm volume control; V_2 = 0–20 voltmeter; V_1, V_3, V_4 = 0–300 voltmeters; V_5 = 0–10 voltmeter; MA = 0–100 milliammeter; B_1 — 7.5 v.

R_1 and R_2. Connect the apparatus as shown in Figure 4–10, and with the 6L6 tube removed from its socket, adjust resistor R_1 for the proper grid voltage of this tube (— 15 v.) as indicated by voltmeter V_2. The value of R_1 will be of the order of 1,000 ohms, while the value of R_2 + R_3 may be of the order of 20,000 ohms. Now adjust the tap on R_2 + R_3 so that the voltmeter V_3 reads approximately 250 v. (*Note:* The actual adjustments of the resistors should be made with the power supply turned off.)

Now read and record the readings of all voltmeters; then set R_4 at a value such that voltmeter V_5 reads zero, and insert the 6L6 tube in its socket. After the tube has warmed up, note and record the new readings of the voltmeters as before. What conclusions can you draw from this change? Note that the readings of V_2 increase while those of V_3, V_4, and V_1 decrease.

Readjust the values of R_1 and R_2 so that, with the 6L6 tube operating, the voltages will be the correct ones, namely, — 15 v. grid and 250 v. screen; then change R_4 so that V_5 changes in 2-v. steps, and record the readings of all meters. From the reading of the plate milliammeter, the values of g_m may be calculated at each step and compared with those specified by the manufacturer of the tube. Can you account for the divergence of your values? The experiment may be repeated with R_1 approximately 500 ohms and $R_2 + R_3$ approximately 10,000 ohms. It is obvious that, in order to realize the true efficiency of the tube, some method must be devised to maintain the voltages at meters V_2 and V_3 at a constant value. If the voltage at V_5 is an A.C. voltage, a large capacitor across R_1 and another across R_2 should be able to maintain these voltages substantially constant at the average value. This control cannot be easily demonstrated without elaborate equipment, but the secondary of a 6-v. step-down transformer may be substituted for R_4 and V_5, and alternately connected to and disconnected from the mains, the effects on all D.C. voltages being noted. The D.C. plate milliammeter will not be affected greatly by the changes in plate current. The value of g_m may be determined approximately by substituting a 1,000-ohm resistor for the plate milliammeter and measuring the voltage across this resistor by means of a 25-v. A.C. voltmeter. The voltmeter must be protected from the D.C. by a large capacitor, as in Experiment 4–1. Assuming no distortion, the current in the plate circuit may be calculated from $E = RI$, and the value of g_m from

$$g_m = \frac{\partial i_p}{\partial e_g}$$

provided the input A.C. voltage is known.

Repeat the measurement of g_m, with a 50-μf. electrolytic capacitor shunting R_1, and an 8-μf. capacitor across R_2. Note that the calculated value of g_m is larger than before. What is the action of these two capacitors?

4–9. Gaseous-tube voltage regulators.

While capacitors are able to maintain constant voltage for relatively short periods, they are entirely useless at very low frequencies or at zero frequency (D.C.), and other methods must be used. Certain types of neon or argon lamps have the property of maintaining a constant

voltage across their terminals over wide variations in total current. This property arises out of the fact that after the voltage has reached a value sufficient for the maintenance of ionization an increase of current results in the production of more ions but the effective resistance decreases as the current increases. The RI drop across the tube thus remains constant.

The characteristics of all of these lamps include a certain starting voltage, or breakdown voltage, that is, the voltage necessary to initiate the ionization of the gases, and a breakoff voltage at which the rate of production of ions is less than the loss of ions resulting from recombination. Below the breakoff point the lamp will cease to function. These two characteristic voltages do not coincide, and the starting voltage may be 30 or 40 per cent higher than the breakoff voltage.

TABLE 4–1

	Type				
	991	874	VR75	VR105	VR150
Operating voltage.........	75	90	75	105	150
Current:					
Low................	6	10	5	5	5
High..............	12	50	30	30	30

EXPERIMENT 4–5

Purpose: To study the characteristics of several gaseous-tube voltage regulators.

Materials: Several voltage regulators 874, 991, VR75, VR105, VR150, G-10, or S-14

Variable load resistor, 30,000 ohms

0-50 milliammeter

0-150 voltmeter

20,000-ohm variable resistor

Procedure. Select one of the tubes shown in Table 4–1, and calculate the value of R_1 in Figure 4–11, so that the current drawn will be almost equal to the full rating of the tube. R_1 may be calculated from the equation

$$R = \frac{E_s - E_t}{I},$$

where E_s is the power-supply voltage and E_t the voltage across the tube. Set R_1 to this value and note the current and voltage with R_2 disconnected. Connect R_2 and slowly decrease its value, noting the current

and voltage as indicated by the meters. A change in R_2 corresponds to a change in load resistance. With a nominal value of R_2, vary the value of R_1 and note the changes in the reading of the meters. This variation corresponds to changes in line voltage. Plot the voltage across the tube as a function of tube current, and note that the voltage is almost constant over a relatively wide range of current.
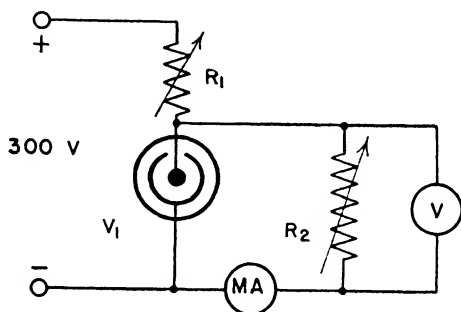
FIG. 4–11. The Use of Voltage-stabilizer Tubes.

The chief limitation of these lamps is the high starting voltage, which results in a considerable wastage when they are used to supply grid voltages of receiving-type tubes.

4–10. Ballast tubes.

If the line voltage rises 10 or 20 per cent above the normal value, some types of electronic equipment may be overloaded and consequently damaged. The so-called ballast lamp may be used as a protection against such eventualities.[3] The lamp consists of an iron wire of the desired resistance in an atmosphere of hydrogen. As the line voltage rises, the current across the lamp increases until a certain critical voltage is reached. At this value, the resistance of the wire rises almost proportionately with voltage, causing the current to remain constant. Time is required to establish equilibrium, so that these lamps offer little or no protection against transients. The operation of the lamp is also affected somewhat by the ambient temperature.

EXPERIMENT 4–6

Purpose: To study the characteristics of a ballast lamp.

Materials: 5A5 or similar lamp
           A.C. 0-1 ammeter
           A.C. 0-25 voltmeter
           Variac transformer
           Load resistor matched to maximum safe current of lamp

[3] Jones, H. A., *Gen. Elec. Rev.*, May, 1925, and Sept., 1925.

Procedure. Connect a 5A5 ballast lamp, or any other similar tube, as shown in Figure 4–12. The voltages and currents used in this experiment are A.C., so that A.C. meters must be used throughout. The Variac
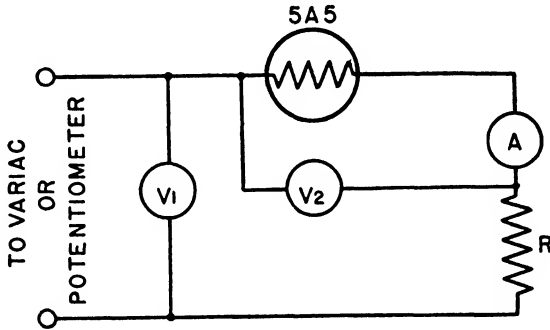
FIG. 4–12. The Use of a Ballast Lamp.

transformer simulates the variable line voltage, and the resistor R_1 serves as a load. The value of R_1 must be matched to the tube. Increase the Variac voltage slowly and note the meter readings, plotting as
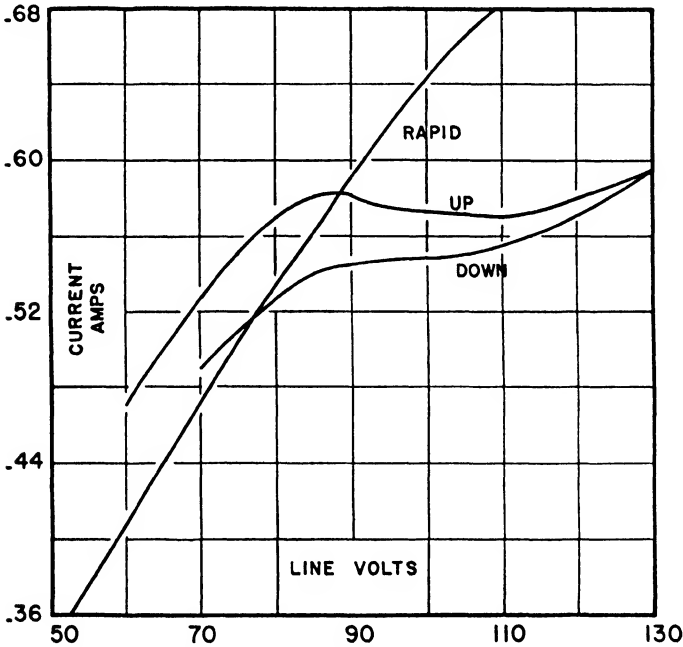
FIG. 4–13. Current-voltage Curves for a Ballast-lamp Circuit.

shown in Figure 4–13. After the maximum allowable reading has been reached, indicated by a distinct glow in the lamp, slowly reduce the voltage and again note the readings and plot as in Figure 4–13.

Repeat the measurements with an assistant, this time changing the voltage as suddenly as possible from a normal value to a series of higher or lower values. Again plot current as a function of artificial line voltage.

4–11. Rectifier voltage doubler.

A useful circuit for the rectification and filtering of current from the A.C. mains is shown in Figure 4–14. The circuit is unique in that the output voltage is twice the peak line voltage. Basically, the circuit is a double rectifier so arranged that the two units are in series. When the upper side of the A.C. line is positive, diode T_1 passes current and charges capacitor C_2 as indicated in the figure. When the lower side of the A.C. line is positive, diode T_2 charges C_1 in the manner indicated.
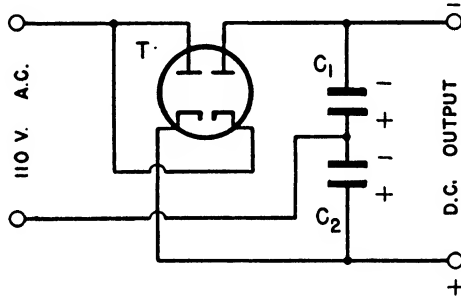
Fig. 4–14. A Voltage-doubler Rectifier.

Thus, at low output current, C_1 and C_2 are both charged to the peak A.C. line voltage and the output voltage is approximately 320 v. at 115 v. root mean square A.C. line voltage.

When the current is drawn at the output terminals by the load, the voltage drops below this value by an amount that depends on the magnitude of the current and the size of the capacitors C_1 and C_2. For capacitor sizes of the order of 16 μf., the voltage drops to only 250 v. at 40 ma., but drops to 200 v. for 4-μf. capacitors at the same current.

Tubes such as the 25Z5, 25Z6, and so forth, are especially adaptable to doubler operation. The D.C. output may be filtered further in the conventional manner. No ground may ordinarily be used with this type of circuit since one terminal of the A.C. line is at ground potential and neither of the output terminals are in common with the line. This difficulty may be overcome if the circuit is rearranged to make one side of the line in common with the negative output terminal. In this circuit, one diode is used to charge a capacitor, which on the following half cycle discharges through the diode in series with the line voltage and another capacitor. The second capacitor is in this manner charged to

twice the peak line voltage on each positive cycle. This circuit is known as a half-wave voltage doubler.

Circuits of this type are often useful at low voltages because of their low cost, and are used to advantage at high voltages, since twice the transformer-output voltage is obtained.

4–12. Electronically regulated power supplies.

The ideal power supply for all applications is not represented by any of the ones so far discussed in this chapter. Fully charged storage batteries or a new heavy-duty dry cell are quite superior to the average power pack in regard to stability and ability to maintain voltage with changes in current demands. However, the bulk, weight, and expense of these units has caused them to be gradually replaced by electronic power supplies in all cases except where extreme stability has to be maintained in precise measurements of small voltages.

The ordinary power supply may be stabilized by electronic methods and in a fairly simple manner.

Let us suppose that the resistor R_1 of Figure 4–5 is adjusted to pass a current of 50 ma. If another load is now connected in parallel with the load R_1 and R_2, the supply will be required to deliver an additional current, resulting in a net reduction of the output voltage, as shown in Figure 4–6. The voltage may be kept at its former value, however, if the resistance of the resistor R_1 is increased so that the total demand from the rectifier unit again becomes equal to 50 ma. If the adjustment could be made exactly, the power supply in effect would seem to have zero internal resistance. This load adjustment fluctuates continually when the load is an electron tube performing a useful operation. If the load R_1 is also made an electron tube, with its grid controlled in the proper direction by the output voltage, the desired effect may be produced.
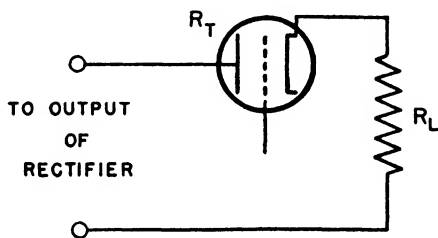
FIG. 4–15.   Elements of a Stabilized Power Supply.

A regulating electron tube may also be placed in series with the load, the voltage being divided between the control tube and the load instead of the current as in the previous case. Such a scheme is shown in Figure 4–15. For a complete discussion and literature of the various

methods of control the reader is referred to an excellent discussion by Hunt and Hickman.[4]

In practice, the use of control tubes to acquire the desired degree of stabilization is complicated by a number of factors, some of which will become evident through a consideration of a simple stabilized power supply shown in Figure 4–16.[5,6]

EXPERIMENT 4–7

Purpose: To study the principle of electronically controlled power supplies.

Materials: Parts shown in Figure 4–16
0-10 voltmeter
B batteries
Bleeder resistor
0-300 voltmeter
0-100 milliammeter

Procedure. Wire the apparatus as shown in Figure 4–16, or use the R.C.A. type TMV-118-B power supply. The circuit shown here differs only in certain details from the commercial supply, but is more flexible in that some of the changes recommended below can be performed without having to dismantle the unit, as would be necessary with the commercial apparatus. The heater supply for the 2A3 regulator tube must be obtained from a separate winding to assure sufficient insulation between the filament of this tube and the other voltages. When the quality of the insulation of the 2.5-v. winding is not known, a separate 2.5-v. transformer may be used for this purpose. If the separate transformer is used, it should be provided with a separate switch, so that the remainder of the unit may be warmed up before the 2A3 is put into operation. The value of R_1 depends on the voltage supplied by the power transformer, and may be calculated from $E_o - 105 = .025\ R$, where E_o is the output voltage of the unregulated power supply, that is, the voltage from (a) to ground of Figure 4–16 when this portion of the supply is *loaded* for at least 25 ma. The value specified in the legend of Figure 4–16 was calculated for 400 v. from (a) to ground.

After the circuit wiring has been checked, switch on the line, and with R_8 toward the positive side, check the output voltage with a 0-300 voltmeter. The output voltage should be between 100 and 150 v. if the regulator is working properly. Shift the potentiometer R_8 through its range, and observe the changes in output voltage. If the value of R_8 is

[4] Hunt, F. V., and Hickman, R. W., *R.S.I. 10*, 6, 1939.
[5] Neher, H. V., and Pickering, W. H., *R.S.I. 10*, 54, 1939.
[6] Working, E. B., *Ind. Eng. Chem., Anal. Ed., 10*, 434, 1938.

FIG. 4-16. A Stabilized Power Supply.
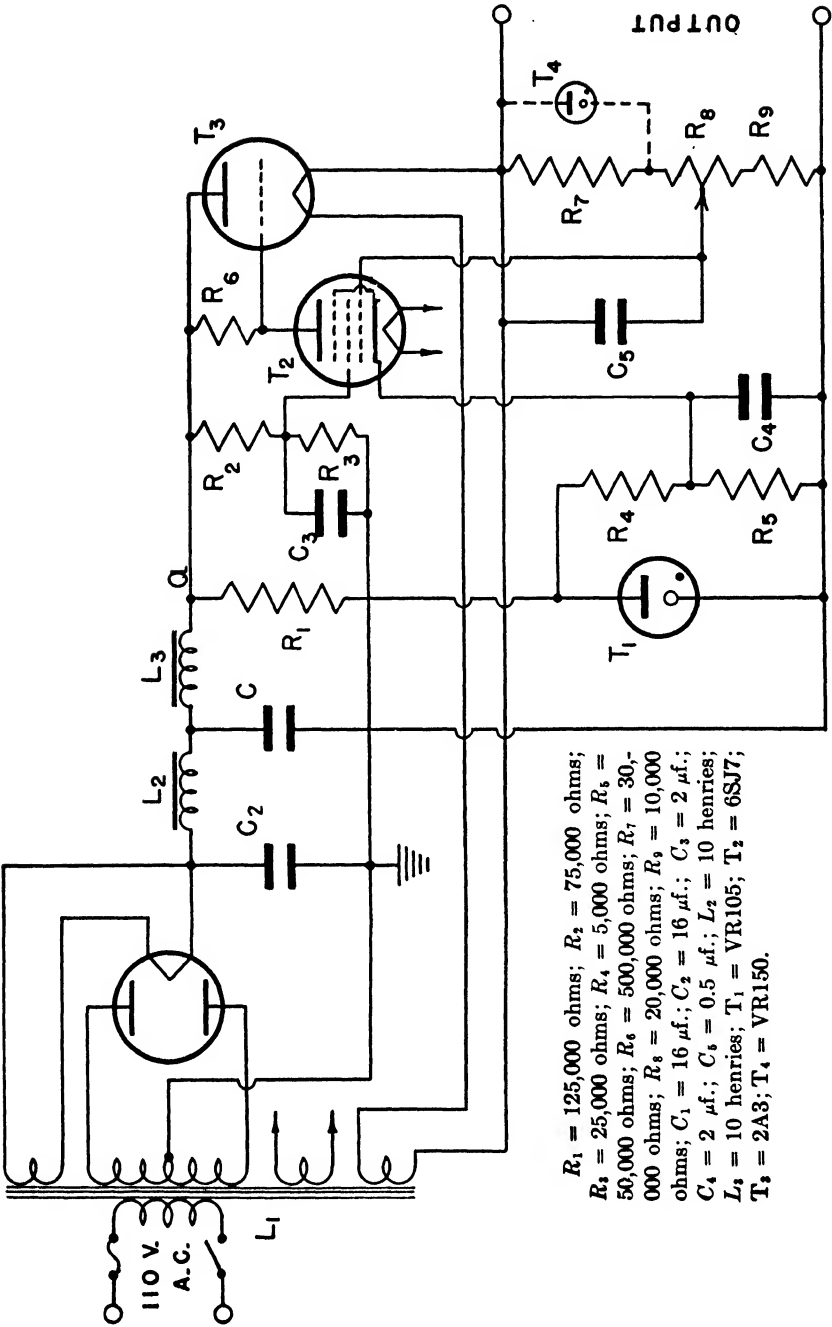
$R_1 = 125,000$ ohms; $R_2 = 75,000$ ohms; $R_3 = 25,000$ ohms; $R_4 = 5,000$ ohms; $R_5 = 50,000$ ohms; $R_6 = 500,000$ ohms; $R_7 = 30,000$ ohms; $R_8 = 20,000$ ohms; $R_9 = 10,000$ ohms; $C_1 = 16$ $\mu f.$; $C_2 = 16$ $\mu f.$; $C_3 = 2$ $\mu f.$; $C_4 = 2$ $\mu f.$; $C_5 = 0.5$ $\mu f.$; $L_2 = 10$ henries; $L_3 = 10$ henries; $T_1 = VR105$; $T_2 = 6SJ7$; $T_3 = 2A3$; $T_4 = VR150$.

correct, the output voltage should change from about 100 to 300 v. If these adjustments produce the proper variations, proceed with the following measurements as in Experiment 4–1.

Set the output voltage to its maximum value; then connect the 30,000- and 3,000-ohm load resistors and the milliammeter in the output, as in Experiment 4–1. Change the resistor, and measure the output voltage as a function of the output current. Plot as shown in Figure 4–17, and note that the output voltage is practically independent of current until the capacity of the supply has been exceeded, after which the voltage drops abruptly. Repeat at other output voltages by changing the setting of R_8. Plot, and note that the current capacity is
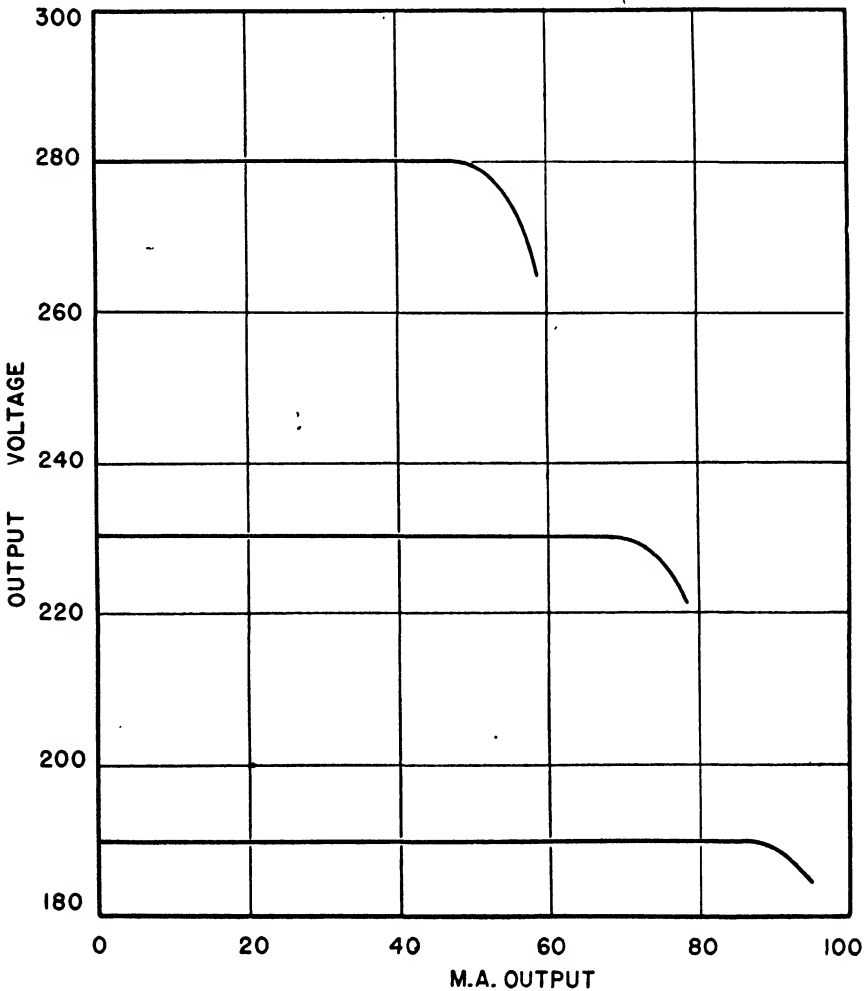
Fig. 4–17.

increased at lower output voltages. Calculate the effective internal resistance of the regulated supply from these data.

The regulation of the supply against line-voltage fluctuations may be performed satisfactorily, provided a sensitive method is employed for following the minor variations produced thereby. One way is to connect, in series opposition with the output, a voltmeter and as many B batteries as may be required to reduce the output voltage to almost zero. If five 45-v. B batteries are used in this manner, the unopposed output voltage may be set to approximately 235 v. and a 0-10 voltmeter used to measure the differences between the supply voltage and the voltage of
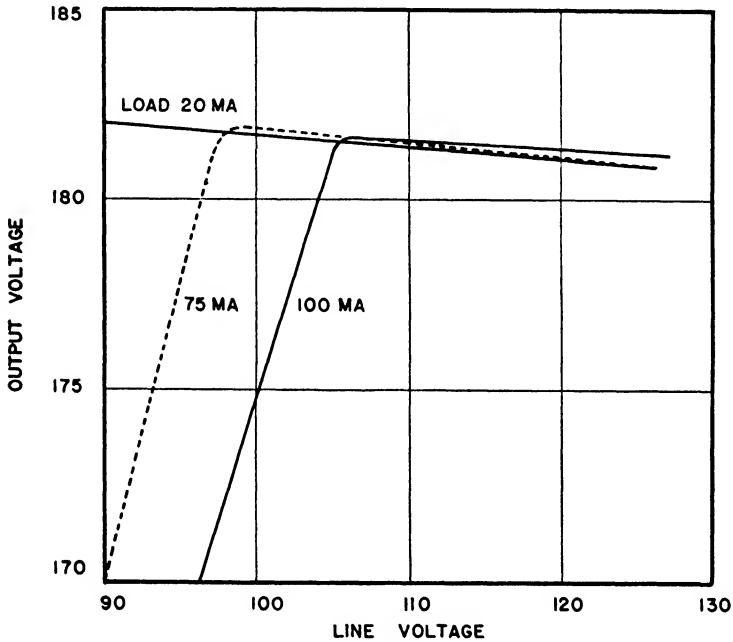
Fig. 4–18.

the batteries. The voltmeter, when used in this manner, will detect a change of .1 v. in the 235-v. output, corresponding to a sensitivity of 1 part in 2,350.

The output voltage may also be measured with a type K or student potentiometer, by connecting this unit from ground to a point on the load resistor at which the potential is approximately 1 v.

After inserting either one of the above voltage-measuring devices, connect the power supply to a variable input transformer and change the A.C. voltage to the supply from 75 to 130 and note the change in output voltage. Repeat at other settings of R_s and plot as shown in Figure 4–18. Note that this method of measurement and plotting em-

phasizes the changes in the output voltage, but that in all cases the percentage change in total voltage is small. Replot the data as percentage change in output voltage against the percentage change in the line voltage. The reciprocal slope of this curve may be represented as the regulation factor for the electron-tube stabilizer.

Measure the ripple voltage or A.C. output voltage as a function of the load by connecting a properly isolated A.C. voltmeter across the output, as in Experiment 4–1. Repeat at various voltages and loads. Repeat this measurement after disconnecting C_5. Note that the use of C_5 places the entire A.C. output voltage across the grid of the amplifier tube, while only the portion of the D.C. voltage represented by R_8 and R_9 is similarly used. Remove C_2 and remeasure the ripple voltage with C_5 in the circuit. Is C_2 necessary? To answer this question, with C_2 removed, measure the changes in output D.C. and A.C. voltage as a function of output current.

Repeat the measurement of stability with reference to line-voltage fluctuations after removing R_1, R_4, and R_5, T_1, and C_4, and replacing them with a 90-v. battery connected so that the cathode of T_2 becomes positive with respect to ground. Note that the purpose of T_1 is to maintain the cathode of T_2 at a constant potential with respect to ground, so that the changes in the output voltage may become effective grid voltages. If this voltage changes slightly, the realized regulation is less than that calculated from the tube parameters. Note also that changes in screen and plate voltage, as well as changes in heater voltages of the 6SJ7 tube, are obtained from the unregulated portion of the supply and serve to enhance the effect of the grid voltage. If the gain of T_2 is large, and if T_1 holds the cathode voltage constant, the stabilization will be almost perfect and the resistance almost zero. Since available tubes produce voltage amplifications of only 100 to 200 as a maximum, the supply under study is not perfect, but offers a very great improvement over the unregulated supply of Figure 4–5.

An improvement in regulation at the expense of output voltage range may be obtained by replacing R_7-C_5 with a voltage-regulator tube, shown dotted in Figure 4–16. This tube concentrates the D.C. output voltage variations across R_8 and R_9, and increases the regulation factor by 3 to 5 times, especially at high output voltages. In this way T_4 provides increased regulation for D.C. in a manner similar to the increased regulation supplied by C_5 for A.C. voltages. Repeat the experiment after substituting the voltage-regulator tube and note the increased regulation at high voltages. Note also that the output voltage may not be reduced to low values without destroying the regulation. Notice that this failure occurs at the point where the voltage becomes too low to permit the maintenance of the arc in T_4.

4-13. Constant-voltage transformers.

By properly connecting two resonant transformers in opposition and using the difference for the output voltage, a regulator transformer is obtained which is relatively independent of line-voltage variations but not independent of line-frequency changes. Changes in frequency accompanying some line-voltage variations are quite small, and an excellent regulation factor may be obtained by this method.

Since the intensity of light produced by a heated-filament type lamp varies as the third or fourth power of the voltage, as shown in Chapter 3, a method based on light intensity may well be used to study the characteristics of these transformers. A photoelectric measurement of the light intensity of a lamp fed from a regulated transformer will serve as an excellent method of determining slight voltage changes in these transformers.

EXPERIMENT 4-8

Purpose: To study the regulation obtained with a constant-voltage transformer.

Materials: Photocells, meters, and so forth, of Experiment 3–7
Constant-voltage transformer
Variac transformer
0-150 A.C. voltmeter

Procedure. Connect the apparatus as in Experiment 3–7, but supply the voltage to the lamp from a regulated transformer, connecting the lamp either to a step-down transformer fed from a 115-v.–115-v. regulated transformer or directly to a regulated step-down transformer. Vary the input voltage to the regulated transformer with a variable transformer, and measure the input voltage with a voltmeter. Plot the photocurrent against the input voltage. Include the curve for the unregulated transformer of Experiment 3–7 for comparison. Set the Variac to 115 v. and note the meter readings with time. If variations appear, the chances are that they are due to line-frequency variations as well as to voltage variations.

4-14. Electronically regulated power supply for light sources.[7]

The basic principles of the power supply shown in Figure 4–16 may be used to regulate a light source. The unit as described will not, however, supply sufficient power to operate present-day incandescent lamps, since the smallest projection bulb requires 500 ma. at voltages of 50 or 100. The power output of the unit may be increased by using five or more

[7] Chance, B., *Electronics*, Feb., 1940, p. 24.
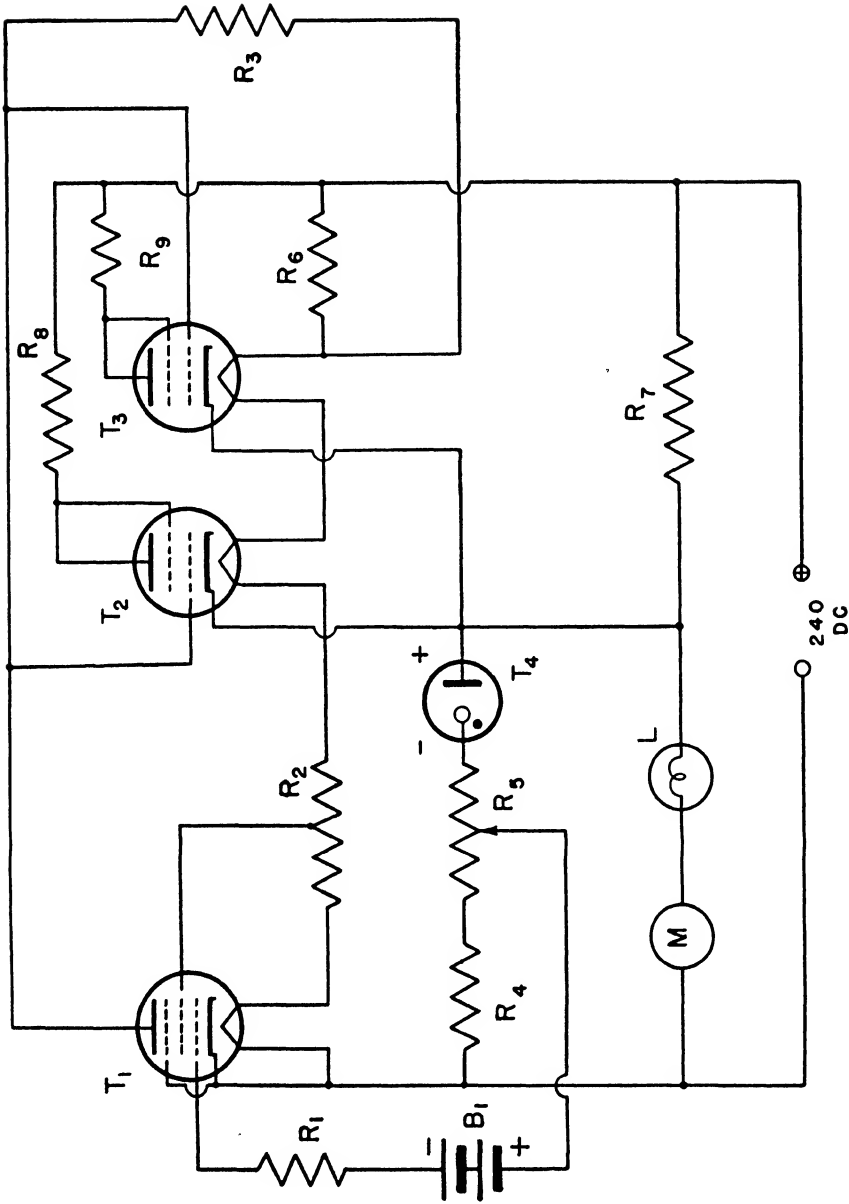
FIG. 4-19.   A Light-source Regulator.

2A3 tubes in parallel, in combination with a power transformer and chokes capable of supplying this current. Since the regulation of light sources for use with photocells is more critical than for some other uses, as has been indicated before, additional amplification must be provided. This amplification may be achieved by the use of an additional stage, but is complicated, as can be seen from the following considerations.
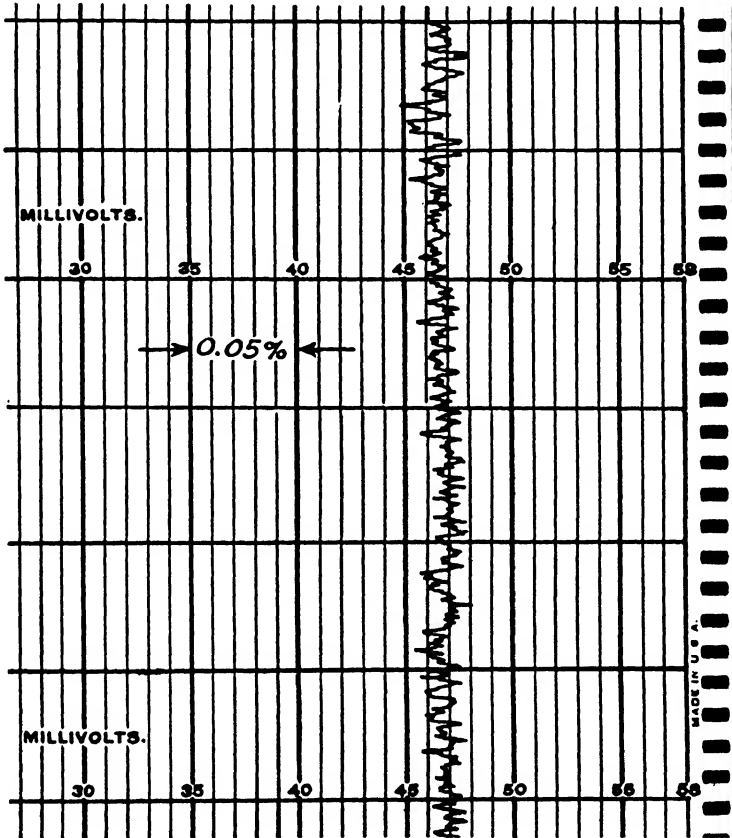
Fig. 4-20. Residual Voltage Fluctuation of a Regulated Light Source.

Since the heater and screen voltages for the 6SJ7 tube of Figure 4-16 are supplied from an unregulated source, this power supply has a tendency to over-regulate. If another amplifier is inserted between the 6J7 and the power tube, small fluctuations of plate current caused by changes in heater and screen voltages will be amplified and the output voltage will thus be regulated at varying voltage levels, depending on the values of these voltages. If the inserted tube has a negative transconductance, its effect will again over-regulate. Although tubes with negative transconductance such as the 6A8 (Chapter 5) have been used successfully by the

authors, the simple circuit shown in Figure 4–19 gives adequate regulation for most light sources when properly adjusted. It may be noted that only a portion of the lamp current flows through the two beam power tubes, the remainder flowing through R_7.

The circuit shown in Figure 4–19 derives all its power from a 240-v. D.C. line, but may be operated from a rectified power supply of sufficient rating. The heaters may be operated by step-down transformers from the same power line.

Briefly, the operation of the circuit is as follows. If the voltage across the lamp changes, owing either to a change in the load or to a change in line voltage, the change is impressed on the grid of the 6J7 tube, for the VR-75 tube retains its nominal voltage and almost half of the change in line voltage is thus impressed across R_4 and R_5. If the line increases by 1 v., the momentary change in the grid voltage will be about .5 v. in the positive direction, resulting in an increase in the plate current of this tube. The grids of the two 25L6 tubes will consequently be made more negative, which has the effect of increasing the resistance of these tubes, and the total resistance in series with the lamp is thereby increased by an amount which almost offsets the .5-v. original change in the voltage across the lamp. That is, the voltage across R_7 has been increased by almost 1 v. and has therefore almost entirely compensated for the line-voltage variation. The stability obtained with this unit is shown in Figure 4–20, in which 1 mv. represents a change of .01 per cent in the actual voltage of the lamp. The graph was obtained by connecting the lamp voltage in series opposition to a battery and the terminals of a 50-mv. recorder. The record shows that the residual variation is of the order of .01 per cent. This is a stability of one part in 10,000 for normal line-voltage variations of about ±5.0 v.

SUPPLEMENTARY LITERATURE

Anderson, H. L., Dunning, J. R., and Mitchell, D. P., "Regulator System for Electromagnets," *R.S.I. 8*, 497, 1937.

Danforth, W. E., "Concerning Thermionic Regulation of D.C. Generators," *R.S.I. 10*, 211, 1939.

Everitt, W. L. (editor), "Fundamentals of Radio," Prentice-Hall, Inc., New York, 1942.

Lawson, J. L., and Tyler, H. W., "A Magnet Current Stabilizer," *R.S.I. 10*, 304, 1939.

PROBLEMS

1. Design a simple power supply capable of delivering 130 v. at 2 ma. with an A.C. ripple voltage less than .1 v.

2. Design a power supply to furnish the polarizing voltage for a phototube at 100 v. with its positive side at ground potential.

3. Design a voltage-doubler circuit which delivers 300 v. at 25 ma. with a ripple voltage of less than .1 per cent of the D.C. voltage.

4. Compare the filtering efficiencies and the voltage loss of two filtering networks, one consisting of a 10,000-ohm resistor used in conjunction with a 10-μf. capacitor, the other of a 20-henry choke of 200 ohms resistance used with the same capacitor.

5. Design a 7,000-v. power supply which will deliver 1 ma. with a ripple voltage of less than 10 v. Specify tubes and insulation required, and show how the operator could be protected from the high voltage during operation and repair.

6. Design a power supply to deliver 300 v. at 100 ma. with a ripple voltage of less than .01 per cent, and with a reactance presented to the load of less than 200 ohms at 50 cycles. The D.C. regulation should be equivalent to that of a series resistance of less than 500 ohms.

7. Design a regulated power supply to deliver 200 v. at 100 ma., with a D.C. regulation factor equivalent to a resistance of less than 10 ohms.

8. Design a stabilized power supply capable of delivering 1,000 v. with a stability of 1 v. for a 10 per cent change in line voltage.

9. Show how several voltage-regulator tubes may be used in series to obtain a stabilized voltage at 600 v. D.C.

10. Show how a stabilized voltage of 75 v. at 2 ma. may be obtained from a circuit using a VR150/30 tube.

11. Gaseous-type diode rectifiers often produce high-frequency oscillations which cause radio interference. Show how these disturbances may be eliminated.

12. Let the chokes in the filter section of the power supply given in Figure 4–5 be placed between ground and the mid-tap of the transformer. Show how this would interfere with good filtering action.

CHAPTER 5
Multigrid Tubes

Introduction.

Tubes with many desirable characteristics may be obtained by adding one or more grids to the basic triode. When a grid which is called the screen grid or shield grid or G_2 is placed between the control grid and plate, the tube becomes a tetrode. If an additional grid is inserted between the screen grid G_2 and the plate, the tube is known as a pentode. In order to avoid confusion, the grids are usually numbered consecutively starting from the cathode. In a pentode therefore, the control grid is G_1, the screen grid G_2, the suppressor grid G_3. If additional grids are used, as in pentagrid converters (septodes or octodes), the same system is used. The construction of a screen-grid tube is shown in Figure 5–1 and the diagram for tetrodes and pentodes is shown in Figure 5–2.

5–1. Tetrodes; grid-plate capacitance.

The impetus for the design of the tetrode arose from the fact that the capacitance between control grid and plate of a triode is large enough to be important at radio frequencies. Current flowing in this capacitance induces oscillation at these frequencies. The oscillation can be controlled by using external networks to neutralize the effect of the internal capacitance. The familiar neutrodyne circuit may be cited as one example of this type of compensation. The capacitance can be reduced within the tube itself by placing a shield in the form of a screen grid between the control grid and plate as indicated in the introductory section. The shield must be in the form of a grid to allow electrons to pass freely between the grid wires to the plate and in order to realize the full effect of this shield it should be extended completely around the plate, as shown in Figure 5–1. In use, the shield is connected electrically but not mechanically to the cathode by means of a large capacitor, so that no A.C. voltage can be developed between these two elements.

5–2. Input and output capacitances of tetrodes.

It is apparent from Figure 5–1 that, although from the geometry of the construction the capacitance between the grid and plate is reduced, the reduction is accomplished only by an increase of the grid-cathode capacitance as well as the plate-cathode capacitance, since the shield grid

is effectively connected to the cathode. This is not objectionable in tuned amplifiers at ordinary radiofrequencies, since these capacitances may be made a part of the tuning capacitor. In untuned amplifiers, however these capacitances are important, since they are in shunt with the grid

SCREEN

GRID

CATHODE

HEATER
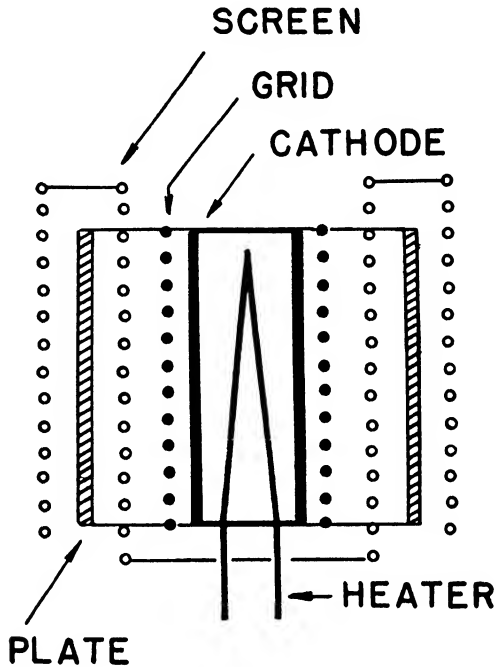
PLATE

Fig. 5–1.   Internal Construction of a Tetrode.

and plate circuits and therefore lower the impedance of these circuits, especially at high audiofrequencies.

5–3. The effect of the screen grid on the electron current.

The effect produced by the screen on the electron current depends on its construction, its disposition within the tube, and its D.C. voltage with respect to the cathode. The screen may be connected to any D.C. potential and still satisfy the shielding requirement previously outlined if a low-impedance path is provided for all A.C. voltages. This requirement is easily met in practice by connecting a sufficiently large capacitor from the screen to the cathode. If the shield is connected directly to the cathode, its potential will be negative with respect to the space charge of the electrodes in its vicinity and electrons will thus be repelled by this electrode. If the shield is connected to a positive potential, some electrons will be attracted to it and the rest accelerated. The collected electrons produce a screen current. Since the screen has a grid structure, only a small portion of the electrons are so intercepted. If the potential

is sufficiently high in relation to the separating distance, the space charge in the screen-cathode space is greatly reduced, causing a larger electron
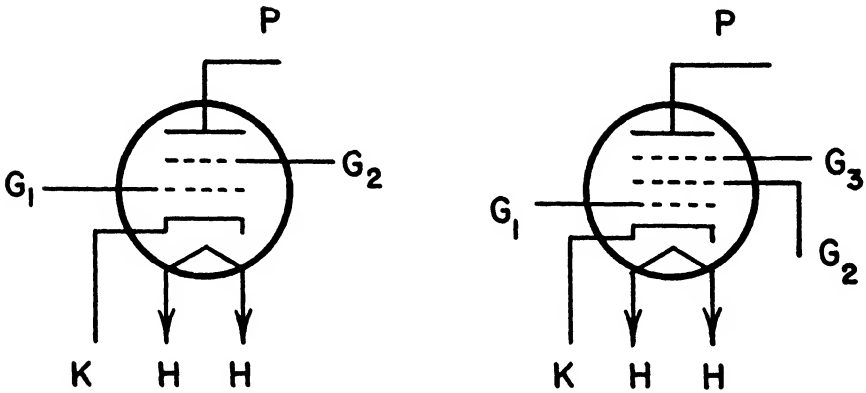
FIG. 5-2. Tetrode and Pentode Symbols.

current to flow; and since the screen collects but a small proportion of these electrons, the net plate current is increased.

5–4. The amplification factor of screen-grid tubes.

The shielding action of the screen also prevents the plate from greatly affecting the space charge in the vicinity of the cathode, and hence, although the D.C. plate resistance is decreased (the total plate current increased) the dynamic or A.C. plate resistance is actually increased by the presence of a positive screen. That is, the plate voltage is less effective in determining the plate current than in a corresponding triode. Since the value of the transconductance is not greatly reduced by the presence of a positive shield grid, it follows that the amplification factor of a tetrode must be much larger than that of a corresponding triode. Tetrodes are therefore characterized by normal values of g_m; high values of μ (50–1,000 or larger); high values of r_p (10^5 or larger); low grid-plate capacitances (10^{-13} f. or smaller); high input and output capacitances (10^{-11} f. or larger).

5–5. Dynatron Characteristics.[1, 2, 3]

The characteristics discussed in the preceding sections have for the most part been desirable. The presence of the positive screen grid, however, introduces a property which may be undesirable under certain conditions of operation.

When electrons, called primaries, strike metals, secondary electrons are emitted. The number of secondaries so emitted depends on the ve-

[1] Hull, A. W., *Proc. I.R.E. 6*, 535, 1918.
[2] Scroggie, M. G., *Wireless Eng. 10*, 527, 1933.
[3] Gager, I. M., and Russell, J. B., *Proc. I.R.E. 23*, 1536, 1935.

locity of the primaries, the nature of the metal, and the space charge in the vicinity of the emitter of the secondary electrons. At velocities corresponding to a 100 v. or less, secondary electrons are produced at the plate of a triode; but since the negative space charge is high in the entire cathode-plate region, the electrons are returned to the plate. If the screen in a tetrode is at a more positive potential than the plate, these secondary electrons are attracted to the screen. This flow results in a decrease of plate current and an increase of screen-grid current. Consequently, as long as the screen grid is at a higher potential than the plate and therefore in a position to attract secondary electrons from the plate, an increase in plate voltage will actually produce a lower plate current due to the increase in the number of secondary electrons produced. If this phenomenon is compared with Ohm's law, that is, $dE = R\,dI$, R would appear to have a negative value. These properties are commonly referred to as dynatron characteristics, and may be used to produce a simple single-tube oscillator.

The characteristics of the tetrode summarized in §5–4 are understood to apply only to the conditions where the secondary-emission current does not flow to the screen, that is, at plate voltages which are higher than the corresponding screen voltages. The usefulness of a tetrode as compared to a triode is thus extended by the factors previously outlined, but limited to cases where the plate voltage in normal operation never becomes less than the screen voltage. The tetrode should not be used with a high plate-load resistor if the grid-voltage changes are large. The voltage output of a tetrode is therefore lower than that of the triode. The use of a tetrode is chiefly limited to voltage amplification where the output voltage is comparatively small (10–50 v.) in relation to the power-supply voltage (300 v.).

EXPERIMENT 5–1

Purpose: To determine the characteristics of a tetrode.

Materials: 6J7 tube
Octal socket
200-ohm volume control
2,000-ohm volume control
100-ohm 1-watt resistor
0-150 voltmeter
0-5 voltmeter
0-5 milliammeter
0-10 milliammeter
6 45-v. batteries
6-v. storage battery
Single-pole double-throw switch

Procedure. Connect the apparatus as shown in Figure 5–3, using a portion of the 6-v. battery for the grid potential. The grid voltage is changed by the 200-ohm volume control and read on the 0-5 voltmeter V_1. The 6J7 tube is a so-called triple-grid amplifier, and may be used as a double-grid or tetrode tube by connecting the second and third electrodes together. This connection is accomplished with the single-pole double-throw switch, as shown in Figure 5–3. The screen potential is determined by battery B_1, and is changed by selecting the proper taps on this battery. The plate potential is changed in small amounts by the
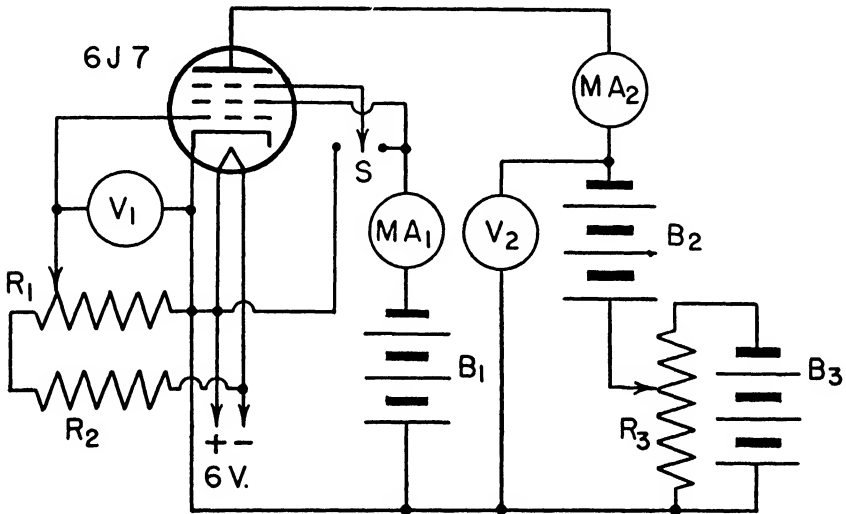
FIG. 5–3. Circuit for Tetrode or Pentode Characteristics. R_1 = 200-ohm volume control; R_2 = 100-ohm resistor; R_3 = 2,000-ohm volume control.

2,000-ohm potentiometer R_3, which is connected across the first 22.5-v. section of plate battery B_2-B_3. Gross variations in the plate voltage may be obtained by changing the taps on B_2.

With approximately 45 v. on the screen and 0 v. on the plate, set the grid to –0.5 v. and read the screen and plate currents. Then, with other voltages fixed, slowly increase the plate potential with R_3 and read the plate and screen currents. Increase the voltage slowly in the region where large changes of plate current occur. After the voltage has been increased to the limit of R_3, set the plate voltage again to zero and increase the voltage of B_2 by 22.5 v.; then proceed by slowly increasing R_3. After the plate voltage has reached a value higher than the screen voltage, the voltage may be increased in larger steps. Plot the screen and plate currents as shown in Figure 5–4.

Repeat the experiment with a more negative grid voltage, and plot again. If time permits, curves differing by .5 v. grid potential should be

run, after which the same curves are obtained at 67.5 and 90 v. screen potential. Plot and compare the various curves.

Suggestions for further work. Set the plate potential to its maximum value (180 v.), and with a plate-load resistor of 50,000 ohms and at a screen potential of 90 v., vary the grid potential over the whole range, noting the screen and plate currents for each setting. Repeat with
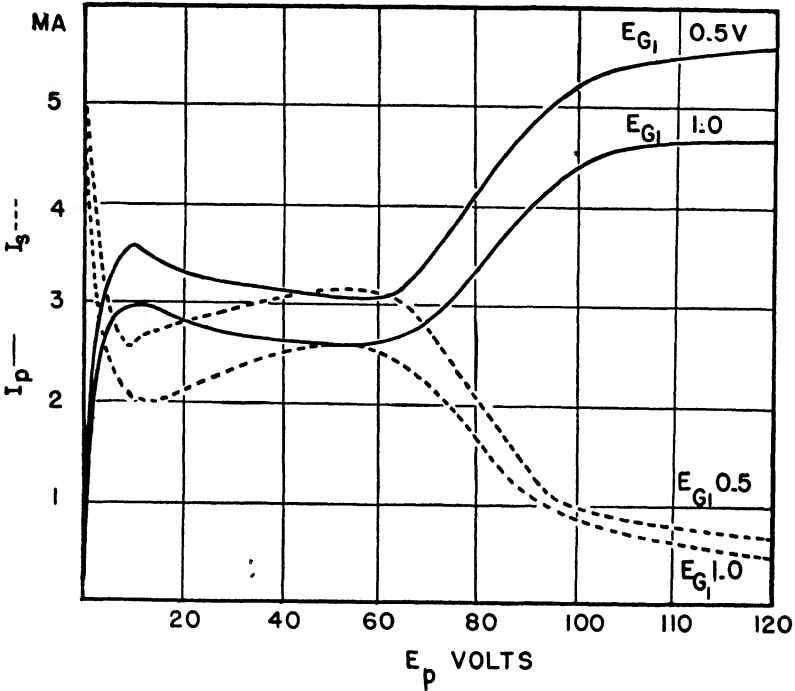
FIG. 5–4. i_p-e_p Curves for a Tetrode.

100,000 ohms as a plate load. Repeat both of these measurements with 45 v. on the screen. Compare the curves so obtained with i_p-e_g curve for zero plate load resistance. Also compare the results so obtained with those of a triode, as shown in Figure 2–8.

From curves obtained with the tetrode, calculate the value of

$$r_p = \left(\frac{\partial e_p}{\partial i_p}\right)_{e_g};$$

the value of

$$g_m = \left(\frac{\partial i_p}{\partial e_g}\right)_{i_p};$$

and the value of

$$\mu = -\left(\frac{\partial e_p}{\partial e_g}\right)_{i_p}.$$

In all of these cases, the value of the screen potential must be specified. The value of the control-grid–plate transconductance should be written

$$g_{m(g,p)} = \frac{\partial i_p}{\partial e_g},$$

with e_p and e_{g2} constant. But since the screen potential is understood to be constant, and the corresponding g_m value for the control-grid–screen-grid is of no great importance, the values of g_m, r_p and μ are understood as applying to the control grid and plate even if this is not so stated. However, the value of the screen potential must always be specified. Compare the calculated values of the tetrode constants with those obtained for the triode in Chapter 2.

5–6. The pentode.

All of the characteristics of the tetrode for voltage amplification, with the exception of dynatron characteristics, seem to be superior to those of the corresponding triode.[4] These, however, as we have seen, limit the application of the tube to low-level voltage amplification. The effects of secondary electron emission, and consequently the dynatron characteristics, are almost entirely eliminated by placing an additional grid (called the suppressor grid or G_3) between the screen and the plate. If this grid is made highly negative with respect to the plate, the secondary electrons are returned to the plate. This may be understood by remembering that since the secondary electrons are emitted by the plate, this electrode becomes the cathode for these electrons while the screen is in effect the plate; the suppressor grid is thus the control grid for this virtual triode, and if it is sufficiently negative serves to cut off the secondary-emission current. If the suppressor grid is properly constructed and connected to the cathode, the effects of secondary electron emission are thus eliminated without alteration of the other characteristics of a tetrode. This is illustrated by the following experiment.

EXPERIMENT 5–2

Procedure. Repeat Experiment 5–1, using the same apparatus, but connect the third grid to the cathode with the single-pole double-throw switch. Plot the results as in Experiment 5–1, on comparable scales, and

[4] Terman, F. E., "Radio Engineering." New York: McGraw-Hill Book Co., Inc. 1937; p. 127.

compare these curves with those of Figure 5–4. Calculate the values of g_m, r_p, and μ, remembering to specify the screen and suppressor voltage.

Determine the i_p-e_g curve for 45 and 90 v. screen potential, and with and without a 100,000-ohm plate resistor. Plot as shown in Figure 5–5, and compare the values so obtained with similar ones for the tetrode. Calculate from $\Delta E = R \Delta I$ the undistorted plate-voltage output of a pentode and tetrode. This may be accomplished by determining the
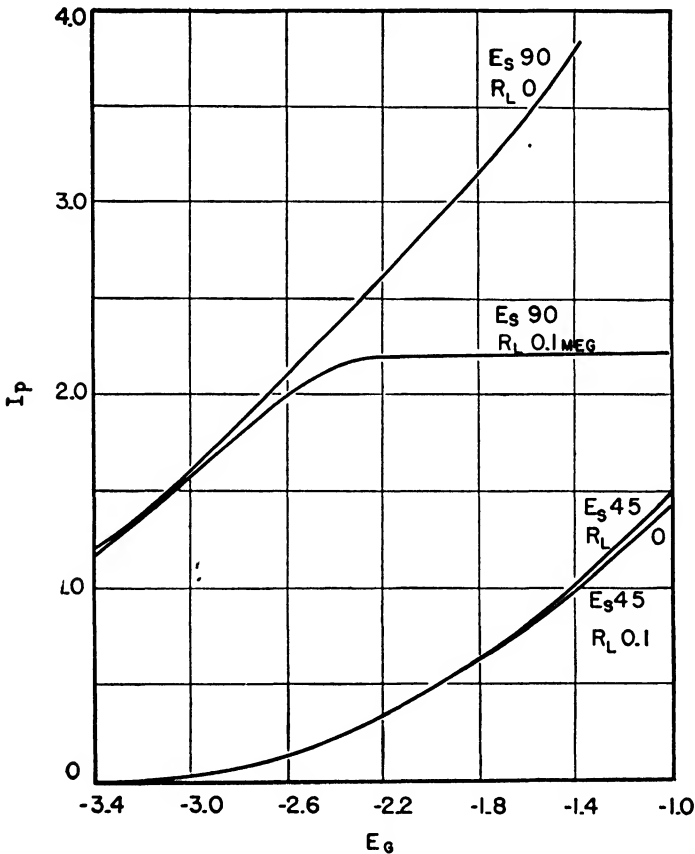
FIG. 5–5. i_p-e_g Curves for a Pentode and Effect of Plate Load.

change in plate current between the limits of zero i_p and the maximum value appearing on the linear portion of the curve. Compare this value of voltage output with the plate-supply voltage for both tetrodes and pentodes. Why is the slope of the i_p-e_g curve relatively unaffected by the plate-load resistor? In this case, compare these curves with the corresponding triode curves of Figure 2–8. If maximum power is to be developed in the plate circuit, what method would you use to calculate the best value for the load resistor?

Suggestions for further work. Determine the characteristics of a variable-μ[5,6] tube by substituting a 6K7 tube for the 6J7 of Experiment 5–2. Disconnect R_1 and R_2 from the 6-v. battery and use a 22.5-v. battery across potentiometer R_1.

5–7. Multigrid power tubes.

From §5–3 and Figure 5–4, it will be seen that as the screen is made progressively more positive the plate current becomes increasingly larger, owing to the decrease of the space charge in the cathode-screen region. Since the function of a power tube, as its name implies, is to develop controllable power, a high plate current is one distinct requirement. Accordingly, while the screen potential in Experiments 5–1 and 5–2 was held to 90 v., a higher screen voltage would have increased the plate current to larger values. Consequently, when the screen voltage is made equal to the power-supply voltage, it is utilized most efficiently from an economic point of view. This equality cannot be secured for the ordinary tetrode, since the plate potential could not then be reduced in use without the development of dynatron characteristics. This difficulty is particularly serious in a power tube because, as is shown in §2–4 and §2–5, a power tube is efficient only when the plate voltage at maximum power output varies from zero to the maximum, that is, supply voltage. The tetrode plate current would be far from linear with grid voltage under these conditions.

A pentode, however, permits more efficient operation. It was shown in Experiment 5–2 that the i_p-e_p curve is approximately linear to a plate voltage of approximately 20 v. This represents a loss of 10 per cent when operating with a 200-v. plate supply. A full discussion of pentode power tubes is beyond the scope of this book, and the reader is referred to standard texts for the complete treatment. It is evident, however, that although the pentode tube is less efficient than the triode in the development of undistorted plate power from a given power supply, the grid voltage required to develop this power is much smaller. This advantage results from the fact that in a pentode the i_p-e_g curve has a steeper slope when the plate is carrying a load than for the triode. This fact justifies the extensive use of pentode power tubes.

5–8. Beam power tubes.[7,8,9,10]

The construction of a beam power tube is shown in Figure 5–6. Mechanically it is a tetrode, in that the active elements are the cathode, the

[5] Ballantine, S., and Snow, H. H., *Proc. I.R.E. 18*, 2102, 1930.

[6] Cocking, W. T., *Wireless Eng. 12*, 87, 1935.

[7] Burnap, R. S., *R.C.A. Rev. 1*, 101, 1936.

[8] Dreyer, J. F., *Electronics*, Apr., 1936; p. 18.

[9] Schade, O. H., *Proc. I.R.E. 26*, 137, 1938.

[10] Salzberg, B., and Haeff, A. V., *R.C.A. Rev. 2*, 336, 1938.

control grid, the screen grid, and the plate. Shields are connected to the cathode and are known as beam-forming plates. These plates, and other details of the construction, give the tube some remarkable properties. Electrons emitted by the flat cathode are focused by these plates as a consequence of the disposition of the other electrodes. The control grid and screen grid have the same shape and size, and in consequence the electrons are focused in sheets between the wires of the screen grid. This focusing produces two important effects. First, since the focal point of the electrons lies between the screen-grid wires, very few electrons are intercepted by the screen. Second, the concentration of electrons at these focal points is so high as to generate a large space charge in its vicinity.
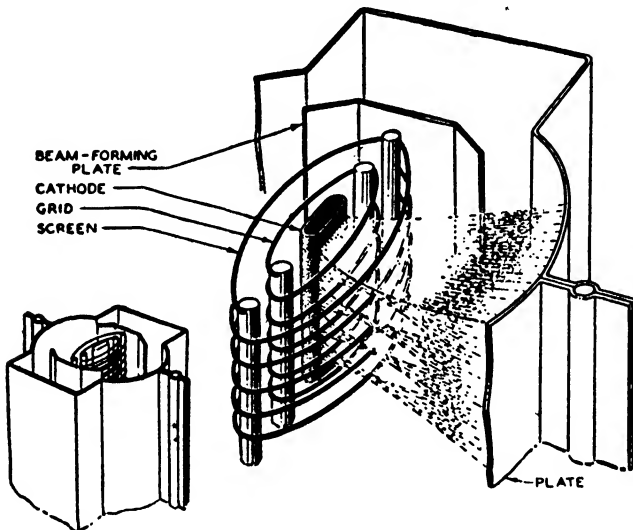
FIG. 5–6.   Internal Structure of Beam Power Tube.

Secondary electrons from the plate are repelled by this charge, and the dynatron characteristics are therefore suppressed. The focal points act as virtual cathodes, and serve the same function as the suppressor grid of the ordinary pentode.

The beam power tube has practically replaced the pentode and triode power tube in modern radio receivers. It might be added that this effect has been accomplished without increasing the output capacitance of the tetrode. This capacitance, although small, is of great importance in tuned amplifiers at high radiofrequencies, and in untuned amplifiers at low radiofrequencies such as those used in television.

The outstanding characteristics of the beam tube are, therefore, high value of $\dfrac{\Delta i_p}{\Delta e_g}$ in the presence of a load; a high plate current; a low screen

current coupled with a plate efficiency which is much higher than for the ordinary tetrode.

EXPERIMENT 5–3

Purpose: To determine the characteristics of a beam power tube.

Materials: 25L6 and 25Z6 tubes
               2 octal sockets
               0-10 milliammeter
               0-100 milliammeter
               0-150 voltmeter
               0-20 voltmeter
               22.5-v. battery
               90-v. battery
               230-ohm resistor, 25 watts; or 230-ohm line cord resistor
               10- or 20-henry choke
               2 20-μf., 200-v. electrolytic condensers
               Variac transformer

    Procedure. Determine the characteristics of a 25L6 beam tube with the aid of the circuit shown in Figure 5–7. The screen- and control-grid

Fɪɢ. 5–7.   Circuit to Determine the Characteristics of a Beam Power Tube.

voltages may be obtained from batteries, but the plate current is so large that ordinary heavy B batteries are not suitable for this purpose. A Variac transformer, in conjunction with a 25Z6 rectifier, may be conveniently used. A similar rectifier, employing a 25Z6-rectifier–voltage-doubler and a Variac, may also be used to advantage in the determination of the characteristics of other tubes. The heater voltage is obtained from the A.C. mains, using the proper current-limiting resistor R_2.

Determine the plate current as a function of plate voltage for grid voltages of —2.5, —5.0, —7.5, —10, —12.5 and —15 v. at a screen potential of 90 v. The determination may be repeated for other values of
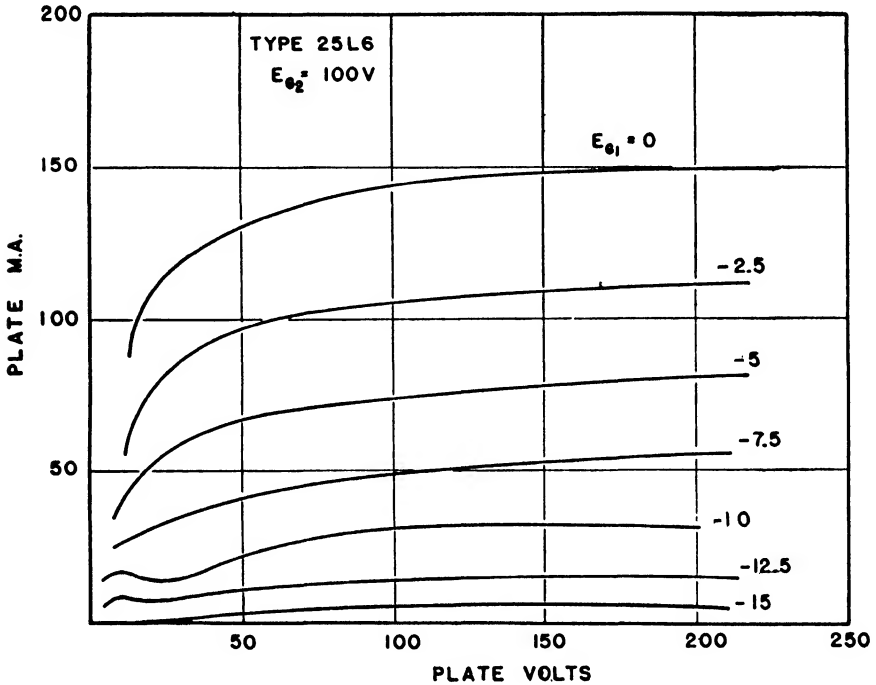
Fig 5–8. i_p–e_p.

screen voltage. Record the values of the screen current and voltage and plot these values as shown in Figure 5–8.

5–9. Electronic relays using beam power tubes.[11]

Because these tubes have a high power capacity, they may be used in the construction of electronic relays; the circuits shown in Figures 5–9 and 5–10 are particularly useful. The circuit shown in Figure 5–9 employs a voltage-doubler power supply, one side of which is used to furnish grid voltage at low current while the other side is used for plate and screen voltages. The doubler may also be used to furnish potential to a phototube connected between 1 and 3. Under these conditions, an increase of photocurrent impresses a negative voltage on the grid of the power tube. On the other hand, if the phototube is connected between 1 and the positive side of the supply, the grid becomes less negative.

[11] Serfass, E. J., *Ind. Eng. Chem., Anal. Ed., 13*, 262, 1941.

5–10. Beam tubes in parallel.

Several of these tubes may be connected in parallel, thus increasing their power and transconductance. Due to the high value of g_m it is, however, difficult to avoid the tendency toward transfer oscillation. Small resistors may be placed in series with the plate or screen to prevent the rapid transfer of the load from one tube to the next.

EXPERIMENT 5–4 (OPTIONAL)

Purpose: To study some of the unusual properties of tetrodes and pentodes.

Materials: Same as Experiment 5–1, plus extra B batteries and voltmeters

Procedure A. Arrange the parts of the circuit of Figure 5–3 so that the suppressor potential may be changed with respect to the cathode.[12] Determine the plate current as a function of the plate voltage at the following suppressor voltages: —7.5 v.; —3 v.; +22.5 v.; +45 v.; +67.5 v.; and +90 v. Plot the results as before.

Procedure B. Repeat Procedure A at various control-grid potentials.

Procedure C. Connect the suppressor grid to the plate and disconnect the positive potential from the screen, substituting a potentiometer voltmeter so that the screen may be varied from 0 v. to —7.5 v. with respect to the cathode. Make the control grid positive by 7.5 v., and put a 0-10 milliammeter in this circuit in order to measure the grid current. Now, determine the plate and control-grid currents as a function of the negative screen voltage. Plot both these currents. This type of connection utilizes the control grid to reduce the cathode space charge, and the screen grid is used as the control element. As the screen becomes more negative, the plate current decreases, but the current of the first grid increases. (*Caution!* In some types of tubes the control-grid current may be so high as to overheat the grid at 7.5 v. positive.) If the grid current is larger than 10 ma., a lower positive grid voltage should be used.

Electrometer tubes, such as the FP-54, are designed for screen-grid control. In these tubes, special precautions are taken to insulate the true control grid (G_2), as well as to reduce the control-grid current to a very small value. The space-charge-grid G_1 aids materially in the reduction of grid current in the control element. In some cases, the suppressor grid is used as the control element; a high-input resistance may be obtained in this manner. The suppressor transconductance is lower than that of the normal control grid G_1.

5–11. Pentagrid converters.

These tubes may employ four, five, or six grids in addition to the cathode and plate, in order to attain certain desirable characteristics.

[12] Gabus, G. H., and Pool, M. L., *R.S.I. 8*, 196, 1937.

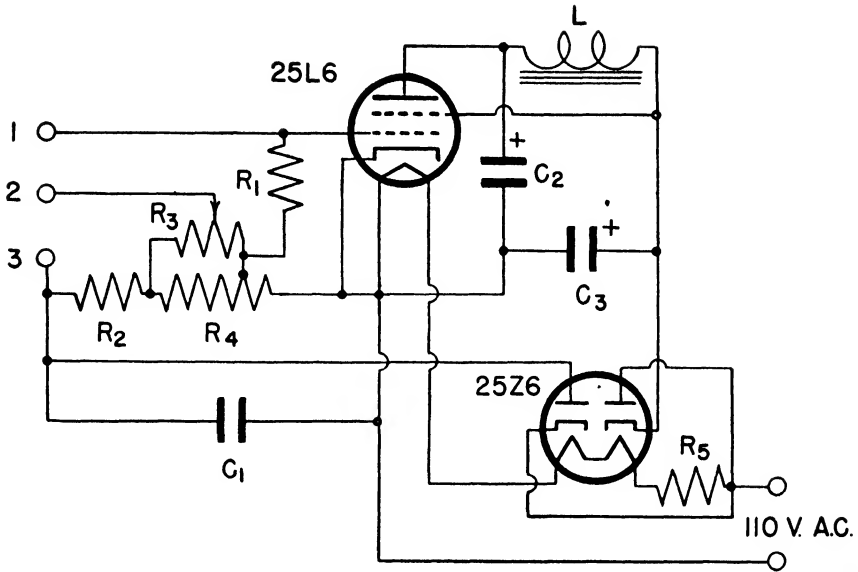FIG. 5-9.   A Beam-power-tube Relay Circuit. R_1 = 5 megohm, $\frac{1}{2}$ watt; R_2 = 10,000 ohms, 2 watts; R_3 = 25,000-ohm volume control; R_4 = 4,000 and 1,000 ohms, 1 watt each; R_5 = 230-ohm line cord resistor; C_1 = 10-μf. 200-v. electrolytic condenser; C_2, C_3 = 16 μf. 200-v. electrolytic condenser.
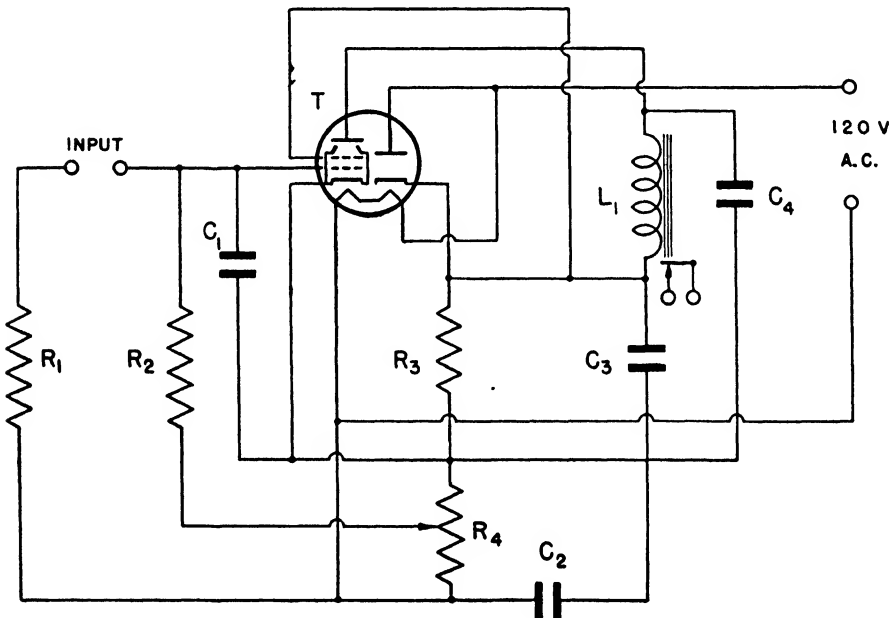
FIG. 5-10.   Beam-power-tube Rectifier-type Relay Circuit.

Their function usually is to act as oscillators, as mixers of the oscillations with the voltage impressed on the control grid, and as amplifiers— all in the same tube envelope. For this reason, the first grid is often named the oscillator grid and the second the oscillator plate. The grids G_3 and G_5 are tied together and form a shield for the control grid G_4 in a manner which shields this electrode from the plate as well as from the remainder of the tube. The control grid controls the electron stream only as it exists within the screen space, while the grid G_1 controls the total electron current. If the control grid is made negative, the plate current is reduced in normal fashion, but the screen current and the grid G_2 current are increased.[13] Most of the increase goes to G_2, the oscillator plate.

EXPERIMENT 5–5

Purpose: To study the current relationship between the grids of a pentagrid converter.

Materials: 1A7G tube
Octal socket
3 0-5 milliammeters
2 0-3 voltmeters
45-v. battery
2 3-v. batteries
2 1,000-ohm potentiometers

Procedure. Connect a 0-5 milliammeter to each of the following electrodes: the plate, screen, and oscillator. Connect a 1,000-ohm potentiometer across a 3-v. battery and connect to the control G_4. Connect a second 1,000-ohm potentiometer to G_1 as shown in Figure 5–11. With 45 v. on all positive electrodes, set grid G_1 to zero volts and determine the plate, screen, and oscillator-grid currents as a function of control-grid G_4 voltage. Plot as shown in Figure 5–12. Repeat with —1.5 and +1.5 v. on G_1. Plot again and compare the curves. Calculate the grid-plate transconductance, indicating the sign of each value. From a comparison of the three curves, the G_1-plate and screen–oscillator-grid transconductances can be calculated. A practical circuit for a D.C. voltmeter based on these characteristics is described in Chapter 7.

5–12. Multi-control-grid tubes.

Multi-control-grid tubes, as represented by the 6L7, are so constructed that two grids control the electron stream to the plate.[14,15,16] These tubes do not differ materially from the corresponding pentagrid converters, except in that the two control grids are so disposed that each

[13] Garman, R. L., and Droz, M. E., *Ind. Eng. Chem., Anal. Ed.*, *11*, 398, 1939.
[14] Sinnet, C. M., *Electronics*, Nov., 1935, p. 14.
[15] Nesslage, Herold, and Harris, *Proc. I.R.E. 24*, 207, 1936.
[16] Wing, A. H., *Proc. I.R.E. 29*, 121, 1941.
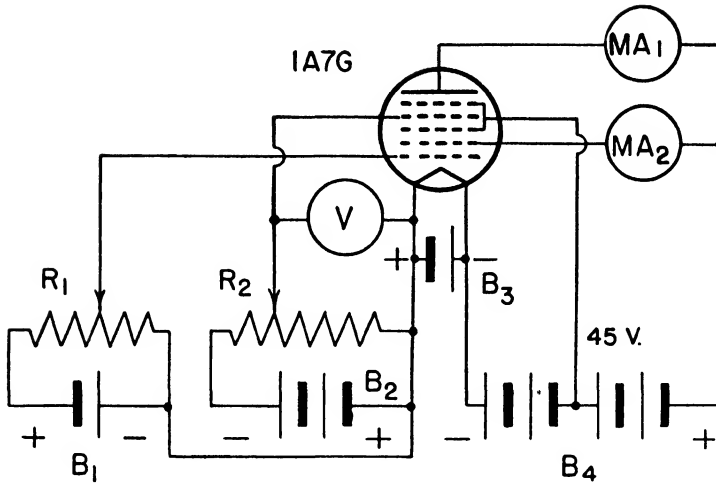
FIG. 5–11.   Circuit for Pentagrid Converter Characteristics.
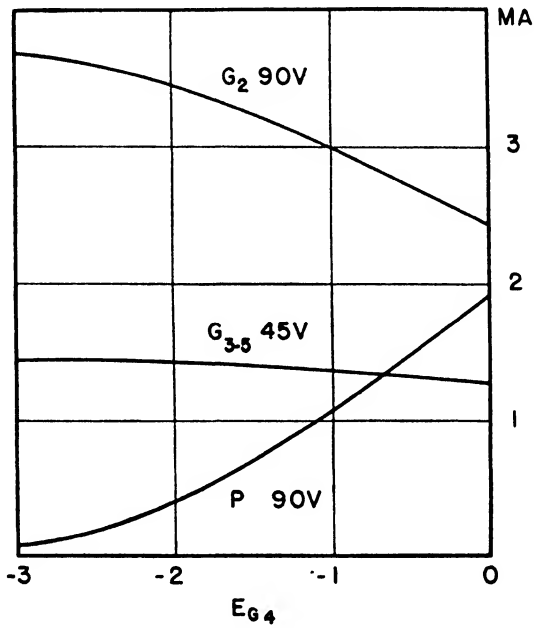
FIG. 5–12. i_p, $i_{g_{3.5}}$ and i_{g_2} as a Function of e_{g_4}.

exerts the desired control and the oscillator plate electrode is eliminated. If both grids are essentially equivalent, the plate current serves as an indication of the product of the two grid voltages. This property suggests some useful application in measurements or control.

The use of this tube is largely limited to the mixing of two audio- or radiofrequencies (frequency conversion), and to amplification control. Its usefulness as a radiofrequency mixer or converter is due to the fact that the capacitance between the two control grids is extremely small (.004 $\mu\mu$f.) and that only negligible power is required from both signal-voltage generators. Coupling between these generators is thus avoided, and a high degree of frequency stabilization results (Chapter 11).
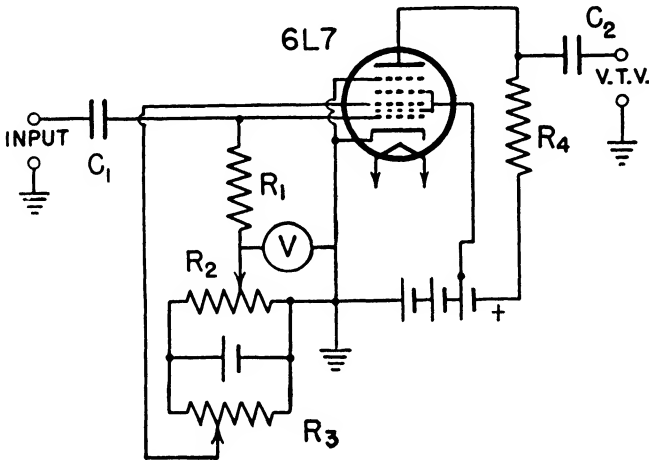
FIG. 5–13. 6L7 A.C. Amplifier. R_1 = 1.0 megohm; R_2 = 10,000 ohms; R_3 = 10,000 ohms; R_4 = 50,000 ohms; C_1 = .05 μf.; C_2 = .05 μf.

If the tube is used as an amplifier, its gain possibilities are controllable by the second grid, and with the expenditure of negligible power, so that the control may be achieved electronically by means of a control tube. This principle is used in volume-expansion and volume-compression circuits, that is, where the gain of the tube is either increased or decreased with signal voltage on the first grid by applying a portion of this rectifier signal to the second control grid in proper phase to effect the desired control. The properties of the tube necessary to effect this function can be shown from Figure 5–13, where the amplification of the input A.C. voltage is controlled by the D.C. voltage on grid G_3 as supplied by potentiometer R_3.

EXPERIMENT 5–6

Purpose: To study the amplification of a 6L7 tube as a function of the D.C. grid voltages applied to the two control grids.

Materials: 6L7 tube
Socket
2 5,000-ohm volume controls
2 15-v. batteries
2 0-15 D.C. voltmeters
0-5 D.C. milliammeter
Power supply or 225-v. B battery
6.3-v. transformer or storage battery

Procedure A. Replace the load resistor R_4 with a 0-5 milliammeter and wire the remainder of the apparatus as shown in Figure 5–13. De-
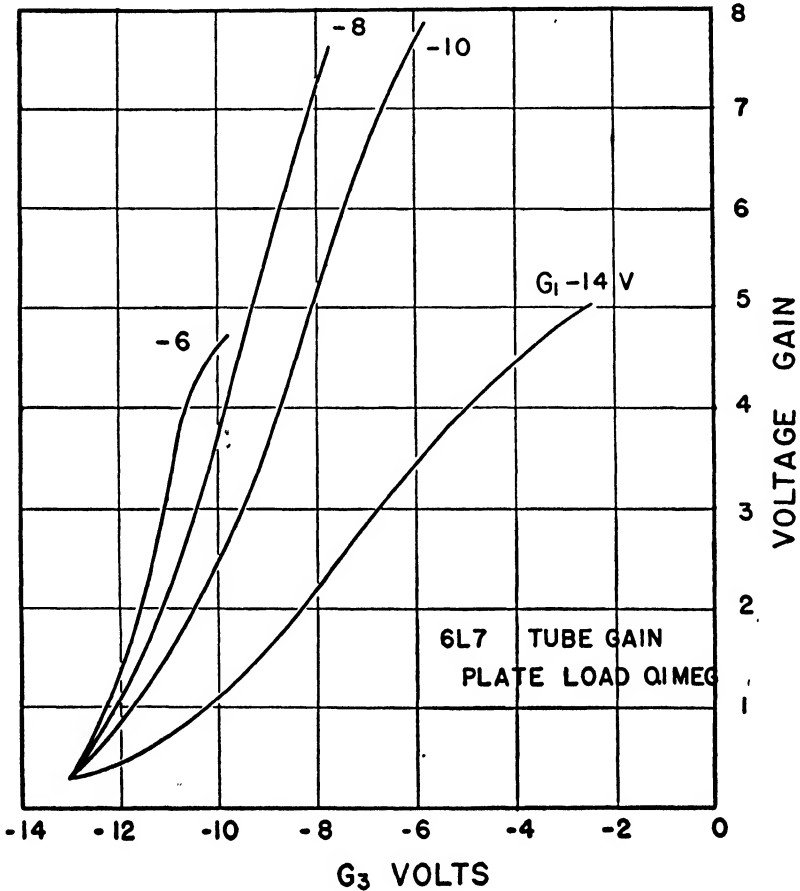
Fɪɢ. 5–14.   Voltage Gain of a 6L7 Tube as a Function of e_{g_3}.

termine the plate current as a function of the voltage of grid G_1 as well as grid G_3. Set grid G_3 to —2 v. and determine plate current as a function of the voltage of grid G_1. Repeat this measurement at —4, —6, —8,

—10, —12 v. on grid G_3. Plot plate current as a function of grid G_1, keeping G_3 constant; then cross plot the data as plate current as a function of voltage on grid G_3, keeping G_1 constant. Calculate the transconductance for each grid at several values of the other grid voltage. Note that the two grids are not equivalent, and that grid G_1 is of the remote cutoff type (variable pitch).

Procedure B. In order to simulate the properties of the tube as it is actually used in gain control, wire the apparatus as shown in Figure 5–13. Connect an oscillator or 60-cycle A.C. voltage to the input terminals (across R_1) and an A.C. vacuum-tube voltmeter to the output terminals. Set the oscillator voltage to obtain a suitable output reading on the vacuum-tube voltmeter (1–2 v.). Measure the gain of the tube as a function of the D.C. voltages on both grids, and plot as shown in Figure 5–14. Note that the gain depends on the voltage of both grids, and may decrease with a decrease in G_3 grid voltage. This decreased gain results from the high plate current causing an RI drop in the plate resistor almost equal to the power-supply voltage.

A list of constants for some of the modern pentodes in comparison with corresponding triodes is given in the following table.

TABLE 5–1

Tube type	g_m	μ	r_p	i_p	e_g	Input capacity $\mu\mu f.$	Output capacity $\mu\mu f.$	Grid-plate capacity $\mu\mu f.$
6F5 triode..........	1,500	100	66,000	.9	−2.0	5.5	4.0	2.3
6J7 pentode.........	1,225	1,500	>1.0 megohm	2.0	−3.0	7	12	.005
2A3 triode power.....	5,250	4.2	800	60	−45	7.5	5.5	16.5
6L6 beam power.....	6,000	135	22,500	72	−14			
6J5 triode...........	2,600	20	7,700	10	−8.0	3.4	3.6	3.4
6AC7 pentode.......	9,000	6,750	.75 megohm	10	−2.0	11	5	.015

SUPPLEMENTARY LITERATURE

Everitt, W. L. (editor), "Fundamentals of Radio," Prentice-Hall, Inc., New York, 1942.

PROBLEMS

1. List some electrical functions which can be performed better with a pentode than with a triode.

2. Analyze a typical pentode tube for the magnitude of the expected grid current, and compare with the expected grid current of a triode at comparable values of e_p and g_m.

3. List some useful functions which can be performed with a tetrode, operated at a point where dynatron characteristics are fully developed.

4. Show how the properties of pentagrid converters, such as the 1A7G, may be used to advantage for voltage measurements.

5. Devise a circuit which could be used with a 6L7 tube to control the gain of a D.C. amplifier. (*Note:* Compensate for the effects of changes in plate current with changes in gain as determined by the G_3 voltage.)

6. Compare the i_p-e_p characteristics of a typical beam power tube with those of a typical power pentode.

7. Devise a plate-load resistor for 6J7 tube which matches the value of r_p for this tube but maintains 200 v. at the plate of this tube, with a 400-v. power supply.

8. Devise a circuit using a 117GT tube capable of operating a 15-ma. relay at an illumination differential of .1 lumen and possessing a safety factor of 300 per cent.

CHAPTER 6

Characteristics of Gaseous Tubes

Introduction: ionization.

In the study of the ordinary triode, reference was made in Chapter 2 to the space charge developed by electrons emitted from the cathode. Since this charge is always present, the amount of electron current that can be obtained in high-vacuum is of rather small value. In receiving tubes, currents of the order of 100 ma. are considered large. If a triode or tetrode is filled at low pressure with gas (mercury vapor, argon, neon, or others), its characteristics are altered considerably. The gas is ionized by the electrons in their travel to the plate. The positively charged ions are now accelerated to the negative cathode, and in traveling there they clean up the space charge of the electron stream in this vicinity. This situation allows more electrons to move towards the plate and a new crop of gaseous positive ions to be produced. The plate current thus builds up to a higher and higher value and is finally limited only by the plate-load resistance. The time required for this build-up of current is very short, being of the order of 10^{-4} second or less. In this discussion, the grid electrode has not been considered. A deionized gaseous tube is similar to an ordinary triode and the grid is effective in holding electrons from passing to the plate. If, however, the negative grid potential is slowly reduced, more and more electrons are allowed to go to the plate, and a larger number of positive ions are thus produced. As soon as the number of positive ions produced per unit time exceeds the number deionized in the grid-plate space, the grid loses control and the previously described building-up process begins. (1) The grid is now powerless to stop the process. The plate current suddenly rises to its maximum value, and its value is independent of the grid voltage, within limits. (2) This independence is occasioned by the fact that a sheath of positive ions surrounds the grid structure. The grid control therefore serves only as a trigger to start the current.[1] Current may be stopped by opening the plate circuit momentarily. Due to the very low space charge in a conducting gaseous triode, the cathode may be constructed by concentrating a large amount of emitter material in a small space. Heater power may

[1] Reich, H. J., "Theory and Application of Electron Tubes." New York: McGraw-Hill Book Co., Inc., 1939; p. 393.

be reduced by using folds and other devices in the cathode structure to conserve heat. Small gaseous triodes, therefore, may produce currents of the order of amperes, while high-vacuum tubes of comparable size are limited to currents of the order of milliamperes. Larger gaseous triodes may produce a few hundred amperes at comparatively low voltages.

In preceding discussions it has been assumed that electrons originate only from hot cathodes, as in high-vacuum tubes. Actually, however, electrons may also be emitted from a cold cathode, and gaseous tubes have been designed to utilize this emission. Electron emission from most
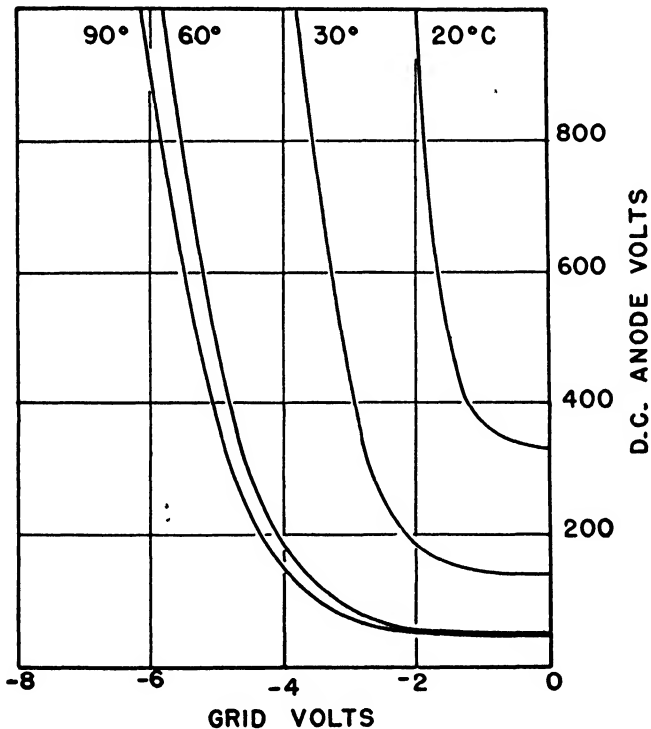
Fig. 6-1.   Anode Voltage vs. Grid Voltage Required to Prevent Breakdown in a Typical Gaseous Triode at Various Temperatures.

cold cathodes is, however, very low, and special construction must be employed to obtain desired control characteristics. While there are many types of cold- and hot-cathode gaseous types now available, the following discussion is limited mostly to small hot-cathode triodes and tetrodes. In the last section, the characteristics of one type of cold-cathode gaseous triode are given.

6-1. Characteristics of gas-filled triodes.

Calculation of g_m and r_p is meaningless for this type of tube, since the grid exercises control only when there is little or no plate current,

and when control is lost the plate current is limited by external resistance only. In Figure 6–1 is shown a plot of plate voltage as a function of grid volts required to just allow the tube to conduct. This may be compared to a triode, in which plate current was plotted as a function of grid volts and at a constant plate voltage. At a given grid voltage, any plate voltage above the curve will start the gaseous tube on its conducting cycle, while voltages below this line will hold the tube nonconducting.
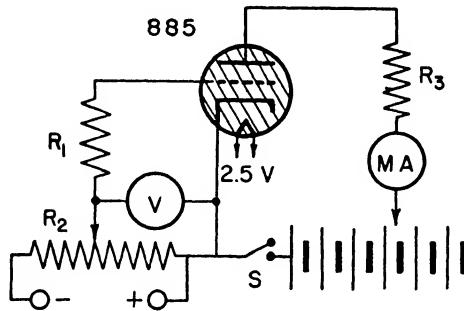
FIG. 6–2. Circuit for Determination of Characteristics of 885 Gaseous Triode. R_1 = .1 megohm, ½ watt; R_2 = 5,000-ohm volume control; R_3 = 25,000 ohms, 1 watt.

Once the tube is conducting, however, the plate voltage may be decreased considerably without affecting the conductance. To stop the current, the plate voltage must be reduced until the value of the ionization potential for the gas is almost reached, at which value the ionization of the gas ceases and the plate current suddenly disappears.[2]

EXPERIMENT 6–1

Purpose: To study the grid-plate characteristics of a small gaseous triode.

Materials: Type 885 or 884 tube
2.5-v. or 6.3-volt heater transformer
4 B batteries
22.5-v. C battery
Tapping switch
5,000-ohm volume control
.1-megohm grid resistor
0-20 voltmeter
0-5 milliammeter
50,000-ohm plate resistor

Procedure. Connect the apparatus as shown in Figure 6–2. Set the grid voltage to its maximum negative value and connect a 45-v. B bat-

tery through a tapping key switch to the plate-load resistor. Hold the key down and decrease the grid bias until the tube conducts. Interrupt the plate current with the key and find the smallest grid voltage at which the tube will just not conduct current. By decreasing this voltage by very small steps, a value may be found when the tube will always conduct when the key is depressed but will not conduct if the negative grid voltage is increased slightly. Note that the interval between these two values is very small, and within the experimental error of the determination. Repeat with 67.5, 90, 112.5 and 135 v. on the plate, and plot results as shown in Figure 6–1. Repeat the experiment with a larger value for R_3.

6–2. A.C. plate voltages with the gaseous triode.

Instead of using an interrupted source of D.C. potential, the plate potential may be interrupted with the 60-cycle A.C. main. This source is automatically interrupted 120 times each second. It differs in other respects, however. The voltage is positive for only half the time, and this positive voltage rises slowly to a maximum, receding slowly to zero and on to negative values. Hence, with low grid voltage, a tube may start conducting when the plate voltage reaches a positive value of about 25 v. and plate current will continue through the maximum voltage and back to 25 v. If, however, the grid is at a more negative potential, the tube may not start to ionize (due to lack of electron current) until 50 v. or more are on the plate; but once this ionization has started, the conduction will continue until the plate voltage has dropped to 25 v. or less. As more negative grid voltages are used, a point is finally reached at which the tube fires only at the peak of the A.C. cycle. But current still flows for approximately half the positive cycle. Higher voltages than this will abruptly reduce the current to zero. It may be seen that, since the plate meter indicated the average current flowing throughout the cycle, the grid exercises apparent control over the plate current within certain limits.

EXPERIMENT 6–2

Purpose: To study the plate-current characteristics of a gaseous triode with A.C. plate voltages.

Materials: Same as for Experiment 6–1, but substitute the 115-v. A.C. line for the B batteries

Procedure. After replacing the plate batteries of Figure 6–2 with the 115-v. A.C. mains, set the grid voltage to its maximum negative value and measure and record the plate current as a function of the grid voltage. Plot the results as i_p-e_g, but label the curves properly in order not

to confuse these values with those of Figure 6–1 or with those obtained in Chapter 2 for the high-vacuum triode. Note the abrupt change in plate current to zero at a definite grid potential. Remember that the peak value of the A.C. plate voltage is $\sqrt{2}$ times the meter reading.

6–3. Limitations and applications of trigger circuits using gaseous triodes.

The use of the gaseous triode circuit shown in Figure 6–2 is limited to applications where trigger action is desirable. If the grid is made just slightly more negative than is required to hold the tube from conducting, any small positive pulse on the grid fires the tube, that is, starts plate current flowing. A relay placed in the plate circuit will be energized and maintain its action even when the positive pulse has disappeared. The gaseous-triode relay will thus lock in without any mechanical latch. It may be reset mechanically by momentarily breaking the plate circuit, or it may be reset electrically after a certain time interval has elapsed, or it may be reset almost instantly by using A.C. for the plate supply. Applications of this type are numerous. Other trigger circuits are used for rapidly discharging or charging a capacitor after its voltage has reached a critical value. These circuits may be used for counting, or for the generation of sawtooth waves.

The plate voltage may be interrupted by any desired method, depending on the performance sought. A gaseous tube may be used to interrupt the plate voltage of another gaseous tube, as shown in Figure 6–3. In this circuit, T_1 is conducting and the grid potential of T_2 is so adjusted that it will not conduct except under the action of a momentary positive pulse. At this moment there will be a surge of current through capacitor C_1, reducing the positive potential at the plate of T_1 and causing the tube to cease conducting. If the grid of this tube is also adjusted so that no conduction can start at the existing power-supply voltage it will remain in the nonconducting state. Another positive pulse delivered simultaneously to both grids will start conduction in T_1 and interrupt T_2. Hence, if a relay or counter is placed in the plate circuit of one of these tubes, it will register only alternate pulses, and is therefore called a scale-of-two counter.[3,4,5,6] This scale may be increased by using another pair of tubes fed from the first set. If the voltage feeding the next pair is taken from the plate circuit of T_1 or T_2, the resulting pulses will be negative when the tube fires. In some cases, another conventional amplifier tube is placed between these units for phase reversal.

[3] Wynn-Williams, C. E., *Proc. Roy. Soc.* (London), *132*, 295, 1931.
[4] Hull, H. W., *Physics 2*, 409, 1932.
[5] Shumard, C. C., *Electrical Engineering 57*, 209, 1938.
[6] Lord, H. W., and Livingstone, O. W., *Electronics*, Jan., 1934, p. 37.

This four- or five-tube network will respond to every fourth pulse if the counter is placed in the plate circuit of one of the second pair of tubes.

EXPERIMENT 6–3

Purpose: To determine the characteristics of a scale counter.

Materials: 2 885 or 884 tubes
2 sockets
2 50,000-ohm resistors
Relay or meter
.01-μf. capacitor
2 5,000-ohm volume controls
22.5-v. battery
D.C. power supply or batteries
2 .05-μf. capacitors
2 .1-megohm grid resistors
1 tapping-key switch
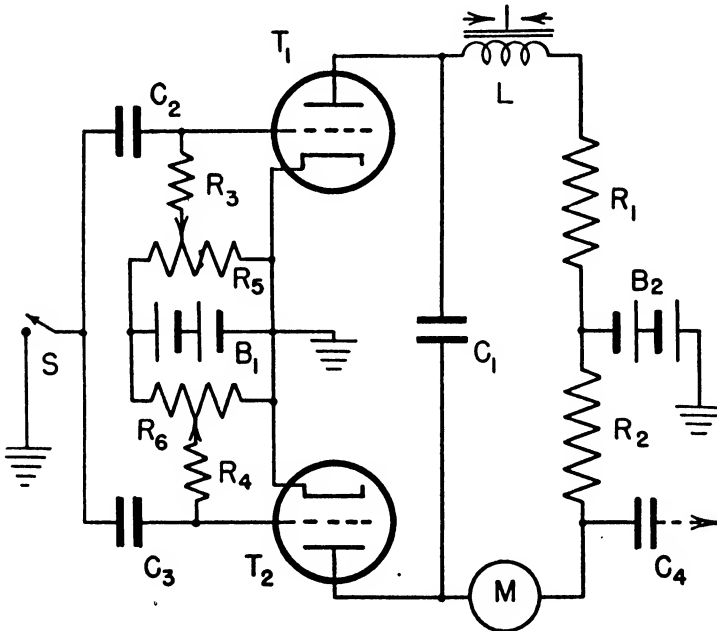
FIG. 6–3. Scale-of-two Pulse Counter. R_1, R_2 = 25,000 ohms, 1 watt; R_3, R_4 = .1 megohm, 1 watt; R_5, R_6 = 25,000-ohm volume control; B_1 = 22.5-v. battery; B_2 = 180–225-v. battery or power supply; L = counter or relay; C_1 = .05 to 4 μf.; C_2, C_3 = .1 μf.

Procedure. Arrange the apparatus as shown in Figure 6–3, and with C_1 disconnected from the circuit, adjust each grid voltage to a value

somewhat more negative than the minimum required to hold the tubes nonconducting when the plate voltage is applied. Connect capacitor C_1 and apply a small positive potential to the input by momentarily connecting C_2 and C_3 to ground through a tapping-key switch. Note that one of the tubes is now conducting. Discharge the capacitors by connecting the tapping switch to the negative end of B_1. Then apply the pulse again and note that the other tube is now conducting. Apply the pulses more rapidly and observe the results.

Use various values for C_2 and C_3 in relation to C_1 and observe the effects. Note that the positive pulse on C_1 and C_2 must disappear before equilibrium is re-established in C_3, otherwise one pulse may be counted as two.

Reduce the grid voltage on the tubes simultaneously, and observe that when the grid voltage is very small both tubes seem to be conducting simultaneously. A circuit of this type may be used as an oscillator and in the conversion of D.C. to A.C.

6–4. Phase-shift thyratron circuits.

The versatility of the gaseous triode may be extended by using phase shift between plate and grid voltages as the controlling element. The theory of this mode of control may be understood from a study of Figures 6–4 and 6–5.[7]
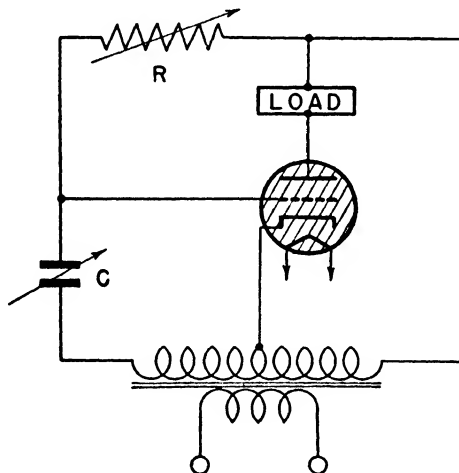

FIG. 6–4. Phase-shift Control of a Gaseous Triode.

In the circuit shown in Figure 6–4, grid and plate voltages are obtained from the center-tapped transformer T_1. When the terminal on the left of the transformer is negative, the one on the right is positive. The instantaneous voltage appearing at the grid of the tube depends on the

[7] Reich, H. J., op. cit.

value of C and R. For example, if the capacitative reactance X_C is very small in comparison to the value of R, the grid voltage will be almost 180° out of phase with the plate voltage; that is, the grid will be as negative as the plate is positive during the entire cycle. Under these circumstances the tube will not conduct current. Lack of conduction arises from the fact that during that portion of the cycle when the plate voltage is higher than the ionization potential, which is the requirement for conduction, the grid is always sufficiently negative to hold the tube from conducting.

However, if the phase shift of the grid voltage is less than 180° so that, at the point where the plate voltage is above the ionization or
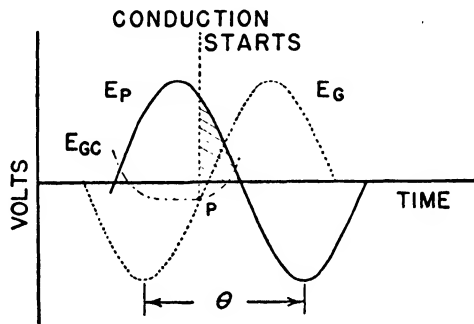
FIG. 6–5.   Relation of Phase Angle to Gaseous-triode Control.

breakdown potential, the grid has not as yet become as negative as the critical grid potential for the existing plate voltage, then the tube will conduct and will continue to conduct throughout the positive cycle of the plate voltage, regardless of further changes in the grid voltage. Hence, by changing the phase of the grid voltage with respect to the plate voltage, the tube may be fired at almost any point of the positive cycle. Figure 6–5 illustrates the process, where E_p represents the voltage from the right side of the transformer and E_g represents the voltage at the grid as derived from the phase-shifting network C-R. The dotted curve E_g (critical) represents the grid voltage required to just keep the tube from conducting at the corresponding plate voltage. When the grid voltage is equal to or higher (more positive) than this critical voltage, the tube conducts and continues to do so throughout the positive E_p cycle. The phase-shifting network R-C shifts the E_g curve from left to right, or in reverse, depending upon which of the values of R or C are made larger or smaller.

In order to follow this shift, replot the E_g curve to scale on a piece of transparent paper. Superimpose the zero axes; then, shifting the E_g curve backwards and forwards, note the points where this curve intersects the dotted curve. Divide the entire cycle of the E_g curve into 36

equal parts, beginning with zero at left. Then mark off and number points 1–36 on the E_p curve. Each division will represent a 10° phase shift. Determine in this way if any dead spots exist in the network, that is, if there is any part of the cycle where there can be no conduction under any circumstances. For a more detailed discussion, the reader is referred to standard works on this subject.[8]

Phase shift may also be accomplished by the use of resistance and inductance. Since the phase-shifting characteristics of an inductor are just the opposite of those of the capacitor, the capacitor of Figure 6–4 is replaced by a resistor, and the resistor R is replaced by an inductor. In many modern circuits, the phase shift is produced in external circuits, such as transformers, tubes, and so on, and the shifted voltage is then applied to the control tube.[9]

The resistance may be in the form of an electron tube or photocell, in either case. Various practical circuits using these devices as phase shifters are shown in Figures 6–6, 6–7, and 6–8. Phase-shifting networks are not limited to those shown here, but may take many different forms.

EXPERIMENT 6–4

Purpose: To determine the characteristics of some practical phase-shift networks in controlling plate currents of gaseous triodes.

Materials: FG27 or equivalent gaseous triode
Suitable load resistor for the tube
Lamp or motor
1 to 1 transformer with ample current rating
Filament or heater transformer with adequate volt-ampere rating
Variable air condenser with scale
Variable resistor with scale
Photocell
6F5 and 6J7 tubes
Grid potentiometer
Grid battery
0-5 voltmeter
Milliammeter

Procedure A. Wire the apparatus as shown in Figure 6–6, selecting a load which will not overtax the particular gaseous tube used. Connect a suitable milliammeter in series with the load. Use a 1,000-$\mu\mu$f. variable condenser for C_1 and a 20-to-50-megohm resistor for R_1. Determine the

[8] Reich, II. J., *op. cit.*
[9] Henney, Keith, "Electron Tubes in Industry." New York: McGraw-Hill Book Co., Inc., 1937.

plate current as a function of the capacitance of C_1, with several values for R_1. Plot as shown in Figure 6–9. If a resistor which does not heat appreciably is used as a load, the current may be calculated from

$$I = \frac{1}{2} I_{crest} \left(\frac{1 + \cos \theta}{\pi} \right),$$

where θ is the phase angle.

Procedure B. Replace resistor R_1 with a high-vacuum photocell, as shown in Figure 6–7. With a suitable variable light source, as in Experi-
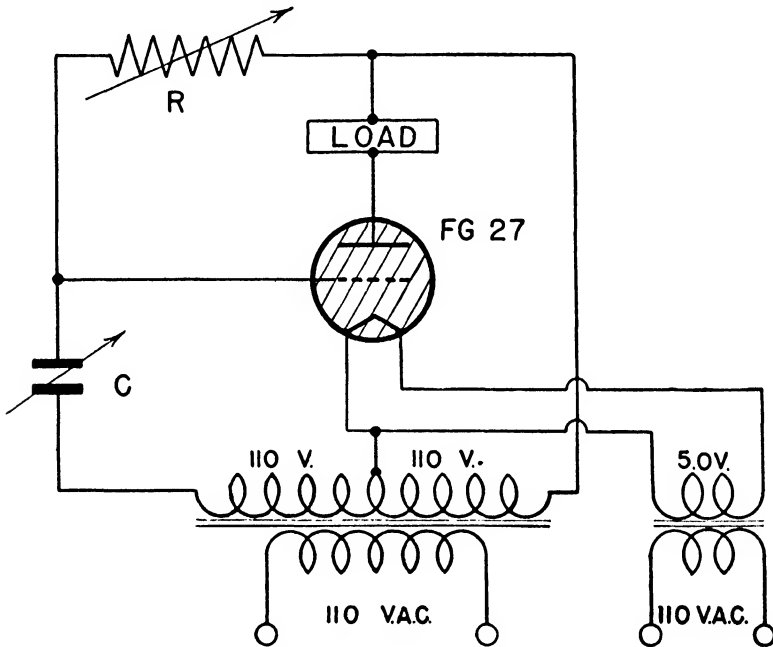
Fig. 6–6.   R-C Phase-shift Gaseous-triode Circuit.

ment 3–1, determine the plate current as a function of the illumination on the photocell for various settings of C_1.

Repeat the experiment with various loads, such as lamps or motors. Note that, since the circuit furnishes current only on the positive plate cycle, the current will be one-half of the D.C. current for the same supply voltage. Thus, a 50-watt lamp will pass only about 250 ma. as read on a 250-ma. D.C. meter.

Procedure C. Rewire the apparatus as shown in Figure 6–8, and determine the gaseous-triode plate current as a function of the grid voltage of the 6F5 tube. Since the plate resistance of this tube is much lower than the resistances used in Procedures A and B, the proper value of C_1 may be determined by setting the grid voltage of the 6F5 tube to about
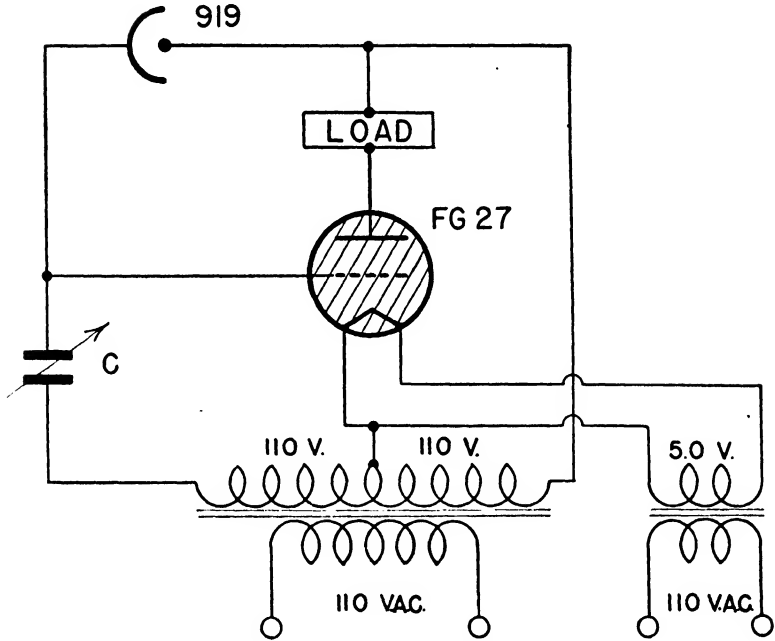
FIG. 6–7. Phototube-*C* Phase-shift Circuit.

FIG. 6–8. Triode-*C* Phase-shift Circuit.

Fig. 6-9.   Plate Current of a Gaseous Triode at Various Values of R and C. $R = 10$ meg-ohms for capacitance control; $C = 350$ μf. for resistance control.

5 v. and then varying C_1 until the gaseous triode is just rendered non-conducting. Then slowly decrease the voltage of the 6F5 tube and read the gaseous-triode plate current. Plot plate current as a function of 6F5 grid voltage. Repeat the experiment after the heater voltage of the 6F5 has been reduced to 5 v. Repeat again with 4 v. on the 6F5 heater.
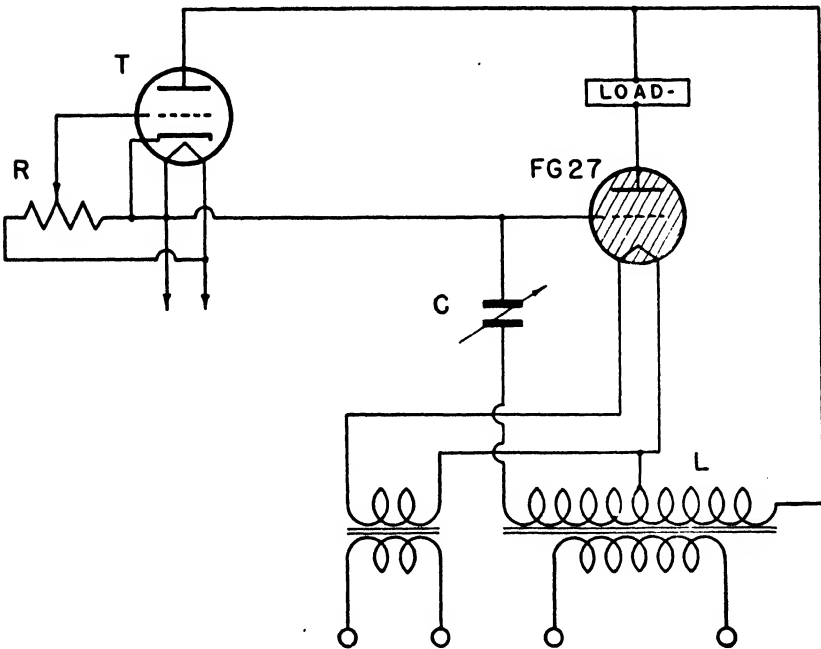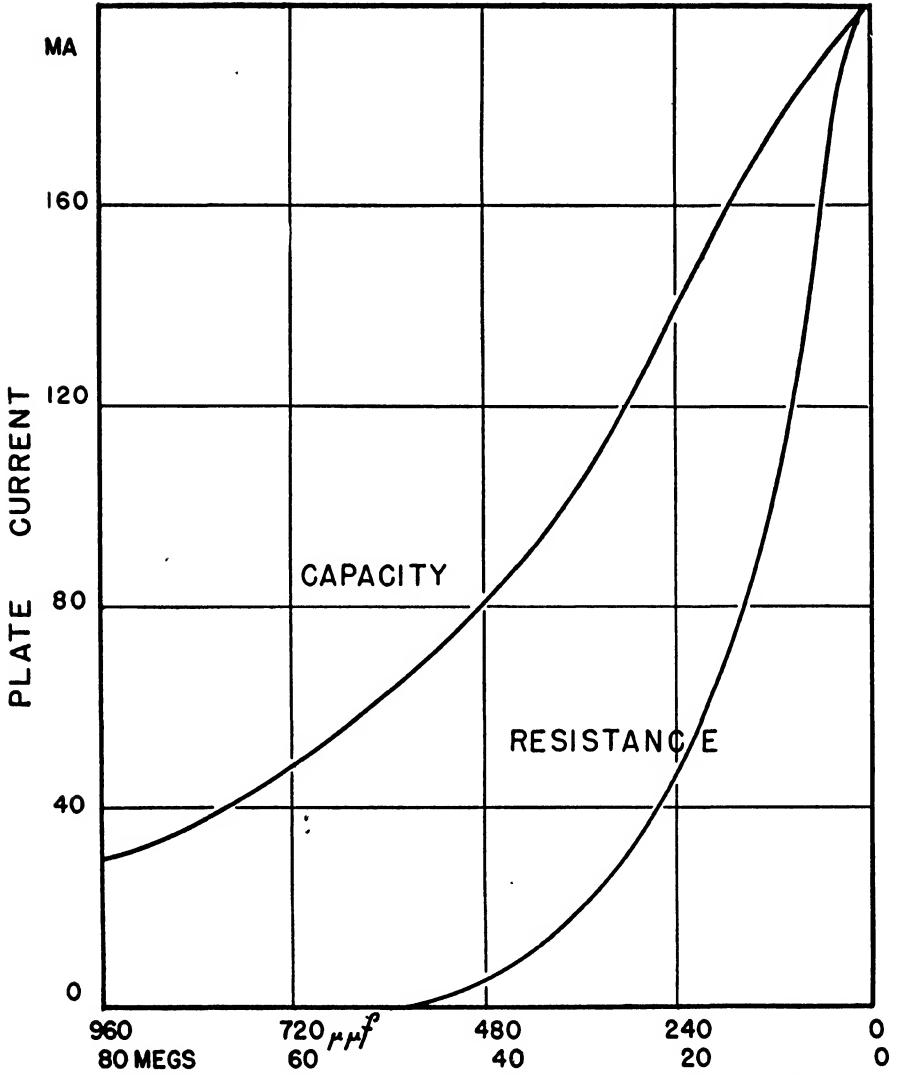
The grid current of the 6F5 tube is quite large when A.C. is used for the plate supply. This condition may be avoided by using a pentode in place of the 6F5 and using a separate 45- or 90-v. battery for the screen supply.

Repeat the experiment with a 6J7 tube at 45 and 90 v. screen potential. In each case, set the grid to about —4 v., then adjust C_1 until the gaseous triode ceases conducting. Then slowly decrease the grid voltage of the amplifier or phase-shift tube, noting the plate current of the gaseous tube. Plot as shown in Figure 6–10.

If time permits, a photocell may be used to develop grid voltage for the 6J7 tube, with the circuit of Figure 6–8 changed to include this cell. The cell may be connected in either direction, but the most interesting results are obtained when it is connected so that a negative grid potential is developed. To do this, connect the cathode of the photocell to the left end of the power transformer of Figure 6–8, and the anode to the grid of the 6J7 tube. The grid may be connected to the grid potentiometer with a 10-to-20-megohm resistor.

Procedure D. Shield the photocell from the light of the room but mount a variable diaphragm in front of the cell. Attach a lamp load in the gaseous-triode plate circuit and place the lamp in front of the diaphragm. With the diaphragm closed, set the grid voltage to approximately 4 v. and adjust C_1 until the tube ceases conducting. Reduce the grid voltage until the lamp burns brightly; then open the diaphragm until the lamp is appreciably dimmer than before. Now, reduce the grid voltage to zero, and open the diaphragm until the lamp just begins to dim perceptibly. In this condition the photocell tends to hold the intensity of the lamp constant. In order to check this relation, reduce the line voltage feeding the gaseous-triode plate current with a variable transformer, and note the constancy of the lamp. This constancy may be checked physically by the use of another photocell in an independent circuit. For comparison purposes, measure the variation of illumination with voltage by connecting the lamp directly to the variable transformer. Decrease the reading of the Variac until the independent photocell circuit indicates the same value of light as with the gaseous-triode circuit. Then decrease the voltage and plot the photocurrent as a function of the percentage by which voltage is reduced. Plot the photocell readings for the light intensity as controlled by the circuit of Figure 6–8 on the same scale, and compare.
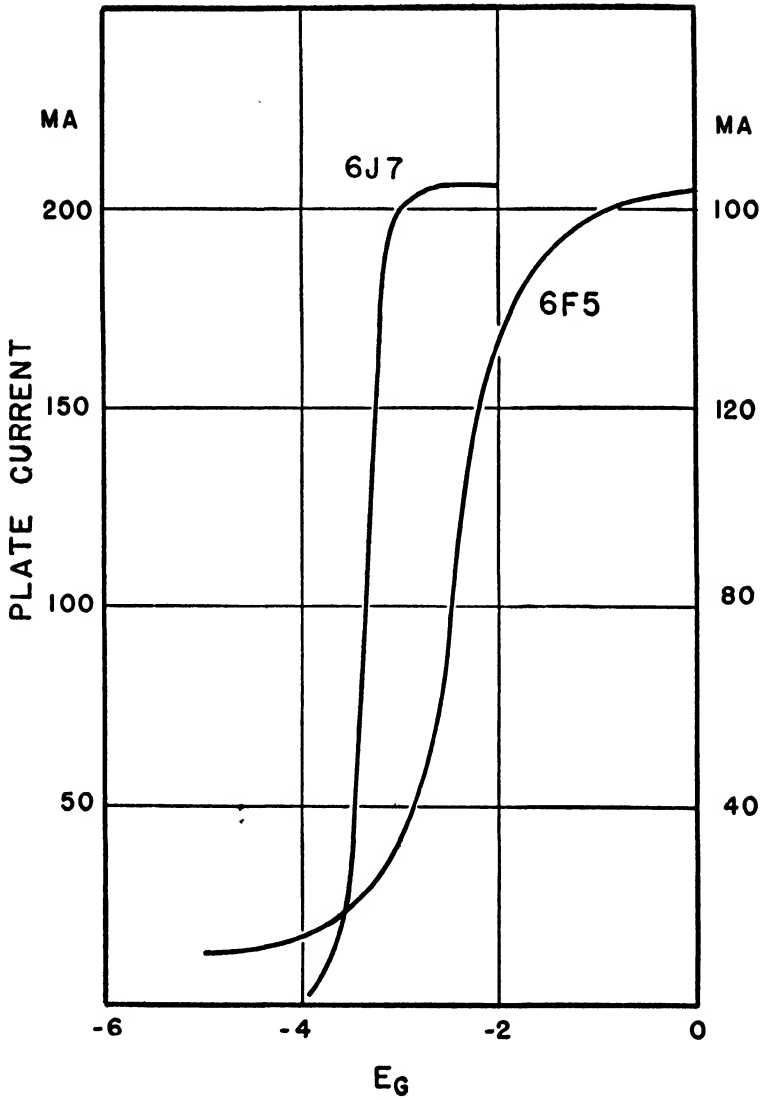
FIG. 6-10.   Triode-pentode Control of a Phase-shift Circuit.

How can you make the lamp burn at full brilliance in spite of the half-wave rectification produced by the gaseous triode? In what simple manner could you increase the effectiveness of control in the circuit just measured?

6–5. Gaseous tetrodes.[10,11]

The control-grid current in a gaseous triode is high in comparison to that found in the ordinary triode. The grid current may be limited to smaller values by placing a shield grid between the cathode and control grid, so arranged that the anode or plate current flows through its baffles. The control grid is located adjacent to these baffles, and is thus protected from the sputtering of the hot cathode. Since the control grid is physically smaller and is protected by baffles, the grid current is very small. The extra grid also serves another purpose, in that the control-grid-anode starting characteristics may be altered by changing the potential of the shield grid.

EXPERIMENT 6–5

Purpose: To determine the characteristics of a gaseous tetrode.

Materials: R.C.A. 2050 or 2051 tube
Octal socket
6.3-v. heater transformer
B batteries or variable power supply
Tapping-key switch
4.5-v. C battery
2 0-5 voltmeters
0-25 milliammeter
10,000-ohm 25-watt resistor (plate load)

Procedure. Wire the apparatus as shown in Figure 6–11. With the shield-grid potentiometer set to 0 v., set the control grid to the maximum negative voltage and apply 45 v. to the plate. Decrease the negative grid voltage slowly until the tube fires. Increase the anode voltage to 90 v. and redetermine the firing grid voltage. In a similar manner, determine the critical grid potential as the anode voltage is increased in 45-v. steps until a maximum of 315 v. is reached.

Repeat the experiment with +1 and —1 v. on the shield grid. Note that if the tube does not fire at zero control-grid voltage, the grid battery should be reversed and the requisite positive potential determined in this manner. Plot the curves, as in Experiment 6–1. Note that the

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[10] Livingston, O. W., and Maser, H. T., *Electronics*, April 1934; p. 114.
[11] Bahls, W. E., and Thomas, C. H., *Electronics*, Sept., 1941; p. 33.

starting or critical grid potential varies from —3.0 to +5.0 v. for a change of shielded grid potential of 0 to —6.0 v.

6–6. Phase shift in shielded-grid tubes.

In cases where the shield grid is connected to the cathode, any of the phase-shift circuits discussed before may be used with these tubes. The circuit shown in Figure 6–12 is interesting because it is highly sensitive to small changes in capacity and because no special parts are required for construction. The plate voltage is obtained from the 110-v. or 220-v. A.C. mains. The grid phase-shifting network is connected to one end of the heater transformer while the cathode is connected to the other
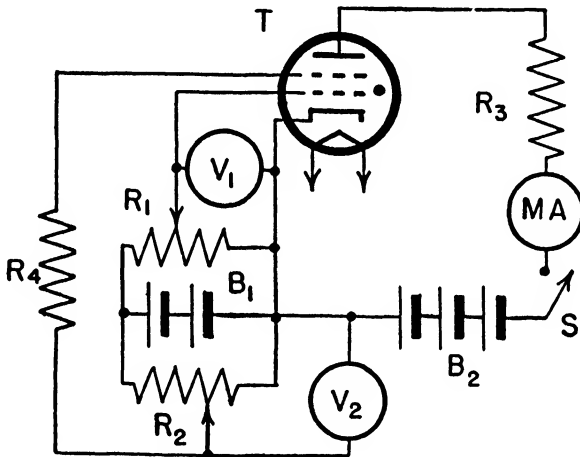
Fig. 6–11.   Circuit for Determination of the Characteristics of a Gaseous Tetrode.

end. The voltages on the phase-shift network are thus unsymmetrical, but if a 100-to-1,000-megohm resistor is used on the anode end of the phase-shift network, a capacitance change of 100 $\mu\mu$f. will give full control of the plate current.

Leakage must be avoided across the tube socket when these large resistors are used. A coating of wax, lucite, or varnish on the tube base and sockets will give adequate insulation. If a photocell is used in place of this high resistance, very small light levels will control the anode current. Leakage across the photocell terminals must also be avoided.

A circuit for on-and-off control recommended by R.C.A. is shown in Figure 6–13. The circuit resembles the ordinary triode photocell control circuit. The current capabilities of the types 2050 and 2051 R.C.A. tubes are much higher than for corresponding triodes, and the shielded grid allows the use of a 10-megohm grid resistor.

6–7. Uses of gaseous triodes and tetrodes.

The most extensive uses and applications of gaseous tubes are to be found in industrial operations requiring large amounts of controllable power.[12]

These may take the form of controllers for motors, welders, furnaces, or other heavy industrial equipment. Extensive applications are also made in the conversion of A.C. to D.C. or the inversion of D.C. to A.C. Most of the applications to measurements and control in the laboratories are based on the power capabilities of the tubes or on the triggering ac-
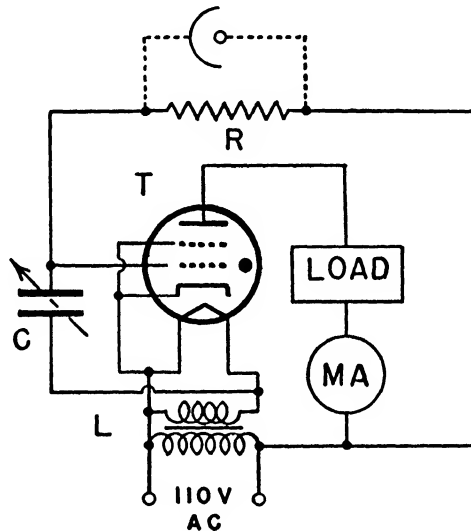
Fig. 6–12. Phase Shift with a Gaseous Tetrode. $R = 100$ to $1,000$ megohms; $C = 100~\mu\mu$f.

tion of the grid. Small or large thermostats may be controlled by the use of gaseous tubes in circuits in which the heating current is either supplied directly by the tube or in which the tube merely functions as an energizer for a relay.

Extensive applications in the control of motors,[12,13,14] small furnaces, or other laboratory tools have been made in the past, and as the capabilities of these tubes become more widely appreciated many new and improved applications will undoubtedly appear.

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[12] Henney, K., "Electron Tubes in Industry." New York: McGraw-Hill Book Co., Inc., 1937.

[13] Garman, D. W., *Electronics*, Jan., 1937; p. 20.

[14] Ryder, J. D., *Electronics*, Dec., 1938; p. 20.

6–8. Thermostat control.[15,16]

Any of the circuits shown in the preceding sections may be used for thermostatic control. The circuits employing the small 885 tubes may be used to energize relays in order to control large heating currents with the conventional mercury or mercury-toluene regulator. It is only necessary to arrange the mercury contacts so that a negative voltage is placed on the grid when the temperature has reached the desired value. If the
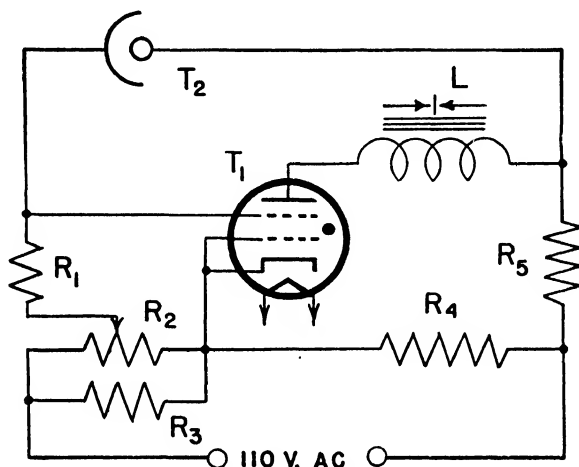
FIG. 6–13. Gaseous-tetrode Relay Circuit. $R_1 =$ 10 megohms; $R_2 = 25,000$ ohms, 1 watt; $R_3 = 1,000$ ohms, 1 watt; $R_4 = 15,000$ ohms, 2 watts; $R_5 =$ current-limiting resistor.

plate voltage is A.C., the plate current ceases abruptly and the relay interrupts the heater current.

The circuits shown in Figure 6–7 may be used to effect continuous control over the temperature of the thermostat by using a lamp-and-scale galvanometer to energize the photocell[17] when the temperature of the bath drops below the desired value. The galvanometer may be energized with a thermocouple, or preferably by a temperature-controlled Wheatstone bridge. If one arm of a balanced Wheatstone bridge is in the form of a platinum, nickel, or similar resistance, a small decrease in temperature decreases the resistance of this arm and effects an unbalance of the bridge. If this unbalance causes the galvanometer beam to move in a direction to increase the light on the photocell of Figure 6–7, the tube will be energized and heating current applied to the bath. If

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[15] Benedict, M., *R.S.I. 8*, 252, 1937.

[16] Sturtevant, J. M., *R.S.I. 9*, 276, 1938.

[17] Zabel, R. M., and Hancox, R. R., *R.S.I. 5*, 28, 1934.

the temperature drop is relatively large, the gaseous triode produces a large current; if it is small, only a small current; and otherwise in proportion to the temperature drop. The voltage from the unbalanced bridge may be used to operate the gaseous-triode grid after suitable amplification. Since the voltage from the bridge, for small changes in temperature, is extremely small, this method is not advisable except for rough temperature control. It may be noted that if the platinum resistance is precalibrated against temperature, a definite temperature may be set up on the Wheatstone bridge without the aid of auxiliary thermometers.

6–9. Follow-up mechanisms.[18]

In many cases it is desirable to record or otherwise measure the position of a moving system of low torque in such a manner that no physical contact is made with this system. Examples of this type are numerous, and may include meters, galvanometers, analytical balances, pointers, and other delicate laboratory instruments. One method of accomplishing this follow-up or recording is shown in Figure 6–14. Two photocells placed side by side, or a twin photocell, are used to feed the respective grids of a 6F8 tube; an optical system from a galvanometer or other device is arranged to illuminate one or the other cell or to illuminate both cells equally, depending on its position. The amplified voltage actuates the grids of the 6AC7 tubes, which in turn energize the grids of the gaseous triodes. Consequently, if the photocell connected to the upper section of this circuit receives more energy, this tube produces more plate current, which in turn causes the grid of the 6AC7 tube to become more negative, shifting the phase of the grid voltage of the gaseous triode in a direction which will make this tube conducting. The split-field motor is thus energized, and if its shaft is connected mechanically to the photocell, the photocell position may be restored for the reestablishment of light equilibrium. This motion may be recorded at some convenient point. If the other photocell is energized, the opposite motion occurs in the motor, and the speed of the motor is proportional to the amount of instantaneous off-balance of the light, in either direction.

Instead of having the photocells moved to a new position, these cells may be fixed and the motor used to impress a restoring force on the primary element until light equilibrium is attained. The same effects may be achieved by duplicating the circuit shown in Figure 6–7 so that one photocell energizes one gaseous triode while the other one energizes the second gaseous triode, the common load of the tubes being a split-field motor, as shown in Figure 6–14. Other methods of achieving this effect have been described in the literature.

[18] Müller, R. H., and Garman, R. L., *Ind. Eng. Chem., Anal. Ed.,* 10, 434, 1938.

FIG. 6–14. Thyratron Motor Control. $R_1 = 20$ megohms; $R_2 = 10,000$ ohms; $R_3 = 1,000$ ohms; $R_4 = 10,000$ ohms; $R_5 = 50,000$ ohms; $R_6 = 50,000$ ohms; $R_7 = .1$ megohm; $R_8 = .1$ megohm; $R_9 = .5$ megohm; $R_{10} = .5$ megohm; $C_1 = .05$ μf.; $C_2 = .05$ μf.; $C_3 = 1.0$ μf.; $C_4 = 1.0$ μf.; $L_1 = 200$ henries; $L_2 = 200$ henries; $L_3, L_4, L_5 =$ dual-field reversible motor; $T_1 =$ power transformer; $T_2 =$ heater transformer.

6–10. Counter operation.

The gaseous triode is well adapted to counting operations, since the grid exercises tripper control. The simple circuit shown in Figure 6–15 is used extensively with mechanical counters for rapid and precise counting operations. The grid is made so negative that the tube is nonconducting at the prevailing plate voltage. A small positive pulse will trigger the plate current, and the capacitor in the plate circuit will discharge through the tube, until the voltage drops to a value so low as to effect deionization of the tube, after which the capacitor recharges again through the plate
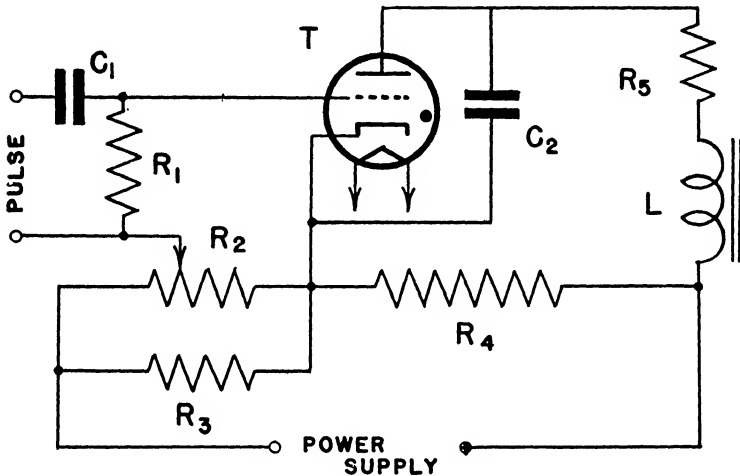

FIG. 6–15. Single-tube Gaseous-triode Counter. R_1 = .1 megohm, 1 watt; R_2 = 10,000-ohm volume control; R_3 = 1,000 ohms, 1 watt; R_4 = 10,000 ohms, 5 watts; R_5 = 20,000 ohms, 2 watts; C_1 = .1 μf.; C_2 = .001 to .05 μf.

resistor. If the grid voltage has in the meantime returned to its normal value, the unit is ready for the next pulse. If, however, the grid is not back to normal, the tube will again conduct and energize the counter a second time. It is essential, therefore, to select the capacitor C_1 with a time constant for recharge through R_3 so that recharge is slightly longer than the duration of the longest expected pulse. If some of the pulses are unduly long, special circuits may be employed ahead of the counter tube to reshape these pulses properly. If the frequency of the pulses to be counted is too high for use with a mechanical counter, scale counting may be employed, as outlined in §6–3 and Experiment 6–3.

The use of a gaseous discharge tube as an oscillator is discussed in Chapter 12, and the reader is referred to the extensive literature for details on many other interesting applications. (The use of gaseous discharge tube counters with Geiger-Müller ionization chambers is dis-

cussed fully in the literature.)[19] The complete Geiger-Müller counting unit thus consists of an ionization chamber followed by an A.C. amplifier, as described in Chapter 10, and a counter unit as above. Many variations of this fundamental circuit have appeared in the literature for this highly developed art.

6–11. Cold-cathode gaseous tubes.

Practical gaseous tubes may be constructed without the use of hot cathodes. Indeed, many of the present types, including those which allow the rectification and control of high currents, are made with cold cathodes. The theory of these tubes differs only in certain respects from the hot-cathode types already discussed. The electrons which ionize the gas are obtained in smaller numbers from the cold cathode, and must in a sense be extracted from the cathode. In the absence of a retarding field on the grid of a hot-cathode gaseous triode the tube will fire at an anode potential only slightly higher than the potential required to ionize the gas within the tube, if the grid voltage is such that electrons may emerge from the cathode. If the anode potential in this type is reduced slightly from this value, the tube no longer conducts.

In the cold-cathode type, the tube will usually not start when the anode potential is just above the ionization potential, since an additional potential is required to initiate and maintain the required electron density. After a tube of this type starts, the anode potential may be reduced considerably without rendering the tube nonconducting. Most of these tubes are also characterized by a cathode dark space, which has been shown to be due to the potential required for the acceleration and extraction of the electrons. For tubes of this type, the starting potential and the drop-out potential must be stated. The electrodes of these tubes may be made from ordinary metals, the cathode being much larger than the plate, in which case the tube will conduct only in one direction below a certain voltage; or the cathode may be small if made from a material which has considerable electron emission at room temperatures. Cold-cathode tubes are not limited to the diode type, but may contain a grid or control element as do hot-cathode gaseous triodes. In this case, the grid is placed close to the plate and so arranged that a relatively small negative voltage will reduce the electrostatic field of the plate in the vicinity of the cathode, preventing the extraction of electrons to initiate discharge except at high anode potentials. As in the case of hot-cathode triodes, the positive-ion sheath which surrounds the grid once cathode-plate conduction takes place will prevent the grid from exercising further control.[20]

[19] Strong, J., Neher, H. V., et al., "Procedures in Experimental Physics." New York: Prentice-Hall, Inc.; pp. 259–304.

[20] Bahls, W. E., and Thomas, C. H., Electronics, May, 1938; p. 14.

EXPERIMENT 6–6

Purpose: To study the characteristics of a cold-cathode gaseous triode.

Materials: R.C.A. OA4G tube
Octal socket
10,000-ohm volume control
90-v. battery
0-100 voltmeter
0-10 milliammeter
20,000-ohm resistor
B batteries or variable power supply
50,000-ohm resistor
0-300 voltmeter

Theory. The grid referred to in the above discussion is P_1 in Figure 6–16, and is really a plate or starting anode. The cathode has been treated so that a relatively large electron emission is possible at room
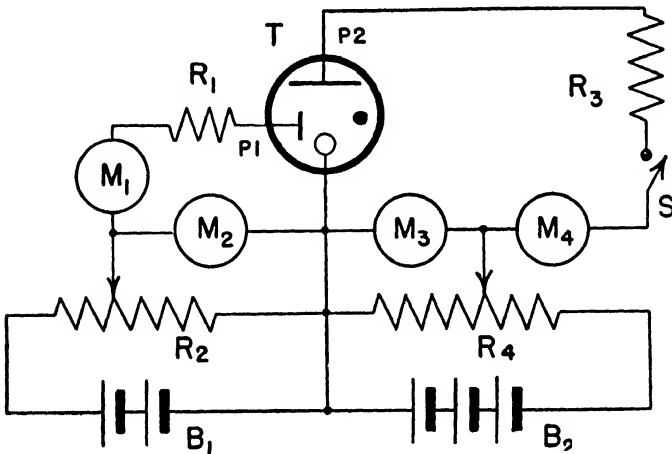

FIG. 6–16. Circuit for Determination of the Characteristics of a Cold-cathode Gaseous Triode. R_1 = 50,000 ohms, 1 watt; R_2 = 10,000 volume control; R_3 = 20,000 ohms, 1 watt; R_4 = 20,000-ohm volume control; M_1 = 0–5 milliammeter; M_2 = 0–100 voltmeter; M_3 = 0–300 voltmeter; M_4 = 0–10 milliammeter.

temperatures. In actual operation, the arcing may occur across six dif-ferent pathways. The current may go from cathode to anode or from anode to cathode, from cathode to starter anode (grid) or from starter anode to cathode, from starter anode to anode or from anode to starter cathode, all depending on the voltages as well as the polarity between
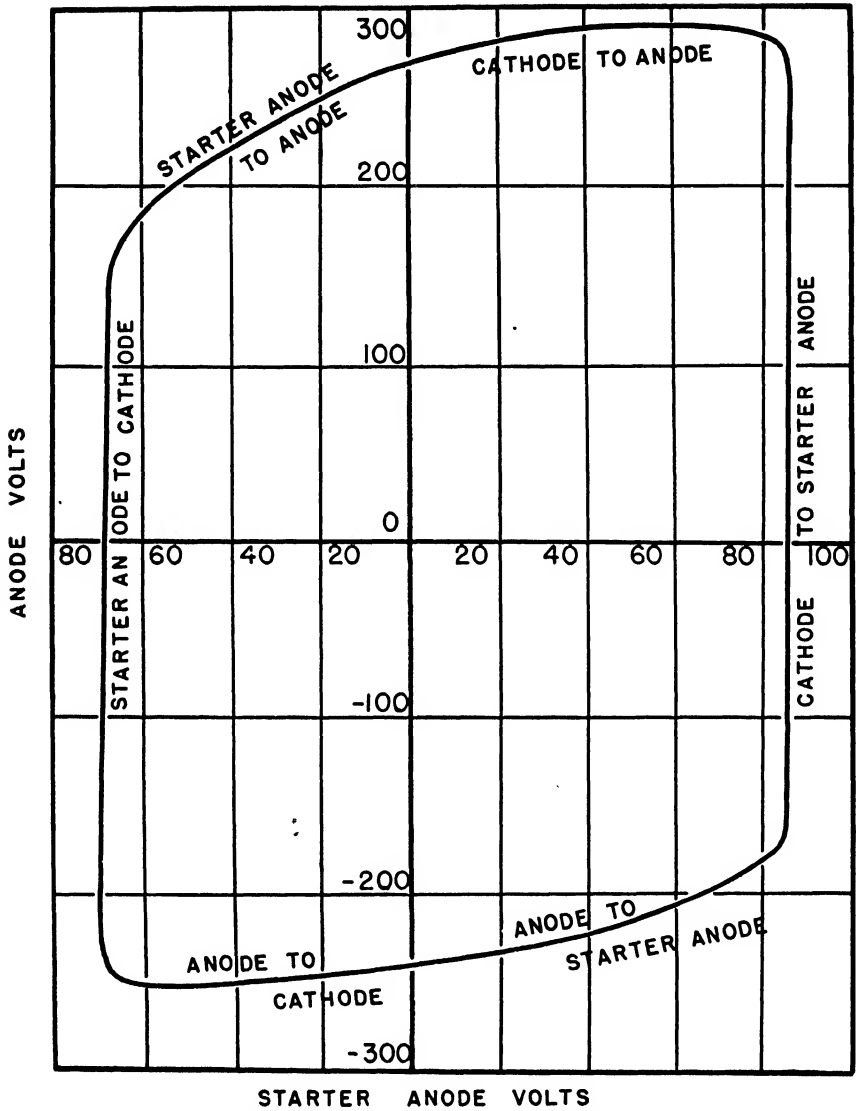
FIG. 6–17. · Characteristics of Cold-cathode-tube Conduction at Any Point Inside of Diagram.

the various electrodes. The actually intended method of operation is for the starter anode to initiate a current from the cathode causing ionization within the tube, the arc immediately transferring to the anode, the starter anode serving merely to initiate the discharge. In order to apply the tube properly, all starting characteristics must be known.

Procedure. Connect the apparatus as shown in Figure 6–16, and with 250 v. positive on the anode, connect the starter anode battery B_1 so that P_1 may be made progressively more positive. Close switch S_1 and slowly increase the voltage on P_1 until the current to P_1 increases suddenly. Note the voltage at this point, and plot results on a sheet of cross-section paper divided into four quadrants as shown in Figure 6–17. The y-axis represents anode voltages and the x-axis P_1 voltage. Plot anode voltages on the y-axis, positive voltages as $+ y$ and negative as $— y$. In a similar manner, plot the P_1 voltages on the x-axis. Decrease the anode voltage to 200 v. after opening S_1 and reducing P_1 to zero. Then slowly increase the P_1 voltage again until ionization sets in.

Repeat in this manner for the following anode voltages: 150, 100, 50, 0, — 50, — 100, — 150, — 175, — 200, — 225, — 250, — 275 v. Change the polarity of the meters whenever the deflection is reversed, but record the direction of current flow in each case. Note that the direction of the discharge is changed when the anode is made more negative than about 175 v. The current will then flow from the anode to the starter anode. Note also that when the anode is made more negative than 250 v. or more positive than 275 v., the starter anode P_1 loses all control.

Now repeat the entire experiment with a negative potential on P_1 and with anode voltages varying from — 250 v. to + 300 v. Change the anode voltage in small steps between — 200 and — 250 and between + 150 and 300 v. Plot measurements again as shown in Figure 6–16, plotting in addition the actual starter-anode P_1 current as a function of anode voltage. Calculate the potential drop in the tube at various voltages from the equation $E = E_{tube} — RI$, where R is the load resistor and E the applied potential.

The use of the OA4G tube is limited chiefly to relay operation, and is economical for intermittent operation since no current is required during the stand-by period. Its disadvantages are the appreciable starter-anode current and the low allowable inverse voltages. Several applications have already been described for this tube, besides its application to remote radio receiver tuning and control.

SUPPLEMENTARY LITERATURE

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PROBLEMS

1. Devise a circuit which is capable of partially controlling the plate current of a gaseous triode with 60-cycle plate voltage.

2. Devise a phase-shift circuit using inductance and resistance to control a gaseous triode.

3. If the resistance associated with the inductor of Problem 2 is 1,000 ohms, what is the maximum phase shift which can be obtained in this circuit?

4. Devise a counting circuit using a gaseous tube, suitable for registering the number of cars passing a given point.

5. Devise a circuit using a gaseous-discharge tube which could be used to set signal lights upon the approach of a car from a side street to the main highway.

6. Show how the circuit shown in Figure 6–12 can be used to control the temperature of an oil thermostat.

7. Show how a gaseous tube may be used as a relaxation oscillator.

8. Show how a gaseous triode may be used as a water-level indicator.

9. Show how a gaseous triode or tetrode may be used to sort dark objects from white ones.

D. C. Electron-tube Voltmeters

Introduction.

A D.C. electron-tube voltmeter, as the name implies, is used to measure D.C. voltages. It may take many forms, but in all cases the voltage to be measured is impressed on one set of the tube electrodes and the resulting change in current from another set of electrodes is used as an indirect measure of the unknown voltage. For example, if — 1 v. is applied to the grid of a triode of §2–3, the plate current will decrease about 1 ma. A milliammeter, a triode, and associated batteries, therefore, represent the elements of D.C. vacuum-tube voltmeter.

7–1. Voltage gain.

The voltage sensitivity of a good vacuum-tube voltmeter is not greater than that of ordinary D'Arsonval meters, and may be considerably less. Meters, however, require considerable current from the voltage under measurement, while the grid of an electron tube requires no current in a perfect tube and the practical tube grids allow currents from 10^{-15} to 10^{-9} amp. to flow. The current and voltage gains of D.C. electron-tube voltmeters may be discussed by an example. The ordinary 0-1 milliammeter usually has a resistance of 50 ohms and will, therefore, deflect full scale for a voltage of 50 mv. Consider, therefore, a voltage from a certain source of small internal resistance to be 50 mv. If the 0-1 milliammeter is connected to this source, the meter will go full scale. Consider the same meter inserted in the plate circuit of a 76 tube, in such a manner that it does not read the normal plate current of the tube but only responds to changes from this plate current. If now our same voltage source is inserted in the grid circuit, or in other words if the grid voltage is changed by 50 mv., the meter will show a deflection of .05 ma. which is only $\frac{1}{20}$ of full scale. Evidently a net loss in sensitivity has resulted through the use of the amplifier tube in conjunction with this meter.

The voltage drop across the meter will be .05 ma. $\times$ 50 ohms or 2.5 mv., which is less than the input voltage. Again a loss has been obtained. The voltage gain is less than unity, being exactly .05. To secure high voltage gains it is necessary to use a high resistance in the plate circuit.

This necessity can be seen by from the equation for voltage amplification given in Chapter 2:

$$\text{V.A.} = \frac{R_L}{r_p + R_L}.$$

The milliammeter considered in the problem could not be used to read the voltage developed across the resistor. It would effectively reduce the load resistance to 50 ohms and cause the voltage amplification to disappear. Hence, in order to realize a voltage amplification greater than unity, the plate load must be coupled to a high-resistance circuit such as the grid of another electron tube. The second electron tube, however, would again produce a gain of .05 if a meter were placed in the plate circuit. A two-tube unit, therefore, utilizing the first tube as a voltage amplifier with a gain of 20 and the second tube as an electron-tube voltmeter, will have an overall gain of 1, that is, its voltage sensitivity will be no greater than that of the meter alone.

7-2. Current gain.

If the grid resistor in the above example for the first tube is 10^7 ohms, and the grid current is negligible, a calculation from $E = RI$ shows that the current from the voltage source is only 5×10^{-9} amp. This may be compared to the current required by the meter, namely 10^{-3} amp.; a current gain or amplification of 200,000 times has been attained for the two-tube circuit. A similar calculation shows that the current gain of the one-tube circuit described previously is 10,000. These comparisons show that most of the current amplification occurs at the grid of the first tube, and that it is proportional to the resistance of the grid circuit. With special tube design, the grid resistance may be made as large as 10^{15} ohms and tubes of this type may produce current gains as high as 10^{10}. A single-tube D.C. electron-tube voltmeter thus produces extremely high current amplification but less than unity voltage amplification, and the important tube characteristics are grid resistance and transconductance. Vacuum-tube voltmeters are therefore useful in measurements of voltage where no currents or extremely small currents are to be drawn from the voltage source.

A practical circuit, which makes provision for setting the meter to zero before the voltage to be measured is connected to the grid, is shown in Figure 7-1. Provision is made to set the meter to zero with R_2 and R_3 when R_1 is adjusted to the operating grid voltage. The switch is then connected to the left so that the voltage to be measured is placed in series with the operating grid voltage from R_1; then any change in the meter reading must be due to the additional voltage on the grid, that is, the unknown voltage.

The characteristics will be similar to those determined in Chapter 2 except in that the resistor R_2 is in shunt with the meter and thus reduces its sensitivity. Since the value of R_2 is normally large in comparison to the internal resistance of the meter, its effect on the sensitivity of the meter is negligible. The plate-load resistance is the meter resistance. It may be desirable at this point to summarize the advantages and disadvantages of the electron-tube voltmeter over the corresponding D'Arsonval meter. The only apparent advantage is the current amplification. The disadvantages may be enumerated as follows: (1) The voltage amplification is less than unity. (2) The operation of the tube requires a heater or filament supply, a grid supply, a plate supply, and a meter-
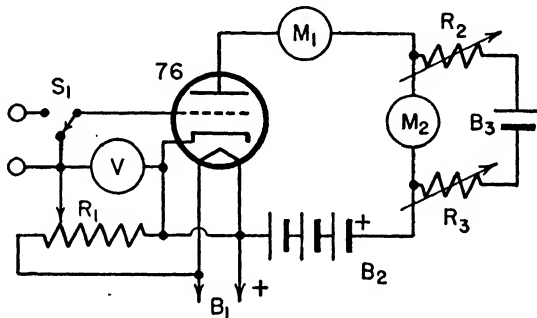

FIG. 7-1. Simple Vacuum-tube Voltmeter. R_1 = 500 ohms; V_1 = 0–10 voltmeter; M_1 = 0–10 milliammeter; M_2 = 0–1 milliammeter; R_2 = 1,500 ohms; R_3 = 100 ohms.

bucking current supply, a considerable expense of power. (3) The vacuum-tube voltmeter requires a zero adjustment which is not permanent and provision must, therefore, be made to check this at various intervals. (4) The readings are not linear with input voltage. In Figure 7–1, the required units to make the various adjustments are represented by S_1, R_1, or R_2. The lack of permanence of these adjustments is caused by the aging of batteries and tubes.

In many cases, these disadvantages are completely cancelled by the one advantage. If, for example, it is desired to measure the voltage of a source which has a resistance of 10^6 ohms, the milliammeter alone would produce an error of 99.9 per cent and is thus completely useless. The error of the vacuum-tube voltmeter caused by the high resistance of the source is only .1 per cent, a negligible quantity. Examples of this type of voltage source are numerous. Measurements using a glass electrode, a high-vacuum photocell, or an ionization gauge may be cited as typical examples. Cells which are not suitable for D.C. electron-tube voltmeters include, among others, thermocouples,[1] barrier-layer cells,

[1] Gunn, R., *R.S.I.*, *9*, 267, 1938.

polarograph cells, or in general any low-voltage low-resistance units. In addition, for units characterized by high internal resistance, the electrochemist must limit the current of the measuring instrument in order to avoid errors caused by polarization of the electrochemical cells. The importance of these measurements is indicated by the literature, which is replete with references to this subject. It will be possible to list only a few of the known articles on this subject. (*Note:* See end of chapter for references.)

7–3. Electrometer tubes.

The origin of the various currents which contributed to the net grid current were summarized in Chapter 2. The reduction of all of these currents is possible in tubes constructed especially for this purpose. In the General Electric type FP54 tube, for example, the grid current is reduced by (1) using good insulation for all electrode structures, (2) by thoroughly evacuating the tube envelope, (3) by operating the specially chosen filament at a low temperature in order to prevent degassing and to limit the emission of photoelectrons from the other electrodes, (4) by operating all electrodes at voltages lower than that required for the ionization of the residual gases, (5) by isolating the control grid from the high-velocity electrons and the small positive-ion emission of the filament with a space-charge grid. Under these conditions of operation, the tube is characterized by micro characteristics. The value of g_m is 25.0 micromhos, while the value of μ is 1. These low values are offset by the extremely low grid current, making current amplification of the order of 10^9 or 10^{10} quite feasible. In order to achieve these high values of current amplification, the circuit must be arranged to cancel out the drift caused by the aging of batteries and tubes. These methods are well-known today, and the reader is referred to the extensive literature on the subject for further information.[2-5]

EXPERIMENT 7–I

Purpose: To determine the characteristics of an FP54 electrometer circuit.

Materials: FP-54 tube, 4-prong socket (good quality)
                 2 6-v. storage batteries
                 Galvanometer with current sensitivity of 10^{-8} or 10^{-9} amp. per millimeter
                 4 314A General Radio 50-ohm potentiometers

[2] Bearden, J. A., *R.S.I. 4*, 271, 1936.
[3] Du Bridge, L. A., and Brown, H., *R.S.I., 4*, 532, 1933.
[4] Penick, D. B., *R.S.I. 6*, 115, 1935.
[5] Turner, L. A., *R.S.I. 4*, 665, 1933.

Galvanometer shunt
4,000-ohm wire-wound resistor
1 314A General Radio 10,000-ohm potentiometer
2,000-ohm wire-wound resistor

Procedure. Wire the apparatus as shown in Figure 7–2, building the whole unit in a light-tight metal box. All the grid leads must be well insulated, kept clear of other wires, and not allowed to touch the metal box at any point. Where the grid lead passes from the inside to the outside of the box it should be insulated from the box by means of a sleeve made of lucite, quartz, or sulphur. If the box happens to be air-tight, it should be dried with a chemical drying agent. Place a jumper across the termi-
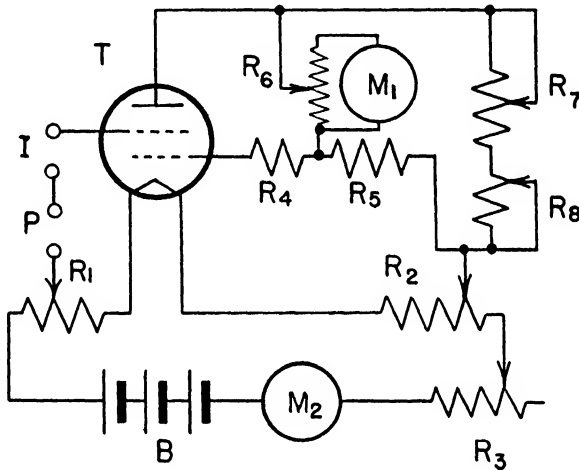
Fig. 7–2. Electrometer Tube Circuit. T = FP54; R_1 = 50 ohms; R_2 = 50 ohms; R_3 = 50 ohms; R_4 = 4,000 ohms; R_5 = 2,000 ohms; R_6 depends on M_1; R_7 = 10,000 ohms; R_8 = 50 ohms; B = 12-v. battery; M_1 = galvanometer; M_2 = 0-100 milliammeter.

nals P and I and with the galvanometer shunt adjusted to its lowest sensitivity connect the two 6-v. storage batteries in series, as indicated in the circuit. Reduce the sensitivity of the galvanometer nearly to zero by adjusting the Ayrton shunt R_6 (down in the circuit). Adjust R_3 until the 0-100 milliammeter shows the correct filament current for the tube. Then, with R_2 fully to right and R_1 to the left, adjust R_7 and the fine control R_8 until the galvanometer reads zero. Increase the sensitivity of the galvanometer and check the zero again.

With a 10^{-10} amp. per millimeter galvanometer at about .01 of full sensitivity, change the value of R_3 slowly, and note the deflection of the galvanometer as well as the reading of the milliammeter. Proceed with the adjustment of R_3 until a minimum is reached in the change in gal-

vanometer readings with a variation of R_3. If the galvanometer goes off scale during this adjustment it may be brought back to zero by adjusting R_7 and R_8. After the minimum point is reached, note the reading of the milliammeter, and if it differs by more than a few per cent from the current recommended by the manufacturer for the filament, repeat the above adjustment after decreasing the voltage on the plate and space-charge grid with R_2. When the point of stability has been found as the minimum change in galvanometer reading per unit change in filament current, mark these points on the potentiometer R_2. Also note and record the filament current. As the batteries lose their charge, gross variations in current may be compensated for with R_3. In general, only good batteries should be used, and only between 90 per cent and 50 per cent of full charge. In some cases, it may be necessary or advisable to change the grid voltage to a lower value with R_1. When this adjustment is made the point of stability must be redetermined.

After the point of maximum stability has been determined, prepare a galvanometer calibration chart by removing the jumper from P and inserting a good-quality potentiometer into this circuit. With the galvanometer at full sensitivity, change the setting of the potentiometer by units of 1 mv. and read the galvanometer. Plot galvanometer readings as a function of potentiometer volts. Repeat this measurement at .1 and .01 galvanometer sensitivity. Note that the galvanometer readings are not strictly linear with the potentiometer readings, especially for low galvanometer sensitivities.

In use, the high resistance is inserted at I and the galvanometer readings taken as an indication of the voltage developed across this resistance; or the galvanometer may be kept at zero with the potentiometer, thus giving the same voltage directly. The former procedure is more rapid, the latter more accurate.

7–4. The inverted triode.[6, 7]

The grid current of any commercial tube may be reduced to very low values by operating the tube at low voltages. This is particularly true today, since most tubes are thoroughly evacuated and the insulation of the grid is very good. An interesting way in which the input current of a triode may be reduced still further consists of operating the tube backwards, that is, making the plate serve the function of the control grid while the grid serves as a plate. Under these conditions the new value of μ will be approximately the reciprocal of the old one, and thus quite small. In current amplifiers this is of no great consequence, since in single-stage amplifiers the value of g_m is the only parameter normally

[6] Terman, F. E., *Proc. I.R.E. 16*, 447, 1928.
[7] Cherry, R. H., *Trans. Elec. Chem. Soc. 78*, 11, 1940.

considered. The new value of g_m is also lower than for the normal triode and depends on the electrode structure. In order to achieve high insulation in the new control element, the connection is usually brought out at the top of the tube. Several tubes of this type are manufactured by Westinghouse. In use, the excess grid current is bucked out as in Figure 7-1, and a similar switch is used to connect and disconnect the plate, that is, the new control grid. A variation of the inverted triode consists of using the suppressor grid of a 954 pentode as the control grid, with the plate as a measuring electrode.[8]

EXPERIMENT 7-2

Purpose: To determine the characteristics of an inverted triode.

Materials: Type 76 or 32 or special Westinghouse tube
Sockets
Filament battery
4.5-v. C battery
0-100 and 0-500 microammeters
0-5 voltmeter or 0-20 voltmeter
5,000-ohm volume control

Procedure. Connect the apparatus as shown in Figure 7-3, using a special electrometer tube if it is available. A type 76 or 6C5 will, however, serve equally well for this purpose of the experiment. Use the proper filament or heater battery, as recommended by the manufacturers of the tube. With $+1.5$ v. on the triode grid, determine the conductance of this grid as a function of the negative triode plate voltage. Plot the i_g-e_p curve as shown in Figure 7-4. Determine the slope of the curve and calculate the change in grid-cathode conductance for a 1-v. change in negative plate voltage. Repeat the experiment with $+3$ and $+4.5$ v. on the grid. Use caution in placing the sensitive 0-100 microammeter into the circuit by first checking the approximate value of the current with a sturdier meter. Plot all values as shown in Figure 7-4. From a cross plot of these values, calculate the dynamic grid resistance as well as the value of μ for this mode of operation. Note that the value of

$$\left(\frac{\partial e_g}{\partial e_p}\right)_{i_g}$$

is less than unity. (*Note:* In spite of the inversion of the control functions of the electrodes, the old terminology is still used.) Most small receiving-type triodes used today have rather large values of μ, and when these tubes are inverted the new value of μ becomes exceedingly

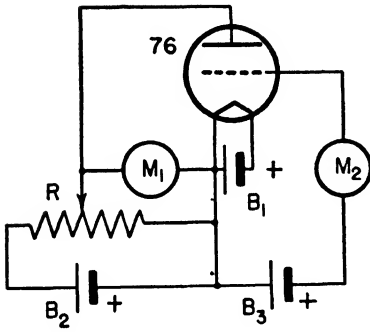8 Gabus, G. H. and Pool, M. L., *Rev. Sci. Inst. 8,* 196, 1937.

FIG. 7–3. Inverted-triode Volt-
meter. $R = 5,000$ ohms; $M_1 = 0–20$
v.; $M_2 = 0–100$ or $0–500$ microam-
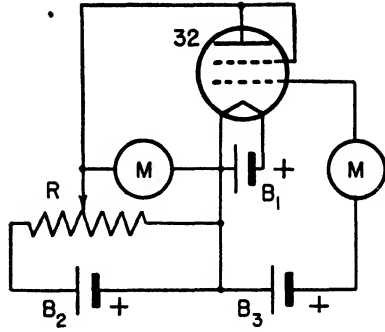meter; $B_2 = 22.5$ v.; $B_3 = 1.5–4.5$ v.

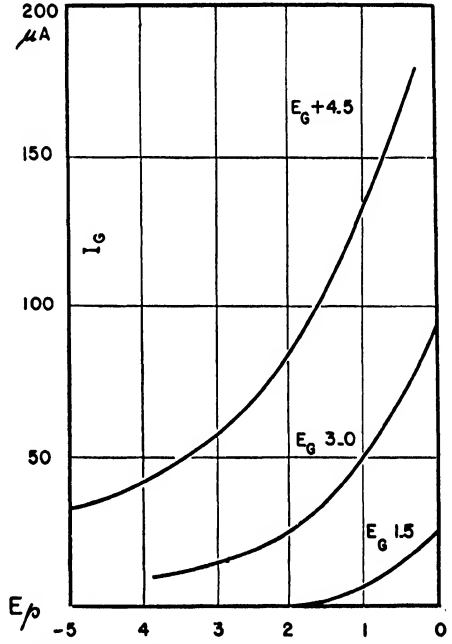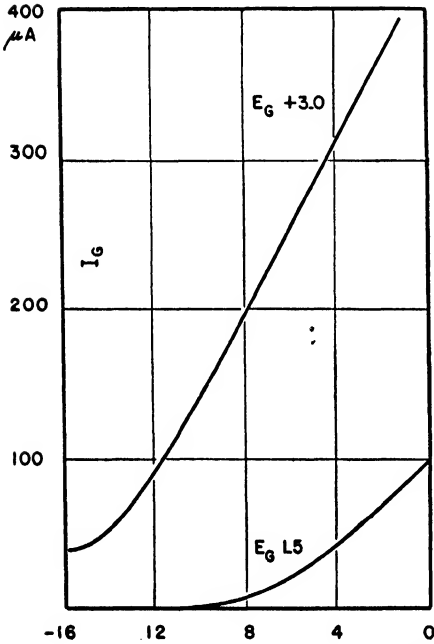FIG. 7–5. Inverted Triode Using
Type 32 Tube.

FIG. 7–4. Inverted-triode Characteristics.

small. The characteristics of the Westinghouse inverted triodes can be approximated by the use of a type 32 tetrode used as an inverted triode by connecting the screen grid to the plate and using these two electrodes as the control grid, as shown in Figure 7–5. Repeat the experiment with $+ 1.5$ v. on the grid, using the 0-100 grid meter and with $+ 3$ volts on the grid using the 0-500 grid meter. The μ of this inverted tube is still quite small, so that a plate potential of the order of 20 v. will be required to reduce the grid current to near zero. Calculate the conductance, resistance, and dynamic grid resistance for inverse operation as before. Also, evaluate the new value of μ.

7–5. The linearity of vacuum-tube voltmeters.

The linearity of any vacuum-tube voltmeter using a meter in the plate circuit may be estimated by an examination of the constancy of g_m as a function of the grid voltage. In most cases, this is not constant except for relatively small changes in grid voltage. Similarly, it is subject to change with the aging of the tube and batteries. A calibration chart obtained by plotting input voltage versus meter reading will eliminate the difficulty resulting from lack of linearity; however, any change in g_m due to aging of tubes or batteries will render such a chart valueless.

These difficulties may be avoided in two ways, either by using a circuit in which small variations in g_m have little or no effect on the calibration curve, or circuits where the variation of g_m is of no importance because the effective value is a constant and thus relatively independent of the grid voltage. Both methods will be discussed in some detail in later sections.

7–6. Slide-back voltmeters.

The circuit shown in Figure 7–1 may be used as a slide-back voltmeter by adding a voltmeter to the potentiometer R_1 so that the grid voltage may be read.[9,10,11] The principle of this slide-back voltmeter may best be understood by showing how it is used.

With S_1 set to right position, adjust R_1 to a value which will cause the output meter to read half scale. Then connect the unknown voltage by throwing S_1 to the left. The voltage across the potentiometer and the unknown voltage are now in series, and form the new grid potential. The output meter will, of course, no longer read half scale. Readjust R_1 until the plate meter is again *exactly* on half scale, the value of the un-

[9] Hiken, C. B. and Birdsall, L. C., *Trans. Am. Inst. of Elec. Eng. 57*, 173, 1938.
[10] Heising, R. A., U. S. Patent 1232919.
[11] Reich, H. J., Marvin, G. S., and Stoll, K., *Electronics*, Sept., 1931; p. 109.

known voltage is equal to the difference between the readings of the voltmeter before and after readjustment.

The linearity of this measurement is independent of the electron-tube circuit characteristics but depends only on the linearity of the voltmeter. The sensitivity of the instrument as a whole will, however, be dependent on the amplification of the tube and the sensitivity of the plate meter.

The sensitivity of the plate-current meter may be made large, since the normal plate current is canceled by the bucking-current adjustor network. There is a practical limit, however, imposed by the drift caused by the aging of the tubes and batteries, as well as by the possibility of damage to the sensitive output meter. If the output meter requires 100 μamps. for full scale, the limiting sensitivity at the grid will be approximately 10^{-4} v. but the meter may have current of the order of 5 ma. passing through its elements if the input voltage becomes large. Since this current is in excess of the normal current by a factor of 50, the meter may be seriously damaged. The sensitivity may also be increased by an increase of the transconductance. If the increase of the transconductance is accompanied by a comparable increase in plate current, no great advantage is gained as shown above. For this type of use, the tube should be selected for the highest value of $\frac{g_m}{i_p}$ rather than for the value of g_m alone.

EXPERIMENT 7–3

Purpose: To study the characteristics of a 6F5 slide-back voltmeter.

Materials: 6F5 GT tube
              Octal socket
              6-v. battery
              180-v. B battery
              1,000-ohm volume control
              1,000-ohm fixed resistor
              0-1.5 milliammeter
              Student potentiometer (10^{-4} v.)

Procedure. Wire the apparatus as shown in Figure 7–6, and with S_1 in position 2, note and record the reading of the milliammeter. Close S_1 to position 3 and set R_1 until the plate meter reads a little lower than with S_1 open (position 2). Record this new value. Connect an unknown but steady voltage (a Weston standard cell is good) to the terminals and change the position of S_1 to 1. Change the reading of the student potentiometer until the meter reads the same value as before. Repeat this cycle several times, noting the reading of the potentiometer in each

case. From the variation in readings, calculate the mean deviation and record it as the usable sensitivity of the instrument. If time permits, measure other voltages in a similar manner. Why was the reading of the milliammeter made lower for S_1 in positions 1 and 3 than for position 2?

7–7. Multistage null indicators.

The possibility of damage to a sensitive plate meter may be avoided by using two or three stages of voltage amplification ahead of the voltmeter, shown in Figure 7–1. If the amplifier tube provides a voltage gain of 100, a 0-10 milliammeter in the plate circuit of a 76 tube will be sensitive enough to detect about 10^{-4} v., and the meter cannot be damaged since the maximum plate current of this tube is about 10 ma. Small
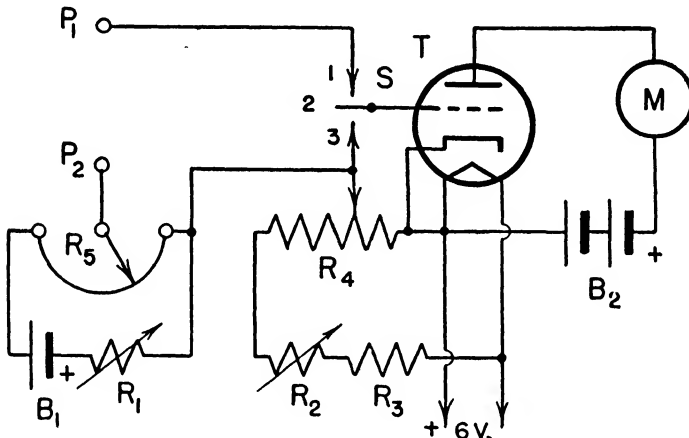
Fig. 7–6. Slide-back Voltmeter. $R_1 = 200$ ohms; $R_2 = 100$-ohm potentiometer; $R_3 = 1,000$ ohms; $R_4 = 1,000$-ohm potentiometer; $R_5 = 100$-ohm calibrated slide wire; M = 0–1 milliammeter.

variations in the batteries and aging of the first tube will have considerable effect on the reading of the meter. The ultimate sensitivity is thus decreased rather than increased, but the meter is protected from damage.

In the slide-back voltmeters, the meter is used only as a null indicator, and the electron-ray tube may be used successfully as a substitute for the meter. One suitable circuit is shown in Figure 7–7, in which the 6A8GT tube serves as a current amplifier followed by the 6J7 voltage amplifier operating the electron-ray tube. The 6A8GT tube is used in the first stage, since the grid current at low electrode voltages is less than 10^{-12} amp. The sector on the electron-ray tube is adjusted with the plate resistor R_2 until it assumes a definite position. The switch S is moved to left, thus connecting the known voltage E in series with an external potentiometer. If the setting of the potentiometer is changed

until the sector on the electron-ray tube returns to its former position, the unknown voltage will be given by the reading of the potentiometer. A reference mark may be placed on the envelope of this tube and another one a short distance away to serve as sights for precise determinations of the null point.

7–8. Line operation of D.C. vacuum-tube voltmeters.

The reading of any vacuum-tube voltmeter will be influenced by line voltage fluctuations if the unit is operated from the commercial A.C. or D.C. mains. Line voltage fluctuations are usually of the order of 5 to 10 per cent, and an uncompensated voltmeter would, therefore, fluctuate by a similar amount. A vacuum-tube 0-1 voltmeter under such conditions cannot be expected to read voltages as small as 10^{-3} v., since the fluctuations may be equivalent to 10^{-1} v.
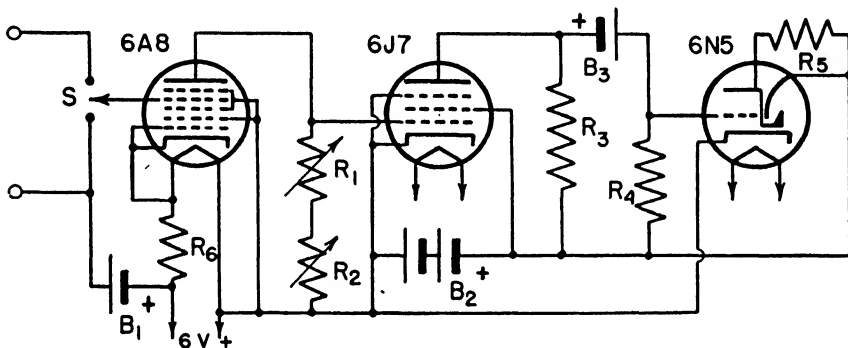
FIG. 7–7. Electron-ray Voltmeter. $R_6 = 3$ ohms. $R_1 = .2$ megohm; $R_2 = 2.0$ megohms; $R_3 = .5$ megohm; $R_4 = 1.0$ megohm; $R_5 = .5$ megohm.

The various methods which have been devised for overcoming this difficulty divide themselves into two general categories: those in which the power-supply voltage is made constant in spite of line-voltage fluctuations, as shown in Chapter 4, and those in which an attempt is made to cancel the effect of power-supply variation in the voltmeter itself. The various methods which may be used to stabilize power supplies have already been discussed, so that only the second type of stabilization will be discussed here. The theory of the various methods for compensation is discussed adequately in the literature and will not be detailed here.[12-18]

[12] Wold, D. I., U. S. Patent 1232879, 1917.
[13] Wynn-Williams, C. E., *Phil. Mag. 6*, 324, 1928.
[14] Razek, J., and Mulder, P. J., *R.S.I. 18*, 460, 1929.
[15] Turner, L. A., and Siegelin, C. O., *R.S.I. 4*, 429, 1933.
[16] Turner, L. A., *R.S.I. 4*, 665, 1933.
[17] Offner, F., *R.S.I. 8*, 20, 1937.
[18] Schmitt, O. H., *R.S.I. 8*, 126, 1937.

The effect of the variations caused by line fluctuations in plate and grid voltage may be made compensating by selecting plate and grid voltages which are in the ratio of the μ of the tube. If the grid voltage is —3 and the plate voltage 300 for a tube with a μ of 100, the equation of μ, namely,

$$\mu = -\left(\frac{\partial e_p}{\partial e_g}\right),$$

when i_p is constant, is satisfied, and i_p is independent of the power-supply voltage as long as both grid and plate voltages are derived from the same power source.

This adjustment is known as μ balance. The practical difficulty is that for commercial tubes the plate current is at cutoff when the grid voltage is made equal to $-\frac{e_p}{\mu}$. This difficulty can be overcome by decreasing the high negative grid voltage with a small but constant battery. Since the grid draws practically no current, the battery will have shelf life. The other difficulty is caused by the fact that μ is not strictly a constant, as was evident from the calculations in Chapter 2. This is particularly true for filament-type tubes.

The effect of changes in heater or filament voltage may be partially canceled by a number of methods, if the variation of emission with voltage is known. The FP-54 circuit shown in Figure 7–2 was compensated for this effect. In heater-type tubes, this effect may best be compensated for by employing two tubes in a bridge circuit, in a manner such that an increase in emission of one tube will be balanced by the increase in the other tube.

A circuit which employs both forms of stabilization is shown in Figure 7–8. The 6N7G tube combines two tubes in the same envelope. If these two sections are used in a bridge circuit in which μ balance is employed for the various voltages, a stability corresponding to 10^{-4} v. input may be obtained, even if the line voltage fluctuations are as high as 10 per cent. The operating grid current from these high-μ triodes is, however, fairly high (10^{-8} amp.), and the usefulness of the instrument is therefore greatly limited. Other methods are detailed in the literature.

7–9. Direct-reading linear vacuum-tube voltmeters.[19–22]

The experiments with the triode showed that the linearity of the i_p-e_g curve may be improved either by adding resistance to the plate cir-

[19] Brunbauch, J. M., and Vance, A. W., *Electronics*, Sept., 1938; p. 16.
[20] Roberts, S., *R.S.I.* **10**, 181, 1939.
[21] Terman, F. E., *et al.*, *Proc. I.R.E.* **27**, 649, 1939.
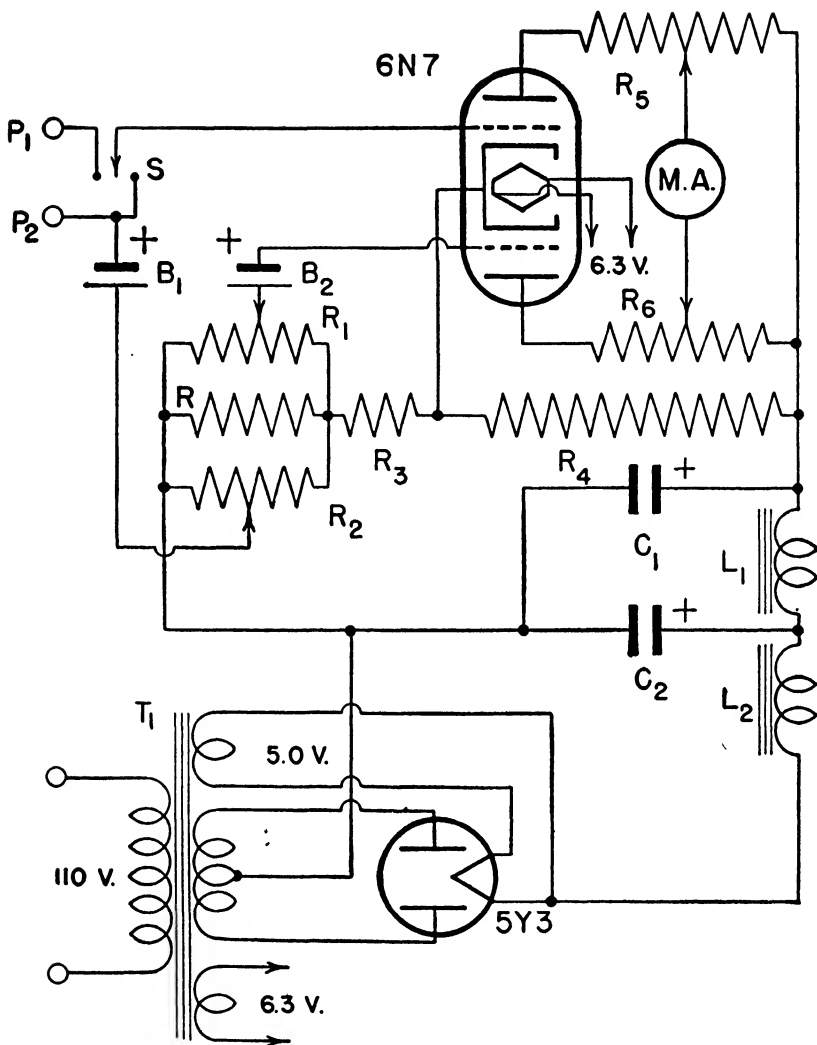[22] Vance, A. W., *R.S.I.* **7**, 489, 1936.

FIG. 7–8. Balanced Voltmeter. R_2, R_1 = 500 ohms; R = 300 ohms; R_3 = 200 ohms; R_4 = 8,000 ohms; R_5, R_6 = 20,000 ohms; T_1 = 150–0–150-v. transformer; B_1, B_2 = 3-v. bias cells.

cuit or by employing degeneration in the cathode circuit. For the latter case, the equation

$$g' = \frac{g_m}{1 + g_m R}$$

was derived, in which g_m is the transconductance in the absence of degeneration and g' the value of the same quantity with a cathode resistor of value R. It was shown further that the linearity of the i_p-e_g curve is increased as the value of R increases, and the increased linearity is approximately proportional to the ratio of g_m to g'. This change may be shown by considering a tube with an extremely large value of transconductance reduced to a nominal value by the use of a feedback resistor. If the transconductance without degeneration is 500,000 micromhos and is reduced to approximately 1,000 micromhos by the use of 1,000-ohm resistor, the value of $g_m R$ will be 500, which is large in comparison to 1, and the equation is simplified to $g' \cong \frac{1}{R}$, thus showing that the transconductance before regeneration is no longer the determining factor. The student can prove this by substituting various values in the exact equation to show that the value of g' is only slightly influenced by g_m when the value of $g_m R$ is large in comparison to 1.

At the present time the highest transconductance of single tubes is of the order of 10,000, but if two or three tubes are used in cascade the effective transconductance may be made very high. If a 6J7 tube is used as a voltage amplifier for a 6J5 tube, the effective transconductance will be about 200,000. If this is reduced by the use of a 1,000-ohm feedback resistor properly placed to effect degeneration, the resulting transconductance will be 995 micromhos, a value that differs from 1,000 by only .5 per cent. The curvature of the transconductance of the 6J5 tube is thus reduced to approximately .5 per cent of its former value, and the resulting curvature will be negligible over the normal operating range.

The same conclusions may be drawn by considering the voltage amplification. If we designate the voltage amplification by μ', a signal voltage e will be equal to $\mu'e$ at the output in the absence of degeneration. If part of the output voltage is fed back to the input so that a portion of the input voltage is canceled, the new input voltage will be $e + \beta E$, where E is the output voltage and β the fraction of this voltage fed back to the input. The output voltage under these conditions will be given by $E = \mu'(e + \beta E)$. Solving,

$$\frac{E}{e} = \frac{\mu'}{1 - \mu'\beta}.$$

If the feedback voltage opposes the input voltage, the sign of β is regarded as negative.

Again, if the voltage gain μ' of the amplifier is large when no degeneration occurs, the value of $\mu'\beta$ will be large in comparison to 1 if β is not too small, and the equation reduces to

$$\frac{E}{e} = -\frac{1}{\beta}.$$

The output is therefore independent of the gain of the amplifier under these conditions.

Large values of μ may be obtained from two- or three-stage amplifiers, and the output from these amplifiers is strictly proportional to the input voltage. In one three-stage amplifier used by the authors, the output is proportional to the input with an accuracy greater than .05 per cent at the lowest reading. Since these low readings may be canceled out in various ways, it is safe to say that a properly constructed three-stage degeneration amplifier is more accurate and linear than a 15-inch precision meter.

The use of degeneration provides other advantages, such as decrease in the drift due to aging batteries and tubes. Drift is not, however, entirely eliminated, because drift of plate current in the first tube represents an input voltage equal to the magnitude of the drift in volts divided by the voltage gain of the first stage. Since the gain for the first stage is not very high, the drift is not entirely eliminated. Variations in heater and filament voltage of the first tube cause similar but even larger fluctuations. These may, however, be reduced by a combination of μ balance and filament balance for the first tube as already discussed. Any steady grid voltage which is not obtained from the feedback network must be held constant or its effect effectively canceled by a resistance bridge circuit in which one part is formed by the output meter.

EXPERIMENT 7–4

Purpose: To study the characteristics of a two-stage feedback D. C. voltmeter.

Materials: 6J7GT and 6J5 tubes
Sockets
0.25-megohm $\frac{1}{2}$-watt resistor
1,000-ohm potentiometer
100-ohm volume control
Resistance box
Student potentiometer
Accurate 0-1 milliammeter
6-v. storage cell
45-v. battery

22.5-v. battery

Single-pole double-throw switch

Procedure. Connect the apparatus as shown in Figure 7–9, and with S_1 to right, set the coarse adjustment R_3 and the fine adjustment R_4 until the meter reads exactly full scale with the value of the resistance box R_2 at zero. Wait for 10 or 15 minutes, or until the tubes have reached temperature equilibrium. Then connect a student potentiometer or other device capable of producing voltages with an accuracy of approximately

FIG. 7–9. Inverse-feedback Voltmeter. $R_1 = .25$ megohm; $R_2 = 0$–10,000-ohm resistance box; $R_3 = 1,000$-ohm potentiometer; $R_4 = 100$-ohm potentiometer; $T_1 = 6J7GT$; $T_2 = 6J5$; $B_1 = 45$ v.; $B_2 = 22.5$ v.; $M = 0$–1 milliammeter.

10^{-4} v. to the input terminals. Connect the positive terminal of the potentiometer to the grid side of the input. Set the potentiometer to zero, and readjust R_3 and R_4 for full scale on the meter; then, with S_1 to the left, slowly increase the reading of the potentiometer in steps of about 1 mv. and read the output meter. Tabulate these values of potentiometer and milliammeter readings and calculate the value of the effective transconductance at the middle of the range. Calculate the value of R_2 for a g_m value of 10,000 micromhos from the equation

$$g' = \frac{g_m}{1 + g_m R},$$

where the average value of g_m was calculated from the above measurement. Set the value of R_2 to this calculated value, and after readjusting R_3 for full scale, again increase the reading of the potentiometer in steps of about 10 mv. and note the milliammeter readings. Plot the readings so obtained on a large scale, and calculate the actual effective trans-

conductance (slope of line). Repeat the experiment with values of R_2 as calculated above to give other effective values of g'. The following values are recommended: 5,000, 2,000, 1,500, and 1,000. Plot the curves on a large scale in each case. Note that the curvature decreases as the value of R becomes larger. Compare the reduction in curvature (at corresponding meter readings) actually obtained with the theoretical prediction given in §7–7. Repeat the entire experiment with a 90-v. plate supply and a 45-v. interstage battery. Repeat the experiment after placing a 1.5-v. battery and a 1,500-ohm resistor across the meter in a manner which will buck out 1 ma. of current with a 90-v. plate supply.

7–10. Portable inverse-feedback amplifiers.

The circuit shown in Figure 7–9 does not require the use of heater type tubes but may use the new high-efficiency dry-battery-operated tubes.[23] In this case, separate batteries are required to heat the filaments of the tubes and a separate battery must be used to supply the potential to R_3-R_4. Since the gain possibilities of these tubes are lower than those used in Experiment 7–4, the linearity will not be as good. This difficulty may be overcome by the use of an additional tube, thus providing more gain than in the two-tube circuit of Figure 7–9. If the first tube is properly chosen and operated at micro characteristics, its grid current will be less than 10^{-12} amp.

EXPERIMENT 7–5

Purpose: To determine the characteristics of a three-stage inverse-feedback voltmeter.

Materials: 1 1N5GT and 2 1S5 tubes
Sockets
Double-pole double-throw switch
3-ohm, 30-megohm, 1-megohm, and 5,000-ohm $\frac{1}{2}$-watt resistors
1,000-ohm General Radio 314A resistor with dial
5,000- and 500-ohm volume controls
1.5-v. heavy duty battery
45-v. battery
15-v. and 22.5-v. C battery
Good grade, large size 0-1 milliammeter

Procedure. Connect the apparatus as shown in Figure 7–10 in a shielded cabinet, using a well-insulated switch for S_1 and keeping all leads as short as possible, using straight runs for all wiring of the first two stages. After the filament battery has been turned on a few minutes, set the 1,000-ohm potentiometer R_3 to zero, that is, to the left, and ad-

[23] Smith, N. R., and Schooley, A. H., *R.C.A. Rev. 4*, 496, 1940.

just R_7 and R_8 until the meter reads zero. Determine the voltage gain by connecting a potentiometer to the input terminals with the positive to the grid. With the potentiometer set to zero, throw S_1 to left, then slowly increase the reading and take readings on the plate meter. The 0-1 milliammeter in the plate circuit, used in conjunction with the 1,000-ohm resistor, represents (approximately) a 0-1 voltmeter, providing its internal resistance is lower than 100 ohms. Plot voltage output as a func-
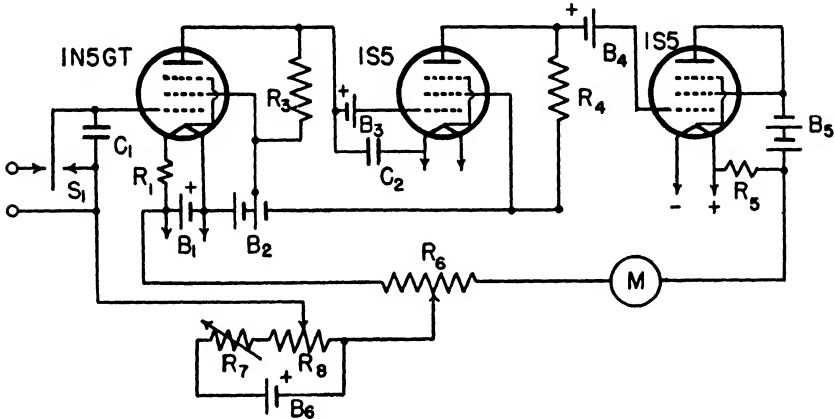
Fig. 7-10. Three-stage Inverse-feedback Voltmeter. $C_1 = .001\mu f.$; $C_2 = .01\mu f.$; $R_1 = 3$ ohms; $R_3 = 30$ megohms; $R_4 = 1$ megohm; R_6 1,000 ohms; R_7 500 ohms; $R_8 = 5,000$ ohms; $B_1 = 1.5$ v.; $B_2 = 45$ v.; $B_3 = 15$ v.; $B_4 = 22.5$ v.; $B_4 = 45$ v.; $B_6 = 3$ v.; $M = 0$-1 milliammeter; $R_5 = 4,000$ ohms.

tion of input voltage. Set R_6 to .1 of full scale ($\beta = -.1$) and redetermine the voltage gain. Replot on a new scale. Repeat the experiment with β values of $-.2$, $-.5$, $-.75$ and -1.0, plotting output volts as a function of input volts in each case. Use a new scale for each plot. Check the equation

$$\frac{E}{e} = \text{voltage gain} = \frac{\mu'}{1 - \mu'\beta}$$

from the values obtained above, remembering that μ' is the voltage gain when β is zero. Note that the linearity is greater than the accuracy of the meter, especially at the higher values of plate current (note the resistor R_5 serves to buck out .3 ma. of plate current; the meter may thus go off scale in either direction).

7-11. Pentagrid converter: bridge voltmeter.

The characteristics of a pentagrid converter tube were discussed in Chapter 5 and it was shown that in these tubes the plate exhibits normal or positive transconductance while the oscillator plate has a negative

transconductance. This property may be utilized in the construction of a bridge voltmeter which has twice the sensitivity of the ordinary bridge circuit shown in Figure 7–8. The circuit is shown in Figure 7–11. Resistors R_2 and R_3 form two arms of the bridge, while the filament-grid G_2 and filament-plate resistance form the other two arms. When the grid is made negative, the filament-grid G_2 resistance decreases and the filament-plate resistance increases. The microammeter A reads the off-balance voltage.

EXPERIMENT 7–6

Purpose:　　To determine the characteristics of a 1A7GT D.C. voltmeter.

Materials:　　1A7GT tube
Socket
0-50 or 0-100 microammeter
2,000-, 7,500-, 15,000-, and 75,000-ohm volume controls
1.5-v. filament battery
1.5-v. small-size cell
45-v. Minimax battery
Single-pole double-throw switch
Potentiometer graduated in millivolts

Procedure. Connect the apparatus as shown in Figure 7–11, and if the tube is new, age it for 24 to 48 hours by connecting all voltages, but disconnecting the grid cap and meter from the circuit. Then, with grid still
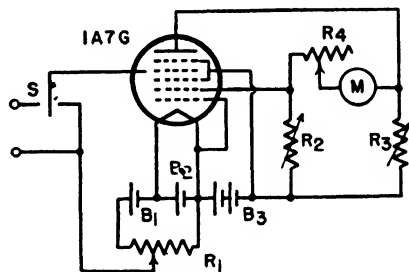
FIG. 7–11.　1A7GT Direct-current Voltmeter.　$B_1 = 1.5$ v.; $B_2 = 1.5$ v.; $B_3 = 45$ v.; $M = 0$-100 microammeter; $R_1 = 2,000$ ohms; $R_2 = 7,500$ ohms; $R_3 = 15,000$ ohms; $R_4 = 75,000$ ohms.

disconnected, set R_2 to 1,000 ohms and with R_4 at its maximum position connect the meter. Change the value of R_3 until the meter reads exactly zero. Connect the grid cap and with S_1 to the right adjust R_1 until the meter again reads zero. Set R_4 to zero resistance and again adjust R_1 until the meter reads zero. Connect a potentiometer to the input ter-

minals, and with S_1 to left determine the meter reading as a function of input voltage. Plot the readings so obtained. Repeat the entire experiment, but set R_2 initially to 2,000 ohms. Plot as before. Repeat also at values of 3,000, 5,000, and 7,500 ohms for R_2. In each case, be sure to adjust R_3 until the meter reads zero when the grid is disconnected. What is the optimum value of the resistor R_2?

Repeat the entire experiment with resistors of 1,000 and 2,000 ohms in the screen circuit. In what manner does the screen voltage affect the sensitivity? If a high-sensitivity galvanometer is available, measure the grid current in each of the above experiments. To be satisfactory, the galvanometer must have a current sensitivity of at least 10^{-10} amp. per millimeter.

7–12. Ballistic slide-back voltmeters.[24,25]

The errors caused by the grid-current RI drop in high-resistance voltage sources may be partially eliminated by the use of a ballistic voltmeter. If a small capacitor is charged to the voltage of an unknown
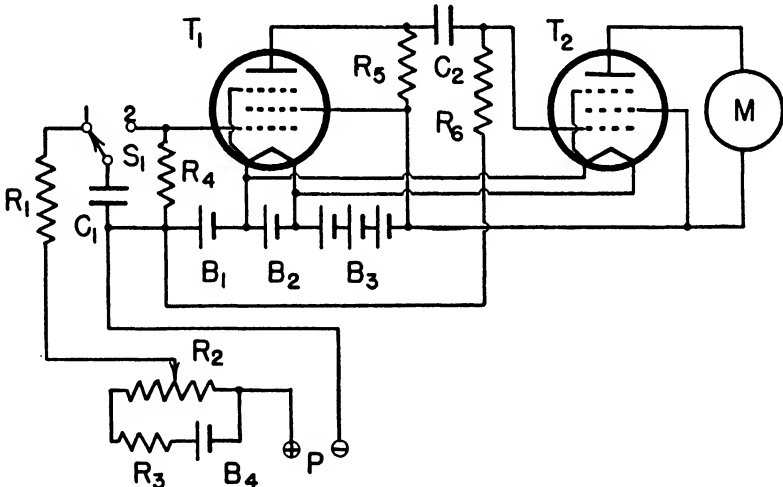
Fig. 7–12. Ballistic Voltmeter. T_1, T_2 = 1S5; R_4 = 20 or 50 megohms; R_1 = 1 megohm; R_2, R_3 = standard potentiometer; R_5 = 1.0 megohm; R_6 = 5.0 megohms; C_1 = .01 μf. or less; B_1 = 13 v.; B_2 = 1.5 v.; B_3 = 67.5 v.; C_2 = .1μf.; M = 0–1 milliammeter.

cell, the current will be zero after the capacitor is fully charged, providing the insulation is perfect. Since air capacitors may be obtained with insulation resistance of approximately 10^{14} ohms, the equilibrium current will be of the order of 10^{-14} to 10^{-15} amp. If the capacitor is now discharged into the grid of a vacuum-tube voltmeter the output meter

[24] Hemingway, H., *Ind. Eng. Chem., Anal. Ed.*, 7, 203, 1935.
[25] Finlay, R., *Electronics*, Nov., 1937; p. 39.

will momentarily indicate the voltage of the capacitor. If the capacitor is small, however, the discharge rate may be so rapid that the output meter does not reach the correct reading before the capacitor is discharged appreciably.

This problem, coupled with the fact that taking a maximum excursion reading of a meter is both laborious and inaccurate, has resulted in the combination of the slide-back voltmeter with charged capacitor. If the capacitor C_1 of Figure 7–12 is charged by both the unknown voltage V and a known and opposite voltage from P, the voltage across the capacitor will be zero when $V = P$ and of one polarity if $V < P$ and of the other polarity if $V > P$. If switch S_1 is put in position 2, the output meter will show no change in reading when $V = P$ and will deflect either to right or to left if $V \neq P$. P may be adjusted so that its voltage is equal to V by alternating charges and discharges of C_1 with switch S_1, until the output meter remains approximately stationary.

If the resistance of the unknown voltage and capacitor are both small, the charging period is short and the time required to make a measurement comparatively short. If C_1 is made very small to accommodate large values of resistance R_1 of the unknown voltage at short charging periods, the corresponding discharge periods may be so small in comparison to the inertia of the meter needle that the sensitivity is seriously reduced. Capacitor C_1 should nevertheless be as small as possible for use with such voltage sources as glass electrodes or other polarizable electrodes, since energy is required to charge the capacitor. The energy in joules is given by $\epsilon = CE^2$ where C is in farads and E in volts. At the instant the uncharged capacitor is connected to the unknown voltage, the current will be limited only by its internal resistance. The RI drop across the cell at this point will be equal to the net voltage, causing a very large voltage error. However, as the capacitor charges and develops a back e.m.f., the current drops until it reaches the value determined by the leakage resistance. The charging current may cause at least temporary damage to certain types of cells.

Since the first stage of the amplifier is coupled with a capacitor, the second stage may be similarly coupled, and common batteries used for the two tubes. The drift caused by the aging of the first tube and its associated batteries is thus not passed by this coupling capacitor, and the voltmeter is very stable.

In certain cases capacitor C_1 is substituted for the grid resistor and the drift of the output meter noted while the grid current alone is charging the capacitor. The additional current from an unknown added to the capacitor modifies the rate of drift and its magnitude may be calculated from these data. In this manner, currents as small as 10^{-17} amp. (30 electrons per second) have been measured.

EXPERIMENT 7-7

Purpose: To determine the characteristics of a ballistic vacuum-tube voltmeter.

Materials: 2 type 1S5 tubes
Sockets
0-500 microammeter
45-v. battery
1.5-v. battery
1.25-v. Mallory bias cell
1-megohm and 10-megohm resistors
2,000-ohm volume control
5,000-ohm resistor
Small 1.5-v. battery
Potentiometer
Resistors and capacitors indicated in Table 7-1.

Procedure. Wire the apparatus as shown in Figure 7-12. With the potentiometer P set to 50 mv., set R_2 until the output meter shows relatively no deflection when S_1 is moved from position 1 to position 2. The voltage from R_2 is now 50 mv. Reduce the potentiometer voltage to zero and recharge capacitor C_1; then discharge and note the maximum reading of the meter. Repeat the charge and discharge with a potentiometer reading of 100 mv. Note the deflection for other values of potentiometer readings. Reduce the voltage from R_2 and P to zero, and note that throwing the switch may still cause a deflection of the meter. With R_2 set to zero and P set to 100 mv., throw the switch from position 1 to position 2 and back to position 1 after P is rapidly reduced to zero. Change the switch back to position 2 again immediately. Why did the meter deflect in the second case, although the voltage of P was zero?

Repeat the entire experiment for the values shown in Table 7-1, as well as for other combinations.

<div align="center">TABLE 7-1</div>

R_1 (megohms)	R_4 (megohms)	C_1 (μf.)	C_2 (μf.)
10	10	.1	.1
10	10	.001	.1
10	10	.0001	.1
100	10	.00001	.1
100	1.0	.0001	.1
100	10	.1	.1
10	10	.1	.01

Take notes to show how the sensitivity and charging time decrease with smaller values of C_1. Estimate the sensitivity in volts for the various values of C_1 and R_4. How could you improve the sensitivity without adding more tubes to the circuit?

7–13. Step potentiometer combined with electronically balanced potentiometer.

The circuit shown in Figures 7–9 and 7–10 may be combined with the conventional step or selector-switch potentiometer, if the feedback re-
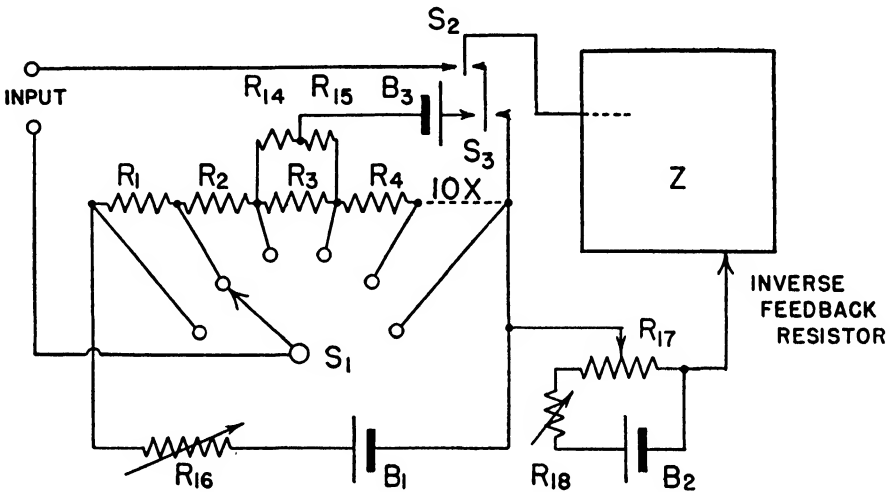
Fig. 7–13. Schematic Diagram for Combination of Inverse-feedback Amplifier with Step Potentiometer. R_1 to R_{13} = 100-ohm resistors; R_{16} = RI dropping resistor; R_{14}, R_{15} = standard-cell matching resistors.

sistor is adjusted so that the meter reads the increment between steps. The circuit of Figure 7–13 shows this application. The resistors R_1 to R_{13} are all of equal values and the voltage across each resistor is adjusted to a definite value by calibration against a standard cell. The value of the feedback resistor is adjusted so that the meter goes full scale for a voltage equal to the voltage across one resistor in the R_1-R_{13} chain. The circuit shown may be adjusted for any voltage across these resistors by properly selecting the position to which the standard cell is connected. If the scale is to read pH, the voltage across each resistor should be adjusted to .06 v. at 30° C. and the feedback resistor so selected that a 0-1 milliammeter reads full scale for a change of .06 v.

Adjustment of this circuit for use as a 0-1.4 voltmeter is illustrated by the following directions.

Select thirteen 100-ohm resistors for R_1 to R_{13} and connect them in series and to switch S_1, as shown in Figure 7–13. With R_{14} equal to

250,000 ohms, select R_{15} so that the ratio of one tenth its value to the sum of R_{14} and R_{15} is equal to the standard-cell voltage less 1.000. Connect the standard cell and battery B_1 with the indicated polarity. Connect two double-pole double-throw micro switches, or equivalent push-button switches, as shown in Figure 7–13, so that both switches will be to the right in the rest position. With R_{16} equal to about 300 ohms, adjust the zero of the electron-tube voltmeter of Figure 7–9 or 7–10 with the grid voltage (R_{17} and R_{18} as shown in Figure 7–13) until the meter reads zero. Throw switch S_3 to left (push down) and adjust R_{16} until the meter again reads zero. Each resistor from R_1 to R_{13} will now represent an RI drop of .1 v. if R_{14} and R_{15} are correctly matched to the standard-cell voltage.

Check the value of the feedback resistor of the electron-tube voltmeter by shorting the input terminals, adjusting R_{17} until the meter reads maximum, then throwing S_2 to left, and with S_1 at .1 note the meter reading. If the meter reads less than zero, increase the value of the feedback resistor; if more, decrease the value of this resistor until this operation produces full-scale deflection. If the meter scale is divided into 100 equal parts, it will read millivolt increments directly. The polarity of B_1 and the standard cell must be reversed from that shown in Figure 7–13 if the circuit of Figure 7–10 is used as the vacuum-tube voltmeter unit Z.

In use, the standard cell is balanced as indicated, the unknown voltage is connected to the input terminals, and with S_2 to the left, S_1 is rotated until the meter reads on scale. The correct voltage is given by the sum of the reading of S_1 and the meter reading.

The unit may be used as a pH meter to read pH directly by connecting the standard cell to a set of properly chosen resistors inserted between R_1 and R_{16}.

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CHAPTER 8
A.C. Vacuum-tube Voltmeters

Introduction.

An A.C. vacuum-tube voltmeter consists essentially of a circuit ar-ranged to rectify or detect an impressed A.C. voltage. The rectified current is read on a D.C. meter. Preamplification is often employed to increase the sensitivity of the instrument. Voltmeters of this type differ only in the methods used for rectification and amplification.

Inspection of any typical transconductance curve, such as that given in Figure 2–5, shows that the plate current i_p of a tube is not a linear function of the grid voltage e_g. At high values of i_p, the relationship is almost linear, but as the value of i_p decreases the curvature becomes quite marked. The linearity is improved by the use of a cathode or plate resistor, as may be seen from an inspection of Figure 2–13 and Figure 2–9.

In the design of amplifiers it is essential to insure operation over the most linear portion of this curve, since nonlinearity of the charac-teristic leads to distortion.

Distortion arising from nonlinearity of the transconductance curve is essentially rectification, and may be used as a basis for the design of A.C. vacuum-tube voltmeters. The remaining sections of this chapter describe typical A.C. vacuum-tube voltmeter (A.C. V. T. V.) circuits, with appropriate experiments to illustrate their special properties and uses.

8–1. Low grid-bias A.C. V. T. V., employing plate rectification.

Examination of the transconductance curve in Figure 2–5 in the region of $e = -3.0$ v. will show that if an A.C. voltage is impressed on the grid, the plate-current reading on the meter will increase during the positive half cycle, and will decrease on the negative half cycle. Due to the pronounced curvature of the characteristic, the decrease will be considerably less than the increase, and the resultant will be a net in-crease in the reading.[1] The inertia of the pointer system in the meter limits its ability to follow the rapid fluctuations in current, and results in an equilibrium value of deflection. These deflections will increase with

[1] Reich, H. J., "Theory and Application of Electron Tubes." New York: McGraw-Hill Book Co., Inc., 1939; p. 560.

further increase in the impressed A.C. voltage, but they will not be directly proportional (linear) to its value. Since the net deflection or response of this vacuum-tube voltmeter depends upon the nonlinearity of the i_p-e_g curve, the principle is known as plate rectification.

'Theoretically, lower A.C. voltages may be detected by using correspondingly more sensitive plate meters. If a sensitive meter is used, the normal plate current of the tube must be canceled or balanced out, as shown in Figure 8–1. This procedure has the one disadvantage that the normal plate current as well as the reverse current must be held very constant. The lower limit of sensitivity is imposed by another factor, namely, the constant decrease in the efficiency of rectification with a decrease in input voltage. This relation is simply the consequence of the mathematical property of the curve, that is, that as the total portion of the curve under consideration becomes smaller and smaller, its properties approach those of a straight line as a limit, and the degree of rectification decreases.

8–2. High grid-bias A.C. V. T. V. employing plate rectification.

Some improvement over the preceding circuit may be obtained by operating the voltmeter at a lower value of plate current.[2] If a grid voltage of — 8 (90 v. on the plate) is chosen as the operating point, the plate current may decrease from 100 μamps. to zero during the negative half cycle and may increase to 5 ma. during the positive half cycle, before grid current begins to flow in appreciable amount. A meter-bucking current is unnecessary in this case; the zero adjustment on the meter may be used to cancel this small reading.

As before, the maximum A.C. voltage which can be measured, is equal to or slightly less than the grid-bias voltage. In this case, too, the meter readings are not a linear function of the impressed A.C. voltage, the deviation being most marked at low voltages.

EXPERIMENT 8–1

Purpose: To determine the relationship between plate current and plate voltage of a plate rectifier at various operating points.

Materials: Type 76 or 6C5 tube
            0-10 D.C. voltmeter
            0-10 A.C. voltmeter
            0-10 D.C. milliammeter
            3 45-v. B batteries
            7.5-v. C. battery
            0.1-megohm resistor

[2] Moullin, E. B., *Wireless World*, *10*, 1, 1922.

1.5-v. battery
2 6.3-v. transformers
1,000-ohm volume control
3 5,000-ohm volume controls
200-ohm volume control
Tube socket
Hookup wire

Procedure. Connect the components as shown in Figure 8–1. Apply 90 v. to the plate and set the grid potentiometer R_2 for a D.C. grid potential of — 3 v. Adjust resistors R_3 and R_4 until the meter reads zero, with R_1 so adjusted that the input A.C. voltage is zero. Now, gradually increase the input A.C. voltage by means of R_1 and record the values of plate current for each value of A.C. voltage as indicated by V_2. Plot the results as shown in Figure 8–2. Repeat the measurements at several higher grid voltages. In each series of measurements, adjust the meter to zero with R_3 and R_4 before applying A.C. voltages to the input. A few sets of readings may be taken with a plate voltage of 135, under which conditions the tube transconductance will be greater. Note that at low input voltages the sensitivity is small, owing to a low efficiency of rectification as well as low transconductance, while at high values of A.C. input voltages the tube grid becomes positive to such an extent that the sensitivity drops as a consequence of the high grid current.

8–3. Linear A.C. V. T. V.

The utility of the vacuum-tube voltmeter of Figure 8–1 would be greatly increased if it could be made more linear, and if its voltage range could be extended.[3-7] Both improvements are secured when all or a portion of the grid-bias voltage is obtained from a cathode resistor, as described in §2–6.[8] The linearity, but not the range, may be improved by introducing resistance in the plate circuit, illustrated in Figure 2–9.

The range may be further extended by using a resistive voltage divider in the input circuit. Some care must be exercised, however, if operation is to be extended to high frequencies, since all resistors have some distributed capacitance, and the portion of the resistor which is across the grid is shunted by the additional capacitance, represented by the input capacitance of the tube. This effect can be overcome by adjusting the capacitance-resistance ratio to be equal to the resistive ratio, and

3 Nottingham, W. B., *J. Franklin Inst. 209*, 287, 1930.
4 Heising, R. A., U. S. Patent 1232919.
5 Reich, H. J., Marvin, G. S., and Stoll, K., *Electronics*, Sept., 1931; p. 109.
6 Hiken, C. B., and Birdsall, L. C., *Trans. Am. Inst. of Elec. Eng. 57*, 173, 1938.
7 Likel, H. C., *Electronics*, Dec., 1940; p. 32.
8 Medlam, W. B., and Oschwald, U. H., *Wireless Eng. 5*, 56, 1928.
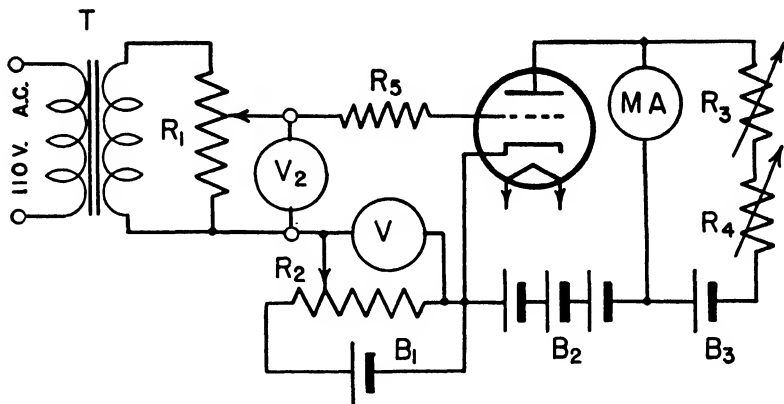
FIG. 8–1.   A.C. Vacuum-tube Voltmeter Employing Plate Rectification.
R_1 = 1,000-ohm potentiometer; R_2 = 5,000-ohm potentiometer; R_3 = 5,000-ohm potentiometer; R_4 = 200-ohm potentiometer; R_5 = .1 megohm; V = 0–10 D.C. voltmeter; V_2 = 0–10 A.C. voltmeter; MA = 0–10 D.C. milliammeter.
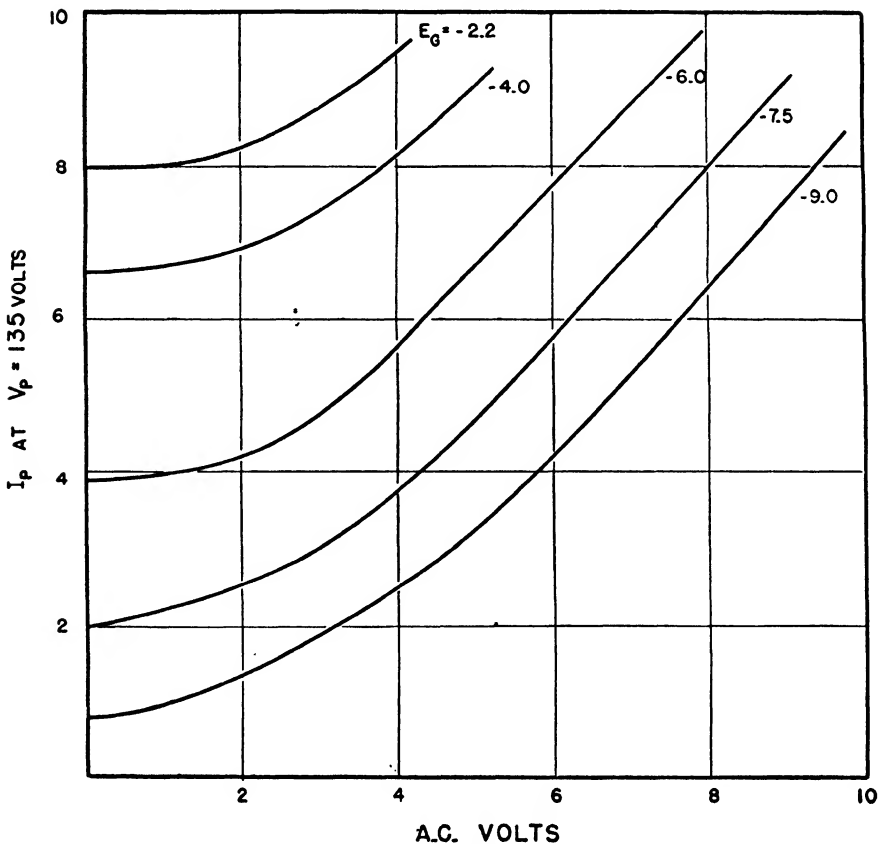
FIG. 8–2.   Plate Current versus A.C. Grid Volts.

a number of fixed divider steps may thus be provided to extend the range of the instrument, as shown in Chapter 12.
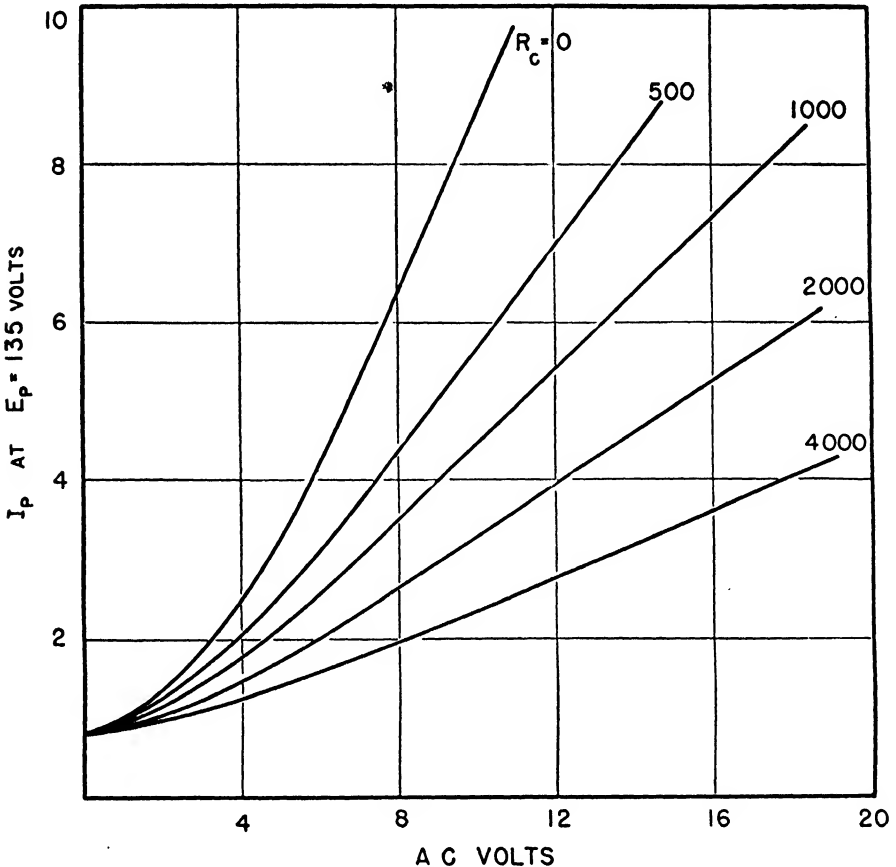
FIG. 8-3.   Plate Current versus A.C. Grid Volts; Cathode Resistor.

EXPERIMENT 8-2

Purpose: To determine the relation between average plate current and A.C. grid voltage for a triode operated with a cathode resistor.

Materials: 5,000-ohm variable cathode resistor
Apparatus of Experiment 8-1

Procedure. Connect the 5,000-ohm variable resistor in the cathode lead (Figure 8-1), this is, between the cathode and the grid potentiometer. Set the resistor to 500 ohms and disconnect battery B_3. Adjust the grid potentiometer R_2 until the plate current is of the order of 0.1 ma. Reconnect B_3 and adjust R_3 and R_4 until the meter reads zero.

Increase the value of R_1 and observe and record the plate-current values as before. Plot the plate-current readings against the corresponding input voltage, as shown in Figure 8–3, and compare with Figure 8–2.

Repeat the experiment with the cathode resistor set at 1,000, 2,000 and 4,000 ohms in turn, adjusting R_2 until the plate meter reads .1 ma. in each case. Plot the results obtained in the form of a series of curves. In order to complete the curves taken with the higher values of the cathode resistor, it may be necessary to use higher input voltages. For this purpose, the source T_1 and R_1 may be replaced by a Variac and an appropriate A.C. voltmeter.

Repeat the experiment after connecting a 25-μf. condenser across the cathode resistor.

Note that the linearity has been improved, especially at the higher values of the cathode resistor, but the sensitivity is considerably lower. The loss in sensitivity may be made up by using a more sensitive plate meter or by using preamplification of the signal.

8–4. Multistage voltmeters.

If the A.C. voltage which is to be measured is very small, rectification will not occur, even under the most favorable conditions, and preliminary amplification will be required. Any amplifier, the gain of which is accurately known, may be used for this purpose. The ideal amplifier would amplify equally well at all frequencies and its gain would be independent of the supply voltages and age of the tube. This ideal has not been achieved, but an amplifier using inverse feedback approaches it.[9] The amplifier shown in Figure 7–9 or Figure 7–10 may be employed as an A.C. V. T. V. by making the grid voltage high enough to produce plate current cutoff in the final tube. Other changes must be made in the amplifier in order to permit the first tubes to amplify the A.C. voltage. The capacitors which are used in these circuits to eliminate oscillation must be removed. The various stages can be isolated from D.C. voltages, as shown in Chapter 10.

Since these voltmeters are essentially a combination of amplifier, as discussed in Chapter 10, and a single-tube voltmeter as discussed in the preceding sections, no further description is required for our present purpose.

8–5. Diode rectifiers as vacuum-tube voltmeters.

A diode is a rectifier and may be used to rectify small as well as large voltages.[10,11,12] The general properties of diodes were studied in

[9] Ballantine, Stuart, *Electronics*, Sept., 1938; p. 33.
[10] Barber, A. W., *Electronics*, Oct., 1934; p. 322.
[11] Tuttle, W. N., *Gen. Radio Expt.* 11, 1, 1937.
[12] Boyle, H. G., *Electronics*, Aug., 1932; p. 32.

Chapter 4. The use of the diode as a voltmeter has the disadvantage that some current is drawn from the circuit under test. However, small diodes are now available for this purpose which are quite satisfactory. Any electron tube may be converted to a diode by connecting all grids to the plate.

If a high load resistance is chosen for the diode, the power required from the source may be made quite small. If the load resistor is shunted with a suitable capacitor, the voltage appearing across the resistor will be the crest or peak A.C. voltage. The voltmeter may, however, be calibrated to read the root mean square value of a sinusoidal source.

A simple diode voltmeter is shown in Figure 8–4, in which the diode serves as a rectifier for the voltmeter. The current which is drained
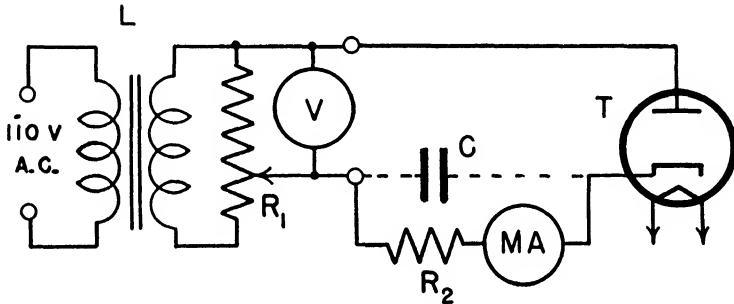
Fig. 8–4. Diode Voltmeter. $R_1 = 1,000$ ohms; $R_2 = 5,000$ ohms; $V = 0$–20 v. A.C.; $T = 7A6$; $L =$ step-down transformer.

from the source under test will be the current required to deflect the meter. The meter readings will not vary linearly with the impressed A.C. voltage, nor will the meter necessarily read zero when the input terminals are short-circuited. This residual current, flowing at zero plate voltage, arises from the initial velocity of electrons emitted by the cathode. This trouble can be overcome by supplementing the circuit of Figure 8–4 with a small battery, which keeps the plate negative by an amount sufficient to turn back these electrons.

EXPERIMENT 8–3

Purpose: To study the relation between the output voltage of a diode rectifier and the impressed A.C. voltage.

Materials: 6H6 diode
6.3-v. transformer
0-500 microammeter
0-20 A.C. voltmeter
1,000-ohm potentiometer
5,000-ohm resistor

Procedure. Connect the circuit components as shown in Figure 8–4, set the A.C. voltage to zero, and read the D.C. voltmeter (microamperes $\times R_2$). Increase the A.C. voltage in measured steps and record the corresponding D.C. values. Repeat the experiment after connecting a 50-μf. condenser across the terminals of the D.C. voltmeter. Plot
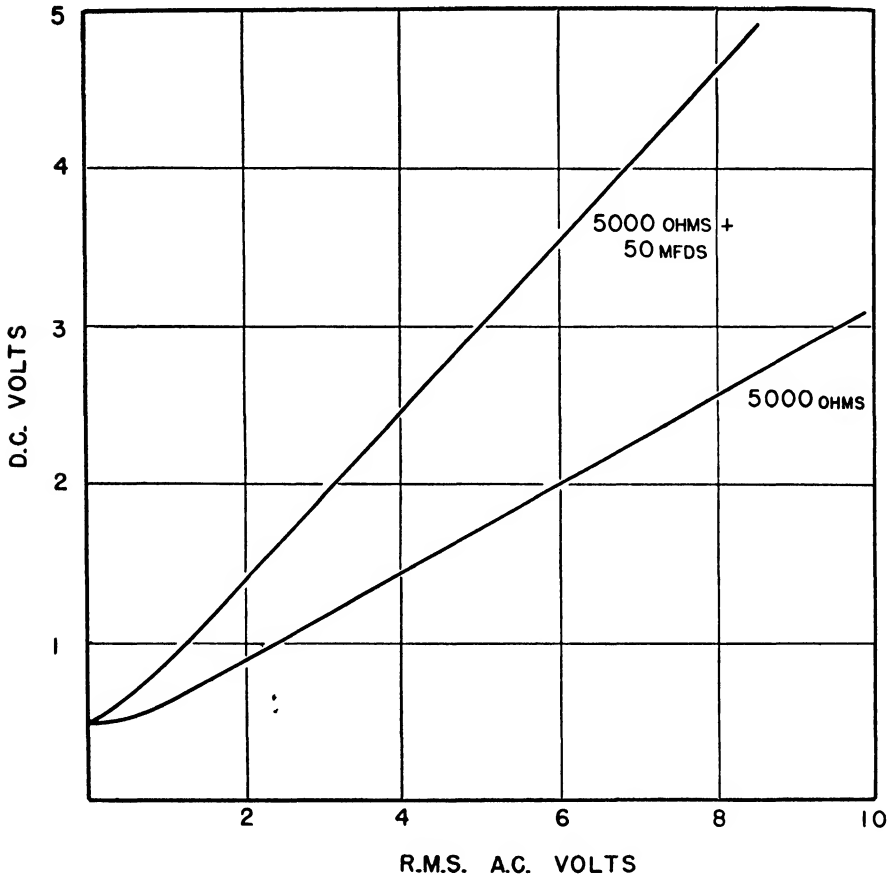
Fig. 8–5. Output Voltage of Small Diode versus Input A.C. Volts, for Relatively Large Currents.

the two sets of results as indicated in Figure 8–5. Compare the results with those obtained in Experiment 8–2. Repeat the experiment, changing the value of R_2 to 500,000 ohms and reading the voltage drop across R_2 by means of a D.C. vacuum-tube voltmeter.

8–6. A.C. V. T. V. employing grid rectification.

If the grid of an electron tube is connected to the cathode through a high resistance, grid current will flow through this resistance, establish-

ing an equilibrium grid potential which is negative. If now an A.C. potential is impressed across this resistor (grid leak) through a capacitor, it will increase the grid current during the positive half cycle, causing the capacitor to charge. During the negative half cycle the grid current decreases and the capacitor starts to discharge through the resistor. If the value of the capacitor C is large compared with the resistor R, the amount of charge which can leak from the capacitor during the negative half cycle will be small.

In the absence of an A.C. signal, the equilibrium potential forms the fixed bias of the tube and it is usually negative enough to limit the plate current to a nominal value. During operation, the grid voltage will be at all times the sum of the charge of the capacitor plus the A.C. voltage, so that the plate current will follow all of the negative half cycle and part of the positive.

This type of rectification is similar in action to that described in §8–2, except that, in the previous case, the requisite bias was obtained from a battery and rectification occurred in the plate, while in this instance it is obtained from the grid current, with automatic adjustment by the signal voltage to the point of greatest operating efficiency, and rectification occurs in the grid.

Grid rectifiers have the disadvantage of absorbing some power from the source under test. They have the great advantage that with small signals, they adjust themselves automatically so that operation occurs about a point of high transconductance and therefore at high rectifying efficiency.

EXPERIMENT 8–4

Purpose: To determine the characteristics of an A.C. V. T. V. using grid rectification.

Materials: 6C5 tube and socket
2 6.3-v. transformers
0-10 milliammeter
0-10 A.C. voltmeter
3 45-v. B batteries
1-megohm resistor
0.1-μf. paper capacitor

Procedure. Connect the circuit components as shown in Figure 8–6. With no signal applied, adjust the voltage of B until the milliammeter reads maximum. Then increase the A.C. voltage by steps, and record the corresponding plate currents. Plot the results as shown in Figure 8–7.
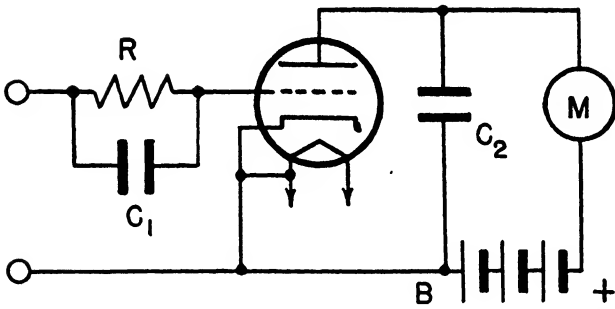
FIG. 8–6. Grid Rectification. $R = 1$–5.0 megohms; $C_1 = .02$–1.0 $\mu f.$; M = 0–10 milliammeter.
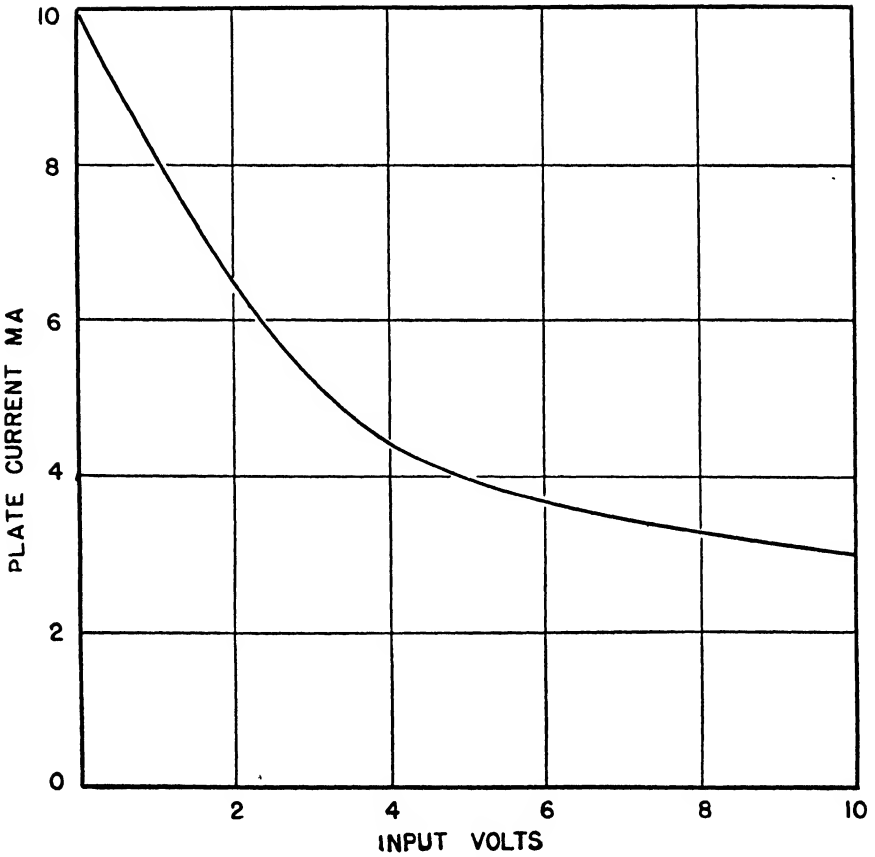
FIG. 8–7. Plate Current versus A.C. Volts; Grid-leak Bias.

8–7. Frequency and wave-form errors of vacuum-tube voltmeters.

Most vacuum-tube voltmeters calibrated at 60 cycles will maintain the calibration at frequencies as high as 20,000 c.p.s. At higher frequencies, it becomes necessary to by-pass the indicating meter with a suitable paper condenser, since the impedance of the meter coil increases with frequency. At the higher frequencies, the type of wiring and the specific properties of the tube itself assume great importance. Short, direct leads are imperative, and a tube with very low interelectrode capacitance becomes essential. The acorn tubes, such as the 955, converted to diodes are satisfactory provided they are so arranged that their prongs may be placed directly across the source of voltage to be measured.[13] When these precautions are taken, calibration can be maintained at frequencies as high as 40 megacycles.

Vacuum-tube voltmeters which have been calibrated with sinusoidal sources to read root-mean square values will give incorrect readings when used in connection with other wave forms. It is possible to apply suitable correction factors, provided the wave shape is known. A full discussion of this problem, including the computation of such factors, is given in Reich's "Theory and Application of Electron Tubes." [14]

8–8. Diode-triode A.C. voltmeters.

The rectified voltage from a diode can be measured by any of the D.C. voltmeters discussed in Chapter 7. In the circuit discussed in Experiment 8–3, the load resistor of 10,000 ohms may be increased to 10^6 or 10^7 ohms with a corresponding reduction of input current. These large values are permissible because, as shown in §7–2, the vacuum-tube voltmeter does not require appreciable power for the grid circuit. Several instruments embodying this principle are commercially available.[15]

8–9. Bridge-balance indicators

In general, a linear relationship between input and output of a vacuum-tube voltmeter is preferred. For special purposes, other types of response may, however, be desirable. In sound measurements, for example, the results are expressed in decibels, and a logarithmic vacuum-tube voltmeter could be calibrated directly in the desired units. This and other functions have been achieved.[16,17]

A voltmeter the response of which decreases with increasing signal is particularly suitable as a null indicator for A.C. bridges.

[13] Tuttle, *loc. cit.*
[14] Reich, *op. cit.*
[15] Tuttle *loc. cit.*
[16] Ballantine, S., *Electronics*, Jan., 1931; p. 472.
[17] Hunt, F. V., *R.S.I. 4*, 672, 1933.

The ideal bridge-balance indicator should have two important properties. Its sensitivity should vary inversely as the signal strength, because it is in the immediate vicinity of the balance point that high sensitivity is required. Also, its response should decrease with increasing signal strength, so as to make it almost impossible to damage the instrument, or exceed its range, during trial balance.[18-21]

A circuit containing these desirable features is shown in Figure 8–8.[22] The signal is fed by the bridge isolation transformer T_1 to the 6F5 tube which serves first as an A.C. amplifier. The amplified voltage is fed by transformer T_2 to the rectifying 6H6 diode, and the pulsating D.C. voltage appears across resistor R_2, the cathode end of which is positive at all times. The negative end of this resistor is connected to the grid through R_3 and the pulsating D.C. is filtered or smoothed out by the R_2-R_3-C_1-C_3 network. This D.C. potential, which biases the triode and therefore reduces its plate current, was originally produced from the input A.C. signal. Hence, the plate-current reading decreases with increasing signal. The indicator is quite sensitive since there are, in effect, two stages of amplification. Furthermore, as the grid becomes more negative, the transconductance of the tube decreases, and the over-all sensitivity decreases, thus achieving the second desirable property. Resistor R_4 is used to decouple the A.C. plate current from the power supply, and R_5 serves to adjust the grid voltage and so set the plate current for the condition of zero signal.

EXPERIMENT 8–5

Purpose: To study the characteristics of a bridge-balance indicator.

Materials: 6F5 and 6H6 tube
          2 octal sockets
          General Radio Co. bridge transformer or equivalent interstage audio transformer
          200-300-v. power supply
          10,000-ohm volume control
          50,000-ohm 10-watt resistor
          3 1-megohm $\frac{1}{2}$-watt resistors
          3 .01-μf. paper condensers
          1 0.5-μf. paper condenser.

Procedure. Connect the circuit components as shown in Figure 8–8, keeping all grid leads short and well separated from the rest of the wir-

[18] Breazeale, W. M., *R.S.I.* 7, 250, 1936.
[19] Tulauskas, L., *Electronics 2*, 478, 1931.
[20] Garman. R. L., *R.S.I. 8*, 327, 1937.
[21] Lamson, H. W., *R.S.I. 9*, 272, 1938.
[22] Garman, R. L., and Kinney, G., *Ind. Eng. Chem., Anal. Ed.*, 7, 319, 1935.
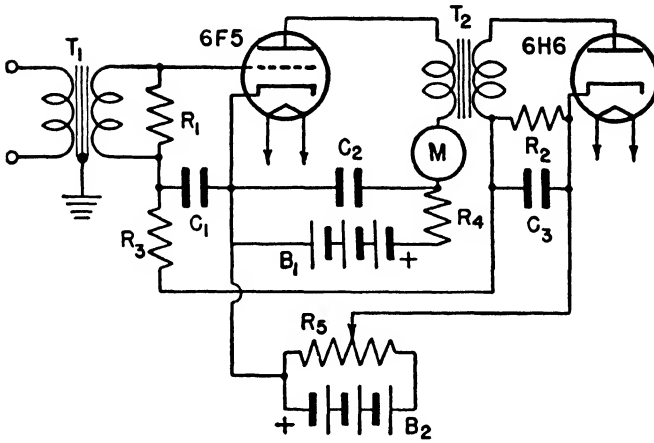
FIG. 8–8. Bridge-balance Indicator. R_1, R_2, R_3 = 1.0 meg-ohm; R_4 = 10,000 ohms; R_5 = 10,000 ohms; B_1 = 180 v.; B_2 = 3 v.; C_1, C_2 = .01 μf.; C_3 = .5 μf.; M = 0–1 milliammeter.
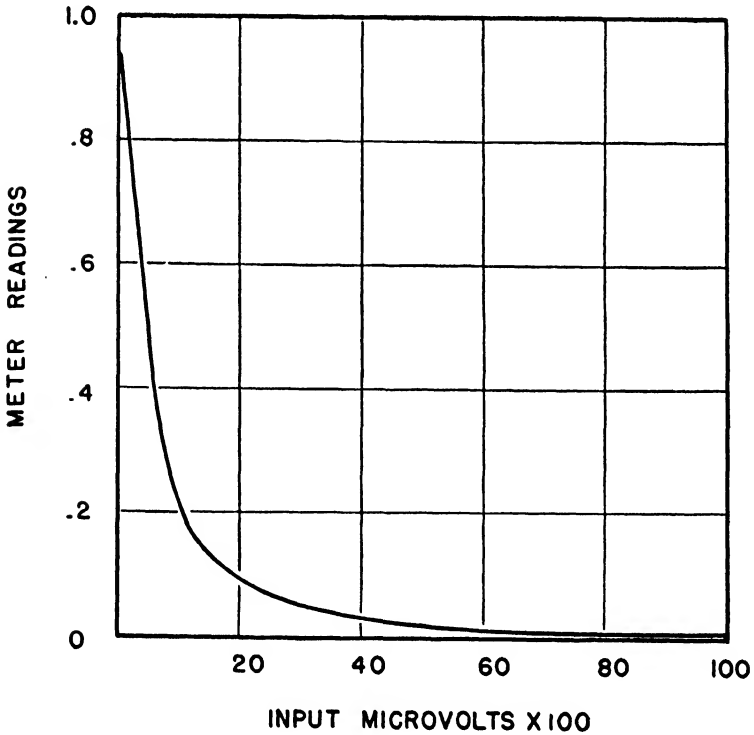
FIG. 8–9. Characteristics of Bridge-balance Indicator.

ing. The unit should be mounted in a shielded cabinet with the grid wiring on the top of the chassis and all other wiring under the chassis. Transformer T_2 must be properly poled to prevent oscillations. If it is incorrectly poled, the meter needle will oscillate slowly even when the input terminals are short-circuited.

The indicator can be tested by applying small, measured voltages to the input and noting the corresponding meter readings. This is done most conveniently with a microvolter. If a microvolter is not available, the equivalent may be constructed by installing in a shielded cabinet a 200-ohm General Radio type 314A potentiometer in series with a 200,000-ohm resistor. The two are connected to the output terminals of a step-down transformer or oscillator. If the total potential across the two resistors is adjusted to 1 v., the potential appearing across the 200-ohm section will be 1 mv. (actually 0.999 mv.). This signal may be further subdivided by means of the potentiometer scale.

Plot the results as shown in Figure 8–9 and note that the sensitivity becomes a maximum at A.C. input voltages of the order of several μv., then decreases rapidly for larger input voltages. This low sensitivity at very small potentials is due to the low rectifier efficiency at this point.

It may be of interest to study the frequency response of the bridge-balance indicator. For this purpose, connect a variable audio oscillator to the microvolter as indicated above, and determine the input voltage required to maintain a standard deflection on the meter for various available frequencies.

PROBLEMS

1. Summarize the advantages and disadvantages of plate-rectification electron-tube voltmeters.

2. Design a vacuum-tube voltmeter which uses plate rectification and can be used to measure voltages up to 100 v. in one range.

3. Design a vacuum-tube voltmeter as in Problem 2 but with three ranges: 0-1 v., 0-10 v., and 0-100 v.

4. Design a linear A.C. V. T. V. capable of measuring voltages from 1 mv. to 1 v.

5. Draw a circuit diagram for a logarithmic A.C. V. T. V.

6. Modify the circuit shown in Figure 7–9 so that it may be used to measure A.C. voltages.

7. Redesign the circuit shown in Figure 8–8 to include a stage of preamplification.

8. Redesign the circuit of Figure 8–8, avoiding the use of transformers.

9. How may tuning best be employed with the circuit of Figure 8–8?

10. Explain the action of the cathode capacitor as used in the second part of Experiment 8–2.

11. Design a slideback A.C. V. T. V. based on the circuit of Figure 7–1. See Reich *et al.*, *Electronics*, Sept., 1931; p. 109.

12. Design a slideback A. C. V. T. V. using an 885 tube from the circuit of Figure 6–2.

13. Design an A.C. V. T. V. based on the inverted triode as shown in Figure 7–3.

14. Convert a suitable A.C. V. T. V. circuit so that crest values of current may be measured.

CHAPTER 9
Application of Photocells

Introduction.

The application of photocells to measurement, control, and detection is so extensive that several monographs would be required to cover these fields adequately. The use of photocells is not confined to the measurement and control of light intensities but is limited only by the ingenuity of the designer of mechanical and optical devices in converting other phenomena into corresponding changes of light intensity.

Only a few of these applications will be reviewed in the following sections and the reader is referred to the extensive literature for the details.

9-1. Control by the interruption of light beams.[1,2]

Such familiar devices as automatic openers, burglar alarms, and safety devices for industrial machinery are usually based on the interruption of a light beam causing a photocell relay system to perform the desired function. Visible, ultraviolet, or infrared illumination may be used in a burglar alarm so placed that an intruder is most likely to interrupt the beam and set off the alarm. Safety devices for presses are controlled by a sheet of light thrown around the press and so arranged that the operator must be clear of the press before it can be put in motion. In most of these devices the photocell relay systems are quite simple and the problems involved are in the fields of mechanical and optical design. It is obvious that these devices must be rugged and foolproof—otherwise their safety-insuring features would be completely nullified.

Counting, inspection, and sorting operations are carried out on the same principles. Small or large, light or heavy objects may be counted by the interruption of the light beam, and it is obvious that no effort is required for the interception *per se*. Inspection may be carried out as to size, shape, or color by arranging the optical system so that the change in light intensity is either recorded or else used to control a relay and perform sorting automatically. Here again the mechanical and optical " gadgeteering " is far more complex than are the photocell circuits.

[1] Bendz, W. I., *Electronics*, Feb., 1938; p. 14.
[2] Powers, B. A., *Electronics*, July, 1941, p. 17; Aug., 1941, p. 33.

Control may be accomplished by the interruption of reflected light in cases where the nature of the problem demands this solution. Position control may be achieved by using either direct or reflected light in such a manner that when the position of the object to be controlled changes, the change in light intensity is registered on the photocell and the relay or motor is caused to apply a restoring force to the object until it assumes its former position. In other cases the position of the object may be remotely recorded by causing the photocell or optical system to move until light balance is re-established and recording the resultant movement. This method is practically useful in the recording of galvanometer or meter deflections and other devices where the torque of the moving object is very small.

Velocities may be measured in a number of ways depending on the nature, size and speed of the moving object. The simplest consists of two light beams, a known distance apart, one or two photocells being used to start and stop a time-measuring device or put marks on a suitable chronograph.

9–2. Measurements.

The photocell may be used to measure or record absolute values of light intensities, as in photographic exposure or illumination meters, or it may be used to determine or record the amount of light absorbed by a gas, liquid, or solid. By proper optical design the photocell may be used to measure the amount of light absorbed in almost any region of the spectrum. When the portion of the spectrum to be used is selected with optical filters the method is known as filter photometry, while if a spectrometer is used to define the region the method is known as spectrophotometry.

The photocell may be used to measure and record refractive indices by arranging the optical system so that changes in the angle of refraction cause an increase or decrease in intensity of the light reaching the photocell. Turbidity may be evaluated by measuring either the scattered or the absorbed light. Fluorescence may be measured satisfactorily by the use of a high-vacuum cell followed by an appropriate amplifier in an arrangement similar to that used for absolute measurement of light intensities. Density may be measured by a combination of mechanical and optical methods. Viscosity may be evaluated from time-of-flow data and the photocell may be used to record this time as described above.

9–3. On-or-off phototube control.

The general characteristics of photocells are discussed in Chapter 3 and suitable amplifier circuits are covered in Chapters 2, 5, 6, and 7.

Although the current from a phototube is small, as was pointed out in these discussions, this small current flowing through a high resistance is capable of producing a comparatively large voltage. This voltage may in turn be utilized if the measuring instrument has an equally high input resistance. A photocell in series with a high resistance connected to the grid of an electron tube, as shown in Figure 3–1, is thus capable of actuating a relay in the plate circuit in response to small changes in light intensity. A large number of photocell applications are based on this simple circuit. The photocell may be connected so that an increase of photocurrent will make the grid either more negative or less negative. When it is connected so that the grid is made less negative the polarizing voltage for the photoelectric cell can be obtained from the source that furnishes the plate potential of the amplifier tube. In such circuits the photocell is connected from grid to plate of the amplifier tube.

Since relays are usually equipped with back and forward contacts, this circuit can be used in practically all cases, that is, whether control is desired for an increase or decrease of illumination. Practical examples of this type of control are numerous. Control of such operations as opening and closing doors, counting, sorting, inspection, gauging, and so forth, are some typical examples.

9–4. Electrical time-delay circuits.

In many applications control is desired some definite time after the photocell has been actuated, or in other cases control is to be maintained for a certain interval after the controlling element has been energized. The charge and discharge rate of a capacitor through a resistor may be used for such time delays. Since the photocell circuits are of comparatively high resistance, long time delays can be obtained even with small capacitors. A 1-μf. capacitor in series with 10^7 ohms requires 10 seconds to charge to a value of 67 per cent of the impressed voltage (see §1–34).

Either the charge or the discharge of a capacitor may be used in time-delay circuits, depending on the effect which is to be produced. The circuit shown in Figure 9–1 will cause the relay to pull in rapidly if the photocurrent is large, but when the illumination on the photocell is decreased a longer time is required for the capacitor to discharge through the 10-megohm grid resistor. The capacitor will be charged rapidly if the photocell receives a flash of bright light from an object. This charging causes the relay to pull in and it remains in this position for a relatively long time. If the flash is of too short a duration the relay will not be actuated; this characteristic may be utilized in certain sorting applications.
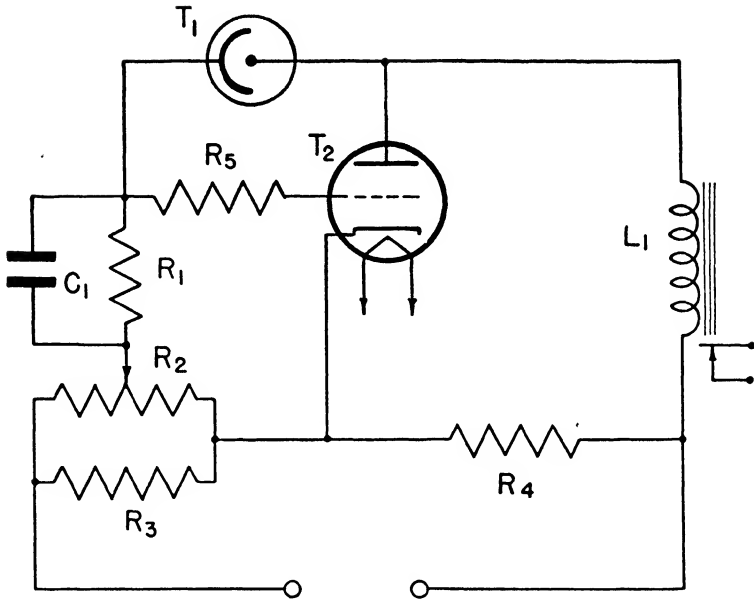
FIG. 9–1. R_1 = 10–20 megohms; R_2 = 10,000-ohm potentiometer; R_3 = 200 ohms; R_4 = 5,000 ohms; R_5 = .5 megohm; T_2 = 6J5; C_1 = .01–1.0 μf., variable; L_1 = relay.
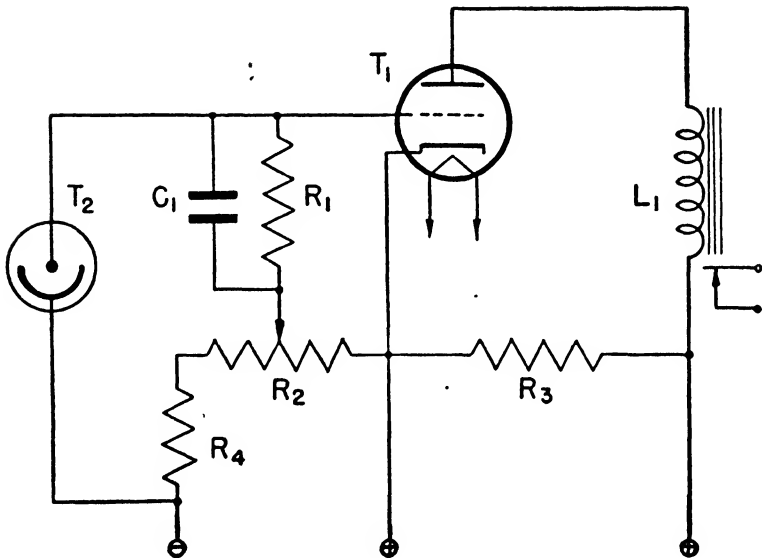
FIG. 9–2. R_1 = 10–20 megohms; R_2 = 15,000 ohms; R_3 = 100,000 ohms; R_4 = 100,000 ohms; C_1 = variable condenser; T_1 = 6J5; L_1 = relay.

It may be noted that C_1 of Figure 9–1 will not charge to a very high potential unless the grid voltage is made very large. This failure arises from the fact that when the voltage of C_1 becomes slightly larger than the grid voltage from R_2 the grid draws appreciable current and discharges the capacitor more rapidly than photocurrent can charge it. This result may be avoided by increasing the negative grid voltage or by using the circuit shown in Figure 9–2. In this circuit the capacitor charges in the opposite direction, making the grid become so negative
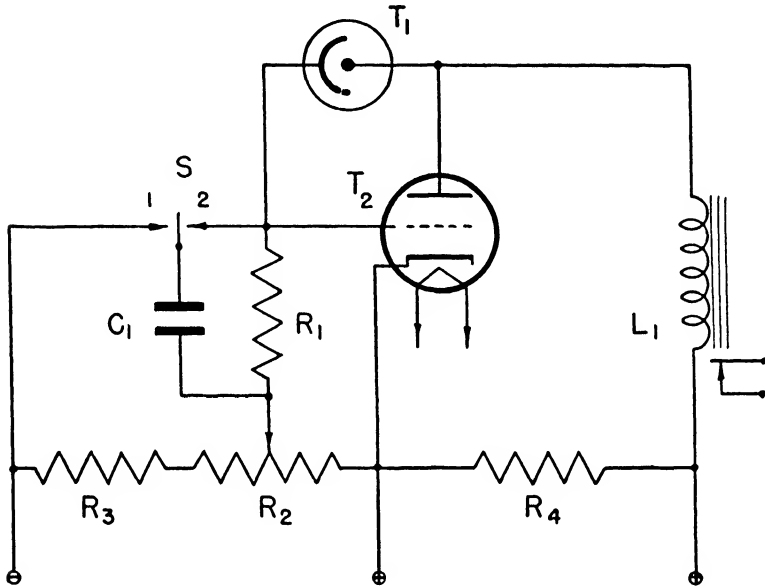
Fig. 9–3. R_1 = 10–20 megohms; R_2 = 15,000 ohms; R_3 = 100,000 ohms; R_4 = 100,000 ohms; S = single-pole double-throw switch operated by relay.

that the plate current is driven to cutoff. The grid current in this case is due only to the positive-ion current from the cathode and the surface leakage current. The rate of discharge is therefore controlled almost entirely by R_1.

The separate voltages required may be obtained from a common power supply since the two voltages are in series, or they may be obtained from a voltage-doubler rectifier circuit as shown in Figure 5–9. In the latter case the value of resistors R_2 and R_4 can be large, since the amplifier-tube plate current will not flow through these resistors. R_3 may also be large or may be eliminated entirely, since it serves only as a safety load or voltage stabilizer. In the circuits of both Figure 9–1 and Figure 9–2 a flash of brilliant light will actuate the relay and a definite time interval will transpire before the relay again becomes

de-energized. It may be noted that an increase in illumination on the photocell of Figure 9–1 causes a pull-in of the relay, while the same increase on the cell of Figure 9–2 causes the relay to drop out.

Other types of time-delay circuits are shown in Figures 9–3 and 9–4. Switch S of Figure 9–3 is actuated by the relay and so arranged that when plate current is high the contact is at the left. A momentary drop
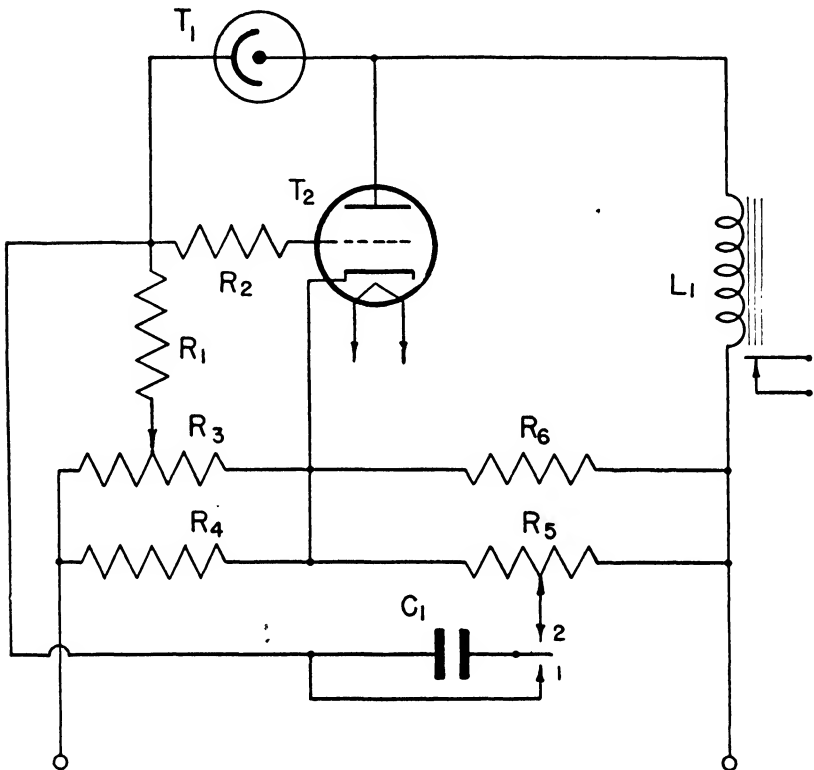
Fig. 9–4. R_1 = 10–20 megohms; R_2 = .5 megohm; R_3 = 10,000-ohm potentiometer; R_4 = 200 ohms; R_5 = 50,000-ohm potentiometer; R_6 = 4,000 ohms; L_1 = relay.

in photocurrent operates the relay, simultaneously throwing S to the right. Since C_1 was charged to the full potential across R_3, the grid becomes highly negative while C_1 is discharging through R_1 and the photocell. The time required will depend on the magnitude of the voltage, the value of the photocurrent, and the size of R_1 and C_1. After the capacitor C_1 has been discharged, the relay pulls in, recharging C_1 for the next operation. The relay switch S must be well insulated to prevent discharge across the terminals.

The circuit of Figure 9–4 operates on the same principle but acts in reverse. If the phototube current increases momentarily, the relay pulls in and closes the switch to position 2, thus charging C_1. While it is charging through R_1 the negative grid voltage will be small and the relay will hold. The charging takes place through R_1 and the grid circuit. After the capacitor is charged to a certain value the relay drops out and the capacitor discharges through the back contacts of the switch. Both of these units represent electrical lock-in relays. The same time delay can be achieved mechanically by a relay, as described in Chapter 1.

The switch may be replaced in all cases by electron tubes and the same purpose achieved. The circuit arrangements are, however, more complex.

EXPERIMENT 9–1

Purpose: To determine the characteristics of several photocell time-delay relay circuits.

Materials: 6J5 tube
Socket
Relay, double-pole-double-throw contacts
10- or 20-megohm resistor
2 5,000-ohm volume controls
2 50,000-ohm resistors
5,000-ohm bleeder resistor
250-ohm bleeder resistor
High-vacuum photocell
Assortment of capacitors or decade condenser boxes from 1.0-μf. to .001-μf.

Procedure A. Wire the circuit shown in Figure 9–1 and place a 0-10 milliammeter in the plate circuit. With no illumination on the photocell adjust R_2 until the plate current is almost zero. Illuminate the photocell with an ordinary lamp and control the amount of illumination with an iris diaphragm or other variable aperture. Arrange the setup in a manner which will permit rapid interception of the light beam. An old camera shutter and iris diaphragm will serve admirably for this purpose. Increase the illumination until the plate current exceeds by 1 ma. its value when the relay pulls in. Shut the light off abruptly and measure with a stop watch the time required for the relay to drop out. Repeat the measurement at various values of capacitance for C_1 (from 1 μf. to .001 μf.). At large values of C_1 measure also the time required for the relay to pull in. Increase the value of the light intensity until the plate current is greater than 10 ma., and repeat some of the measure-

ments. Change the value of R_1 and note the effect on the time delay. Note that the delay depends on C_1, R_1, and the total voltage developed by the photocell load.

Procedure B. Connect the apparatus as shown in Figure 9–2, using *separate power supplies or batteries for each circuit*. For the photocell and grid supply 45 v. is sufficient, while 135 to 150 v. may be used for the plate supply. Both voltages may be obtained from the voltage doubler shown in Figure 4–14. With the photocell dark, adjust R_2 and R_4 until the relay pulls in; then adjust the light intensity until the relay drops out, and measure the time required for the relay to operate as in Procedure A. Note that by increasing the light intensity beyond the value required for plate-current cutoff the time delay may be increased many fold over that of the circuit shown in Figure 9–1. Note also that at weak light levels considerable time is also required for sufficient charging of the capacitor to actuate the relay, while at high light levels the time elapsed is much shorter. Explain these apparently inconsistent results.

Procedure C. Connect the relay circuit as shown in Figure 9–3 so that contact 2 is made when the relay drops out. Set R_2 until the relay just drops out with the photocell dark, then increase the illumination on the cell until the relay just pulls in. Interrupt the light source momentarily or until the relay drops out. Note that considerable time now elapses until the relay again pulls in, even at fairly high levels of illumination on the photocell. The charge on C_1 leaks off through R_1 and the photocell. Repeat the measurements as in Procedure A for various levels of illumination and at several values of C_1 and R_1.

Reverse the connections to 1 and 2 so that contact 1 is made when the relay drops out. Note that under these conditions oscillations are produced, since C_1 discharges through R_1 making the grid highly negative when the relay is pulled up; the relay therefore drops out and C_1 is partially recharged during the time required for the photocurrent to re-establish sufficient plate current to pull up the relay. This time interval may be controlled at will by permanently connecting a capacitor across R_1. Measure the period of this blocking oscillator at various light intensities for different values of the permanent capacitor across R_1.

Reverse the polarity of the photocell, connecting the anode to the top of R_1 and the cathode to the negative end of R_3 of Figure 9–3. Connect terminals 1 and 2 so that contact 2 is made when the relay drops out. Set the plate current with the phototube dark until the relay just pulls in, then increase the light intensity until it drops out. Under these conditions, when the light is interrupted the relay drops out and remains in this position for a relatively long period. Measure this period for various values of C_1 and R_1.

Procedure D. Rewire the circuit as shown in Figure 9–4 so that contact 2 is made when the relay pulls up. Adjust R_3 so that the plate current is nearly zero when the phototube is dark. With steady illumination on the cell, adjust the light intensity until the relay pulls in. Arrange the light source so that momentary flashes of illumination can be produced, and measure the time the relay remains in the pulled-in position after the light to the phototube is cut off at various values of C_1 and R_1. Note that with the phototube connections reversed the same time delay can be obtained after a momentary interruption of light. In general the circuits of Figures 9–3 and 9–4 are quick-acting in one direction and slow-acting in the other direction. This differentiation is achieved by switching a charged capacitor into the circuit only when required for time delay. The circuits of Figures 9–1 and 9–2, on the other hand, achieved time delay in both directions since the capacitor was in the circuit at all times.

Either lock-in or oscillation may be obtained in the relay circuits of Figure 9–1 or Figure 9–2 if the light source actuating the photocell is controlled by the relay. In Figure 9–1, for example, if the light source is connected to the forward contacts and the photocell momentarily actuated with a match or gas lighter, the relay pull-in closes the lamp contacts and the resulting light on the photocell holds the relay locked in. If the lamp is connected to the back contacts of the relay, the lamp puts itself out and oscillations are produced, the time constant depending on the time constant of the armature and the heating time of the lamp with C_1 disconnected. If C_1 is large the time depends on the same factors as in Procedure A. A light blinker may be controlled in this way. The other circuits will work in the same manner, but the opposite contacts must be used if the photocell current produces a negative grid voltage.

9–5. Amplification of a small electromotive force with a photocell.[3, 4, 5]

The difficulties involved in the measurement of small D.C. voltages were detailed in Chapter 7 and the effects produced by thermal agitation in the input load resistors are discussed in §10–20. Low-resistance galvanometers are available with high voltage sensitivities, but the low torque developed by these instruments precludes their use for direct recording. If a light beam is used in conjunction with a mirror galvanometer of high voltage sensitivity, a small deflection of this galvanometer may be translated into a large change in current by the use of a photo-

[3] Amdur, I., and Pearlman, H., *R.S.I. 9*, 194, 1938
[4] Fairchild, C. O., and Parsegian, V. L., *R.S.I. 9*, 422, 1938.
[5] Taylor, A. H., *R.S.I. 8*, 124, 1937.

cell amplifier. This change is accomplished by allowing a uniform beam from the galvanometer to traverse across a V-shaped aperture, the exit light being photometered with a suitable photocell circuit. The circuit shown in Figure 3–2 is suitable for this purpose, although the circuit shown in Figure 2–14 may be used. In this manner a change in deflection of .1 mm. may be made to produce a change of 1 ma. or more in
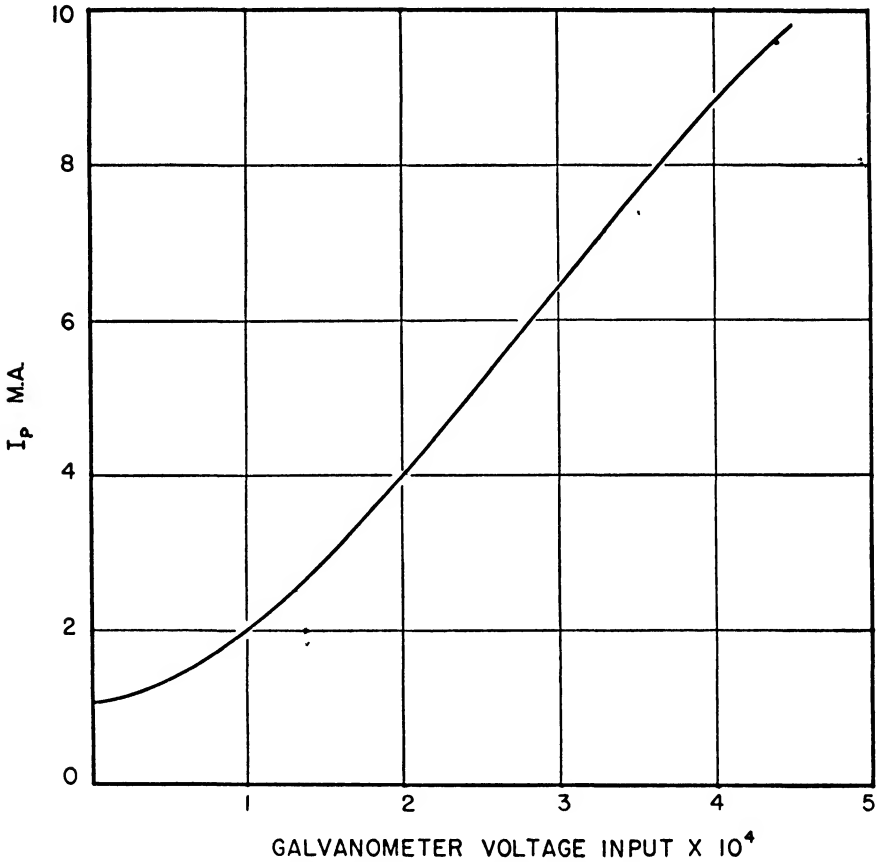
Fig. 9–5.   Plate Current versus Galvanometer Deflection.

the plate current of the amplifier tube, depending on the intensity of the illumination obtained from the mirror and the value of the photocell load resistor. In a typical case the voltage developed across a load resistor of 20 megohms will be 1 v. per millimeter, so that if the galvanometer sensitivity is 1 μv. per millimeter the amplification attained by the optical photocell system will be 10^6. In order to utilize this gain the galvanometer must be free of vibration.

This system may also be used to translate or record the galvanometer readings. For this purpose a twin photocell may be used, so connected that when the beam goes to the right a relay controlled by the photocell on this side is actuated, starting a motor and moving the photocell to the right until light balance is restored. If the beam moves to the left the opposite movement takes place. The position of the photocell may be recorded either directly or in magnified form without disturbing the galvanometer deflection.

The same effect may be achieved with a single photocell and amplifier if two relays are used in the plate circuit of the amplifier tube, so arranged that one of them operates when the light to the photocell is increased while the other one operates when the light is decreased. A V-shaped slot or other suitable aperture may be used to translate the galvanometer deflections into corresponding changes in light intensity at the photocell.

EXPERIMENT 9–2

Purpose: To demonstrate the principle of voltage amplification with a photocell and light-beam galvanometer.

Materials: Internal lamp-and-scale low-resistance galvanometer such as Leeds and Northrup 2420B
Photocell and voltmeter used in Experiment 3–1

Procedure. Remove the ground-glass scale from the galvanometer and replace it with a piece of black cardboard into which a V slot has been cut, so arranged that when the galvanometer beam moves across the slit the light intensity increases uniformly with deflection. For the purpose of the experiment, however, the relation need not be perfect. Mount a photocell in front of the slit and focus the light on the photocell with a medium-size short-focus lens. Connect the photocell as in Figure 3–2, using 20 megohms for R_1. Connect the .015-v. range of a standard potentiometer, such as the Leeds and Northrup student model or the Type K, to the galvanometer terminals. Increase the potentiometer readings in small steps and note and record the plate milliammeter reading. Plot plate current as a function of voltage input to the galvanometer. Note that the milliammeter readings are not linear with voltage. This is due to the imperfect optical system and may be remedied either by changing the shape of the V slot or by improving the focusing system or both. A calibration chart may be used to correct for these errors. A typical plot obtained by the use of twin photocells without the use of a slit is shown in Figure 9–5.

This system is chiefly used as a null indicator either for measurement or control. If the galvanometer is used as a null indicator in a

Wheatstone bridge of which a platinum or nickel resistance forms one arm, the photocell amplifier system of Figure 9–1 may be used to control temperature. The unit may be made sufficiently sensitive that a drop in temperature of 10^{-4} °C. will actuate a relay, which in turn can introduce heat to maintain the temperature constant.

9–6. Light-beam galvanometers and inverse feedback.[6,7]

In order to make the meter readings strictly linear with voltage across the galvanometer terminals, the principles of inverse feedback as outlined in Chapters 2 and 7 may be used.
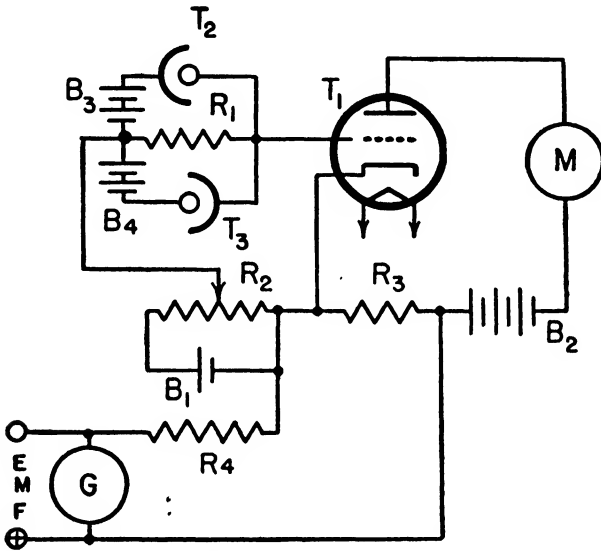
FIG. 9–6. R_1 = 50 megohms; T_2, T_3 = R.C.A. 920 twin photocell; R_2 = 1,000-ohm potentiometer; R_3 = 1.0 ohms; R_4 = galvanometer damping resistance (5,000 ohms).

If the principle is extended to include the galvanometer, the output current will be linear regardless of the galvanometer linearity or the linearity of the vacuum-tube voltmeter. A simple battery-operated circuit that achieves this end is shown in Figure 9–6.

The moving light beam from the galvanometer falls on either one of the surfaces of the R.C.A. 920 twin photocell. If the beam is caused to move from the lower cathode of Figure 9–6 to the upper cathode, the plate current of the amplifier will increase and cause an increase in the RI drop across the resistor R_3. A portion of this voltage is impressed

[6] Gilbert, R. W., *R.S.I.* **7**, 41, 1936.

[7] Gilbert, R. W., *Proc. I.R.E.* **24**, 1239, 1936.

across the galvanometer terminals through the critical damping resistor R_4 and in a direction which tends to offset a portion of the original voltage from the potentiometer. The galvanometer deflection is thus greatly reduced, but the milliammeter reading is proportional to the voltage of the potentiometer and may be used as a measure of this voltage if an unknown is used across the galvanometer terminals. If R_1 is sufficiently large, so that several volts are developed across this resistor, the relation between volts across the galvanometer terminals and plate current will depend only on the value of R_3 and R_4 for a given galvanometer. The sensitivity of the galvanometer may be decreased by increasing R_3 or by reducing R_4. The intensity of the galvanometer light beam and the value of R_1 serve only to determine the actual net movement required by the galvanometer mirror to generate a voltage across R_3 equal to the impressed voltage across the galvanometer terminals. R_2 serves a useful function in that the galvanometer zero may be changed with this control, but a better arrangement consists of impressing a controlled voltage across R_4 from an external source.

EXPERIMENT 9–3

Purpose: To study the fundamental principles of an inverse-feedback galvanometer amplifier.

Materials: 6J5 tube
Socket
50-megohm resistor
R.C.A. 920 photocell
Leeds and Northrup or equivalent lamp-and-scale galvanometer
4 B batteries
7.5-v. C battery
6-v. battery or 6.3-v. transformer
1,000-ohm potentiometer
1-ohm resistor
5,000-ohm potentiometer
D.C. 0-10 milliammeter

Procedure. Remove the scale from the galvanometer and mount the photocell so that the light beam can move from one active surface to the other one. Shield the cell from the light of the room and connect it to the amplifier tube as shown in Figure 9–6. With resistor R_4 connected to R_3, adjust the mechanical zero of the galvanometer until the plate milliammeter reads almost zero current. Final adjustment may be made electrically with R_2, but the gross adjustment must be made with the light beam. Now disconnect resistor R_4 and reconnect as shown in

Figure 9–6. Adjust R_2 *until meter reads 1 ma. If oscillations occur when* R_4 *is connected, reverse the galvanometer terminals.*

Measure the voltage sensitivity of the unit by connecting a standard potentiometer in series with a large resistor to the terminals of the galvanometer.

Increase the potentiometer in small steps and record the milliammeter readings. Plot as shown in Figure 9–7. Repeat the measurements

GALVANOMETER VOLTAGE INPUT X 10^4
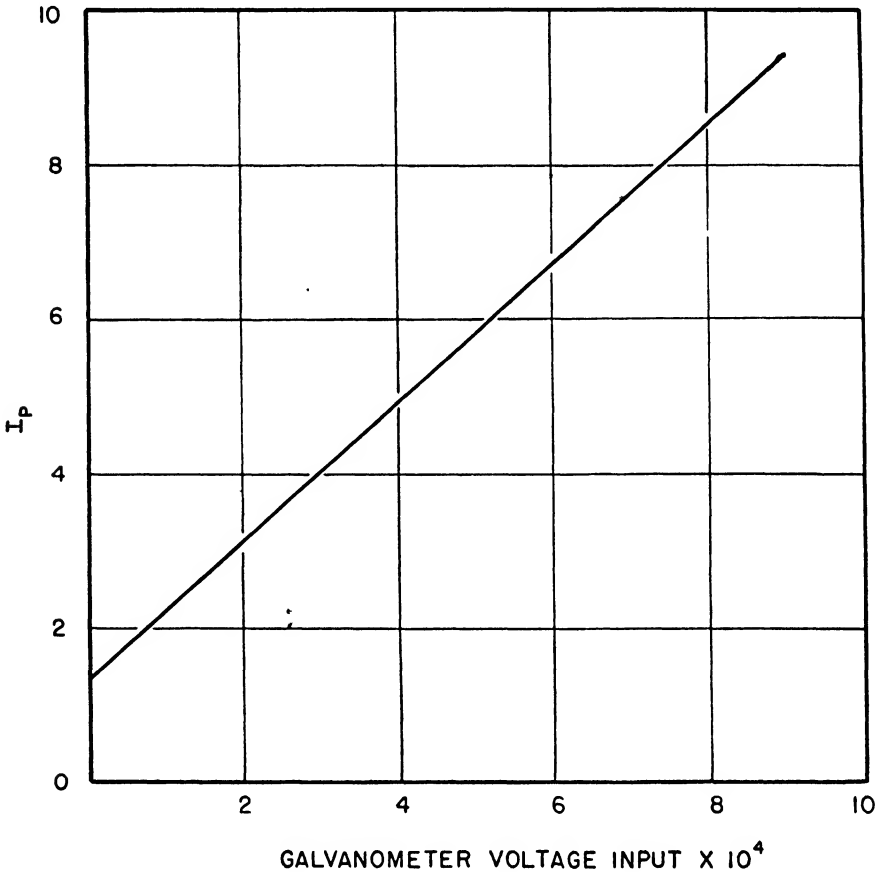
Fig. 9–7.   Plate Current versus Galvanometer Deflection—Using Inverse Feedback.

at various values of R_3 and calculate the expected milliampere-voltage sensitivity at each point. Include R_3, R_4 and the internal galvanometer resistance in your calculations. Calculate the current amplification produced by the unit. Notice that the actual movement of the galvanometer beam for a full plate-meter deflection is of the order of several millimeters. Repeat some of the measurements at a smaller value of R_1 or at a lower light intensity or both. Change the light intensity during op-

eration to simulate changes in line voltage. Repeat the measurements after several small capacitors (.0001-μf. to .001-μf.) are placed across resistor R_1. Connect a large capacitor (4–20-μf.) across R_4 and repeat the measurements.

It will be noticed that these capacitors do not affect the amplification of the circuit. They do, however, control the time constants of the circuit. This control may be demonstrated simply by changing the potentiometer setting suddenly and noting the time required for the indicating meter to record the change. The time constant of the indicating meter is also involved. If the effect of the capacitors is to be noticed it is necessary to use a milliammeter with a relatively short period. The time constant may then be measured as a function of the various capacitors indicated above. A precaution must be observed on the performance of this experiment. With large capacitors the time constant may become so large that during the time required to establish the balancing feedback voltage the galvanometer will swing off scale and hence off the photocell. This in turn causes the amplifier to " hunt." Measurements should be confined to time constants below such values.

EXPERIMENT 9–4

Purpose: To study the fundamental principles of a photocell position translator.

Materials: Motor with 50- or 30-to-1 reduction gear
Motor chuck
Relay of Figure 9–1
Galvanometer of Experiment 9–2
Cardboard sector

Procedure. Cut a spiral sector from markings formed in the following way. Attach one end of a string about 12 inches long to a cylinder $\frac{1}{2}$ inch in diameter and the other end to a pencil. Hold the cylinder firmly on a piece of black cardboard. Then, by moving the pencil, wind the string once around the cylinder, keeping the string taut, the pencil vertical, with the pencil point touching the cardboard, making sure that the string does not travel up and down the cylinder. A 360° spiral will be traced by the pencil during the winding. Mount the spiral on the shaft of a motor with a chuck and a size 8 screw. The center of the spiral should coincide with the axis of the motor. Mount a piece of black cardboard with a rectangular aperture slightly longer than the maximum travel of the 360° spiral in place of the ground-glass scale of the galvanometer. Mount the motor so that the shaft is at the same height as the galvanometer beam and to the left or right at a sufficient distance so that

the spiral will just about cut off all of the light from the galvanometer when the spiral is in its maximum position.

Place the photocell so that the light from the galvanometer strikes the cathode as in Experiment 9–2; connect the motor so that the relay starts the motor when about half the light is cut off by the spiral. Connect a potentiometer to the galvanometer as in Experiment 9–2, and note that the photocell relay controls the position of the spiral but in one direction only; that is, as the galvanometer beam deflects away from the spiral the motor starts and moves the spiral until the light intensity is reduced in value, but if the galvanometer moves in the other direction no action takes place. Mark a 360° scale on the spiral and plot sector position as a function of galvanometer voltage. (*Note:* If the motor runs too fast considerable overshooting may occur; if it does, slow the motor down to a suitable speed by means of a series resistor.) Note that the mechanical difficulties encountered with this simple setup are more complicated than the electrical ones. In practice the photocell is moved with a linear motion so that the same portion of the photocell surface is illuminated at equilibrium. Provision is also made for operation in the reverse direction.

9–7. Photoelectric photometers.

Although the photocell is used extensively in the evaluation of radiation, its main use in measurement lies in the field of photometry. Photometry in general may be defined as the measurement of amounts of light transmitted, absorbed, or reflected. Photometric measurements are usually made at definite wave lengths. If filters are used in the selection of the desired wave-length band, the instrument is called a filter photometer; if a spectrometer is used for the same purpose the instrument is called a spectrophotometer. These names apply even if visual methods are used throughout the measurement. When a photocell is used for the measurement the instrument may be known as a photoelectric filter photometer or photoelectric spectrophotometer.

9–8. The filter photometer.

The complete optical design of a filter photometer does not lie in the province of this book, but a few simple considerations are in order, especially as they apply to the characteristics of the photocell. It was shown in Chapter 3 that the color-response curves of different photocells differ widely. Furthermore, for any particular type the response curve may be quite steep in certain regions of the spectrum. The theory of optics demands that, if the absorption of a certain solution is to be measured for the purpose of obtaining an accurate index of its concentration, the wave

length selected for the measurements should lie preferably in a region where the absorption of the solution is high and where the absorption does not change widely over the wave-length band used in the measurement. Likewise the sensitivity of the photocell over the chosen region should not vary too rapidly. The selection of proper filters is made on this basis. The energy distribution of the light source and the color-response curve of the photocell must be used in the calculation of the final response curve. If the light source is a black-body radiator, and if the photocell response curve is that shown in Figure 3–6, a filter selected to transmit in the yellow region of the spectrum will have a net effect on the photocell quite different from the filter curve as given by the manufacturer. The correct curve may be constructed graphically by correcting the filter curve for the energy distribution of the light source and the response of the photocell; a measuring technique to achieve the same result will be discussed in a later section.

The other optical requirements of an elementary filter photometer are quite simple. The rays from the light source should be rendered parallel by means of a medium-aperture lens and should be passed through the solution, which should be placed in a cell with plane parallel windows. In order to avoid the possibility of photochemical action with light at frequencies other than those used in the measurements, the light is usually passed through the filters before it enters the solution. With fluorescent solutions the procedure may be reversed, or additional filters may be inserted between the solution and the photocell in order to absorb the fluorescence. In all cases the use of an infrared filter is advisable to eliminate heating effects. A solution of ferrous sulphate may be used for an infrared filter, or glass filters designed for this purpose may be placed between the light source and the band-isolation filters. All the exit light from the solution cell is collected and directed to the photocell in a manner which will fill most of the collector electrodes. This is particularly important in using barrier-layer cells. For high-vacuum phototubes this is of minor importance if the light is so directed that the anode or collector does not intercept an appreciable portion of the light. In use, the light source or the sensitivity of the circuit is so adjusted as to give a large but readable value on the measuring scale when the filtered rays from the source pass through the cell filled with the same solvent that was used in the preparation of the solution to be measured. This standardization compensates for all absorptions and reflections except that of the colored substance to be measured. Its value is called I_0. The value of the photocurrent when the colored substance is in position is called I, and the relation

$$\log \frac{I}{I_0} = -kcd$$

may be used to calculate the concentration if the thickness of the solu-
tion and the value of the constant K are known.

EXPERIMENT 9–5

Purpose: To construct a filter photometer using a phototube and am-
plifier.

Materials: Light-tight box about 20 by 7 by 7 inches with removable
sides
32-candlepower 6–8-v. headlight bulb
Short-focal-length lenses
Filters
Absorption cells
Lens holders
Photocell

Procedure. Construct a filter photometer in accordance with the prin-
ciples discussed in the preceding section. This may be accomplished quite
simply by procuring a box about 20 by 7 by 7 inches divided lengthwise
into three compartments of equal size. Drill 1-inch holes into the com-
partment separators about 2 inches from the bottom of the box. Mount a
32-candlepower auto headlight lamp in the first compartment. Mount
a set of movable absorption cells in the second compartment and mount
the photocell and amplifier tube in the third compartment. Mount a lens
on the lamp side of the first partition and arrange the position of the
lamp so that parallel light passes through both holes in the partitions.
Attach a filter holder to the cell side of the first partition. Provide the
second partition with an additional filter holder and a slider to shut off
all the light from the lamp. The double absorption cell may be mounted
on a slider so that either cell may be selected at will.

Combine a photocell and resistor with the circuit of Figure 7–6, as
shown in Figure 9–8. The photocell and amplifier tube should preferably
be housed in the same compartment to avoid long grid leads, but they may
be placed in separate compartments if shielded leads are used. Potenti-
ometers and similar apparatus may be placed in any convenient position.
The photocell load resistor may be made variable and divided into two
parts, a fine and coarse control. A 10-megohm volume control in com-
bination with a .1 megohm volume control are adequate for most pur-
poses. Somewhat larger values may, however, be used for R_1 if the light
intensity is very low. If a meter potentiometer is used in the circuit, R_4
may be a General Radio type 314-A 200-ohm resistor, a Leeds and
Northrup slide wire or its equivalent. The functions of R_4 and M_2 may
be performed by the ordinary precision potentiometer such as a Leeds
and Northrup student model or Type K, as shown in Figure 7–6.

Prepare solutions containing .05-, .04-, .03-, .025-, .02-, .015-, and .010-molar copper ammonia sulphate made by adding a considerable excess of ammonia to .1-molar copper sulphate and diluting to .05M for a stock solution. Use an H.R. Red, 4-mm. Corning filter and a dark shade Aklo 3-mm. Corning filter for this solution with a 1-cm. cell.

With 135 to 180 volts constant potential for B_2 connect S to the right and set the plate meter to 1.0 ma. with the photocell dark. Throw S_1 to left, set M_2 to full voltage; allow the light through the solvent to illuminate the photocell and adjust R_1 until M_1 again reads exactly 1 ma.
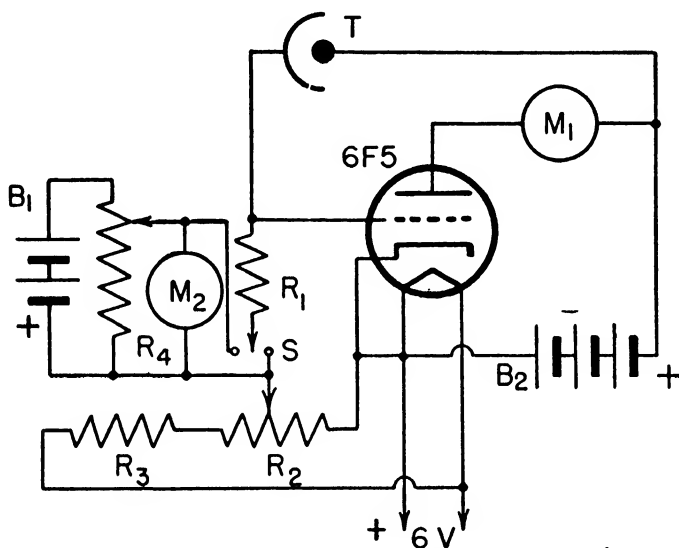
FIG. 9–8. $R_1 = 20$ megohms; $R_2 = 1,000$-ohm potentiometer; $R_3 = 1,000$ ohms; S = single-pole double-throw switch; $M_1 =$ 0–1 milliammeter. *Note:* A standard potentiometer may be used instead of R_4 and M_2.

Put the colored solution in place and adjust R_4 until meter M_1 reads the same value as before. The full-scale reading of the voltmeter represents I_0 and the reading with the solution represents I. The accuracy is determined by the precision of the setting, the accuracy of the voltmeter, and the linearity of the photocell. If a precision potentiometer is used the accuracy is limited only by the photocell if reasonable care is used in making the various settings. The two absorption cells must be identical in the above method. Identity can be checked by placing the solvent in both cells and determining the reading for each. If they are not identical correction factors must be applied or the technique changed to avoid this error.

Check the above measurement several times and note that the setting of R_1 increases slowly with time, owing mainly to a gradual de-

crease in the voltage of the storage battery used to feed the light source. Note also that the meter reading, with S_1 to right and with no illumination on the photocell, changes only slightly over a period of 30 minutes after the initial warm-up period.

Repeat the measurements with other solutions, selecting the proper filter in each case.

9–9. An electron-ray photocell filter photometer.

The principles of electron-ray tubes are discussed in detail in Chapter 12 but the tube may be used without an understanding of the principles involved. Briefly, the tube consists of a fluorescing target and con-
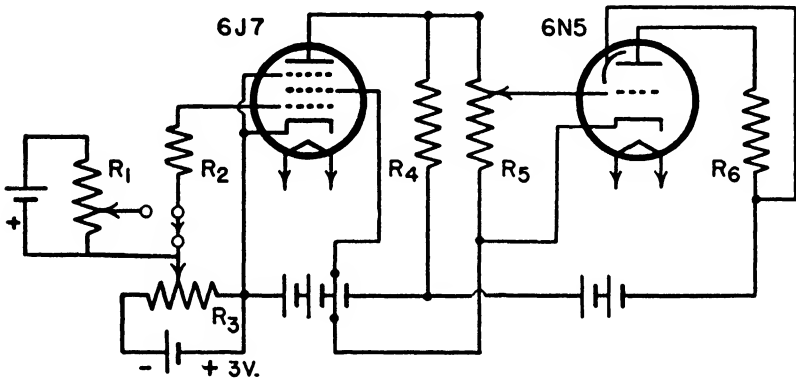
FIG. 9–9. R_1 = standard potentiometer or voltmeter as in Fig. 9–8; R_2 = 20–100 megohms; R_3 = 10,000 ohms; R_4 = .5 megohm; R_5 = 5.0 megohms; R_6 = .5 megohm.

trol electrodes which cause a shadow to be cast on the target. The size of the shadow varies with the voltage impressed on these control electrodes. The distance over which the shadow moves is small so that precise readings of the shadow are impossible, but if sufficient voltage amplification precedes the indicating tube it may be used as a null instrument to replace the meter M of Figure 9–8. In order to realize a large voltage amplification, the 6J7GT pentode precedes the 6N5 electron-ray tube as shown in Figure 9–9. The operation of the amplifier is quite simple. A small change in the grid voltage of the 6J7GT tube causes a change in plate current through R_4, and since the value of this resistor is large the voltage change caused by this current will be large. The same voltage also appears across R_5 and the grid of the 6N5 tube. The voltage is further amplified by the triode section of the 6N5 before it is applied to the target of this tube. The 6J7GT tube permits a voltage amplification of 100 or more and the 6N5 tube about 20, so that the over-all voltage amplification is approximately 2,000. This amplification is adequate to

cause a perceptible movement of the shadow with a signal at the grid of the 6J7GT tube of less than 1 mv.

9–10. The linearity of photocells.

The linearity of the response of present-day high-vacuum photocells to illumination is quite good. Indeed, for some cells the response is so good that it taxes the ingenuity to design adequate optical methods for the measurement of this quantity with the apparatus at hand in the ordinary laboratory of chemistry and physics. Cells tested by the authors over a period of years deviated from linearity by less than .1 per cent for
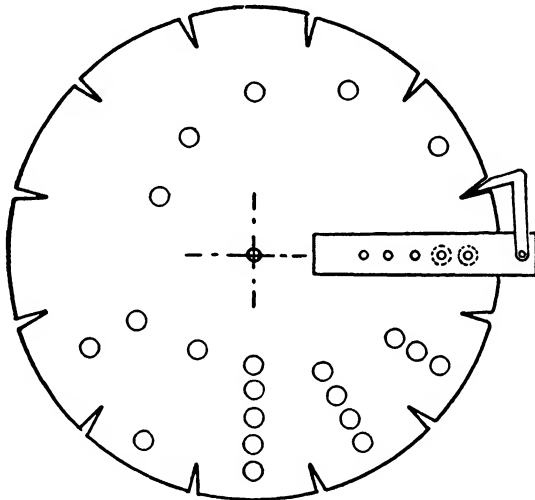
FIG. 9–10.   Calibration Disks for Photocell.   Fixed holes determine final apertures.

a change in illumination from 10 to 100 units. For this precision the ordinary optical methods for changing illumination by known amounts are inadequate. The difficulty of maintaining a light source constant with an effective precision better than .1 per cent over a period of half an hour is patent.

One method for checking linearity, used by the authors, easily duplicated with equipment available in almost any laboratory, is shown in Figure 9–10. It consists of a series of five or ten fixed apertures of approximately the same size, so arranged that any combination of apertures may be selected at will by revolving a disk placed in front of them. Each one of the apertures may then be selected separately and the photocurrent determined and recorded. For this purpose the circuits of Figure 9–8 or Figure 9–9 may be used, recording the voltage developed across the constant photocell load resistor as measured by a precision

potentiometer. If apertures 1 and 2 are then opened simultaneously, the photocell current should be the sum of the currents produced when each aperture was opened separately. If it is not, a lack of linearity is indicated and its magnitude is calculated from the data. Other combinations may, of course, be used to obtain a large number of measurements over a range of illumination from 1 to 10 units or larger. The light source must be held constant during the run.

EXPERIMENT 9–6

Purpose: To determine the linearity of a high-vacuum photocell.

Materials: Apparatus of Figure 9–8 or Figure 9–9 or equivalent
Selective apertures of Figure 9–10 or its equivalent
Light source, lens, and electrical controls of Figure 9–11

Procedure. Mount the photocell in a light-tight box close to the face of one of the sides. Drill five or ten small holes into the side of the box directly in front of the photocell window, so placed that all apertures are confined in a space smaller than the photocell cathode. Mount a large disk on this side of the box so arranged that the holes are covered completely. Mark the disk through hole 1 and place a 1 mark at a convenient index on the periphery of the disk. Proceed in turn to mark the other holes, then mark off combinations such as 1–2, 1–2–3, and so on, and place similar markings on the edge of the disk. Remove the disk and drill holes at all markings, making the holes somewhat larger than the holes in the box itself. Paint the whole with a good quality dead black paint and remount the disk. If $\vee$ slots are filed into the edge of the disk a simple indent mechanism may be constructed to align the various positions accurately. If this is to be used it should be mounted in position before the original holes are marked on the disk.

Mount the box rigidly and illuminate the apertures with parallel light employing a fixed source and lens. A 6–8-v. auto headlight lamp operated from two well-charged storage batteries may serve as a source of illumination. Connect the lamp in series with a standard resistance of low temperature coefficient (R_2 of Figure 9–11) and four large-size resistors to two 6-v. storage batteries. The actual values of these resistors depend on the characteristics of the lamp and may be calculated from the following example. A 6-v. lamp that requires 5 amps. may be connected in series with a .2-ohm standard resistor R_2 of sufficient size to dissipate 10 watts of energy, and a .1-ohm 50-watt resistor R_4 shunted with a 1-ohm variable resistor R_3 which in turn is in series with a 10-ohm resistor R_5 shunted with a 1.00-ohm variable resistor R_6 of sufficient wattage to carry the load as shown in Figure 9–11. Connect a sensitive galvanometer in series with a standard cell across the standard resistor R_2 so that the

RI drop in the standard resistor opposes the standard-cell potential. Adjust R_3 and R_6 until the galvanometer reads zero. Check adjustments throughout the calibration of the photocell to keep the galvanometer at zero. If a .2-ohm standard resistor is not available, one may be constructed from B. & S. 20 gauge manganin wire, connecting the ends to large-size binding posts.

Check the compartment for light leaks, and then in a semidarkened room with the photocell dark adjust the grid voltage to a standard meter reading. Open one of the holes and increase the reading of the potentiometer until the plate meter comes back to the same value. Note the
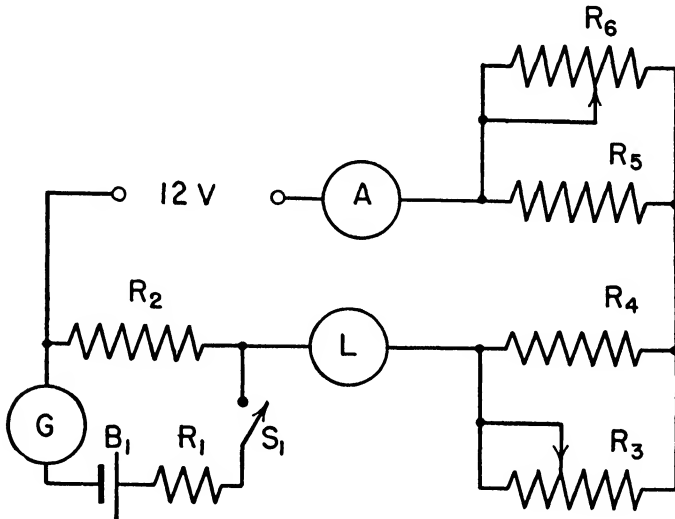
FIG. 9–11. Circuit for Maintaining Constant Lamp Current. R_2, see text; R_3, R_4, R_5, R_6 calculated from lamp constants; $R_6 = $ 50 or 100 $\times$ R_5 and $R_3 = $ 50 or 100 $\times$ R_4.

potentiometer readings. Check the dark position and repeat the reading. Select another hole and repeat the measurement. Continue until the intensity from each of the individual holes has been evaluated. Repeat the measurements with various combinations, and record all results. Plot the observed values for the combinations against the values calculated from the measurement of the individual apertures. Several check runs should yield results that differ by less than .1 per cent.

The method is open to criticism in that the opening of successive apertures introduces different multiple reflections. These can be minimized by proper construction and methods can be devised to check them, for example by using a separate light source in the form of a small flashlight bulb placed directly in front of one of the holes and noting the effect of opening other apertures with the main lamp disconnected and

the apparatus screened from the light of the room. The aperture selector may consist of five or ten individual slides so arranged that any combination of apertures may be selected. The unit must be mounted rigidly so that no movement takes place during adjustments.

9–11. The photocell as a null instrument.

The characteristics of the photocell as well as those of the associated circuits may be rendered unimportant by using optical compensation so that the photocell and amplifier chain are used as null indicators or null restorers. The Hardy Color Analyzer, which illustrates this arrangement, is essentially a flicker photometer so constructed that the light from a sample is alternated with the light from a standard at a rapid rate. When the light from the sample is weaker or stronger than the equivalent beam from the standard, the photocell amplifier chain is energized in a manner to control a motor and effect optical compensation of the difference. The transmittance is recorded by a pen attached to the optical-compensation network. Since the flicker or rate of alternation is 120 c.p.s., fluctuations in the light source of longer duration than this time interval affect both standard and unknown equally and therefore have no influence on the measurement.

The mechanical and electrical construction required for an instrument of the above type is quite extensive but almost the same effect may be achieved by a method employing slower alternations. If the sample in Experiment 9–5 is placed in the path of the beam and R_1 is adjusted until the output reads a suitable value, and if the standard (solvent cell) is thereupon substituted for the sample and the illumination to the photocell reduced by a calibrated optical unit until the output meter reads the same value, then the same principle used in the Hardy Color Analyzer is employed. Due to the relatively longer time required to effect the interchange between unknown and standard the changes in intensity of the light source are capable of producing errors. The characteristics of the photocell and amplifier, however, drop out and the accuracy of the reading is that of the optical compensator and the adjustment.

9–12. Balanced photocells.

In order to avoid the difficulty caused by the general changing of the intensity of light sources many investigators have used two photocells arranged to balance out this source of fluctuations. As shown in Chapter 3, it should be obvious that the fluctuations due to light-source variations are balanced out only if optical compensation is employed, and in general only when the two photocells are producing the same amount of current. For this method the characteristics of the photocells must be

matched so that any lack of linearity in one cell is perfectly reproduced in the other cell. This is almost as difficult to obtain as perfect linearity and, therefore, the only advantage of optical compensation with balanced cells is the apparent freedom from fluctuations due to light-source variations.

The cells may be balanced quite easily by employing a common load resistor for the two photocells and arranging the polarity of the cells so that the current from each flows in opposite directions in the load resistor, as shown in Figure 9–6. If the two cells have different sensitivities or if two sources of light are unequal, balance is achieved by changing either beam with a variable diaphragm.

If polychromatic light is used with photocells so balanced, fluctuations in the light source are not completely canceled if the color-response curves of the two cells are different. This failure arises from the fact that the spectral distribution of a white-light source is a function of its temperature.

9–13. A photoelectric spectrophotometer.

A spectrophotometer is a useful and important instrument. Measurements with the visual spectrophotometer are tedious owing to the large number of readings required to establish a spectrophotometric curve. The labor may be reduced appreciably by the proper substitution of a photocell amplifier for the human eye. This substitution is not easy, since the amount of light available is quite small if narrow slits are used. If broad slits must be used, the advantages of the spectrophotometer over a corresponding multiple-filter photometer diminish rapidly. With modern equipment slit widths from 1 to 10 mμ are permissible but slits of the order of 25 to 100 mμ offer no particular advantages over a corresponding filter photometer. The ideal in spectrophotometers today is represented by the Hardy Color Analyzer, as was indicated before.

Since optical compensation requires facilities that are not always available, and since rapid measurements are the chief requirements of any sound manually operated spectrophotometer, a combination of a spectrometer with a photocell and the amplifier of Figure 7–9 or Figure 7–10 offers attractive possibilities. The amplifier output linearity depends only on the photocell if the amplifier has adequate gains, and the meter may be read rapidly at the different wave lengths. A circuit which has been used successfully by the authors for several years is shown in Figure 9–12. The photocell load resistor totals approximately 10^9 ohms and is made from several sections as follows: ten 100-megohm resistors, selected by a selector switch so that any combination from 10^8 to 10^9 ohms is available, and a 10-megohm variable resistor. If an optical method is available for controlling the intensity of the light

source, a single 10^9-ohm resistor may be used for R_1. The operation of the remainder of the amplifier is covered adequately in §§7–9 and 7–10 and will not be detailed here. Provision is made for attaching a recorder as indicated. Any type of recorder with sensitivities from 50 mv. to several volts full scale or 1 to 10 ma. may be used, if the load resistor of the recorder output is adjusted to adapt the recorder to full scale of the meter. The output meter may be any good-quality 10 ma. instrument
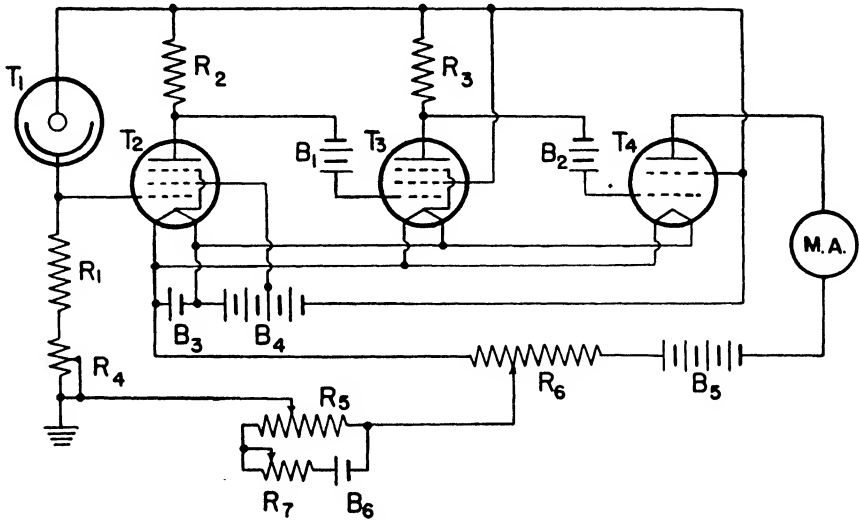
Fig. 9–12. Inverse-feedback Photometer. R_1 = 100 to 10,000 megohms; R_4 = 10 per cent of R_1; R_2 = 30 megohms; R_3 = 1.0 megohm; R_5 = 25,000 ohms; R_6 = 100 ohms; R_7 = 500 ohms; M.A. = 0–10 precision milliammeter; T_1 = 929 phototube; T_2 = 1N5GT; T_3 = 1S5; T_4 = 1T5GT; B_1 = 15 v.; B_2 = 22.5 v.; B_3 = 1.5 v.; B_4 = 45 v., tapped at 22.5 v.; B_5 = 22.5 v.; B_6 = 4.5 v.

and may be a voltmeter of low voltage range. A large-size meter with an accuracy of .1 per cent of full scale is recommended.

EXPERIMENT 9–7

Purpose: To construct and operate a direct-reading spectrophotometer.

Materials: Spectrometer or monochromator
Light-source lenses
Components of Figure 9–12

Procedure. Adjust a good-quality spectrometer or monochromator according to the directions of the manufacturer. This adjustment may be carried out visually with a mercury arc lamp. After the preliminary adjustments are carried out, check the wave-length scale against the known wave lengths of the mercury-arc lines. If the focusing adjuster is not provided with a scale, construct a suitable scale for future reference. The in-

strument must be equipped with an exit slit and adjusted visually for proper alignment of this slit with the collimator slit. Remove the eye-piece and select a lens of proper size to fill the photocell cathode with the illumination from the exit slit. For this adjustment the slits may be opened until the beam is visible. Construct a cell holder directly in front of the photocell and guard against stray light seeping in at any point. The cell holder should be arranged on a slider so that rapid interchange between solution and solvent is possible.

With the mercury arc still in position, reduce the size of the slits and rotate the wave-length drum until an arc line comes through the exit slit, as indicated by an increase in the reading of the output meter. Adjust the exit slit for an opening of very small width and increase the collimator slit if necessary to gain sufficient light intensity. Adjust the focus until the output meter reads a maximum and record the focus position for this wave length. Obtain the focus position for the other lines of the mercury arc in a similar manner. The instrument is now in optical adjustment and ready for use if the mercury arc is replaced by a white-light source.

The source may be a single-filament bulb so adjusted that the slit is uniformly illuminated. The lamp may be operated from well-charged storage batteries or from a compensated power supply as shown in §4–14. Select comparable slit widths for the collimator and exit slit and rotate the wave-length drum through the entire range, plotting response of the meter as a function of wave length. This curve represents the net re-sponse curve of the white-light source and photocell.

Determine the response curve for a number of filters used in Experi-ment 9–2 in the same manner. In order to obtain sufficient accuracy, set the resistor R_1 and the size of the slits so that the meter reads full scale at the maximum transmission point of the filter, then rotate the wave-length drum and record the other points. This curve, if corrected for variation in equivalent slit width, represents the corrected curve for the filter as used in the filter photometer with a light source at the same color temperature and with the same photocell. If the band transmitted by the filter is narrow the variation in equivalent slit width with wave length may be neglected. Determine the actual transmission of the filter by obtaining the output meter reading with and without the filter at all wave lengths, and plot the ratio of the readings as a function of wave length. Determine the transmission of colored solutions such as copper ammonia sulphate or potassium permanganate in a similar manner. Compare the net filter curve with the solution curves in order to find a suitable filter for a particular solution.

The spectrophotometer may be made recording by driving the wave-length drum with a synchronous motor and operating a cam by the same

motor to control the intensity of illumination or to shift the value of R_1 to compensate for the variation of response of the system. The meter readings are recorded by an electrical recorder, as was indicated before.

9–14. Photoelectric densitometer.[8-12]

Photocells are used extensively today to measure the density of photographic spectrum plates. A high degree of accuracy is not usually required for these measurements but certain fundamentals of optics must be observed in the construction of a suitable instrument. Since the
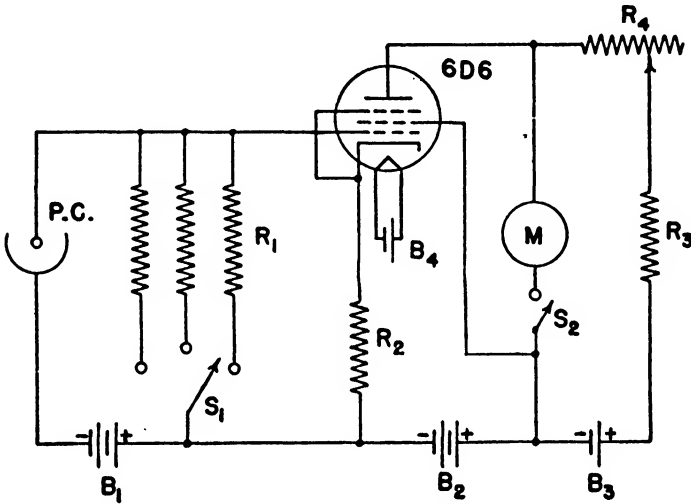
FIG. 9–13. Photoelectric Colorimeter with Logarithmic Response. P.C. = PJ 22; R_1 = 3, 10 and 50 megohms; R_2 = 2,000 to 3,000 ohms (value critical); R_3 = 1,000 ohms; R_4 = 100,000 ohms; B_1 = 90 v.; B_2 = 45 v.; B_3 = 2 v.; B_4 = 6 v.; M = multi-range microammeter.

density produced by the photographic plate represents the logarithm of the original intensity of light, a measuring system which reads the logarithm of the light intensity is desirable for such work: that is, a system which becomes more sensitive as the illumination is reduced. Several circuits have been devised to achieve this end. The optics may consist of a single-filament lamp focused on a good variable bilateral slit; when refocused on the emulsion of the plate, preferably with a short-focus compound lens to produce a reduced image of the slit, the light from the plate may then be collected by a similar lens and focused on a slit placed

8 Russel, J., *R.S.I. 8*, 495, 193.
9 Knorr, H. V., and Albers, V. M., *R.S.I. 8*, 183, 1937.
10 Meagher, R. E., and Bentley, C. P., *R.S.I. 10*, 336, 1939.
11 Taylor, J. P., *Electronics*, Mar., 1937; p. 24.
12 Russel, J., *R.S.I. 8*, 495, 1937.

immediately in front of a photocell. The use of a second slit minimizes the errors due to scattered light. This error may be as high as 100 per cent for a photographic spectrum line with a density of one unit (10 per cent transmission). The instruments represented in Figures 9–8, 9–9, or 9–12 may be used in a densitometer of linear scale. If the field-saturated pentode is used as a load resistor in the above circuits to convert the photocurrent into a logarithmic voltage the same instruments will be converted into logarithmic-scale densitometers.

9–15. Photoelectric colorimeters with logarithmic response.

Since the concentration of a solution is calculated from the logarithm of the percentage transmission, a logarithmic scale on a filter photometer or spectrophotometer is highly desirable. If optical or electrical compensation is used to effect the null point as in §9–12, the scale on these compensation units may be the logarithm of the linear scale. Such a scale is a contracting or expanding scale that is difficult to read, especially with regard to interpolation for the last decimal place. The difficulty may be avoided by using a logarithmically wound slide wire for §9–9 or §9–10, or a logarithmic drive unit for the optical compensation method in connection with a linear scale.

If these units are properly calibrated the accuracy may be made as high as desired.

Facilities for constructing and calibrating these devices are not, however, ordinarily available, hence the circuit shown in Figure 9–13 may be useful in that the electron tube itself extracts the logarithm of the grid voltage. The circuit uses a variable-μ tube and cathode resistor so proportioned that the plate current is a function of the logarithm of the input voltage over a definite range of grid voltage. Since the photocell produces the grid voltage, the plate current represents the logarithm of the photocurrent.[13]

9–16. The photocell and the absolute measurement of energy.

One of the most common uses of barrier-layer photocells is in the measurement of light intensity, typically in photographic exposure meters or illumination meters. The accuracy required for such measurements is not as high as that required for the evaluation of quantum efficiency in photochemical reactions and other laboratory measurement. Although the sensitivity of photoemissive-type photocells does not change appreciably from day to day, it is difficult to calibrate these cells in absolute units owing to their selective spectral character. The cells may, however, be calibrated against a thermopile for a certain spectral region or for a certain light source operated under a specified condition.

[13] Müller, R. H., and Kinney, G. F., *J.O.S.A.* **25**, 342, 1935.

The thermopile in turn may be calibrated in absolute units by means of a *Bureau of Standards standard lamp.* This calibration permits the *measurement of such weak light sources* as fluorescence in the same spectral region.

PROBLEMS

1. Design a phototube counter suitable for counting the number of persons entering a given door.

2. Design a phototube relay which may be used to open a door at the proper time and keep the door open until the person has passed through the door safely.

3. Show how the design of Problem 2 could be changed so that the door remains open if the person pauses for an indefinite time at the threshold. Consider the possibility of the door closing as soon as the person begins to pass across the threshold.

4. Design a photocell burglar alarm using ultraviolet or infrared light. How could this design be arranged so that a power failure would not result in a failure of the relay? Do not operate the alarm continuously on batteries.

5. Show the essential features of a phototube safety device to guard the operator of a large press.

6. Show how a sorting machine may be constructed using a phototube relay system.

7. Design a phototube amplifier meter which could be used to sound an alarm or to read the concentration of poisonous vapors in a room.

8. Design an apparatus which can be used to detect extremely small amounts of H_2S in the air of a room.

9. Design a circuit which can be used to measure the concentration of coal dust in the atmosphere.

10. Design a phototube photometer suitable for the measurement of reflectance at various wave lengths.

11. Show how a phototube may be used to measure fluorescence.

12. Design a double-phototube photometer in which the readings are independent of the intensity of the light source.

13. Design a double-phototube photometer in which the differential sensitivity is independent of the intensity of the light source over wide limits.

14. Design a circuit suitable for the photometry of photographic plates in which the readings are the logarithm of the light intensity in a direct-reading densitometer.

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CHAPTER 10
Untuned Amplifiers

Introduction.

As the name implies, amplifiers of this type are designed to amplify over a band of frequencies. In modern practice amplifiers may be made to amplify at frequencies from zero to several million cycles per second without unduly emphasizing any one particular frequency. Most amplifiers, however, are designed to amplify a smaller band of frequencies. The common audio amplifier will amplify voltages more or less uniformly at frequencies from 100 to 10,000 c.p.s. The amount of amplification depends upon the type and number of tubes employed as well as upon the circuit constants of the associated circuits. The design of the amplifier also determines the quality of the amplification, that is, whether the magnified output is identical with the impressed source voltage in all respects except magnitude. If this is not the case then the signal is distorted. The several types of distortion will be considered in more detail under each measurement.

10–1. Classification of amplifiers.

Practically all the tube circuits already discussed embody amplifiers in one form or another, and the circuits and experiments in this chapter should be considered as continuations of former ones.

Amplifiers may be divided into two classes, voltage amplifiers and current amplifiers. The two functions are not distinct, since most voltage amplifiers also simultaneously amplify current and current amplifiers amplify voltages. The FP-54 circuit discussed in §7–2 is one for almost pure current amplification, in that with a grid resistor of 10^{10} ohms, 1 v. is developed at the grid by a current of 10^{-10} amp. while less than 1 v. appears across the galvanometer terminals. In this case the current amplification is from 10^{-10} amp. to 10^{-5} amp. A current or power amplifier such as the 6L6 tube may convert 10^{-5} amp. to 10^{-2} amp., developing a lower or higher voltage, all depending upon the constants of the associated circuits.

10–2. Amplitude distortion.

Before proceeding with the detailed classification of amplifiers it is advisable to define the various types of distortion which amplifiers pro-

duce. Amplitude or nonlinear distortion is caused by the nonlinear relationship between i_p and the corresponding e_o, as when a sine wave in passing through an amplifier is changed in shape. The new shape might be resolved into a sine wave together with a number of harmonics of various amplitudes. This type of distortion is usually measured by the percentage of the harmonic content of the amplified signal in relation to the applied voltage.

10–3. Frequency distortion.

If the amplifier does not amplify equally at all frequencies, the output voltage of a complex wave will not have the same shape as the input voltage and this phenomenon is referred to as frequency discrimination or distortion.

10–4. Phase distortion.

When the phases of some frequencies are shifted more than those of other frequencies the result is called phase distortion. Frequency discrimination usually results in phase distortion. Phase distortion is of no great importance in audio amplifiers used for reproduction of audible tones. It is of great importance in television and in studies of wave shapes with a cathode-ray tube.

10–5. Coupling between stages.

Amplifiers may be further classified in accordance with the methods of coupling employed between stages. When the grid of a tube is connected directly to the plate of the preceding tube the amplifier is said to be directly coupled. Such an amplifier will amplify at zero frequency (that is, D.C.) as well as at higher frequencies. If the grid of an amplifier is connected to the plate of the preceding tube through a capacitor, and if the plate of this tube is connected to the power supply through a resistor, as shown in Figure 10–1, the amplifier is said to be capacitatively coupled or more specifically R-C coupled. When the plate load resistor in the latter example is replaced by a single inductance L_1, the amplifier becomes L-C coupled. If a transformer is used between stages, the amplifier is transformer coupled.

10–6. Power amplifier: static grid voltage.[1]

Current or power amplifiers may be further subdivided in accordance with the grid voltages used for static operation. When an amplifier is operated at a D.C. grid potential corresponding to a plate current approxi-

[1] Terman, F. E., "Radio Engineering." New York: McGraw-Hill Book Co., 1937.

mately halfway between zero and maximum, it is said to be operating as a Class A amplifier. Such an amplifier wastes half of its maximum power even when a signal is not applied and can never be more than 50 per cent efficient.

The grid of a Class A amplifier is never allowed to become positive and thus requires no appreciable grid-driving power. If, however, the D.C. grid voltage is so selected that only a small plate current flows at zero signal the efficiency of the plate circuit is greatly increased. A high wattage output is obtained by driving the grid highly positive. When the grid is positive in voltage, grid current flows and must be considered in the design. The plate current of an amplifier of this type is never linear
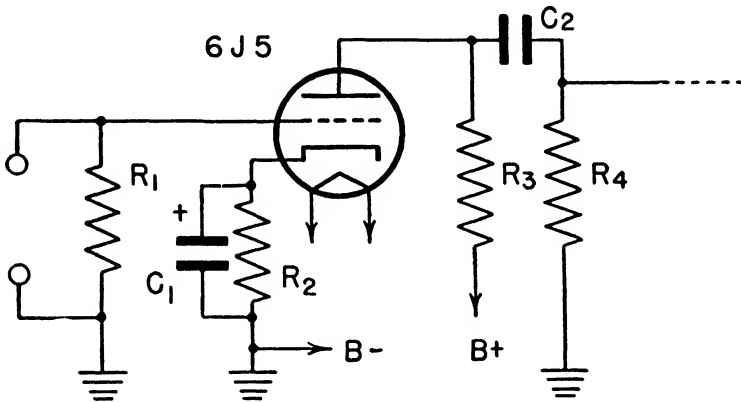
Fig. 10–1. Single Stage of Audio Amplification. R_1 = 1.0 megohm; R_2 = 1,000 ohms; R_3 = 50,000 ohms; R_4 = 1.0 megohm; C_1 = 25 μf., 25 v.; C_2 = .05 μf., 400 v.

with grid voltage and considerable amplitude distortion takes place, resulting in the generation of a large percentage of harmonics. This type is called a Class B amplifier and the tubes are always used in pairs, that is, in push-pull, causing the cancellation of even-order harmonics with a resulting decrease in distortion. In modern practice many amplifiers are designed to operate between the Class A and Class B designs and may be termed Class AB. Class AB amplifiers are further subdivided into Class AB_1 and AB_2. The distinction is made because in the first type no grid current flows while in the second some grid current flows when the positive grid signal voltage is a maximum.

When the D.C. grid voltage used is so highly negative that current flows only during a fraction of the positive grid-voltage wave, the amplifier is called Class C. This amplification, even when used in push-pull, develops such a high percentage of harmonics that it is used only for tuned amplifiers.

10–7. Design of amplifiers.

The design of an efficient and practical voltage or power amplifier is very complicated. The voltage gain depends upon the type of tubes employed, the grid voltage, the plate voltage, the screen voltage (for tetrodes and pentodes), the plate load, and the type of coupling used.[2] The various types of distortion encountered also depend upon these factors. The design of any amplifier must consequently represent a compromise in which the distortion factors must be considered first and the amplifier must be made up of enough minimum-distortion stages to obtain the desired gain. Fortunately, the human ear is not very discriminating in detecting the various types of distortion. An audio amplifier may sound well, but when it is tested objectively the various types of distortion may be found to be fairly high. This distortion must be avoided by the physicist and chemist when using amplifiers in the study of physical phenomena. A measurement of the rapid changes in the electrolysis current of a certain system cannot necessarily be studied with an amplifier which just sounds well, although this might be an improvement over some of the amplifiers which have been used for this purpose in the past. In the remaining sections, therefore, experimental methods will be given to illustrate the measurements of gain and distortion.

10–8. Analysis of a resistance-coupled amplifier.[3]

The action of an amplifier may be understood by tracing the path of the signal through the unit. Consider the amplifier illustrated in Figure 10–1. As the value of the signal, e, rises the grid becomes less negative, thus increasing the plate current progressively. As the plate current increases, the RI drop in the plate resistor R_3 also increases and the voltage across the capacitor C_2 and resistor R_4 decreases by the same amount, causing a small amount of current to flow through resistor R_4 in the direction to make the top of this resistor progressively more negative. The current flowing in this resistor depends upon the value of its resistance and the size of the capacitor C_2. If the impedance of C_2 is low and R_4 is large, the current is limited only by the instantaneous value of the increased RI drop across R_3 and the resistance of R_4. Thus approximately the full voltage produced by the RI drop in R_3 appears across R_4 under these conditions, and is the output voltage E. If C_2 has a low reactance and the value of R_4 is small, then the full voltage may still be impressed across R_4 but the RI drop must be calculated by considering R_3 and R_4 in parallel, as previously indicated. If the impedance of C_2 is an appreciable fraction of R_4, then the full voltage does not appear

[2] *Ibid.*

[3] Reich, H. J., "Theory and Application of Electron Tubes." New York: McGraw-Hill Book Co., Inc., 1939.

across R_4 but is divided between C_4 and R_4. Furthermore, the fraction that appears across R_4 will have undergone considerable phase distortion. Since the reactance of C_4 depends upon frequency, the efficiency of coupling will also vary with the frequency.

After e has reached the positive crest value the instantaneous voltage begins to fall progressively, reducing the RI drop across R_3 until e reaches the negative crest value. Simultaneously the voltage across C_2 increases progressively to a maximum, the upper end of resistor R_4 becoming positive with respect to ground.

If the value of e is large the RI drop in R_3, that is, E, may become equal to the B supply before the positive crest is reached. The instantaneous voltage appearing across R_4 cannot further increase and the sine wave becomes flat. This condition may also be obtained at the negative crest if the plate current is cut off before the crest value is reached. Amplitude distortion therefore results, and in turn causes reduced amplification. Since the sine wave loses its perfect shape by reason of the flat top, new frequencies are generated, resulting in a high harmonic content of the output voltage E.

10–9. Voltage gain.[4]

The voltage gain of a stage of triode amplification cannot be calculated from the value of di_p and g_m, since the value of g_m was determined with zero plate load. It is given by the relation

$$\text{V.A. (or voltage amplification)} = \mu \frac{R_L}{r_p + R_L},$$

as was shown in §2–4, where r_p is the dynamic plate resistance and R_L the corrected load resistance, that is, R_3 corrected for the shunting produced by C_2-R_4 of Figure 10–1. For a pentode amplifier at low plate load the gain may be calculated without serious error from the relation $g_m R_L = \text{V.A.}$, since

$$g_m = \left(\frac{\partial i_p}{\partial e_g}\right)_{e_p} = \frac{\mu}{r_p},$$

and R_L is negligible in comparison to the value of r_p.

10–10. Grid voltage.

The grid voltage for the tube in Figure 10–1 is obtained with the cathode resistor R_2. Plate current flowing in this resistor makes the cathode positive with respect to ground potential and the correct value of this resistance may be calculated from $e_g = R_2 i_p$ if the proper equilibrium value of plate current is known for the tube. Correct values for

[4] Reich, H. J., *op. cit.*

the cathode and plate resistances for various power-supply voltages for each tube type are often furnished by the manufacturers. The purpose of C_1 is to by-pass the fluctuating plate current so that the grid voltage results from the D.C. plate current only. If the capacitor be omitted, degeneration takes place and the gain will thus be reduced. This process is evident from the curves given in Figure 2–12.

10–11. Frequency response.[5]

Since electrons have a very small inertia it would appear that the frequency of the impressed signal e could be increased many fold without any decrease in the stage gain. In practice a decrease in the stage gain results at higher frequencies, since the tube mountings and associated circuits have small but definite capacities associated with them. The grid has a capacitance to cathode and at high frequencies this small capacitor shunts the input resistance so that if the source does not have zero impedance there is a loss of voltage. In a similar manner the plate has a capacity to ground, as do the resistors R_3, R_4 and the grid of the following tube. At high frequencies the reactance of these capacitors will be in shunt with the previously defined value of R_L and a relatively low value of voltage amplification will be attained. At low frequencies the value of C_2 in Figure 10–1 is important. It will be seen that R_3 is really in shunt with C_2 in series with R_4, but at normal frequencies C_2 is regarded as having an impedance of zero. This impedance cannot be considered zero at low frequencies and therefore the voltage across R_4 is not equal to the A.C. voltage across R_3. The value of C_2 in a practical amplifier therefore depends upon the lowest frequency the unit is supposed to amplify, as well as upon the value of R_4. The value of C_2 is usually chosen so that its impedance at the lowest frequency to be encountered is at least less than 10 per cent of the resistance of R_4. The frequency response of an amplifier may be studied by measuring the gain as a function of frequency. If the input voltage and output voltage are known, the gain can be calculated from the ratio E/e.

EXPERIMENT 10–1

Purpose: To study the frequency response of a single-stage amplifier as a function of the R-C constants.

Materials: 76, 6C5, or 6J5 tubes
Tube socket
B supply
Assorted capacitors, .05-μf. to .001μf.
50,000-ohm 1-watt resistor
10,000-ohm 1-watt resistor

[5] Terman, F. E., *op. cit.*

.1-megohm resistor
1.0-megohm resistor
A.C. vacuum-tube voltmeter
Large-size calibrated potentiometer
Double-pole double-throw switch
Variable-frequency audio oscillator

Procedure. Connect the various components as shown in Figure 10–2. For the sake of completeness a vacuum-tube voltmeter is also shown but any type of A.C. vacuum-tube voltmeter is suitable for this purpose. Any errors of this voltmeter do not affect the accuracy of the measurement.[6]
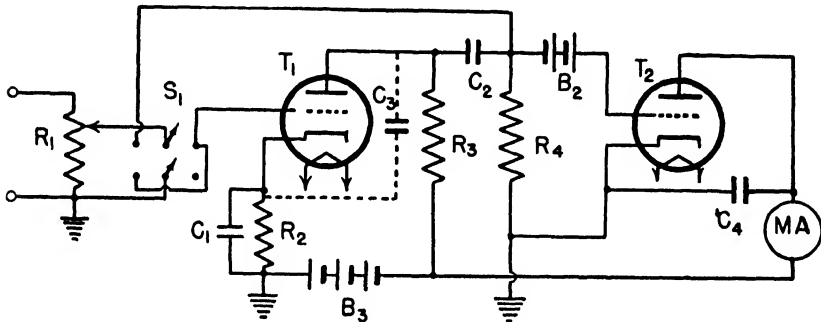
FIG. 10–2. Measuring the Gain of a Stage of Audio Amplification. $R_1 = 10,000$ ohms; $R_2 = 500$ ohms or higher; $R_3 = 50,000$ ohms or higher; $R_4 = 1.0$ megohm; $C_1 = 25$ μf. or omitted; $C_2 = 1$ μf.—see table; C_3, see table; $C_4 = 2$ μf.; $B_2 = 9$ to 12 v.; $B_3 = 135$ v.

Adjust the voltmeter as in Experiment 8–1. Note that the grid voltage for the voltmeter is obtained with B_1 so placed that R_1 does not short-circuit the battery. Set R_1 to maximum resistance and with S_1 to left adjust the output of the audio oscillator until the vacuum-tube voltmeter reads a convenient value, at the lowest frequency available on the oscillator. Decrease the reading of R_1 to zero then throw S_1 to right. Slowly increase R_1 until the voltmeter again reads the same value as before. Read and record both values of R_1. The ratio of the full reading of R_1 to the value just obtained is the voltage amplification of the stage at this frequency. Repeat this measurement at a higher frequency. In general, the frequency may be doubled at each step: 10, 20, 50, 100, 200, 500, 1,000, 2,000, and so on, are suitable values. Plot the gain as a function of the logarithm of the frequency, as shown in Figure 10–3.

The gain and frequency response of this stage are determined by the values of C_1, C_2, C_3, and of R_3 and R_4; a large number of these values should be studied. Table 10–1 summarizes some sets of suitable values.

[6] Kiernan, E. F., *Electronics*, July, 1937; p. 18.

TABLE 10–1

Set No.	R_2 (ohms)	R_3 (ohms)	R_4 (megohms)	C_1 ($\mu f.$)	C_2 ($\mu f.$)	C_3 ($\mu f.$)
1	1,500	50,000	1	.01	10	Removed
2	1,500	50,000	.1	.01	10	
3	1,500	50,000	.1	.05	10	
4	1,000	10,000	.1	.05	10	
5	1,500	50,000	.1	.05	1	
6	1,500	50,000	.1	.05	10	.001
7	1,500	50,000	.1	.05	10	.005

Measurements with sets 6 and 7 of Table 10–1 may be omitted entirely if the audio oscillator extends to sufficiently high frequencies. When C_3 consists only of the tube output capacitance the gain is not reduced appreciably even at 15,000 cycles. The use of C_3 (larger values of C_3 as in sets 6 and 7) demonstrates the effect of output capacitance on the high frequencies, as shown in Figure 10–3.

An alternate method may be used in the study of the frequency response of an amplifier if an A.C. vacuum-tube voltmeter is available whose frequency response is known to be uniform over the range to be studied. In this method the double-pole double-throw switch is eliminated and the voltage divider or attenuator is connected permanently to the amplifier tube. This voltage divider must be fed with the same voltage at all frequencies, either by using a constant-output oscillator or by manually adjusting the oscillator so that its output is the same at all frequencies.

The General Radio microvolter meets this requirement. Select the middle frequency range and increase the reading of the attenuation until the vacuum-tube voltmeter reads a suitable value (10 to 20 v.), then change the frequency to other values and adjust the attenuator for the same reading of the voltmeter or read the voltage output directly, keeping the attenuator fixed.

10–12. Transformer-coupled amplifiers.

The detailed analysis of transformer-coupled amplifiers is quite involved. This complexity arises from the fact that at low frequencies the gain is limited by reactance developed by the transformer, while at high frequencies the gain is reduced by the leakage inductance. At low frequencies the gain of the stage may be represented by

$$\text{V.A.} = n\mu \frac{R_L}{r_p + R_L},$$

where R_L is the equivalent reactance, X_L, of the primary or plate coil of

the transformer and n is the turn ratio of the primary to the secondary. In existing radio tubes, when μ is high, r_p is also high. To make the value of X_L at low frequencies large in comparison to r_p, many turns must be used in the primary of the transformer. Such winding in turn increases the leakage inductance, reducing the gain of the stage at high frequencies. This difficulty can be avoided to some extent if a tube with
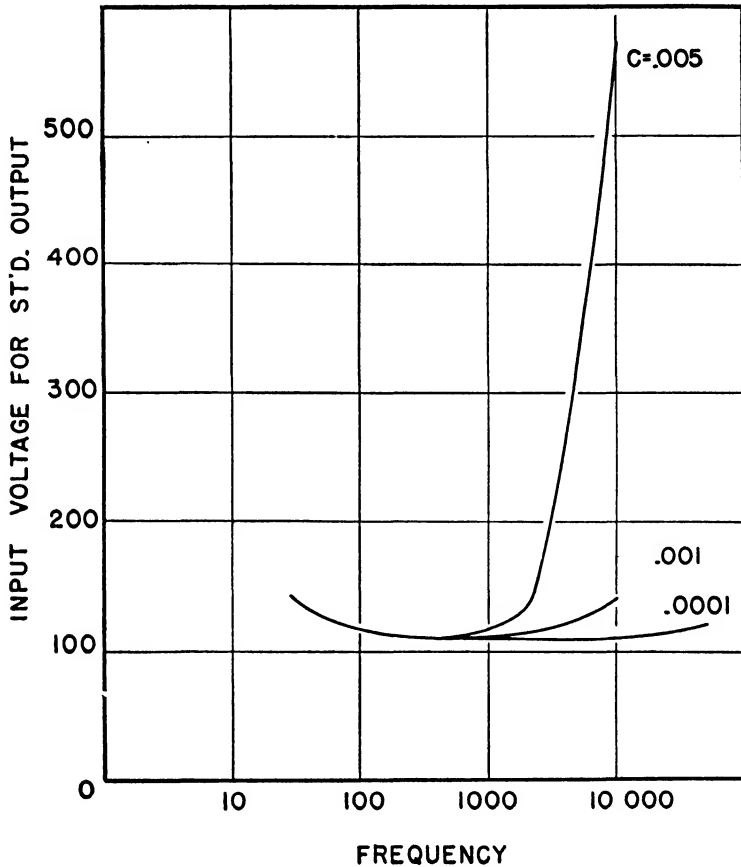
Fig. 10–3.   Frequency Response of Loaded Triode.

a low value of r_p is used, but the gain of such a stage will be small in comparison to the gain obtained with a high-μ tube and R-C coupling, as shown in Figure 10–1. Thus, transformer-coupled stages possess relatively low gains in spite of the fact that the transformer itself furnishes a voltage gain proportional to the turn ratio. The design of a transformer must thus represent a compromise between gain and frequency response.

Transformers are used today chiefly to couple units that differ widely in their required load resistances. This procedure is called matching. In a power amplifier, for example, the required plate load at maximum efficiency may be 5,000 ohms, while the transducer that this stage is driving has an equivalent resistance of only 5 ohms. A transformer with an approximate turn ratio of about 30 to 1 is required to transform the output power in this case, and may be made easily, since the number of turns required to meet the above-named requirement is not large even for the low frequencies. In studying transformers it is well to remember that the effective resistance of the primary depends upon the frequency, on the number of turns, and on the load carried by the secondary as well as on other factors. The complete treatment of transformers is beyond the scope of this book and the reader is referred to standard texts on the subject.

10–13. Inductance-coupled amplifiers.

If an inductance is substituted for the load resistor in Figure 10–2 the amplifier is inductively coupled; if it is to produce the same gain at low frequencies as the resistance-coupled amplifier the reactance must have the same value as R_3. Inductances to replace large values of R_L are difficult to obtain, as the student may readily prove for himself by a simple calculation with the relation $X_L = 2\pi fL$. The inductance-coupled amplifier offers the advantage, however, that the RI drop caused by the D.C. plate current is small in comparison to the equivalent drop in the resistor R_3 of Figure 10–2. The tube may therefore operate at a lower grid voltage, which in turn results in a smaller value of r_p for a triode tube.

The gain of this amplifier, as in the case of transformer-coupled amplifiers, is not uniform with frequency but increases steadily since the impedance of the load increases until it becomes large in comparison to the dynamic plate resistance r_p. At higher frequencies the gain is modified owing to the shunting effect produced by the distributed capacitances. With increasing frequency the reactance of the distributive capacitances decreases. When it attains a value equal to the inductive reactance of the choke coil, the impedance of the combined circuit is a maximum. At this frequency very high amplifications may be attained. At higher frequencies the net impedance as well as the amplification will again decrease. Some of these difficulties may be avoided by shunting the coil with a resistance of a value depending on the reactance of the coil at the frequencies where the amplifier characteristic is to be leveled off. These considerations are common to both transformer and choke or impedance coupling. A further discussion of the latter is therefore not required.

EXPERIMENT 10–2

Purpose: To determine the frequency response of transformer- and impedance-coupled amplifiers.

Materials: Interstage transformer and apparatus of Experiment 10–1.

Procedure A. Transformers. Replace resistors R_3, R_4 and capacitor C_2 with an interstage transformer. Determine the frequency response as in Experiment 10–1, and plot on the same scale in order that the values of voltage amplification obtained with the transformer-coupled amplifier may be readily compared with the corresponding values for the resistance-coupled amplifier.

Repeat the experiment with a .1-megohm shunt resistor connected across the secondary terminals. Plot the frequency response as before, and note that the gain is lower at the higher frequencies; note also that the resonance hump is greatly reduced in magnitude.

Remove the shunt resistor and add capacitance across the primary as in sets 6 and 7 of Table 10–1, and redetermine the frequency response. Note that the resonance rise is shifted to lower frequencies.

Procedure B. Choke-impedance load. Replace the resistor R_3 with the primary of the transformer, but keep C_2 and R_4 in the circuit as in Figure 10–2, the secondary of the transformer remaining unconnected. Determine the frequency response as in Experiment 10–1 and plot the results in the same manner. Compare these values at low and high frequencies and note that the gain is lower at both ends of the frequency spectrum. Shunt the coil with a 50,000-ohm resistor and redetermine the response characteristics. Note that the gain is reduced at the higher frequencies. Repeat the experiment by connecting the secondary as the plate load but leaving the primary open. (Note that the transformer was used as a choke in all cases of Procedure B. The unused coil, however, contributes some capacitance; somewhat better results may be obtained by using a single coil expressly designed for the purpose at hand or by placing the two windings in series.)

10–14. Frequency response and square waves.

The chemist and physicist are often concerned with the amplification and analysis of A.C. voltages which are nonsinusoidal.[7] When amplifiers or other electronic devices are employed in connection with such waves they must be tested to determine whether they are capable of furnishing an output that is a faithful reproduction of the original signal.

Any nonsinusoidal A.C. voltage can be shown to be equivalent to the superimposition of a large number of sine waves of differing frequencies

[7] Marchand, N., *Proc. I.R.E.* *29*, 330, 1941.

varying anywhere from zero to infinity. In most cases fairly faithful reproduction can be obtained with a series in which the frequency range is not as extensive.

One particular type of A.C. wave that imposes taxing requirements on an amplifier is a square wave, as shown in Figure 10–4b. It can be said that an amplifier capable of reproducing such a wave can be used for almost any other nonsinusoidal wave. Square waves can, therefore, be used as a means of determining the faithfulness of amplification. They furthermore offer the advantage of simple interpretation.

A square wave as shown in Figure 10–4b is suitable for testing, since it contains frequencies which extend 10 to 20 times higher and lower than the fundamental frequency.[8,9] From several measurements, therefore, it is possible to predict the frequency response of an amplifier to sinus-
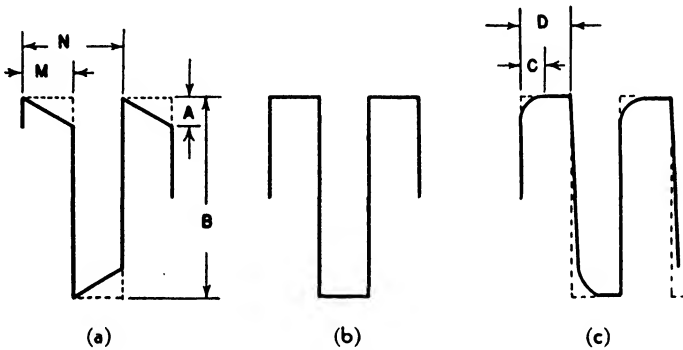
Fig. 10–4.   Square Wave Patterns.

oidal waves over a wide range of frequencies. Actually a perfect square wave contains all frequencies from the fundamental, including all odd harmonics from zero to infinity. The sharp rise may correspond to a wave front of many millions of cycles, while the flat top corresponds to zero frequency or to a D.C. potential of time interval governed by the interruption frequency. At the turnabout position the frequency may be considered to sweep instantaneously from this high figure to zero as a limit, an operation which was performed quite slowly with the variable audio oscillator in Experiments 10–1 and 10–2. In practical square-wave generators the rise is not instantaneous; neither is the turnabout instantaneous. Even if they were, the wave could not be plotted on a scale with an accuracy of one to several million. A square-wave generator with a wave front corresponding to a frequency 1,000 times higher than the fundamental or repetition rate is practical, and generators with ratios of 50 or 100 are useful.

8 Arguimbeau, L. B., *Gen. Radio Exp.* 14, 7, 1, 1939.
9 Swift, G., *Communications* 19, 2, 15, 1939.

A simple square-wave generator is shown in Figure 11–8, and may be used in the following experiment. The experiment can be performed only if an oscillograph equipped with amplifiers capable of reproducing square waves is available. If this instrument is not available the oscillograph amplifier itself may be studied for frequency response with square waves. Both procedures will therefore be outlined.

EXPERIMENT 10–3

Purpose: To study the frequency response of an amplifier, using the square-wave technique.

Materials: Square-wave generator
5-inch oscillograph with amplifiers tested for square-wave response
Apparatus of Experiment 10–1

Procedure A. Connect the square-wave generator of Figure 11–8, or other suitable generator, to the vertical oscillograph amplifier and adjust the amplifier gain and generator output until a pattern of suitable size is obtained. The sweep frequency should be adjusted so that only two or three cycles appear on the screen. Adjust the sweep synchronizer for positive synchronization, but do not increase it further than necessary for this purpose. Run through the available range of frequencies on the audio oscillator of Figure 11–8 and observe the square wave pattern. If the wave pattern is maintained reasonably square from 100 to 2,000 c.p.s., the oscillograph amplifier and square-wave generator are working satisfactorily and the experiment may be continued by inserting the amplifier of Experiment 10–1 between the square-wave generator and the oscillograph amplifier. Resistor R_4 may be maintained in the network as before. The oscillograph amplifier, of course, contains a resistor which takes the place of R_4, but since it is not accessible, it would be difficult to change its value. Readjust the output of the square-wave generator or the oscillograph amplifier gain until a suitable-sized pattern is obtained. Since the amplifier may pick up 60-cycle voltage it is advisable to use as low an oscillograph gain as possible, but care must be exercised in that doing so may change the response of the oscillograph amplifier.

Observe the square waves as before, taking several photographs if time permits. If photographic equipment is not available, a copy of the square wave may be made on semitransparent cross-section paper so that it may be studied at leisure. Make copies at several frequencies and compare them with copies made at the same frequencies with the oscillograph amplifier alone. Repeat the experiment with the various circuit constants shown in Table 10–1. Calculate the high- and low-frequency distortion by methods indicated in §10–15.

Procedure B. If the oscillograph amplifier cannot reproduce square waves from 100 to 2,000 c.p.s., make copies of the patterns so obtained and analyze them in accordance with the outline of §10–15. Vary the value of the coupling capacitor by connecting the square-wave generator to the oscillograph with several different capacitors. The values will depend upon the input resistance of the oscillograph amplifier, and sizes of capacitors ranging from 1.0-μf. or higher to .001-μf. may be tried.

EXPERIMENT 10–4

Purpose: To study a transformer-coupled amplifier for square-wave response.

Materials: Apparatus of Experiments 10–3 and 10–2.

Procedure. Repeat Experiment 10–3, but couple the amplifier to the oscillograph by means of an interstage transformer. Draw the curves on cross-section paper. Study the effect of a load on the transformers as in Experiment 10–2. (*Note:* Procedure 10–3A may be followed in practically all cases, since the response of most oscillograph amplifiers is sufficiently good for the purpose at hand.)

Refer to standard texts on the theory and design of audio transformers for an adequate explanation of the curves obtained in this experiment.

10–15. The calculation of frequency response from square-wave patterns.

The complete calculation of per cent response at various frequencies of an audio amplifier is beyond the scope of this book. Fortunately this is quite unnecessary in most cases. The primary interest to the chemist and physicist is essentially whether a given amplifier will reproduce a complicated wave pattern with fidelity. An amplifier which reproduces a 500-cycle square wave almost perfectly will also reproduce other wave shapes if the fundamental frequency is of the order of 500 c.p.s., and if the amplifier reproduces square waves from 50 to 1,000 c.p.s. there is practically no doubt of its ability to handle a 500-cycle wave of any shape with a corresponding pulse width.

The response of an amplifier to square waves of different frequency is shown in Figure 10–4. Figure 10–4a shows the response at low frequencies, 10–4b at mid frequencies, and 10–4c shows the response at higher frequencies. The first step in the analysis is to determine the pulse interval or pulse width; in Figure 10–4a it is shown as the ratio between M and N. If all pulses are spaced equally the pulse width will be .5. This pulse width is important, since its value as well as the fundamental or interruption frequency of the square-wave generator determines the

time interval of the horizontal portion of the wave. The drop may be calculated as shown in Figure 10–4a, in which a represents the drop in relation to the total voltage b. From the ratio $\dfrac{a}{b}$ and the value of $\dfrac{m}{m+n}$, the phase angle and frequency response may be calculated by reference to tables or graphs prepared for this purpose. The construction of these graphs is a tedious operation involving complex equations, but their use is a simple procedure of graphic analysis. The sensitivity of the method is demonstrated by the fact that the curve shown in Figure 10–4a represents an amplifier with a response which is only 2 per cent low at this fundamental frequency and with a phase shift of about 8°. This amplifier contained no inductance.

Evidence of lack of high frequency response is first indicated by a rounding off on the edges of the square wave, as indicated in Figure 10–4c. The important elements in the calculation are the frequency, the pulse width, and the fraction of a half wave required to reach a steady state as given by $\dfrac{c}{d}$ in Figure 10–4c, the actual calculation for response and phase angle again being referred to graphs. If ·the plate load of an amplifier contains an inductance, the shape of the curve of Figure 10–4c may be changed to that of Figure 10–6, which shows the effect of adding more and more inductance to the plate load while keeping the plate resistor fixed.

10–16. Phase shift in amplifiers.[10]

As was mentioned previously, phase shift is important only if the shift of one frequency is high in comparison to that of another important frequency. It is of no great importance in audio amplifiers used for the reproduction of speech or music, but may be important in amplifiers used for physical measurements. Since the fall in gain of a simple R-C coupled amplifier always produces a calculable phase shift, this quantity is often calculated rather than measured. Conversely, if the phase angle is measured, the gain may be calculated as a function of frequency providing the gain is known at one frequency. If a multistage amplifier contains compensating inductances or transformers, these have to be taken into consideration. A simple method of calculating the stage gain from phase angle is based upon the fact, as Terman has shown, that when the gain of an R-C coupled amplifier drops to 70.7 per cent of its value at mid frequencies the phase angle is 45°.[11] In general, then, if the input and output of an amplifier are plotted on a cathode-ray tube, an ellipse results with its major axis at 45° as shown in Figure 12–13. If the input

[10] Reich, H. J., *op. cit.*
[11] Terman, F. E., *op. cit.*

signal is shifted 45° before it enters the oscillograph, a straight line is produced when the amplifier gain drops to 70.7 per cent.[12]

<div align="center">

EXPERIMENT 10–5

</div>

Purpose: To determine the phase shift of an audio amplifier.

Materials: Apparatus of Experiment 10–1.
Oscillograph with equivalent vertical and horizontal amplifiers

Procedure. Connect the audio oscillator to the vertical and horizontal amplifiers and adjust the amplifiers so that a 45° straight line is produced. Then change the frequency of the oscillator quite rapidly and observe if any changes take place in the appearance of the straight line. If the line changes slope or opens into an ellipse, the amplifiers are not equivalent at this frequency and subsequent measurements must be corrected for this effect.

Connect the oscillator to the grid of the amplifier shown in Figure 10–2, and connect the same input to the horizontal oscillograph amplifier. Connect the output of the circuit of Figure 10–2 to the vertical oscillograph amplifier. Set the oscillator to 1,000 c.p.s. and adjust each of the oscillograph amplifiers for a standard and equal deflection as in §12–5. Change the frequency of the oscillator throughout the range, and at various intervals make copies of the pattern on semitransparent cross-section paper. Calculate the phase shifts as in Experiment 12–1. (*Note:* The oscillograph will detect both phase and amplitude distortion if the latter is due to the stage under test. It is essential, therefore, to operate the stage at a level as low as is consistent with the gain possibilities of the oscillograph amplifier.)

10–17. The gain possibilities of pentodes.

The gain of a pentode stage at low plate loads depends on the value of the plate resistor and the transconductance, but since the maximum value of the plate resistor depends on the plate-supply voltage while the transconductance depends on the control-grid and screen-grid and suppressor voltages, the design of an efficient pentode stage is quite complicated. Manufacturers usually supply design data to satisfy most requirements; nevertheless it may be advisable to show a simple experiment which easily demonstrates the changes in voltage amplification with the variation of the simple parameters. Figure 10–5 shows a single stage of pentode voltage amplification. R_4 and C_4 are usually not employed in a single stage of amplification, but are included for a later experiment. This R-C combination may serve two useful purposes:

[12] Spangenberg, K., and Palmer, W., *Proc. I.R.E.* *27*, 555, 1939.

(1) It may be seen that the capacitor C_4 in combination with R_4 decouples the stage from the power supply, as A.C. signals at frequencies for which the impedance of C_4 is small in comparison to the value of R_4 will flow through this capacitor rather than through R_4 and the power supply. (2) At low frequencies the impedance of C_4 may become comparable to the resistance of R_4, in which case the signal is no longer by-passed, and the gain of the stage therefore becomes larger at these frequencies. Both effects, of course, take place simultaneously. Oscillations due to common plate supply in a multistage amplifier may accordingly be prevented by making the impedance of C_4 small at frequencies
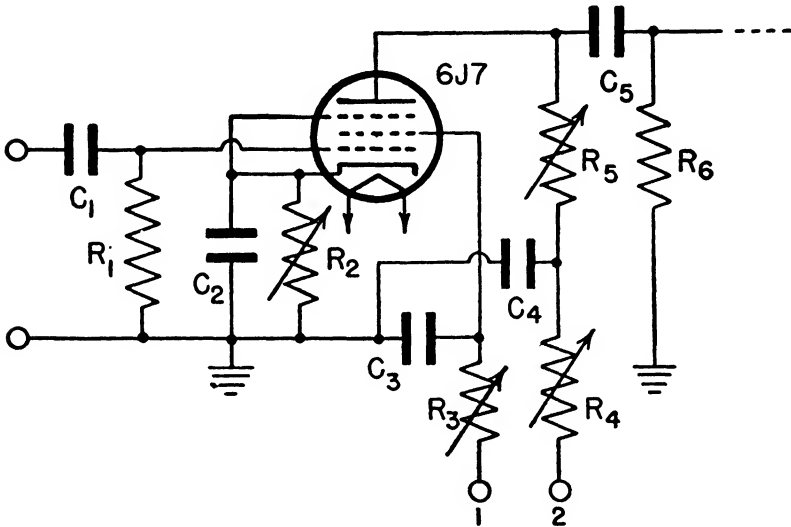
Fɪɢ. 10–5. A Stage of Pentode Amplification. $1, 2 = 300$ v. power supply; for other values see the text.

where the impedance of C_5 is already quite large.[13],[14] We have already learned that if the impedance of C_5 is large the stage gain is seriously reduced, which in itself will stop the tendency to oscillate, while at higher frequencies coupling through the power supplies is avoided by the by-passing effect of C_4. If the impedance rise of C_4 in comparison to R_4 is made complementary to the impedance rise of C_5 in comparison to the grid resistor of the following stage, a value of R_4 may be so chosen in comparison to the value of R_5 that the stage gain is quite uniform with frequency, approaching zero frequency as a limit. The R_4C_4 combination may also be used to compensate for the loss in gain due to the increased impedance of R_2C_2 at the lower frequencies, and is more com-

13 Terman, F. E., *op. cit.*
14 Reich, H. J., *op. cit.*

monly used for this purpose on account of the difficulty of obtaining large capacitors for C_2.

EXPERIMENT 10–6

Purpose: To determine the gain of a pentode stage as a function of the various parameters.

Materials: 6J7 tube
Octal socket
5,000-ohm volume control—R_2
5-megohm volume control—R_3
.5-megohm volume control—R_5
.1-megohm volume control—R_4
0-200 microammeter
0-1 milliammeter
300-v. power supply
Oscillator with attenuator
Vacuum-tube voltmeter or cathode-ray oscilloscope

Procedure. Wire the apparatus as shown in Figure 10–5 and add the necessary meters to measure the D.C. plate and screen current. With the plate resistor R_5 set to .1 megohm and R_3 and R_2 at .5 megohm and 500 ohms respectively, set the attenuator of the oscillator so that the vacuum-tube voltmeter reads an output voltage of 25 to 50 v. Then change the value of R_2 and observe the change in gain of the stage. If an oscillograph is used as a voltmeter it will also be possible to observe gross variations in wave form as the value of R_2 becomes too large or too small. Determine in this manner the optimum value of R_2 for these sets of conditions. The actual D.C. voltages at the plate and screen may be calculated from the respective currents and the value of the dropping resistors R_5 and R_3 after the voltage of the power supply is known. Increase the plate load R_5 to .25 megohm and with R_2 at 1,200 ohms determine the optimum value of R_3 as before. Repeat for various values of plate load and enter all values in a table. Calculate the actual stage gain by measuring the input and output voltage.

EXPERIMENT 10–7

Purpose: To determine the frequency response of an amplifier as a function of its C_4R_4 constant of Figure 10–5.

Materials: Same as Experiment 10–6

Procedure. Connect the apparatus as before, but change the value of C_2 to 1 μf. and C_4 to .025 μf. Then with R_4 at zero adjust the plate-load

resistor to .1 megohm and R_3 and R_2 to .75 megohm and 300 ohms respectively. Measure the frequency response of the amplifier at low frequencies as in Experiment 10–1, either by keeping the input voltage constant and reading the output voltmeter or by keeping the output constant and reading the required input voltage. Repeat the experiment with R_4 at 50,000 ohms and plot the two curves on the same scale. Note that the second curve is flatter at lower frequencies than the curve taken in the absence of R_4. This method of compensation is more effective in cases where the normal plate load is very small in comparison to the plate resistance of the tube. Repeat the experiment with various values of C_2, C_4 and R_4, and plot the comparison curves in each case.

10–18. High-frequency untuned amplifier.

By proper design it is possible to construct an amplifier which will amplify frequencies from 0 cycles to 8 megacycles or higher. Television amplifiers that amplify a band width of 6 megacycles per second are quite common today. From the data of Experiment 10–1 it is easy to see how the frequency of the band may be extended by the following considerations. The low-frequency range is extended by making the product $R_4 C_2$ of Figure 10–1 larger, while the high-frequency range may be extended by decreasing the shunt capacitances of the plate load. These capacitances are made up of the output capacitance of the tube, the capacitance of the wiring and of the physical units represented by $R_3 C_2$ and R_4 to ground, as well as the input capacitance of the next tube.

These capacitances may be reduced by special tube design and proper attention to constructional details. There is a limit below which it is difficult to go. The wiring and unit capacitance of a well-wired amplifier is of the order of 10^{-11} f., while the input and output capacitance may be of the order of 5×10^{-12} f. each. In order to maintain a uniform gain over a wide band of frequencies it is necessary to decrease the value of the load resistor so that the shunt capacitances become less important at the high frequencies. This decrease results in a reduction in the overall gain of the amplifier, and the voltage gain of the ordinary triode or pentode in such a design falls to very low values. At frequencies of 4 megacycles the gain of a 6J7 tube would be less than one. The effect of shunt capacitances may be partially offset by using a properly proportioned inductance in series with the plate load. Special tubes such as the 6AB7, 6AC7, or 6AG7, with low input and output capacitances associated with extremely high values of transconductance and amplification factors, when used with compensated plate circuits, are capable of rendering gains of from 10 to 20 per stage over a frequency band extending to 4 megacycles per second.

10–19. Inductance added to plate circuit of an R-C coupled amplifier.

The effect of adding inductance to the amplifier plate circuit on a square wave is shown in Figure 10–6, in which the various curves show the gradation in effects produced by adding larger and larger values of inductance but keeping the plate resistor and other units at a constant value.[15],[16] It will be noted that adding too much inductance will cause considerable overshoot in the amplifier, and adding still more causes damped oscillations to develop, which may extend for considerable distances on the horizontal portion of the unit voltage wave. These are to
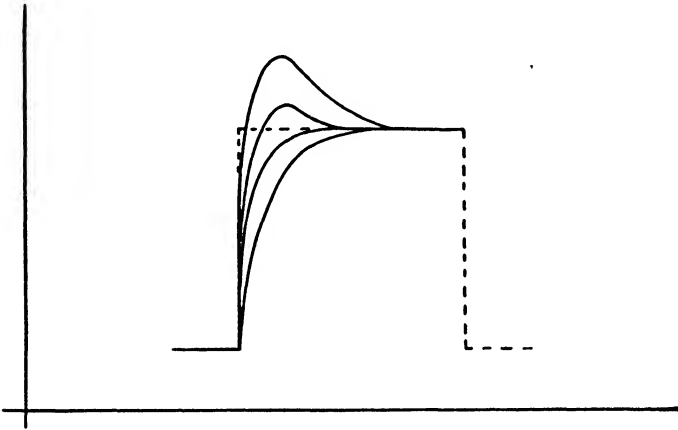
FIG. 10–6.   Effect of Inductance in the Plate Circuit of a Tube on the Shape of a Square Wave.

be avoided in actual practice, since undamped oscillations may be developed in multistage amplifiers and cause serious distortion.[17]–[20] The complete analysis of the effect of inductance on a unit voltage is beyond the scope of this book, but the formulae shown in Table 10–2 for the calculations of the proper value of inductance for the circuits of Figure 10–7a, 10–7b, and 10–7c, have been derived with these factors taken into consideration so that the overshoot found will represent the best compromise between an uncompensated and fully compensated amplifier.[21] Measurement of stage gain with square waves at these high frequencies demands

[15] Everest, F. A., *Electronics*, Jan., 1938, p. 16; May, 1938, p. 24.
[16] Freeman, R. L., and Schantz, J. D., *Electronics*, August, 1937; p. 22.
[17] Preisman, H., *R.C.A. Rev. 2*, 421, 1938.
[18] Seeley, S. W., and Kimball, C. N., *R.C.A. Rev. 2*, 171, 1937.
[19] Schade, O. H., *Electronics*, June, 1937; p. 26.
[20] *Electronics*, June, 1941; p. 51.
[21] Bedford, A. V., and Fredendall, G. L., *Proc. I.R.E. 27*, 277, 1939.
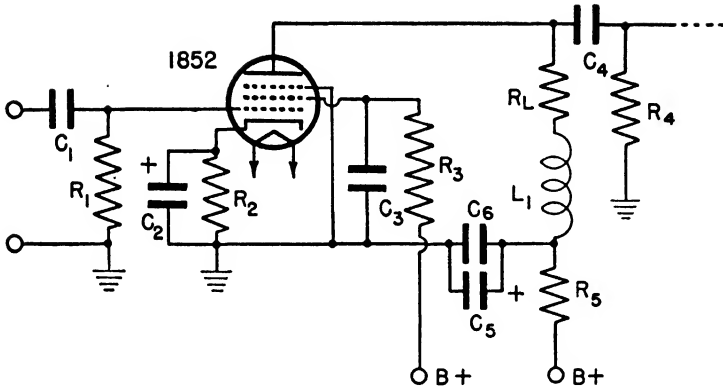
FIG. 10–7a.   A Stage of Video Amplification Series High-frequency
Compensation
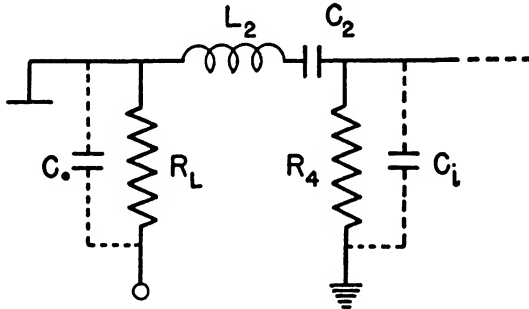
FIG. 10–7b.   Plate Connections for Parallel Com-
pensation.
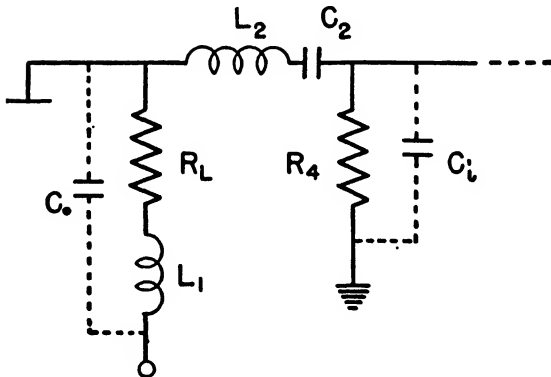
FIG. 10–7c.   Plate Connections for Parallel and Series
Compensation.

<div align="center">TABLE 10–2</div>

Compensation	R_L	L_1	L_2	Relative gain at $f_{max.}$	Variation in time delay
None	$\dfrac{1}{2f_{max.}C_t}$			.707	$\dfrac{.035}{f_{max.}}$
Shunt, Figure 10–7a	$\dfrac{1}{2f_{max.}C_t}$	$.5C_tR_L$		1.0	$\dfrac{.023}{f_{max.}}$
Series,* Figure 10–7b	$\dfrac{1.5}{2f_{max.}C_t}$		$.67C_tR_L$†	1.5	$\dfrac{.011}{f_{max.}}$
Shunt series,* Figure 10–7c	$\dfrac{1.8}{2f_{max.}C_t}$	$.12C_tR_L$†	$.52C_tR_L{}^2$	1.8	$\dfrac{.015}{f_{max.}}$

* $C_t = C_0 + C_i + C_{wiring} = C_{total}$.

† C_{total} must be equal to $2C_0$; if this is not the case, reverse coils of Figure 10–7b and 10–7c.

an oscillograph specially designed for the purpose at hand. If the values of the various capacitances are known the other values may be calculated quite successfully from Table 10–2. The tube manufacturer supplies the values of C_0 and C_i, but to these must be added the wiring capacitance C_{wiring}. With leads kept away from ground this may ordinarily be assumed to be of the order of 10^{-11} f. For experimental measurements the circuit of Figure 10–5 may be used.

EXPERIMENT 10–8

Purpose: To determine the effect of inductance on the shape of high-frequency square waves.

Materials: Square-wave generator and apparatus of Experiment 10–6

Procedure. Use the following values for the various resistors and capacitors in Figure 10–5:

R_2—2,200 ohms	C_2—5 or 10 μf.
R_3—3.0 megohms	C_3—.05 μf.
R_5—.5 megohm	C_5—.01 μf.

With C_4R_4 removed from the circuit, connect the square-wave generator to the input of the 6J7 tube while connecting the output to the vertical oscillograph amplifier as in Experiment 10–3. Increase the frequency of the square-wave generator until the pattern is distinctly rounded as shown in Figure 10–4c. Then, without changing the frequency, connect the square-wave generator directly to the vertical oscillograph amplifier. If the wave form is reasonably perfect, indicating no distortion in the oscillograph, reconnect the units as formerly, attaching

various inductances to the plate circuit as shown in Figure 10–7. Values of the order of 1 to 10 henries may be used. Trace the curves on semi-transparent cross-section paper. At what value of L is the best compensation obtained? Use a lower plate resistor and calculate the value of the maximum frequency and the value of L from Table 10–2, and re-examine the curves with the square-wave generator as before.

10–20. Limits of gain: noise levels.

More than one stage of amplification may, of course, be used, and indeed from the foregoing it might appear that with multiple stages there is no limit to the amount of amplification that may be achieved. Such is not the case, however, owing to the fundamental properties of resistors, the electron stream within the tube, and in many designs owing to mechanical and electrical difficulties with the circuit, that is, instabilities which cause voltage fluctuations larger than that of the signal. Circuit difficulties may be minimized by careful design but the difficulties arising in the tube are more difficult to reduce, while those due to resistors are fundamental and cannot be overcome.

The origin of this voltage within the tube may be made clear when we consider that for a tube with a normal plate current of 1 ma. and a value of $g_m = 1,000$, a voltage of 10^{-6} will produce a change of only 10^{-9} amp. of plate current or 0.000001 of the total current. The stream of electrons within the tube (1 ma.) must, therefore, be held constant at all times to this value of 10^{-9} amp. This high order of stability has not been achieved owing to the corpuscular nature of electrons.

In the case of resistors the thermal movement of the free electrons is random; that is, their net movement averages to zero over a period of time. At any given instant, however, there may be a net current flowing through the resistor, causing a voltage drop across the ends of the resistor. It has been shown by Nyquist [22] that the voltage so generated is independent of the material of which the resistor is made and is a function only of the resistance, the temperature, and the frequency band over which the voltage is measured.

10–21. Optimum power output and optimum load.

The maximum power output of a tube depends on its plate-current capabilities as well as the allowable load resistance or load impedance as shown in Chapters 2 and 5.[23] In design practice, definite distortion limits are set and the load is changed until the maximum power is obtained at distortion factors below these limits. It is generally agreed that a harmonic content of less than 5 per cent is not detectable by the human

[22] Nyquist, H., *Phys. Rev. 32*, 110, July, 1938.
[23] Reich, H. J., *op. cit.*

ear and the maximum output is often established with this distortion. The accurate measurement of harmonic content demands special apparatus.[24-28] These instruments are arranged so that the harmonics may be selected and separated from the other components and then evaluated. The harmonics are usually mixed with the voltage from a variable oscillator before separation. In this manner the fundamental and each harmonic may be selected in turn. A mechanical or quartz filter may be used to obtain the desired separation of the fundamental from the harmonics. The voltage of the driving signal for the stage under measurement must be strictly sine wave, and a filter is usually used to insure this.

Load lines are given by the tube manufacturers, and unless the tube is to be operated under unusual conditions these values should be used.

EXPERIMENT 10–9

Purpose: To determine the power output of a typical beam tube.

Materials: 6L6 tube
Socket
350-v. power supply
10,000-ohm bleeder resistor
4,200-ohm power-output transformer
Audio oscillator
1,000-c.p.s. low-pass filter
Harmonic analyzer or cathode-ray oscillograph
A.C. copper-oxide voltmeter

Procedure. Wire the apparatus as shown in Figure 5–7, using a 4,200-ohm output transformer as the plate load and connecting the grid to an audio oscillator in series with a 1,000-c.p.s. low-pass filter. Shunt the output transformer with a power resistor (25 watts) which matches the manufacturer's designation of the impedance of the secondary or output connection. Connect a calibrated A.C. voltmeter across this resistor. Connect the harmonic analyzer or the oscillograph to the same point. With the bleeder resistor of Figure 5–7 by-passed adequately with large capacitors, set the grid voltage to 18 v. and the screen grid to 250 v. Set the oscillator to about 700 cycles and increase its output until the harmonic analyzer[29] indicates a harmonic content of a few per cent or

[24] Moore, C. R., and Curtis, H. S., *Bell System Tech. J. 6*, 217, 1927.
[25] Landeen, A. G., *Bell System Tech. J. 6*, 230 1927.
[26] Castner, T. G., *Bell Lab. Record 13*, 258, 1935.
[27] Massa, F., *Proc. I.R.E. 21*, 682, 1933.
[28] Reich, H. J., *op. cit.*
[29] Consult manufacturer's directions for the correct operation of the harmonic analyzer.

until the sine wave on the cathode-ray tube shows some signs of distortion. A cathode-ray tube cannot easily be used to evaluate the distortion, but will show some evidence of distortion at values of the order of 5 or 10 per cent. Read the voltage of the output A.C. voltmeter and calculate the power output from E^2/R, assuming the current and voltage to be in phase. Increase the input voltage to a higher value and repeat the measurement. If the harmonic analyzer is used, the power output as well as the percentage harmonic developed may be plotted as a function of grid driving voltage. Repeat the experiment for other values of D.C. grid voltage. If the output transformer is so made that the output impedance may be changed, use other values than 4,200 ohms. If it cannot be changed, increase or decrease the value of the resistor in which the power is developed and repeat the experiment.

Note that there is an optimum power output for minimum distortion at a certain grid voltage and definite load impedance. If the output impedance is changed the grid voltage must also be changed. Note that for this single tube the wattage output under optimum conditions is of the order of 8 watts at a total distortion of about 10 per cent.

10–22. Push-pull operation.

The harmonic content of an amplifier may be reduced considerably by operating two tubes in push-pull, as indicated in §10–6. When two tubes are so operated, the plate current in one tube will be rising while that in the other one will be falling; and it can be shown from the i_p characteristic that under these conditions all even harmonics will be canceled out in the output transformer. Since most of the harmonic content resides in the first even harmonic a considerable reduction in distortion is thus achieved.

Other advantages for this type of operation are obvious. Variation in total plate-current flow to the power supply is reduced. Fluctuations in the voltage of the power supply caused by inadequate filtering or line-voltage changes tend to cancel out. Variations in grid and screen voltages, as obtained from inadequately by-passed bleeders or other common resistors, are also canceled. The power output from the two tubes is combined in the output transformer and the output thus is double that obtained with a single tube if the grid signal for each tube is the same as for single-ended operation.

The grids must be fed from a source such that they are 180° out of phase. The transformer T_1 of Figure 10–8 accomplishes this by splitting the signal from the previous tube or source into two parts such that when the grid of the upper is proceeding toward the positive crest the grid of the lower tube is proceeding toward the negative crest. This signal division may be achieved by other methods; in Figure 10–9, the

signal is fed directly to the upper grid but is passed through on additional tube before it is fed to the grid of the lower tube. The signal is inverted, that is, changed in phase by 180°, in transit through the tube.
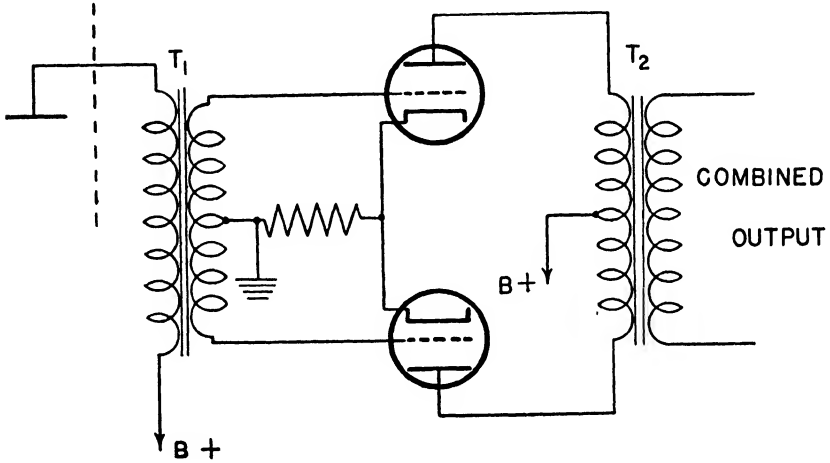
FIG. 10–8.   Push-pull Amplification.

Any amplification which this stage might contribute is nullified by attenuating the signal by the correct amount before it reaches this tube. The ratio of R_3 to R_4 must be adjusted accurately to prevent either of the
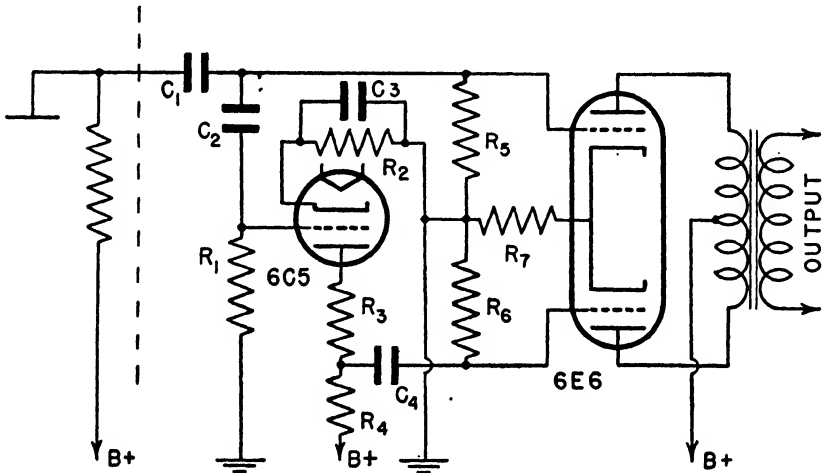
FIG. 10–9.   Phase Inversion to Push-pull Amplification.

output tubes from carrying most of the load. This adjustment may be made quite easily by connecting a pair of phones across the cathode resistor R_7 and adjusting the ratio of R_3 to R_4 until the fundamental

note or tone from a signal generator connected to the input of the amplifier becomes a minimum.

The disadvantages of push-pull operation are the added circuit complexity and the necessity of supplying a driving grid voltage twice that required for a single-ended amplifier.

10–23. Inverse feedback.[30,31]

The harmonic content as well as other distortion factors may be reduced by the use of an inverse-feedback circuit. A consideration of the theory developed for inverse-feedback amplifiers in Chapters 2 and 7 proves that the output of such an amplifier is essentially linear with input. Consequently such amplifiers possess little nonlinear or amplitude distortion.

The reduction in amplitude distortion as a consequence of feedback may also be deduced from the following considerations.[32] An input signal e_s in an ordinary amplifier will develop an output voltage E which can be analyzed as the sum of two components $e_f + e_h$ where e_f represents the voltage of the fundamental and is equal to $e_s \mu'$, and e_h represents the voltage of the harmonic content; that is,

$$E = e_s \mu' + e_h.$$

The harmonic content arises from the nonlinearity of the mutual-conductance curve. Consequently e_h will always have the same value when the same portion of the mutual-conductance curve is being swept, that is, at equal values of e_f.

Consider now the same amplifier operating with feedback. The output for the same signal will be equal to

$$E' = E'_f + E'_h = \frac{e_f + e'_h}{1 - \mu'\beta}$$

$$= \frac{e_f}{1 - \mu'\beta} + \frac{e'_h}{1 - \mu'\beta}$$

$$= e_s \frac{\mu'}{1 - \mu'\beta} + \frac{e'_h}{1 - \mu'\beta}$$

and the total output will be reduced. The fundamental output will be reduced by $\dfrac{1}{1 - \mu'\beta}$. The harmonic content will be reduced even more. First, e'_h is less than e_h, since its value depends upon the output of the

[30] Black, H. S., *Elec. Eng. 53*, 114, 1934.
[31] Terman, F. E., *op. cit.*
[32] Reich, H. J., *op. cit.*

fundamental, which has been reduced to $e_s \dfrac{\mu'}{1 - \mu'\beta}$ from $e_s\mu'$; e'_h is then

further reduced by the factor $\dfrac{1}{1 - \mu'\beta}$.

If now the input signal is increased to

$$e''_s = (1 - \mu'\beta)e_s,$$

then the output becomes

$$E'' = E''_f + E''_h = \frac{e''_f + e''_h}{1 - \mu'\beta}$$

$$= e_s\mu' + \frac{e''_h}{1 - \mu'\beta};$$

that is, the output of the fundamental has been increased to its original value. Under these circumstances $e''_h = e_h$, but the harmonic content of the output E_h is only equal to $\dfrac{1}{1 - \mu'\beta}$ of its original value.

It should be noticed that reduction in harmonic content has been secured at the expense of amplification, since a higher input is now required for the same total output. The reduction in harmonic content arises from the fact that since the signal does not contain these frequencies any harmonics created in the output will be almost completely attenuated by being fed back to the input.

As has been pointed out in Chapter 7, it is possible to obtain a high enough gain in a multiple-stage amplifier to make values of $\mu'\beta$ large with respect to 1. Under these conditions the gain of a feedback amplifier,

$$\frac{E}{e} = \frac{\mu'}{1 - \mu'\beta},$$

will be equal to $-1/\beta$. The gain therefore becomes independent of all circuit constants except those which determine the value of β. Such an amplifier is relatively unaffected either by the aging of tubes and batteries or by fluctuations in the power supply. The gain also remains relatively unaffected by large changes in load impedance such as result when an amplifier is used to drive a loudspeaker, provided the speaker does not form part of the feedback network.

Feedback offers another great advantage. Since β depends only on the feedback network, then by properly combining resistances, capacitances, and inductances it is possible to obtain almost any desired frequency response.

It would appear, therefore, that feedback amplification is a cure-all for ills that attend amplification. It is, therefore, important to point out

that the design of a proper feedback circuit for untuned amplifiers is not quite simple. One must bear in mind that the equations developed in the theory are actually vector equations. The simple interpretations given above hold only when the feedback signal is 180° out of phase with the input. This can only be true at a single frequency. At frequencies removed from this frequency the amplifier will change its feedback.[33] Sometimes it eventually becomes regenerative and if not properly designed the amplifier may even break into oscillations. Such a condition is obtained when the value of β becomes equal to $+$ 1, since under this condition the gain of the amplifier becomes infinite.

A simple illustration of the effect of frequency on feedback is given in Figure 10–10. The circuit to be analyzed is given in Figure 10–10a. Figure 10–10b represents the situation at high frequencies. I is the total plate current and is drawn 180° out of phase with E_g which represents the net A.C. voltage on the grid. At these high frequencies the current i will be practically in phase with I since the coupling condenser C is large and the value of X_{c_0} will be small. The product iR_0 represents the voltage drop across R_0 and iX_{c_0} the voltage drop across C_0, which lags the current 90°. E_f, the sum of iR_0 and iX_{c_0}, represents the voltage fed back to the grid. In turn the sum of E_f and E_s the A.C. signal voltage, must be equal to E_g, the net A.C. voltage on the grid. It is to be noticed that the circuit must adjust itself so that the resulting value of E_g is 180° with respect to I, and of such a magnitude that $E_g g_m = I$. θ gives the phase shift between signal and output.

Figure 10–10c is an analysis of the same circuit but at lower frequencies. C is still assumed to be large enough to show no effect. The value of X_{c_0} is, however, greater. Figures 10–10b and 10–10c have been drawn for equal outputs. It will be noticed that a greater signal voltage E_s is required at lower frequencies. θ is also larger.

Figure 10–10d shows the effect of the lag ϕ introduced by capacitor C at low frequencies. This again results in a further change in the values of E_s and ϕ for constant output.

In the vector diagram of Figure 10–10e, ϕ has reached such a value that the feedback voltage E_f equals E_g and consequently the signal voltage $E_s = 0$. Under such a condition the amplifier oscillates. This condition can be obtained in multistage amplifiers or with a single stage using transformer coupling of output and feedback.

Practical methods for studying actual circuits have been developed by Terman and others.[34–37]

[33] Terman, F. E., *Electronics*, Jan. 1937; p. 12.
[34] Terman, F. E., *loc. cit.*
[35] Day, J. R., and Russell, J. B., *Electronics*, April, 1937; p. 16.
[36] Petrauskas, A. A., and Van Atta, L. E., *R.S.I. 11*, 103, 1940.
[37] Waddel, R. C., *R.S.I. 10*, 311, 1939.

EXPERIMENT 10–10

Purpose: To determine the effect of negative feedback on frequency response and distortion.

Materials: .5-megohm and 100-ohm volume controls
6J5 and 6V6 tube
Sockets
2,500-ohm, .1-megohm, .5-megohm and ½-watt resistors
250-ohm, 10-watt, 5,000-ohm output transformer [38]
Power supply
Audio oscillator
Harmonic analyzer
Output A.C. voltmeter

Procedure. Connect the apparatus as shown in Figure 10–11 and connect a loudspeaker or similar load to the output transformer [38] in a manner which will match the load resistance of the tube. Then connect a 0–5-v. copper-oxide voltmeter across the speaker terminals. Turn the 100-ohm volume control back and forth in order to check the presence of oscillations. If oscillations occur reverse the ground connection of the output transformer. With the 100-ohm volume control set to zero (contact turned to ground terminal) check the frequency response of the amplifier as in Experiment 10–1, keeping the input voltage constant and reading the output voltage on the meter. The output voltage should not exceed 5 v. root mean square. Now set the volume control to obtain a 1-to-3 division of the signal, and redetermine the frequency response. Repeat the experiments at .5, .75, and full setting of the 100-ohm volume control, thus corresponding to β factors of 0, .25, .50, .75, and 1.

Plot a frequency-response curve as in Figure 10–12. Observe the progressive extension of the frequency range as the value of β is increased. Calculate the improvement of this response from the fundamental equations of a feedback amplifier and compare the values with the experimental ones. Note that with an output transformer the phase shift may be such that regeneration takes place even with a two-stage amplifier as shown in Figure 10–11.

If the harmonic analyzer is available, proceed also to determine the effect of various values of β on the harmonic content by determining the harmonic content as a function of the output voltage for these various values. Note that the harmonic content is progressively reduced with an increase of β at the same output voltage. Calculate the expected reduction of the harmonics from the equation given earlier in this section.

[38] A medium-quality output transformer is usually preferable.

10–24. Tuned amplifiers obtained with inverse feedback.

If the feedback network represented by the 100-ohm volume control of Figure 10–11 is so arranged that feedback occurs for all but one frequency, a selective effect is obtained in which the gain of the amplifier will be $\dfrac{\mu'}{1 - \mu'\beta}$ for all frequencies but the one for which there is no

(a)
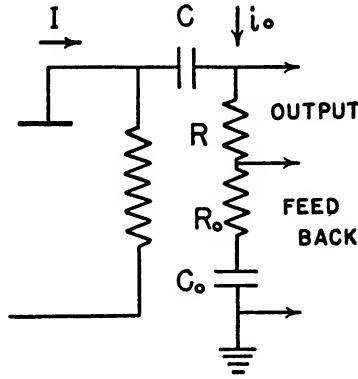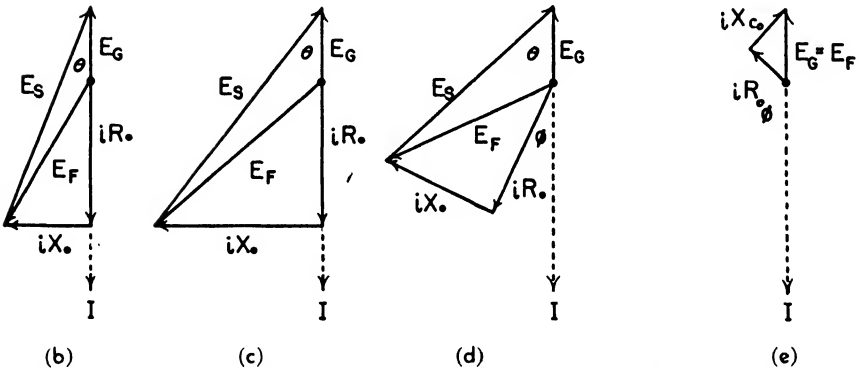
(b)   (c)   (d)   (e)

FIG. 10–10.   Inverse Feedback. (a) Schematic circuit diagram. (b, c, d, e) Vector diagrams for different frequencies.

feedback, that is, $\beta = 0$. At this point the gain will be μ'. The effect can be attained in practice by connecting a Wien bridge to the output of the amplifier of Figure 10–11. If the output of this bridge is used for the feedback voltage, there will be no feedback voltage at the frequency for which the bridge is balanced, but the feedback will increase on either side of this frequency. Since the value of μ' of the amplifier of Figure 10–11 is only of the order of five, the selectivity of the circuit would not be very high. The value of μ' may be made very large, however, and thus a circuit of high selectivity may be produced. Other net-
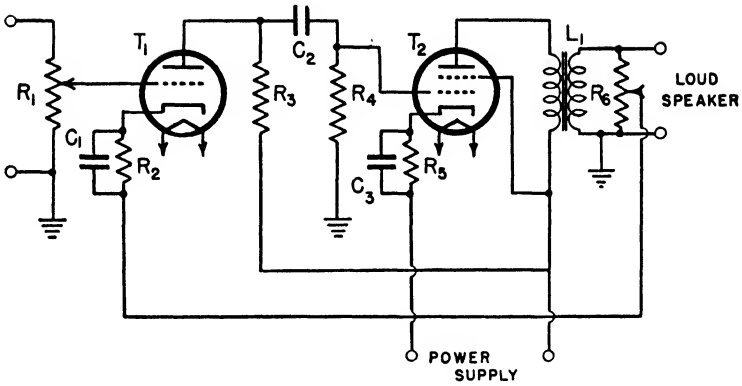
Fig. 10–11. Inverse-feedback A.C. Amplifier. $R_1 = .5$ megohm; $R_2 = 2{,}500$ ohms; $R_3 = 100{,}000$ ohms; $R_4 = .5$ megohm; $R_5 = 400$ ohms; 10 watts; $R_6 = 100$ ohm potentiometer; C_1, $C_3 = 25$ $\mu f.$; $C_2 = .1$ $\mu f.$
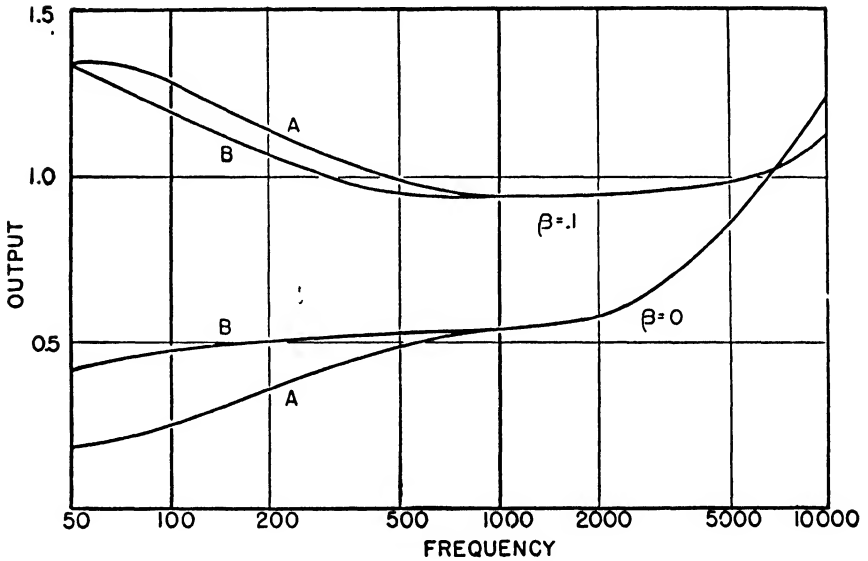
Fig. 10–12. Frequency Response of Inverse Feedback Amplifier with and without Feedback. Plotted on arbitrary scale. A = small value of C_2; B = larger value of C_2.

works than the Wien bridge may be used to achieve the same effect, as shown by Terman.
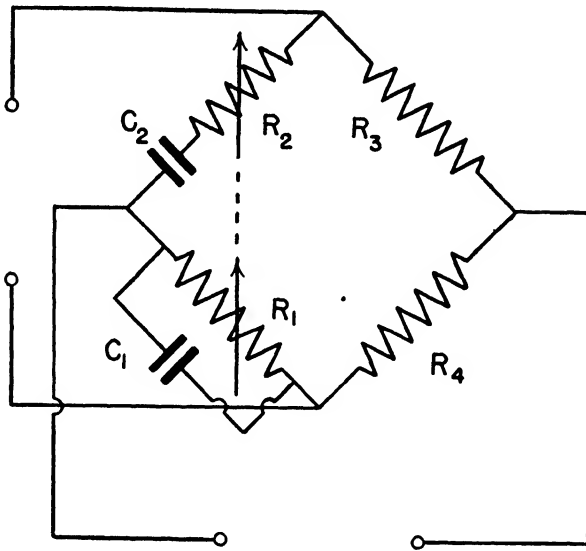
Fig. 10–13. Wien Bridge.

EXPERIMENT 10–11

Purpose: To determine the frequency response of an amplifier using a negative feedback network with a selective frequency response.

Materials: 6J7 and 6V6 tubes

Sockets

1-megohm, .5-megohm, .25-megohm, and 1,500-ohm ½-watt resistors

400-ohm 10-watt resistor

2 25-μf. electrolytic condensers

.05-μf. condenser

.01-μf. paper condenser

Line output transformer

A.C. output voltmeter

Wien bridge or equivalent

Procedure. The gain of the circuit shown in Figure 10–11 may be increased by substituting a 6J7 tube for the 6J5 and by substituting a tube-to-line transformer for the tube-to-loudspeaker transformer. Many transformers can be obtained which contain both types of output windings on the same core to facilitate change-over. Connect the output

transformer to a Wien bridge and shunt the output of the bridge with a 1,500-ohm resistor, connecting one side of the bridge output to ground (that is, to B —). Change the constants of the voltage amplifier to the following: plate load .25 megohm, screen load 1.0 megohm, with .05-μf. by-pass condenser to ground. Then connect the cathode of the 6J7 tube to the ungrounded output of the Wien bridge. Set the Wien bridge to a definite frequency and vary the frequency of the audio oscillator, reading the output voltage across the output transformer, that is, the input to the Wien bridge. Determine the frequency response of the amplifier
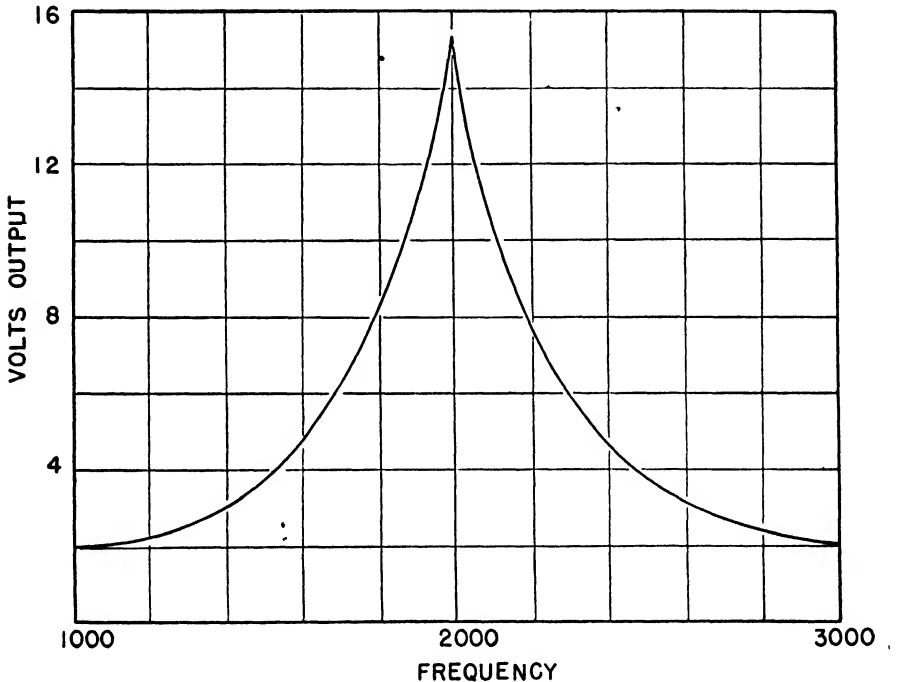
Fig. 10–14.   Wien Bridge Tuned Amplifier.

in this manner. Shift the Wien bridge to a new frequency and redetermine the frequency response.   Plot as shown in Figure 10–14. Note that the frequency-response curve is quite sharp and that the contour of the curve is different from the ordinary response curve obtained from an L-C network. This is due to the characteristics of the Wien bridge. In what ways is this circuit superior to L-C tuning, for audio frequencies?

If a Wien bridge is not available it may be constructed with sufficient accuracy from the diagram of Figure 10–13 in the following manner.[39,40]

[39] Hague, A. C., "Bridge Methods." London: Isaac Pitman & Sons, 1932.
[40] Field, R. F., *Gen. Rad. Exp. 6,* Nov., 1931.

Make R_3 1,000 ohms, R_4 500 ohms, $C_1 = C_2 = 1$ μf., and make R_1 and R_2 by connecting the shafts of two General Radio type 314A variable resistors together so that R_1 is equal to R_2 at all settings. The value of the frequency may be determined from the relation

$$f = \frac{1}{2\pi R_1 C_1}.$$

If R_1 and R_2 are 2,000-ohm variable resistors, the lower limit of the bridge will be approximately 100 c.p.s. For frequencies higher than 1,000 c.p.s. the value of C_1 and C_2 should preferably be changed to .1 μf., and for frequencies of the order of 10,000 c.p.s. to .01 μf., and so forth.

SUPPLEMENTARY LITERATURE

Everitt, W. L. (editor), " Fundamentals of Radio," Prentice-Hall, Inc., New York, 1942.

PROBLEMS

1. Design a single triode stage of audio amplification. Calculate the stage gain and estimate from rough calculations the lower and upper limit for the frequency response of this stage. (The limits may be arbitrarily set when the gain falls to 50 per cent of its value at mid frequencies.)

2. Design a stage of pentode audio amplification which is compensated for low-frequency response with a so-called decoupling resistor.

3. Design a complete two-stage audio amplifier with a voltage gain of approximately 2,000.

4. Design a two-stage amplifier with a gain of approximately 10,000.

5. Design a three-stage amplifier with a net voltage gain of approximately 100,000. Show particularly how oscillations may be avoided by proper design.

6. Show how the gain of the amplifier in Problem 5 may be stabilized by the use of inverse feedback. Calculate the actual gain at various values of β.

7. Design an audio amplifier capable of delivering 15 watts of power (5 per cent distortion) to a loudspeaker with an input voltage of .015 v. Show how the principle of inverse feedback may be applied to this amplifier.

8. Inverse feedback may easily be utilized in each stage of amplification by the use of a cathode resistor which is not by-passed with a

capacitor. Compare the advantages and disadvantages of this type of feedback with those of the type shown in Figure 10–11, where the output voltage of the entire amplifier is fed back to the input.

9. Design a single stage of audio amplification for the band from 20 to 100,000 c.p.s., sine wave, and with a 25-fold gain.

10. Design a single stage of audio amplification to cover the band from 60 to 4,000,000 c.p.s., with a gain of at least 15 per stage.

11. Design a tuned inverse-feedback audio amplifier using a Wien bridge as the feedback element.

12. Design a tuned inverse-feedback amplifier using a two-terminal network as the feedback element.

13. Design an amplifier with a voltage gain of approximately 10^6 tuned to 1,000 c.p.s. What is the advantage of tuning in high-gain amplifiers? Is it possible to obtain a ratio of 1 to 10^5 between the gain at 2,000 cycles and the gain at 1,000 cycles?

14. Design a two- or three-stage amplifier for the band from 0 to 10,000 c.p.s., with a voltage gain of approximately 5,000.

CHAPTER 11
Vacuum-tube Oscillators

Introduction.

The production of controlled alternating current is useful in the physical-chemical measurement of time, conductance, dielectric constant, and speed of chemical reactions. The production of heat in solutions and in metals, smoke precipitation, and many other phenomena also involve the use of controlled alternating current.

An electron-tube oscillator converts D.C. to A.C. by taking advantage of the fundamental property of electron tubes already emphasized, namely that a small amount of energy in the grid circuit can control a large amount of energy in the plate circuit.[1] In any oscillating circuit the tube acts as its own amplifier.

11-1. Principle of an oscillator.

The action of an oscillating circuit may be understood from an analysis of the circuit shown in Figure 11-1. In this circuit, when the plate
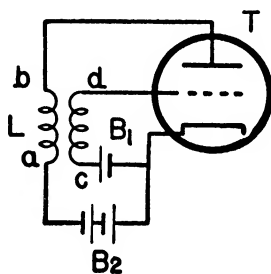
Fig. 11-1. Fundamental Circuit of an Oscillator.

current increases slightly a voltage is produced across the reactance a-b. Since this reactor is coupled to the coil c-d by means of the common core, a voltage appears across the coil c-d. The phase of this voltage, that is, whether c or d is positive at any given instant with respect to a-b, depends upon the relative direction of the windings of these two coils. If these windings are so arranged that when a becomes negative, c becomes positive, a condition of self-amplification will have been obtained, if the

[1] Terman, F. E., " Radio Engineering." New York: McGraw-Hill Book Co., Inc., 1937.

energy dissipated by the grid coil *c-d* is less than the energy available in the plate coil *a-b*.

The small voltage across *c-d* produces a further increase * in plate current which in turn produces a larger positive voltage across *c-d*. The net grid voltage at any instant will then be represented by the difference between the voltage of B_1 and the voltage across *c-d*, while the net voltage on the plate will be represented by the difference between the plate supply voltage B_2 and the voltage across *a-b*. The plate-current increase cannot therefore perpetuate itself, for eventually the net plate voltage will decrease to nearly zero. The amplifying properties of the electron tube are reduced and the increase in plate current ceases.

A decrease in plate current from this maximum value, however, has the effect of making point *d* negative. This negative charge in turn results in a greater reduction of plate current. The reduction continues until the plate current is nearly zero, when the amplifying properties of the tube are again lost and the operation stops. Since the time to carry out these reactions is very small the operation does not occur in steps but produces in effect a continuous curve. The time required in most practical circuits is not limited by the time constants of the tube itself but by the inductive and capacitative reactances of the coils *a-b* and *c-d*. When a capacitor *C* is placed across one of these coils the time required to perform these operations is increased. If the inductance is increased a slower period is also produced.

11–2. Grid voltage produced by grid rectification.

It has already been demonstrated that appreciable grid current will flow from the grid when its potential is not highly negative or actually positive. A resistor is therefore placed between *d* and the grid. The grid current flowing through this resistance produces a negative grid voltage that limits the maximum grid voltage on the positive side. If this resistor is shunted with a capacitor, the A.C. current will be readily by-passed but the resistor will maintain a negative D.C. voltage across its terminals. The grid of the oscillator is thus capable of generating its own voltage and B_1 may be eliminated, resulting in a saving of batteries or power supplies. Further consideration will show that this type of oscillator possesses the property of self-regulation. The oscillator will automatically generate a grid voltage which results in the best operating condition as determined by the characteristics of the tube, the plate voltage and the coils *a-b* and *c-d*. All of these factors contribute to the efficiency of the D.C.-to-A.C. conversion and must be properly selected.

In most measurements in physics and chemistry, oscillators are not

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* In this discussion the term increase of current should be interpreted strictly as an increase in the quantity $\frac{di}{dt}$.

required to produce large amounts of power. The following experiments are designed with this moderate requirement in mind. For a complete discussion of power oscillators the reader is referred to Terman.[2]

11-3. The adjustment of simple audio oscillators.

The output of an oscillator producing strong oscillations (that is, operation at high efficiencies) cannot always be represented by a pure sine wave but may contain many harmonics. The harmonics can be removed by appropriate wave filters, the energy represented by these frequencies being lost. The increased efficiency at the fundamental frequency obtained by operating the tube under these conditions, nevertheless, outweighs the disadvantage of the loss. Wave filters, however, are expensive
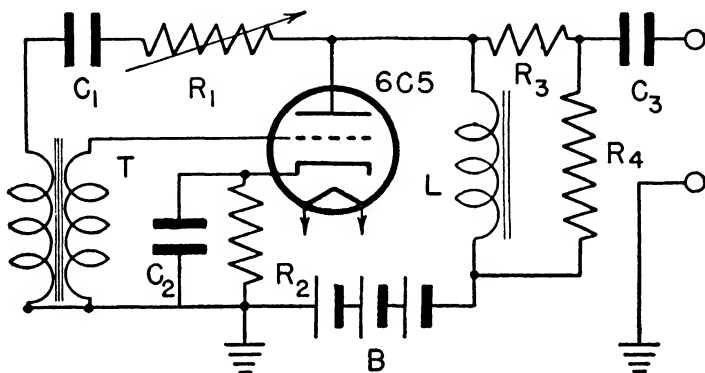
FIG. 11-2. Resistance Feedback Oscillator. $C_1 = .05$ μf.; $C_2 = .5$ μf.; $C_3 = .05$ μf.; $R_1 = .25$-megohm potentiometer; $R_3 = 10,000$ to $100,000$ ohms; $R_4 = 10,000$ ohms; $R_2 = 1,500$ ohms; $L = 10$-henry, 10-ma. choke; $T =$ interstage transformer.

and difficult to adjust, especially at audio frequencies. The ratio of the output of the fundamental frequency to the output of the harmonics increases as the efficiency of tube operation decreases. In many cases a low efficiency will represent the best compromise for laboratory measurements.

The circuit shown in Figure 11-2 may be constructed from commercially available components. The strength of the oscillations (amplification) is controllable by resistor R_1. The frequency of the oscillations can be made relatively independent of R_1 and of the plate voltage, provided R_1 is made large in comparison to the plate resistance of the tube. For a complete discussion of frequency stability, see Terman and others.[3-7]

[2] *Ibid.*, ch. 5.

[3] Terman, F. E., *Electronics*, July, 1933; p. 190.

[4] Terman, F. E., "Radio Engineering." New York: McGraw-Hill Book Co., Inc.. 1937.

[5] Llewellyn, F. B., *Proc. I.R.E. 19*, 2063, 1931.

[6] Lampkin, G. F., *Proc. I.R.E. 27*, 199, 1939.

[7] Dow, J. B., *Proc. I.R.E. 19*, 2095, 1931.

EXPERIMENT 11-1

Purpose: To adjust and study the characteristics of a simple audio oscillator.

Materials: 6C5 or 6J5 tube and socket
Low-ratio audio transformer, preferably R.C.A. type 32898
Volume control depending on type of T
2 .05-μf. capacitors
10,000-ohm volume control
.5-μf. capacitor
Power supply

Procedure. Wire the apparatus as shown in Figure 11–2. A battery or power supply may be used to supply the plate voltage. The plate voltage is fed to the tube through resistor R_3. The plate current flowing through this resistor represents a loss of power. A more efficient system may be obtained by substituting a choke for this resistor. A 5- or 10-henry choke is suitable for this experiment. The resistor, however, is quite suitable for the production of oscillations of low power. It may be noted that in Figure 11–2 the feedback voltage is fed in shunt with the feedback coil, while in Figure 11–1 the coil is fed in series. In the shunt connection the D.C. plate current does not flow through the feedback coil, while in the latter case both currents are found in this coil.

Transformer T must be poled correctly to produce oscillations. If the transformer is color coded the following connections will usually be found to be correct: green, grid; red and black, ground; blue, R_1. If these connections do not produce oscillations, reverse one set of leads.

Connect the vertical deflector plates of an oscillograph (maintaining the horizontal sweep circuit) to the output terminals and slowly reduce the value of R_1 until stable oscillations are produced. Observe the wave form by setting the sweep oscillator until a stationary wave is obtained. Observe the effect on the wave form and frequency caused by a further reduction of the value of R_1.

Study the effect of changes in R_2 on the wave form as well as the total output.

The frequency of the oscillations may be determined with the aid of a calibrated beat-frequency oscillator or of a frequency bridge. If a calibrated audio oscillator is available, connect the output to the horizontal plates of the oscilloscope and change its frequency until a circular pattern is obtained. The two oscillators will now be operating at the same frequency. If the oscilloscope is not available, the output of the two oscillators may be combined by a push-pull audio transformer and beat notes detected with a pair of phones. The frequency bridge may be used

to determine the frequency of the oscillator by following the directions of the manufacturer. Do not expect a sharp balance point unless the oscillator is almost entirely free of harmonics.

A very effective method of analyzing the wave form is to connect the output of the frequency bridge to the vertical terminals of an oscilloscope containing a high-gain preamplifier. The bridge is set to the oscillator frequency. Only the harmonics will be observed on the screen. The effect of the various parameters of the oscillator may then be directly observed.

The standard method of analyzing for harmonic content is by the use of a wave analyzer, which works on the same principle as the above method but usually uses other means of achieving this purpose and reads harmonics directly in percentage. This is discussed in Chapter 10.

The frequency of the oscillator should now be changed by changing the value of C_1 and the oscillator brought back into adjustment by means of R_1. If the oscillator described here is to be used to operate low-impedance bridges or other devices, an amplifier and output transformer should be used to obtain the required power.

11–4. A frequency-stabilized oscillator.

The oscillator just described is sufficiently stable for work at audio-frequencies, since a high order of stability is usually not required over the range.[8] At radio frequencies, that is, frequencies higher than 25 kc., a quartz crystal may be employed to control the frequency of oscillation. An oscillator of this type is sometimes known as a piezo oscillator, since it makes use of the piezo effect exhibited by quartz crystals.

Quartz crystals under the influence of an electrical disturbance will vibrate at a certain frequency, producing a voltage of the same frequency. The specific frequency is determined by the thickness of the crystal and the direction in which the quartz crystal is cut. In Figure 11–3 the quartz crystal has been placed in the grid circuit. Coupling with the plate circuit is obtained through the grid-plate capacitance of the tube. When the plate-circuit load is resonant to the fundamental frequency of the crystal, strong oscillations will be produced.[9–16]

[8] Brunetti, C., *Proc. I.R.E. 25,* 1595, 1937.

[9] Eady, W. G., *Proc. I.R.E. 10,* 83, 1922.

[10] Pierce, G. W., *Proc. Am. Acad. Arts and Sci. 59,* 81, 1923.

[11] Cady, W. G., *Proc. I.R.E. 16,* 521, 1928.

[12] MacKinnon, K. A., *Proc. I.R.E. 20,* 1689, 1932.

[13] Terman, F. E., *op. cit.*

[14] Anderson, J. E., *Electronics,* Aug., 1938; p. 22.

[15] Mason, W. P., *Proc. I.R.E. 28,* 220, 1940.

[16] Reich, H. J., " Theory and Application of Electron Tubes." New York: McGraw-Hill Book Co., Inc., 1939.

If the plate circuit is resonated at another frequency only slightly re-
moved from the crystal's resonant frequency, the oscillations will die
away quite abruptly. The frequency of the output thus depends almost
entirely on the size and cut of the quartz crystal. Quartz possesses a low
coefficient of thermal expansion. The frequency of the oscillations is
therefore only slightly effected by temperature. A V-cut crystal changes
only by about 25 parts per million per degree centigrade. It is theoreti-
cally possible to cut a quartz crystal in a manner which produces a zero
temperature coefficient. The AT-cut crystals currently available exhibit
temperature coefficients of 5 parts per million. The temperature of the
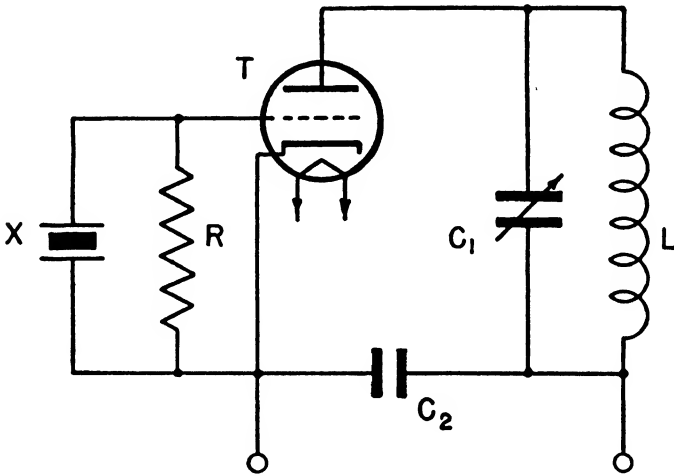
FIG. 11-3. Crystal Oscillator. $R = 1$-megohm resistor; C_1–L
selected to resonate at crystal frequency.

crystal may be maintained constant in a thermostatically controlled
chamber. Stabilities of 1 part per million can by this means be easily
attained in practice. If slow drifts are not objectionable, a low-power
quartz-crystal oscillator may be maintained stable within several parts
per million by placing the crystal in a thermos bottle.

Many circuits have been proposed for these oscillators, some of them
superior to the simple circuit shown in Figure 11-3.

The frequency of the oscillations produced in the circuit of Fig-
ure 11-3 is determined not only by the crystal, but also by the phase
shift in the tube and by the resonant circuit in the plate load. Since
these latter factors are subject to variations even if the temperature of
the crystal is maintained, persistent efforts have been made to overcome
these effects. Meacham has shown how, by the application of inverse
feedback, oscillators may be controlled by the crystal alone. These oscil-
lators are commonly called bridge-stabilized oscillators.

EXPERIMENT 11–2

Purpose: To adjust and operate a quartz-crystal oscillator.

Materials: 6J5 tube and socket
1-megohm $\frac{1}{2}$-watt resistor
Quartz crystal and holder
Radiofrequency coil and adjustable capacitor selected to produce resonance at the fundamental crystal frequency
Power supply
0-25 milliammeter

Procedure. Wire the apparatus as shown in Figure 11–3. Connect a 0-25 milliammeter in the plate circuit, then slowly change the setting of C_1 until the plate current shows a sudden dip.

This reduction in plate current indicates that oscillations have set in. If C_1 is provided with a scale, plot the plate current as a function of the capacitance to show that the range over which oscillations occur is quite small and that the curve is not symmetrical. The frequency deviation caused by the change in capacitance may be measured, if a calibrated high-frequency oscillator is available, by mixing the output of the two oscillators as shown in the next section.

11–5. Beat-frequency oscillator.

A combination of a quartz-crystal oscillator with a stabilized variable oscillator is often used in the measurement of capacitance and frequency. The piezo oscillator is used as a reference frequency standard and the other oscillator is adjusted to the same frequency or to a frequency differing from the standard by a fixed amount.[17,18,19] In the measurement of capacitance, the unknown capacitance is added to the resonant circuit of the variable oscillator and its frequency is brought back to the former value by decreasing the value of a calibrated standard capacitor. The value of the capacitance of the unknown must be equal to the net reduction of the calibrated unit.

A suitable circuit for such a measurement is shown in Figure 11–4. Provision has been made for the insertion of a 1,000-c.p.s. audiofrequency oscillator in the last stage. The initial setting of the variable oscillator is then made so that the frequency of the variable oscillator differs from that of the reference oscillator by exactly 1,000 cycles, as indicated by a zero beat note in the phones. It will be noted that this 1,000-cycle difference may be obtained at two points, one when the variable is higher than the reference and one when the variable is lower than

17 *Ibid.*
18 Hall, H. C., *R.S.I. 10*, 38, 1939.
19 Harnwell, G. P., and Van Voorhis, S. N., *R.S.I. 8*, 194, 1935.
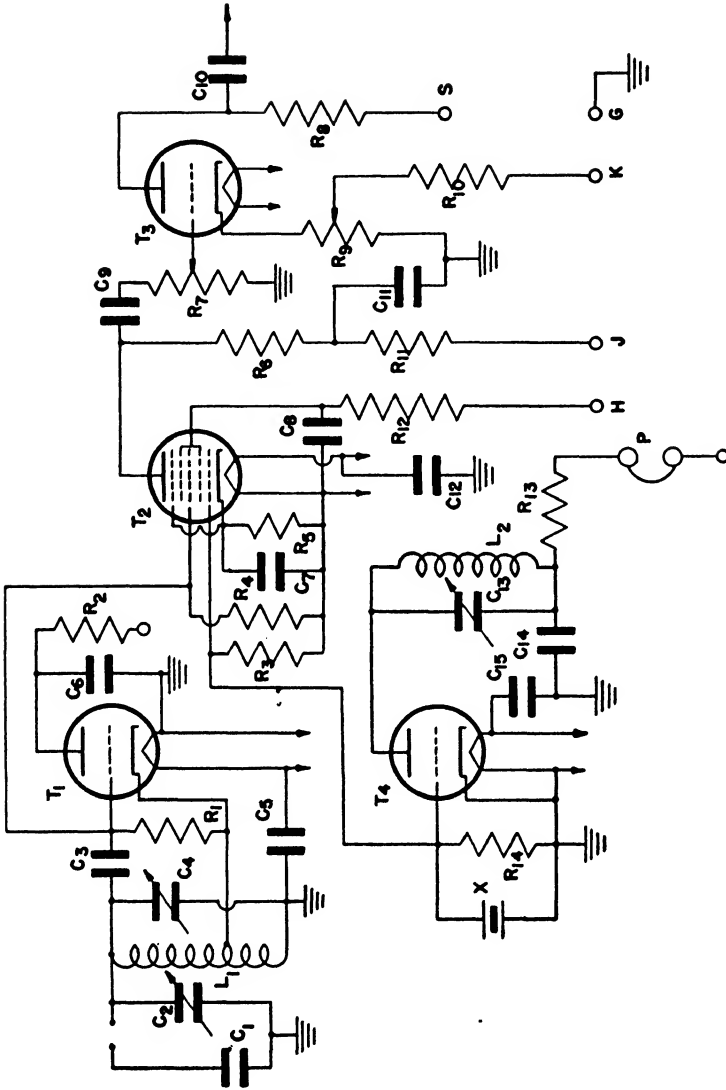
Fig. 11–4. Beat-frequency Oscillator. $R_1 = .1$ megohm; $R_2 = 10,000$ ohms; R_3, $R_4 = .5$ megohm; $R_5 = 1,000$ ohms; $R_6 = 10,000$ ohms; $R_7 = .5$-megohm potentiometer; $R_8 = 25,000$ ohms; $R_9 = 1,000$ ohms; $R_{10} = 1,000$ ohms; $R_{11} = 10,000$ ohms; $R_{12} = 50,000$ ohms; $R_{13} = 5,000$ ohms; $R_{14} = .1$ megohm; C_1, unknown; C_2, known; $C_3 = .0001$ μf.; C_4, matched to L_1; C_5, C_6, C_8, C_{11}, $C_{12} = .01$ μf.; C_9, $C_{10} = .05$ μf.; C_{14}, $C_{16} = .01$ μf.; $C_{13} = .1$ megohm; P, H, J, S = Power Supply; K, G = reference frequency; T_1, T_3, $T_4 = 6J5$; $T_2 = 6L7$.

the reference. In order to avoid confusion the capacitor should always be tuned in the same direction, passing through the two points and selecting the second beat note.

The addition of the third oscillator to serve as an audiofrequency standard is recommended. Oscillators have a tendency to synchronize with each other. In the circuit given in Figure 11–4, the controllable oscillator will attempt to follow the variation of the crystal oscillator as their frequencies approach each other. If it were possible to separate the two oscillators completely this approach would not occur. It is, however, necessary to couple the two at some point to combine their output. In order to avoid coupling of the oscillators at this point, a buffer tube may be used between the two oscillators and the point of junction. The use of a 6L7 tube combines the function of a buffer and a common coupling unit since this tube has two control grids completely separated from each other with a very low intergrid capacitance.[20] Coupling between the two circuits may, however, occur at other points through common heater leads, and so forth. The circuit shown in Figure 11–4 attempts to avoid this coupling by passing all heater and plate leads as close to the tube socket as possible. The variable oscillator should be stabilized by choosing its circuit constants according to Llewellyn's formulas, but it will still possess considerable drift, especially during the initial warm-up. Stranathan has shown how the drift may be kept at a minimum by surrounding the oscillator with a constant-temperature shield.[21] With these precautions, stabilities of the order of one part per million may be obtained for periods of several minutes or longer, a sufficiently long period to make a complete measurement.

EXPERIMENT 11–3

Purpose: To adjust and operate a beat-frequency oscillator.

Materials: Components shown in Figure 11–4
Power supply
Cathode-ray oscilloscope
Head phones
6.3-v. low-power transformer or tuning-fork oscillator.

Procedure. Wire the apparatus as shown in Figure 11–4. The oscillators should be housed in separate cabinets and connected to the respective grids of the 6L7 tube by single wires well separated from each other. A good plan consists in building the crystal oscillator in a cabinet or enclosure on the under side of a suitable chassis, while the variable oscillator is properly disposed on the upper side. This keeps the coupling

[20] Neslage, Herold, and Harris, *Proc. I.R.E. 24*, 207, 1936.
[21] Stranathan, J. D., *R.S.I. 5*, 334, 1934.

at a minimum since connection to the third grid of the 6L7 tube is made at the socket while connection to the first grid is made at the cap of the tube. Some coupling will be present even when these precautions are followed.

Select L_1 and C_4 plus C_2 so that the product LC produces oscillations at the fundamental frequency of the quartz crystal when C_2 is set at its maximum capacitance. C_4 may then be used to effect minor adjustments and to compensate for wiring capacitance and so forth.

Adjust the crystal oscillator as in Experiment 11–2. Then connect a pair of phones to the output tube and, with the power on, change the setting of C_4 and C_2 if necessary until a beat note is heard in the phones.

Connect a 1,000-cycle tuning-fork oscillator in the cathode circuit of the 6J5 amplifier, as shown in Figure 11–4. Readjust C_4 until zero beat is heard in the phones, adjusting R_7 and R_9 for proper balance between the two frequencies. Determine the frequency stability in a rough way by noting the drift from this zero-beat point with time. Notice that beat notes may be obtained at two settings of C_2 differing by 2,000 cycles. Explain.

Connect the output of the 6J5 tube to a cathode-ray oscilloscope and with the output of the audiofrequency oscillator fully attenuated or disconnected observe the wave-form of the beat-frequency note between the two high-frequency oscillators. Notice that the wave form is not a sine wave. In order to obtain a sine wave, the output of at least one of the oscillators must be free from distortion. Since it is difficult to attain this condition without decreasing the frequency stability of the oscillator, wave filters are usually inserted in the amplifier. Properly adjusted square-law detectors are then used to mix or beat the two frequencies. Such a combination can be used as a laboratory beat-frequency instrument. For the measurement of capacitance harmonics are of no great consequence, and provision is not generally made for their elimination.

When the coupling between the high-frequency oscillators is small the two oscillators may be adjusted by using the 60-cycle A.C. line as a standard. This adjustment may be best accomplished by connecting the 60-c.p.s. component to the horizontal plates or horizontal amplifier of an oscilloscope and the output of the beat-frequency oscillator to the vertical plates. Adjustment of C_1 until a single circle or ellipse is obtained on the screen insures that the frequencies of the two oscillators differ by the line frequency. The frequency of most commercial A.C. mains is accurately controlled, and may be made to serve as an adequate standard.

In the measurement of capacitance, the unknown capacitance is connected in parallel with C_2 as shown in Figure 11–4. C_2 is reduced until

the former beat note is re-established. The capacitance of the unknown plus that of the lead wires to the left of the switch (Figure 11–4) will be given directly by the reduction in capacitance of C_2. The capacitance of the lead wires must be determined separately whenever they amount to an appreciable fraction of the capacitance of the unknown.

11–6. Measurements at high frequencies.

In the determination of dielectric constants, capacity measurements must often be made on conducting solutions. Such capacity measurements, when performed as described in §11–5, will be in serious error, this error increasing as the resistance of the solution decreases. The magnitude of the error may be decreased by making the measurement at a sufficiently high frequency to make the capacitative reactance of the cell containing the solution very small in comparison to the resistance of the solution. Two precautions, however, must be observed at these frequencies. First, the dielectric constant may change radically from its value at lower frequencies, information which in itself is valuable; and second, the inductance and radiofrequency resistance of the leads become important. At frequencies of the order of megacycles the inductance offered by 1 ft. of size 18 wire may represent a large fraction of the total impedance of the circuit.

The inductance between the capacitors and the oscillator coil is constant, but that resulting from the wires linking the unknown capacitance with the known must be considered if large errors are to be avoided. The known capacitor may also introduce errors, since the inductance of the parts of the capacitor may differ with the position of the variable plates of the unit. Standard capacitors are now available, in the calibration of which this factor has been taken into consideration. For a complete discussion of these difficulties see the reference.[22]

Since modern broadcast stations maintain a constant frequency by the use of thermostatically controlled crystal oscillators these stations may be substituted for the standard oscillator shown in Figure 11–3.

11–7. The resonance method for capacitance measurements.

A more satisfactory scheme consists in using a quartz crystal as a frequency standard, the quartz crystal being made part of a wave filter, that is, a resonating unit in which the quartz crystal resonates only at a certain impressed frequency suppressing all other values. Under proper conditions of operation, capacitance variations of 1 part in 100,000 may be detected in this manner. A practical circuit of this type is shown in Figure 11–5.

[22] Field, R. F., and Sinclair, D. B., *Proc. I.R.E. 24*, 255, 1936.
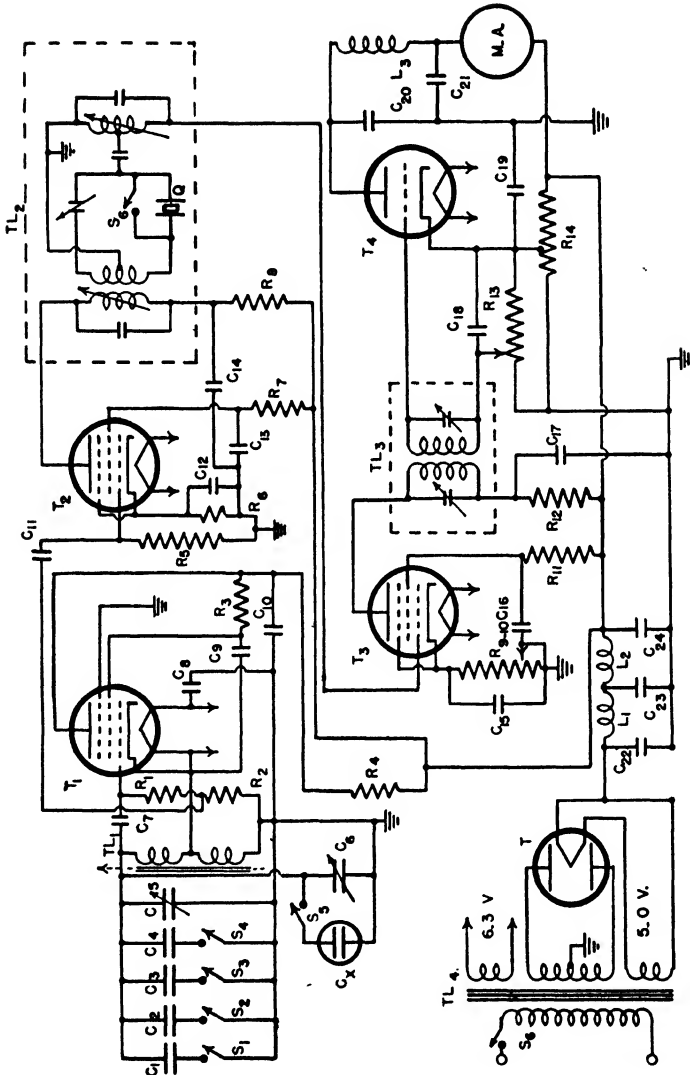
Fig. 11–5. Circuit for Precise Capacitance Measurements. $R_1 = .1$ megohm; $R_2 = 100$ ohms; $R_3 = 50,000$ ohms; $R_4 = 10,000$ ohms; $R_5 = 10,000$ ohms; $R_6 = 300$ ohms; $R_7 = .1$ megohm; $R_8 = 10,000$ ohms; $R_9 = 300$ ohms; $R_{10} = 5,000$ ohms; $R_{11} = .1$ megohm; $R_{12} = 10,000$ ohms; $R_{13} = 10,000$-ohm potentiometer; $R_{14} = 1,000–7,500$ ohms; $T_1 = 6AC7$; $T_2 = 6SK7$; $T_3 = 6SK7$; $T_4 = 6SF5$; $C_1, C_2, C_3, C_4 = 100$ $\mu\mu$f.; $C_5 = 250$ $\mu\mu$f. variable condenser; $C_6 = 100$ $\mu\mu$f. standard variable; $C_7 = .001$ μf.; $C_8, C_9, C_{10} = .01$ μf.; $C_{11} = 10^{-11}$ f.; $C_{12}, C_{13}, C_{14} = .01$ μf.; $C_{15}, C_{16}, C_{17} = .01$ μf.; $C_{18} = .05$ μf.; $C_{19}, C_{20}, C_{21} = .01$ μf.; $C_{22}, C_{23}, C_{24} = .8$-$\mu$f. electrolytics; $TL_1 =$ adjustable iron core radiofrequency coil; $TL_2 =$ crystal transformer; $TL_3 =$ intermediate-frequency transformer; L_1–$L_2 = 20$-henry choke; $L_3 = 20$-millihenry radiofrequency choke; $Q =$ quartz crystal; $C_x =$ unknown capacitor.

selves. The power in this oscillation is unavailable for use in external circuits.

These are usually referred to as parasitic oscillations. Push-pull operation of oscillators is, however, quite satisfactory. In this method of operation parasitic oscillations are easily eliminated. Advantage can also be taken of the fact that the tube capacitances are effectively in series, which facilitates the production of high frequencies. An analysis of push-pull oscillators will show that each tube acts as an amplifier for the other.

11–10. Blocking oscillators.

An oscillator which obtains its grid voltage from grid current as described in §11–2 will block whenever the energy fed back to the grid circuit is increased beyond a certain value. The blocking period is determined by the value of the grid capacitor and the resistances associated with this capacitor.

The blocking action may be analyzed as follows. The grid capacitor charges and discharges with each oscillation. This capacitor may, during the positive excursion of the grid voltage, assume a sufficiently high negative charge to drive the tube to cutoff during the negative grid cycle. As long as the tube is at cutoff no plate current can flow. The oscillations will therefore be interrupted until sufficient charge has leaked off from the capacitor to bring back the grid to an operating condition. The time required for the grid to reassume control depends on the value of the RC constant in the grid circuit and the actual charge on the capacitor with respect to the cutoff grid voltage. The blocking may thus occur at a rate which varies from a relatively long time to one that occupies only a small fraction of the true fundamental period of the oscillator. With a 1-μf. capacitor and a 10-megohm grid resistor the time may be made as large as ten seconds, the actual value depending on the charge which can be obtained on the capacitor. Tubes desirable for this service should have relatively high grid currents at small positive voltages, combined with high plate currents and sharply defined plate-current cutoff on the negative cycle.

Small-size Class B amplifier tubes such as the types 53, 6N7, and others similar, are suitable since their values of μ are rather high and their values of g_m increase rapidly at positive values of the grid voltage.

· The blocking oscillator is used widely today as the timing mechanism for the sawtooth oscillator used in television or other cathode-ray-tube applications. A circuit of this type is shown in Figure 11–7. Here the first section of the 6N7 duo triode serves the function of a blocking oscillator while the second section serves as a sawtooth oscillator. A single tube may be used to perform both of these functions. The circuit of

Figure 11–7 is, however, usually preferred because of circuit flexibility, since with separate circuits the wave shape of the sawtooth oscillations can be changed without affecting the operation of the blocking oscillator.

The operation of the circuit is as follows. A transformer is selected capable of developing a large amount of energy in the primary which is tightly coupled to the secondary. The grid excitation during oscillation is therefore high. As soon as a small amount of plate current flows in the primary, oscillations start. The amplitude of these oscillations increases with time. Within a few cycles the amplitude becomes great enough to
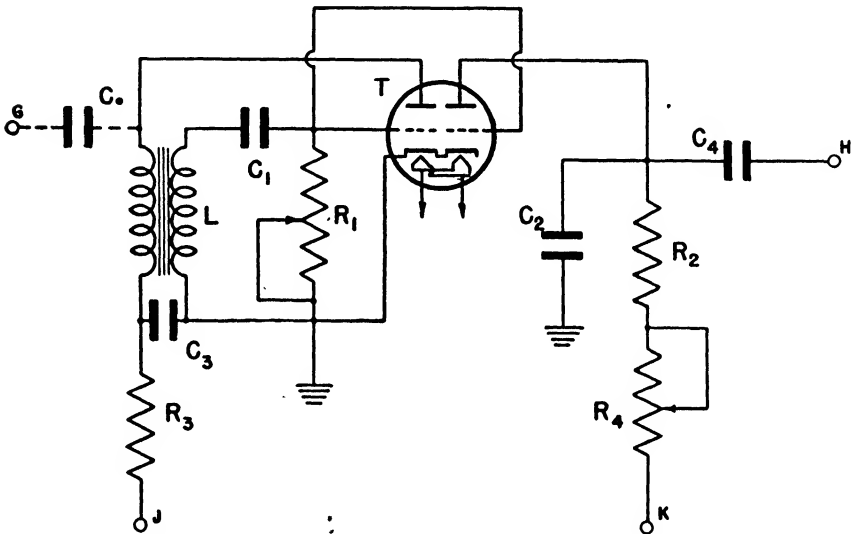
FIG. 11–7. Sawtooth Generator, Blocking Oscillator. $R_1 = 5.0$ megohms; $R_2 = .25$ megohm; $R_3 = .1$ megohm; $R_4 = 5.0$ megohms; $C_1 = .005$ μf.; $C_2 = .1$ μf.; $C_3 = .25$ μf.; $C_4 = .25$ μf.; $L = $ R.C.A. 32898 oscillation transformer; $C_0 = .001$ μf.

charge C_1 negatively with respect to the grid. When this charge becomes greater than the grid potential required for plate-current cutoff, oscillations are broken off quite abruptly. The potential on C_1 may be many times greater than the cutoff potential, since on the last cycle of the oscillation period the voltage across the secondary may become as high as 100 v. With high grid currents and a large capacitor C_1, it is possible for the capacitor to charge to a value approaching 100 v. as a limit in this particular circuit. The charge must now leak off through R_1 or through the grid circuit before oscillations can begin again.

During the period in which the first section of the tube is oscillating the grid of the second section also becomes highly positive on the positive cycles. The resulting high plate current in this section thus effec-

tively short-circuits capacitor C_2. On the other hand, during the blocking period the plate current of the second section of the tube is also at cutoff and capacitor C_2 charges at a rate governed by the value of the resistors R_2 and R_4 and the voltage of the power supply. This charging rate will be logarithmic, but if C_2 is allowed to charge to less than 10 per cent of the power supply voltage the rate is nearly linear. The size of C_2 is selected (in comparison to R_2 and R_4) so that the new cycle of oscillations sets in before the charge on C_2 reaches a value higher than 10 per cent of the power-supply voltage.

The output will consist of a sawtooth wave. Its frequency can be controlled by C_1R_1 and its amplitude by C_2R_4. It should be noted, however, that a change of C_1R_1 also influences the amplitude of the sawtooth voltage, since this constant governs the length of time C_2 charges while R_4 governs the rate at which the charge takes place.

Blocking oscillators may be used for a variety of purposes in which the frequency of blocking may serve as a means of measuring some phenomenon. For example, if a phototube is included in the grid circuit any light falling on it will affect the period of blocking and thus give some indication of the energy received by the photocell.

11–11. Square-wave generators.[25–29]

A square-wave generator may be constructed from the basic circuit of the blocking oscillator shown in Figure 11–7. The circuit constants are, however, rather critical for proper operation. Another generator uses the method, which is none the less instructive, of deliberate distortion of sine waves into square waves.

The circuit shown in Figure 11–8 accomplishes this distortion by first amplifying the output of a variable audio oscillator until the amplitude of the oscillations is very large in comparison to the grid voltage normally required by the 6F5 tube. During the positive cycle the grid voltage reaches a maximum positive value of 2 to 5 v., depending on the values of R_3 and R_4. The plate current is a maximum at the same time. The input voltage, however, continues to rise, the increase being absorbed across C_2 (which charge is negative) and R_3. When the signal reverses the plate current goes to cutoff at some small value of grid voltage as a consequence of the high negative charge across C_2. The cutoff value will be reached early in the cycle. The plate current thus remains at cutoff for a longer time than at its maximum value. Pulses of unequal sizes will

[25] Morgan, J. C., *R.S.I. 10*, 183, 1938.

[26] Fenn, W. H., *R.S.I. 11*, 369, 1940.

[27] Bowman, J. L., *Phy. Rev. 24*, 31, 1924.

[28] Terman, F. E., *op. cit.*, p. 129.

[29] Kallmann, H. E., *Proc. I.R.E. 28*, 351, 1940.

thus be produced, but the inequality can be partially compensated for by properly adjusting R_4 and R_3; or by using a follow-up tube after this wave-form distorter. The quality of the square waves obtained with this
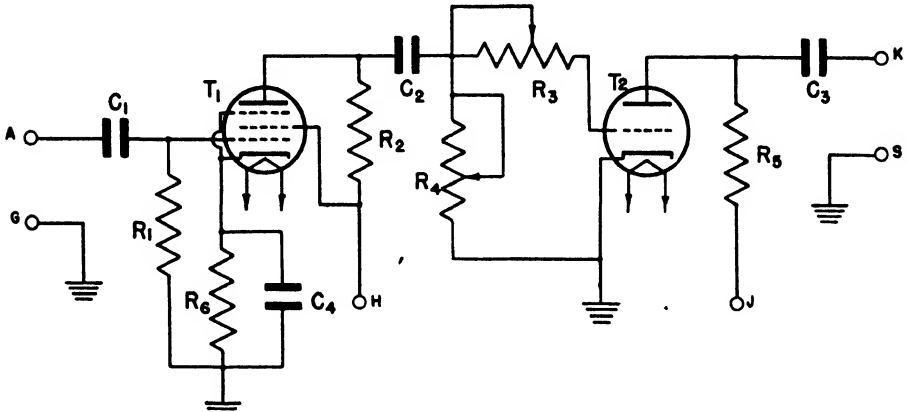
FIG. 11–8. Square-wave Generator. R_1 = .5 megohm; R_2 = 25,000 ohms; R_3 = .5-megohm potentiometer; R_4 = 1.0 megohm potentiometer; R_5 = 2,000 ohms; R_6 = 600 ohms; C_1 = .05 μf.; C_2 = .05 μf.; C_3 = .05 μf. or smaller; C_4 = 50 μf., 25 v.; H, J = power supply; T_1 = 6J5; T_2 = 6F5.

unit is, however, adequate for ordinary amplifier testing as shown in Chapter 10.

PROBLEMS

1. Design a simple single-tube audio oscillator operating on 110 v. A.C.

2. Design a resistance-stabilized oscillator operating at a frequency of 5,000 c.p.s.

3. Design a resistance-stabilized oscillator and amplifier operating on 110 v. A.C. or D.C.

4. Design a crystal oscillator using a pentode tube.

5. Draw a circuit for a beat-frequency oscillator covering the range from 0 to 25,000 c.p.s. Indicate what precautions must be taken to obtain a good sine-wave output.

6. Design a blocking oscillator in which the recovery time is controlled with a phototube.

7. Design a two-tube blocking oscillator producing sawtooth voltages at the output.

8. Design a square-wave generator oscillator.

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Sashoff, S. P., and Roberts, W. K., Simple Pulse Generating Circuits, *Electronics*, Sept., 1940; p. 40.

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CHAPTER 12

The Cathode-Ray Tube

Introduction.

The methods of graphic presentation and graphic analysis in the solution of problems are well known. Since the cathode-ray tube is a plotting device, its importance in the study and solutions of various problems cannot be overemphasized. Its use for many years was limited to a study of voltage and current relationships, but with the introduction of more devices which make possible the translation of many physical phenomena into comparable electrical impulses its use has been considerably extended. These impulses, after undergoing amplification, may be plotted on the screen of a cathode-ray tube. Some of these translating devices are: light with photoelectric cell, pressure with an electromagnetic or electrostatic diaphragm, sound with a microphone, vibrations with a modified microphone, and so on.

12–1. Structure of a cathode-ray tube.

The electrode structure of a cathode-ray tube is shown in Figure 12–1. The cathode, grid, first anode, and second anode comprise the electron gun. The cathode and grid apertures are so constructed as to allow only an electron stream of small cross-section to pass into the accelerating space of the first anode. In addition, the field of the grid determines the number of electrons entering this space. The beam is further defined by the apertures of the first anode and then passes to the second anode. The electrostatic field between these electrodes is so arranged as to produce focusing of the beam in the plane of the fluorescent screen at the end of the tube in a manner somewhat analogous to the focusing of light rays by lenses.[1] The sharpness of focus may be regulated by changing the voltage on the first anode. The approximate voltages for various conditions of operating are given by the manufacturers of these tubes.

The electrons striking the screen impart some of their energy to the active fluorescent material, producing light, the intensity and color of which depend on the screen material and on the current and voltage of the electron beam. The screen may consist of a coating of willemite, activated zinc sulphide, zinc phosphate, calcium tungstate, or other materials and combinations. Almost any color may be produced with modern

[1] Carlisle, S. F., and Mundel, A. B., *Electronics*, Aug. 1941; p. 22.

screen material. But the color, except for television tubes, is secondary in importance to other properties of the screen material. If a rapidly moving image is to be photographed, the screen should have a rapid fluorescent decay constant, while if transients are to be studied visually it is desirable to use a material that has a slow decay constant so that the trace produced will remain an appreciable time. The former is called a fast screen and the latter a slow or persistent screen.

The electron beams may be deflected perpendicular to the direction of their propagation by an electrostatic or electromagnetic field. For electrostatic or so-called electric deflection, two sets of parallel plates are mounted in the tube as shown in Figure 12–1. One set will serve to deflect the beam in a horizontal direction (the x-axis) and the other for the vertical direction (y-axis). If one of these plates is made negative while
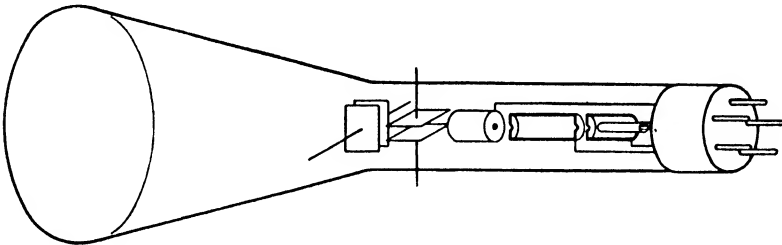
FIG. 12–1.   Internal Structure of a Typical Cathode-ray Tube.

the other one remains at a fixed potential, usually equal to the second anode potential, the beam will be deflected away from the negative plate. In addition, its speed will be reduced somewhat, causing the beam to be out of focus at the edge of the screen. If the second deflector plate is made positive by the same amount that the first one is made negative, no change will occur in the speed of the electrons and the defocusing caused by deflection will be minimized. This is called symmetrical deflection. The symmetrical type provides twice the deflection of the unsymmetrical and is, therefore, always used in the larger tubes at high accelerating voltages. Since the electron beam has practically no inertia, the electrostatic-deflection cathode-ray tube may be used at frequencies from zero to a few hundred megacycles. The limiting value usually depends on the capacitance between the deflection plates and the second anode.

If magnetic deflection is used, the plates shown in Figure 12–1 are omitted and a single or double pair of coils placed around the tube, but in the same relative forward position as the deflector plates in the electric type. The deflection of the beam will be at right angles to the flux created in the coils by the current. If two sets of coils are used the con-

ditions are the same as for the symmetrical electric deflection. The difficulties with electromagnetic deflection arise from the fact that the driving voltage required to produce a certain current in the coil varies with the frequency.

At present, cathode-ray tubes may be obtained with screens from 1 to 20 inches in diameter. The second anode voltage in medium-size tubes is usually of the order of 1,000 v., but in larger tubes, especially those used in television, 8,000 to 10,000 v. is current practice. Since the size of the spots or thickness of the trace for a given intensity of light is inversely proportional to the square of the voltage, tubes used for projection may employ as high as 100,000 v. on the second anode. The beam currents in cathode-ray tubes may vary from 1 ma. to a few microamperes. Nevertheless, the fluorescent screens may be damaged if the beam is allowed to become stationary at a particular point for any length of time. This damage is known as burning. Manufacturers usually publish figures for the maximum average screen input in watts per square centimeter and this value should never be exceeded.

12–2. Lissajous patterns.

If one sine-wave voltage is applied to the vertical plates and another one to the horizontal plates, a stationary pattern is produced if the ratio of their frequency is a whole number. If 120 cycles are plotted vertically and 60 cycles horizontally, the vertical wave will trace two complete cycles while the horizontal makes one complete excursion from one side to the other and back again. The appearance of the pattern depends on the frequency ratio and phase relations between the two voltages.

The actual resultant plot as given by the cathode-ray tube may be duplicated by the ordinary graphical methods. Divide a piece of cross-section paper into quadrants and plot the amplitude of wave on the y-axis and the the time on the x-axis in the upper right-hand quadrant, as shown in Figure 12–2. Plot the other voltage in the third quadrant as amplitude in the x-direction and time in the y-direction. The zero axis of the wave is in the middle of the appropriate quadrant in all cases. Now plot amplitude at the same time markings in the fourth quadrant, by extending amplitude lines to the left from the first quadrant and upward from the third quadrant on the respective amplitude axes until equal time markings intersect. If the two voltages are out of phase the second plot should be started at the proper amplitude at zero time on the plot. From these plots it is obvious that if the frequencies of both voltages are the same, and if they are in phase, a straight line with a slope of 1 is produced if the amplitudes are identical. If the amplitudes are not the same, the straight line will have a slope differing from 45° and may vary from 0° to 90° depending on the ratio of the amplitudes. If the
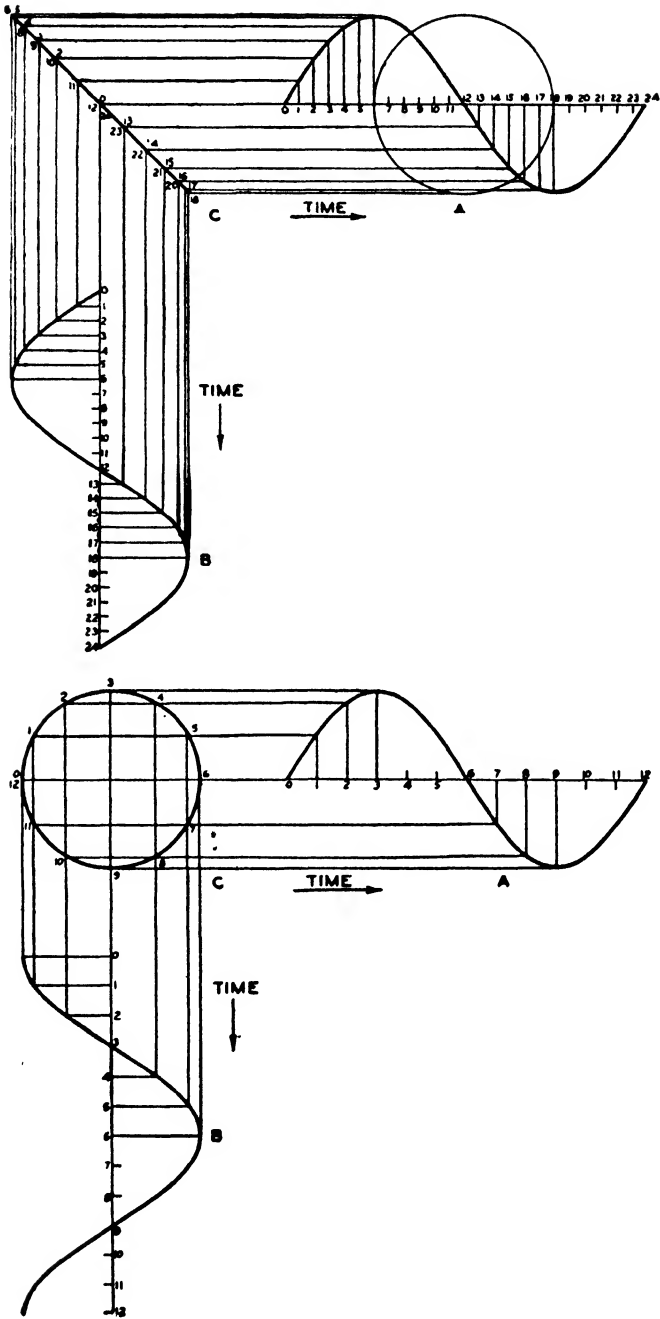
R. C. A. Commercial Engineering.

FIG. 12-2. Plotting Voltages with a Cathode-ray Tube.

phase of one voltage is retarded 90° with respect to the other a circle is produced.

EXPERIMENT 12–1

Purpose: To study several types of patterns produced by various cathode-ray circuits.

Materials: Cathode-ray oscillograph
Variable audio oscillator
6.3-v. transformer
Decade condenser, 1.0-μf. to .001-μf.
1,000-ohm General Radio No. 314-A potentiometer
20- to 60-millihenry coil

Introduction. The following experiments illustrate the more common types of patterns which are used in oscillograph practice. The circuits for producing these patterns are simple and easily assembled. For convenience we shall assume that a standard 3- or 5-inch commercial instrument or its equivalent is available. This instrument contains the cathode-ray tube, a power supply, separate amplifiers for supplying potentials of appropriate magnitude to the horizontal and vertical deflector plates, and a sweep circuit of adjustable frequency for a time axis. In the following circuits, the oscillograph itself is represented by the four deflector plates only. It will be observed that two adjacent plates are connected together and are usually grounded. Independent connection to all four plates can be made, however, if this is necessary. For the circuits which are described below, it will be necessary to use the oscillograph's amplifiers in order to obtain full-size patterns. In order to avoid amplifier distortion or disproportioning of the patterns, it will be necessary to adjust the vertical and horizontal amplifiers for equal gain. This is best done by applying a small A.C. voltage to each deflector system in turn and adjusting the gain controls until a horizontal trace is obtained which is equal in length to the vertical trace.

Since the following experiments are related and the equipment required is in general the same, the theory and procedures will be combined in the general outline of each experiment.

12–3. Sine-wave pattern.

The simplest type of pattern is shown in Figure 12–3, in which a sinusoidal voltage is applied to the vertical deflector plates. The horizontal plates are fed with the sawtooth oscillator, which supplies a linear sweep or time (x) axis. A single sine wave or a number of them can be made to appear on the screen, according to the sweep frequency chosen. Figure 12–4 shows the circuit. Most oscillographs are provided

with a synchronization control in which a portion of the signal under observation is used to initiate each pulse of the sweep circuit. This causes "locking-in" of the pattern and eliminates any drifting that might arise owing to small variations in the sweep frequency.
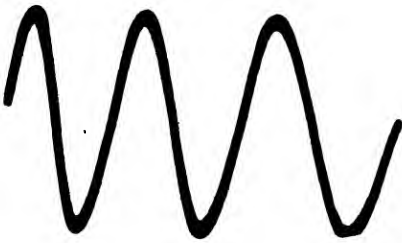
FIG. 12-3.   Sine Wave.
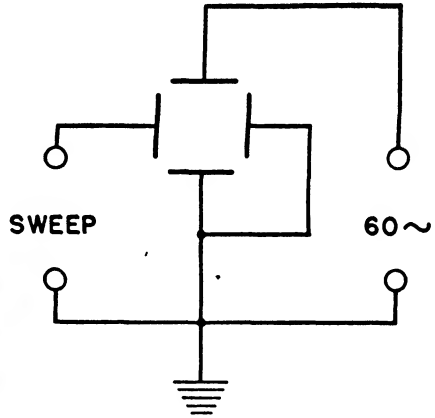
FIG. 12-4.   Schematic Circuit for Plotting Sine Waves.

This simple use of the cathode-ray tube illustrates one of its many functions. It may be used as a rough measure of the frequency of an A.C. source; as an indication of the purity of wave form; to show the presence of harmonics or transient disturbances, and so forth.

12–4. Sawtooth pattern.

It will be instructive to substitute for the A.C. signal the output of a sawtooth oscillator of §12–10 or Figure 11–7. As before, the oscillo-
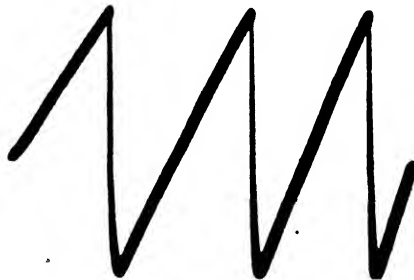
FIG. 12-5.   Sawtooth or Linear Pattern.

graph's own sawtooth oscillator supplies the sweep or timing pulses. The resulting pattern is shown in Figure 12-5. Here we observe that the potential rises in a perfectly uniform and linear manner to some maximum value and then drops abruptly to zero. This illustrates the use of this

type of oscillator as a linear time base. In this use, the rapid return to zero voltage constitutes the return trace. Since the return trace is so very rapid, the resulting image on the screen is comparatively feeble. If for any reason its presence becomes objectionable it is possible to eliminate it completely, as shown in §12–11.

12–5. Patterns of voltages in phase.

With the circuit shown in Figure 12–6 it is possible to produce a set of straight-line traces at any angle in the first and third quadrants, with
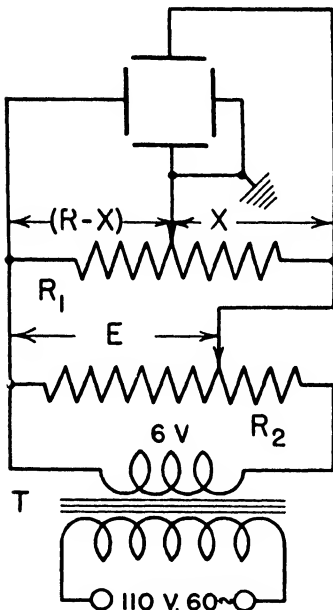
Fig. 12–6. Schematic Diagram Used to Vary the Amplitude in the y and x directions.
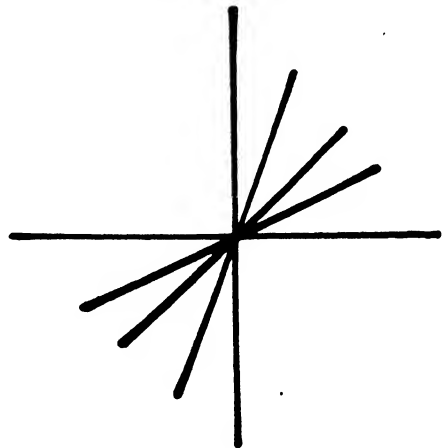
Fig. 12–7. Patterns Obtained with Circuit of Fig. 12–6.

a vertical and a horizontal line as the limiting cases (Figure 12–7). The signal voltages are obtained from a small 110-6-v. step-down transformer, the secondary of which is shunted by a voltage divider controlling the voltage applied to the calibrated divider R_1. For a given value of E, the total drop across R_1 is constant and is equal to E. For any setting of the slider on R_1 it will be seen that the fraction X is applied as a signal voltage to the vertical plates and the fraction $R - X$ to the horizontal plates. The voltages are in phase and a straight line will result. When the slider is at the mid-point, $X = R - X$, and hence the signal voltages e_v and e_h are equal. The slope of the straight line is then unity, or the angle which the line makes with the horizontal is 45°. It is

readily seen that when $X = 0$ a horizontal line results, and when $X = R$ a vertical line is obtained. The above arguments may be stated briefly as follows:

$$\tan \theta = \frac{e_v}{e_h} = \frac{X}{R - X},$$

θ being the angle between the line and the horizontal. The length of the line (if E is constant) is given by:

$$1 = \sqrt{X^2 + (R - X)^2}.$$

These relationships may be verified by measuring the length of each line with a pair of dividers or by measuring the angle with a small protractor. It is assumed, of course, that the amplifiers have been set for equal gain as previously described.

12–6. Patterns of voltages out of phase.

Elliptical traces may be produced with the simple phase-shifting network indicated in Figure 12–8. A variable-frequency oscillator is recommended as a source, and for convenience we may choose 10,000 cycles. The voltage divider that controls the applied voltage may well be the output control of the oscillator. One branch of the network is a calibrated resistor; the other is a variable condenser. The signal voltages applied to the deflector plates are no longer in phase and an elliptical trace must result, because current leads voltage in a condenser and there will be a phase displacement of 90° or less. Reference to Chapter 1 will recall to the reader how the exact values of C and R affect the shape and size of the patterns. The capacitative reactance of C is given in ohms by

$$X_c = \frac{1}{2\pi f C},$$

where f is the frequency in cycles per second and C is the capacity in farads. If at a given instant a current of i amp. flows through C, the potential across the terminals of the condenser will be $\frac{i}{2\pi f C}$ v. The same current flows through R (but not in phase with it), hence the drop across the resistor is Ri volts. If the condenser is set so that the capacitative reactance is equal to the resistance, then the deflecting voltages will be equal and a circular pattern will be obtained. This effect is self-evident if we recall that a circle is an ellipse with equal major and minor axes. For this setting we may change the circle from the size of a pin-head to the limit of the screen diameter by merely changing the value of the total applied voltage (E). Several patterns are shown in Figure 12–9.

The quantitative relationship between the variables can be checked

as follows: Generate several circles by choosing some value for the condenser setting and an appropriate value of resistance. Record the values for a number of circles. A true circle may be judged fairly accurately by inspection, but a simple test with dividers will insure the necessary precision. A series of ellipses may now be produced, by first fixing the value of the resistor at about 8,000 ohms and then successively increasing the capacity. For each setting of the condenser measure the major and minor axis of the ellipse. Repeat the procedure by fixing the capacity at about .002 μf. and varying the resistance. In all the data it will be convenient to express the ratio of the axes as l_V, l_H where these symbols represent
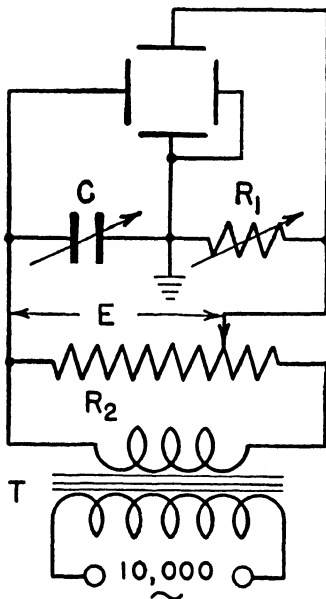
Fig. 12-8.   Phase-shift Network.
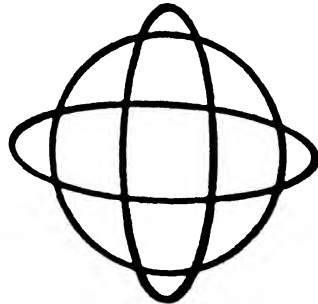
Fig. 12-9. Patterns Obtained at Various Phase Angles with Circuit of Fig. 12-8.

the length of the vertical and horizontal axes respectively. The following analysis of the circuit shows how the data may be plotted.

The signal voltages applied to the vertical and horizontal plates are:

$$E_V = RI \quad \text{and} \quad E_H = X_c I;$$

but the current I is given by

$$I = \frac{E_0}{\sqrt{R^2 + X_c}},$$

from which

$$E_V = \frac{RE_0}{\sqrt{R^2 + X_c^2}} \quad \text{and} \quad E_H = \frac{X_c E_0}{\sqrt{R^2 + X_c^2}}$$

Dividing the first expression by the second, we get

$$\frac{E_V}{E_H} = \frac{R}{X_C} = \frac{l_V}{l_H},$$

since

$$X_C = \frac{1}{\omega C}, \qquad (\omega = 2\pi f),$$

$$\frac{l_V}{l_H} = R\omega C.$$

The data can now be plotted in terms of the above expression. In all cases ω is assumed to be constant.

Case I. Circles.

$$\text{Since } \frac{l_V}{l_H} = 1, \text{ therefore } R \propto \frac{1}{C}$$

Case II. Ellipses.

$$\frac{l_V}{l_H} \propto C \text{ for constant } R;$$

$$\frac{l_V}{l_H} \propto R \text{ for constant } C.$$

The experiment has illustrated a typical case in which there has been a phase displacement. An inductance can be substituted for the condenser and the corresponding case can be worked out. Remember that in this case the inductive reactance is given by $X_L = 2\pi f L$, and the above equations may be treated in a similar manner.

It will be apparent that the oscillograph may be used to study or observe any circuit containing resistance and reactance. The case of the circular pattern illustrates one application of possible interest to chemists. In solutions of electrolytes, reciprocal resistance or conductance is a more convenient quantity to deal with than resistance. If a conductivity cell is connected in place of R (Figure 12–8) and a circular pattern is produced by a suitable adjustment of C, then the settings of C will be directly proportional to the conductance of the solution, since for $\frac{l_V}{l_H} = 1$

$$C \propto \frac{1}{R} \propto G,$$

G being conductance.

12–7. Superimposition of an A.C. voltage on out-of-phase patterns.

A combination of the above method with that of Experiment 12–3 affords a useful method for precise frequency or time measurements. The

modified circuit is·shown in Figure 12–10. A circular time base is generated by the phase-shifting network R and C, but this time the source is 60 cycles. For C a 0.5-μf. fixed condenser may be used, and if R is set at about 5,300 ohms a circle will result. Other values of R will produce ellipses; this additional possibility has its uses, as will be shown presently. In the lead to the vertical deflection plate, the output of a variable-frequency oscillator is introduced. Initially it may be set for 600 cycles. This has the effect of superimposing sine waves upon the circular pattern, thus producing a "bracelet" effect (Figure 12–11). Many adjustments can be made to vary the nature of the pattern. As we have shown, the value of R determines the eccentricity of the elliptical time base. The height of the sine waves can be changed by varying the oscillator output. The size of the time base can be changed by increasing or decreasing E. If the oscillator output is introduced in the common lead to the two deflector plates, the "bracelet" will be inclined at 45°.

The general utility of this method lies in the fact that the circular time base utilizes the limited dimensions of the screen more efficiently than a linear time axis, in the ratio of the circumference of a circle to its diameter. More likely than not the pattern will not be stationary but will rotate or precess, owing to the slow drifting of frequency either of the modulating source or of the time base. This apparent defect is actually advantageous, for if the two frequencies are almost exact multiples, then an extremely small difference in frequency may be measured by timing the rate of drift.

One disadvantage of the method is apparent. The waves at each side of the circle or ellipse are tangent to it and their true contour is distorted; indeed, there is some difficulty in counting the true number of waves by reason of this effect. The obvious solution lies in radial rather than vertical modulation. In this way "gear-wheel" patterns are formed. The simple expedient of modulating the electron beam for this purpose is accompanied by focusing difficulties. Several circuits have been developed which are satisfactory.

The last word in efficient space utilization is offered in the spiral time base. This is a combination of the circular trace and a relaxation oscillator which increases the radius at a uniform rate up to a certain value and then snaps back to the origin. As before, the phenomenon under investigation can be introduced in series with one of the deflector plates.

12–8. Resonant circuit patterns.

A very useful circuit is illustrated in Figure 12–12. One branch of the network contains the calibrated resistor R, the other a variable condenser and an inductor in parallel. For this experiment the inductor may be prepared from a radio-frequency choke coil (air core) by carefully

breaking away the ceramic core and cementing the coil on a suitably sized glass tube. The lead wires should be connected to suitable binding
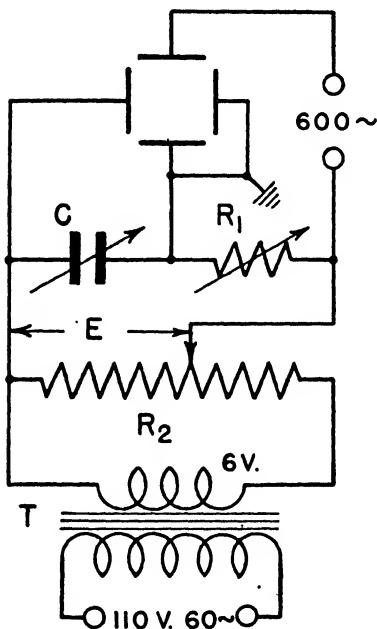
FIG. 12–10.   Phase Shifter and Modulator Circuit Combined.
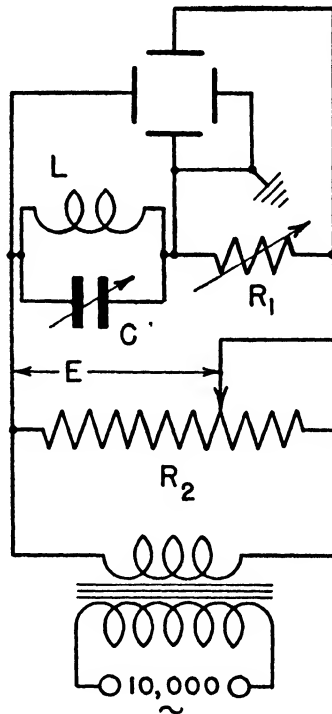
FIG. 12–12.   Phase Shifter Containing Inductance-Capacitance and Resistance.
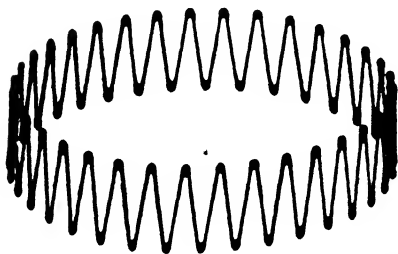
FIG. 12–11.   Pattern Obtained with Circuit of Fig. 12–10.
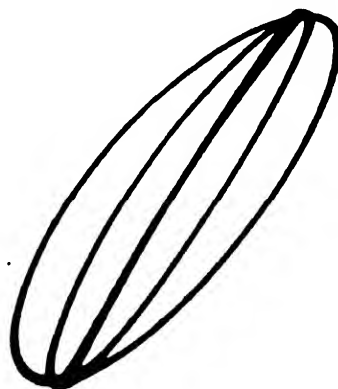
FIG. 12–13.   Patterns Obtained with Circuit of Fig. 12–12.

posts or banana plugs, and the glass tube mounted rigidly in the vertical position. A small shield can should surround the coil and be connected to

ground. The source is a variable-frequency oscillator set at about 10,000 cycles. For this frequency a setting of the condenser can be found at which the combination is resonant. This condition is given by

$$C = \frac{1}{4\pi^2 f^2 L}$$

where L is the inductance of the coil in henries and C is the capacity in farads. The total impedance of this branch can be matched by a suitable value of R. The resultant pattern will be very nearly a straight line tilted at 45°. The slightest change in L, C, or the supply frequency will cause the line to open out into a tilted ellipse. The introduction of a magnetic substance into the core of the coil will produce a large change. Small differences in the magnetic properties can be made apparent. Figure 12–13 shows the difference in pattern produced by rods of nickel and stainless steel of identical dimensions. Rapid inspection methods have been based on this principle. For careful measurements no attempt is made to measure the distortion of the pattern but rather to introduce measured inductance or capacitance to restore the standard trace.

It is apparent that this circuit may be used to detect and render visible small changes in frequency, inductance, capacitance, or any other property which may be translated into changes of these variables.

12–9. Other applications.[2–13]

This discussion does not begin to exhaust the possibilities for the utilization of the cathode-ray oscillograph. It should have emphasized

[2] Cole, R. H., Use of Cathode Ray Tube for Comparison of Capacitances, *R.S.I.* *12*, 298, 1941.

[3] Cosby, J. R., and Lampson, C. W., Electronic Switch and Square Wave Oscillator, *R.S.I. 12*, 187, 1941.

[4] Hughs, H. K., Thyratron Selector for Double Trace Cathode Ray Oscillograph, *R.S.I.* 7, 89, 1936.

[5] Hughs, H. K., and Koch, R. F., Combination Vacuum Tube Switch for Double Trace Oscillograph Amplifier and Mixer, *R.S.I. 12*, 183, 1941.

[6] Loughlin, B. D., A Phase Curve Tracer for Television, *Proc. I.R.E. 29*, 107, 1941.

[7] Mayer, H. F., Cathode Ray Tube Applications, *Electronics*, Apr., 1938; p. 14.

[8] Müller, R. H., *et al.*, Cathode Ray-Tube Polarograph, *Ind. and Eng. Chem.*, *Anal. Ed.*, *10*, 339, 1938.

[9] Reich, H. J., Electronic Switch, *R.S.I. 12*, 191, 1941.

[10] Reich, H. J., Circuits for Oscillographic Frequency Comparisons, *R.S.I. 8*, 348, 1937.

[11] Roess, L. C., Condenser Type High Speed Engine Indicator, *R.S.I. 11*, 183, 1940.

[12] Schrader, H. J., Cathode Ray Engine Pressure Measuring Equipment, *R.C.A. Rev. 2*, 202, 1937.

[13] Talbot, S. A., Multiple Sweep System for Cathode Ray Oscillography, *R.S.I. 11*, 289, 1940.

the fact that the full capabilities of this instrument are not restricted by the simple linear sweep with which it is customarily provided. Fundamentally the electron beam is almost inertia-free, and the upper limit for its agility is usually set by the characteristics of associated equipment, for example the frequency response of the amplifiers, sweep circuit, and so forth.

In common with many other electronic devices, the cathode-ray oscillograph is rarely called upon to perform precise measurements directly. It is usually employed as an adjunct to more fundamental devices such as bridges, frequency monitors, and so on, or for the purpose of intercomparison with such references. As a means for temporal discrimination or the delineation of very rapid and complex phenomena it is unique and has few successful competitors.

The design of a modern cathode-ray oscillograph is a complex problem and is best solved by engineers with years of experience in this field. Since many excellent instruments are available today it is advisable to invest in a complete instrument of a type best suited to one's needs. The following sections are designed to acquaint the reader with the complex problems involved and perhaps to aid him in the proper selection of an instrument for his own use. The experiments are workable but should be carried out only by advanced students who are acquainted with the dangers involved in the use of high voltages.

12–10. A linear time base.[14],[15]

The use of a linear time base is often the best method of plotting wave forms on the screen of the cathode-ray tube since it lends itself to easy interpretation. It is produced by a voltage increasing at a uniform rate to a certain value, then dropping abruptly to zero and repeating the process. The shape of the voltage wave resembles a sawtooth and is often referred to by that name. A typical sawtooth plot is shown, obtained from the circuit shown in Figure 11–7 and in Figure 12–5. When such a voltage is applied to the horizontal plates of an oscillograph the fluorescent spot travels uniformly across the screen and then abruptly moves back to the starting position and begins retracing another cycle. If the rate of the voltage increase is controllable, repetitive patterns at all practical frequencies may be plotted so that one or any number of patterns are included in one excursion of the linear time sweep. It can be shown from $Q = CE$ and $Q = It$ that the voltage developed across a capacitor charged at a constant rate increases linearly with time, and

[14] Bedell, F., and Reich, H. J., *J. Am. Inst. Elec. Eng. 46*, 563, 1927.
[15] Reich, H. J., "Theory and Application of Electron Tubes." New York: McGraw-Hill Book Co., Inc. 1939.

the voltage will be $V = \dfrac{It}{C}$, where I represents the constant current in amperes and C the capacity in farads.

The sudden drop in voltage required to produce the sawtooth wave may be obtained by connecting a gaseous triode across the capacitor and arranging the grid voltage of this tube so that when the voltage reaches a certain value the capacitor is abruptly discharged to an equilibrium value which becomes the zero reference. Decreased voltage thus causes the gaseous triode to deionize and stop conducting, and the charging is automatically resumed. A gaseous tube will discharge the capacitor rapidly; it will be remembered that the peak current of this type of tube is limited only by the resistance in the plate circuit. A small tube is thus capable of passing .1 to .2 amp. for a short time without damage. If the resistance in the plate circuit is only of the order of 1,000 ohms, a .01-μf. capacitor charged to 100 v. may be discharged in approximately 10^{-5} second at these currents, while at a charging rate of .001 amp. 10^{-3} second is required for recharging. This would, therefore, give a 1,000-cycle sawtooth wave in which 1 per cent of the time is consumed in the return trace, a negligible proportion of the total for many applications.

Constant charging rates may be achieved by a number of methods. The most commonly used consists of limiting and maintaining a constant current with a pentode tube. The plate current of a pentode is practically independent of the plate voltage over wide limits and depends only on the control-grid and screen-grid voltage. If these voltages are fixed the plate current may be used to charge the capacitor. In this manner a capacitor may be charged uniformly to about 85 per cent of the supply voltage. The charging rate, and therefore the frequency of the sawtooth wave, may be regulated by the control grid of the pentode charging tube. Gross frequency variations may be effected by changing the capacitance of the capacitor in fairly large steps.

12–11. Capacitor charged through a resistor.[16]

The charging rate of a capacitor placed in series with a resistance and at a constant voltage varies exponentially with time, but the first portion of the charging rate is fairly uniform. If the charging is arrested with the gaseous triode before the voltage of the capacitor has reached 5 per cent of the supply voltage, the rate is sufficiently uniform for most purposes. The voltage to which this capacitor is charged at low power-supply voltages is too small to deflect the beams of most cathode-ray tubes without further amplification. Amplification of a sawtooth wave is, however, a more difficult problem than that encountered with sine waves, as was shown in Chapter 10. An amplifier which does not in-

[16] *Ibid.*

crease the time interval for the "fly back" is especially difficult to design. However, owing to the greater flexibility in procedure for controlling the amplitude of the sawtooth with amplifiers, this method is used almost exclusively today. With a 300-v. supply, one gaseous triode, and a pentode amplifier, approximately 150 v. controllable output may be obtained, as contrasted with 250 v. using the same tubes in the constant-voltage charging method. If three tubes are used with the amplifiers in symmetrical deflection, approximately 400 v. effective output may be obtained from the 300 v. supply.

The problem of coupling the sawtooth generator to the amplifier and controlling the amplitude is difficult to solve, as will be demonstrated in the following experiments.

EXPERIMENT 12–2

Purpose: To determine the characteristics of a constant-current high-voltage sweep generator.

Materials: 1N5GT tube
884 or 885 tube
Sockets
2 5,000-ohm volume controls
300-v. power supply
Assorted capacitors .5-μf. to .001-μf.
45-v. B batteries
1.5-v. A battery
7.5-v. batteries
22.5-v. battery

Procedure A. Wire the apparatus as shown in Figure 12–14, connecting the output to the free horizontal deflector plate as shown. Combine the unit with that shown in Figure 12–18, in order to obtain a complete oscillograph. Impress about 50 volts A.C., either from a variable audio oscillator or from the 60-c.p.s. line, on the vertical deflector plates; then adjust R_3 until the horizontal pattern size is correct. Change the frequency of the sawtooth generator with R_1 until a stationary pattern is obtained. If a large number of stationary waves appear the frequency of the sweep voltage is too small; if, on the other hand, less than one complete cycle appears, the sweep-voltage frequency is too high. Select various capacitors for C_2 until the adjustment of R_1 produces either a single wave or several waves on the face of the tube. To observe the linearity of the sweep voltage, arrange the frequency so that five or more cycles appear·and measure the interval between the crests. If the sweep is perfectly linear the distance between all crests will be equal.

Procedure B. It will be observed that the pattern will not be held stationary for an appreciable time after R_1 has been adjusted correctly. This variation is due to the instability of the 885 tube, in that the tube will progressively discharge the capacitor at a higher or lower voltage as the gas pressure within the tube changes. The variation may be avoided by tripping the 885 grid with the voltage fed to the vertical deflector
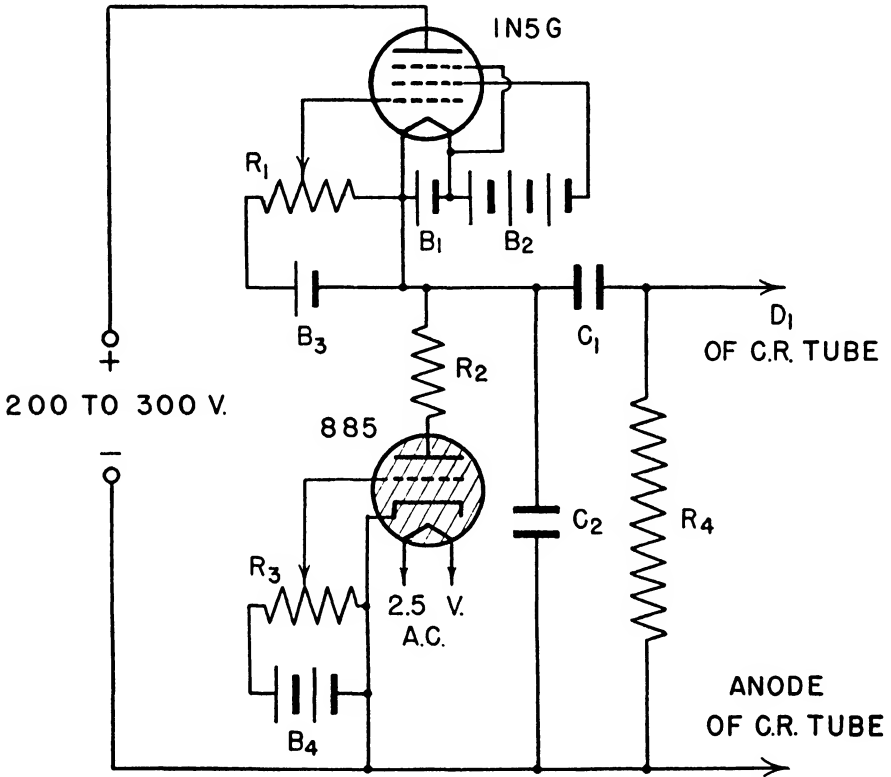
FIG. 12–14. Battery-operated Sweep Circuit. R_1 = 5,000 ohms; R_2 = 500 ohms; R_3 = 5,000 ohms; R_4 = 5.0 megohms; C_1 = .1 μf.; C_2 = .001 to .1 μf.; B_1 = 1.5 v.; B_2 = 45 v.; B_3 = 4.5 v.; B_4 = 22.5 v.

plates. If the .1-megohm volume control is placed in the grid circuit of the gaseous tube and a .001-μf. capacitor is connected to feed the top or grid end of this control from the vertical voltage, positive synchronization may be obtained. The amount of synchronizing voltage applied to the grid of the 885 may be controlled with this volume control. At low frequencies the value of the isolation capacitor may be increased somewhat but only if the synchronization is not perfect. Try the effect of circuit constants on the synchronization.

Procedure C. In a perfect sweep generator the value of the capacitor C_1 should be smaller than C_2, but the value of R_4 large in comparison to

the D.C. resistance of the pentode plate-cathode circuit. Determine the effect of R_4 on the shape of the wave by decreasing the value of R_4 to 1 megohm, to .5 megohm, and to .1 megohm. Observe that the ends of the pattern become crowded at low values of R_4.

Procedure D. A certain fraction of the total time is required for the discharge of C_2 by the 885 tube. The minimum time is limited by the peak current allowable in this tube and the actual time is, in reality, controlled by the value of R_2. The return trace may be made visible on the face of the tube by increasing the intensity, and the fraction of the time required for return can then be estimated roughly. Observe that if R_2 is increased to 5,000, 10,000 or 20,000 ohms the time required for the return trace increases appreciably. This estimating may best be performed at sweep frequencies higher than 1,000 c.p.s.
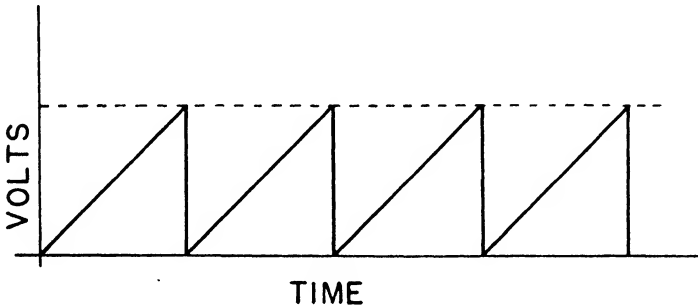
FIG. 12-15. Idealized Sawtooth Wave.

Procedure E. If R_3 is changed, observe that the amplitude of the sweep as well as the frequency are both changed. The amplitude change arises from the fact that the so-called frequency of a sawtooth wave is in reality the reciprocal of the time required for each charge. If the capacitor C_2 is charged to a higher voltage at constant current (R_1 fixed), the time required will be longer, the frequency lower, and the amplitude of the sweep voltage higher.

Procedure F. If a commercial oscillograph capable of reproducing square or sawtooth voltages is available, all of the foregoing determinations may be carried out more satisfactorily by feeding the sawtooth voltage to the vertical deflector system and using the internal sweep circuit of the oscillograph as a time base. The actual shape of the sawtooth wave will be visible and direct interpretation possible. Note, however, that the voltage produced by the experimental sweep generator may reach a value of a few hundred volts. A connection should not, therefore, be made directly to the input of the oscillograph if the manufacturers' specifications do not recommend these high voltages; but in general, connection can be made directly to the vertical deflector plates

of the commercial oscillograph. At average frequencies a perfect saw-tooth wave should appear as shown in Figure 12–15.

12–12. Amplification of sawtooth voltages.

The second type of sweep generator is illustrated in Figure 12–16 and Figure 12–17. The difference between these two circuits is only in the method of coupling used between the sweep generator and amplifier. Both circuits utilize the first portion of the capacitor charge rate to obtain linearity. With a 300-v. power supply the capacitor may be charged to about 50 v. without reaching the appreciably curved por-tion of the charge curve. When the capacitor C_6 discharges, the voltage falls to about 20 v., so that 30 v. peak-to-peak signal is available. This is more than sufficient, since the 6J7G amplifier tube requires less than 10 v. peak-to-peak for full output. The high voltage must be attenuated by means of resistor R_1 and volume control R_4 so as not to overload the grid of the amplifier.

In the absence of C_4 the return-trace time may be considerably in-creased, since the capacitance from the grid end of the 6J7G tube to ground is appreciable at the frequency represented by the return trace. If the value of C_4 is properly chosen so that the capacitance ratio of C_4 to the amplifier input capacitance (including volume-control capac-itance) is the same as the ratio of R_1 to R_4 when R_4 is fully on, the di-vision of voltage will be the same for the forward and backward sweep. At other settings of R_4 this division no longer holds, but small variations in R_4 are possible without upsetting the balance appreciably.

In order that the amplifier may not distort the sawtooth wave the value of R_6 must be kept fairly low and inductors may be added to compensate for shunt capacitances, as was shown in §10–19. The fine control for frequency variations is obtained by R_3 in Figure 12–16. R_3 controls the capacitor charging current and hence the frequency. Gross variations in frequency are effected by changing the value of capacitor C_6. The value of the grid voltage on the 885 tube is usually fixed in practice after its optimum value has been determined. The power supply is, of course, used to supply this voltage in commercial instruments.

In Figure 12–17 attenuation is achieved in the cathode circuit of the first amplifier tube. This triode tube may be likened to an impedance transformer, since it transforms a voltage across a high impedance in the grid circuit to approximately the same voltage at low impedance in the cathode circuit. The capacitance of the associated circuits and the cathode-ground capacitance are of comparatively small importance at resistances of the order of a few thousand ohms. If the input circuit of this tube is properly proportioned to keep stray capacitances to a mini-mum, the value of R_6 may be as high as 5 to 10 megohms and the equi-
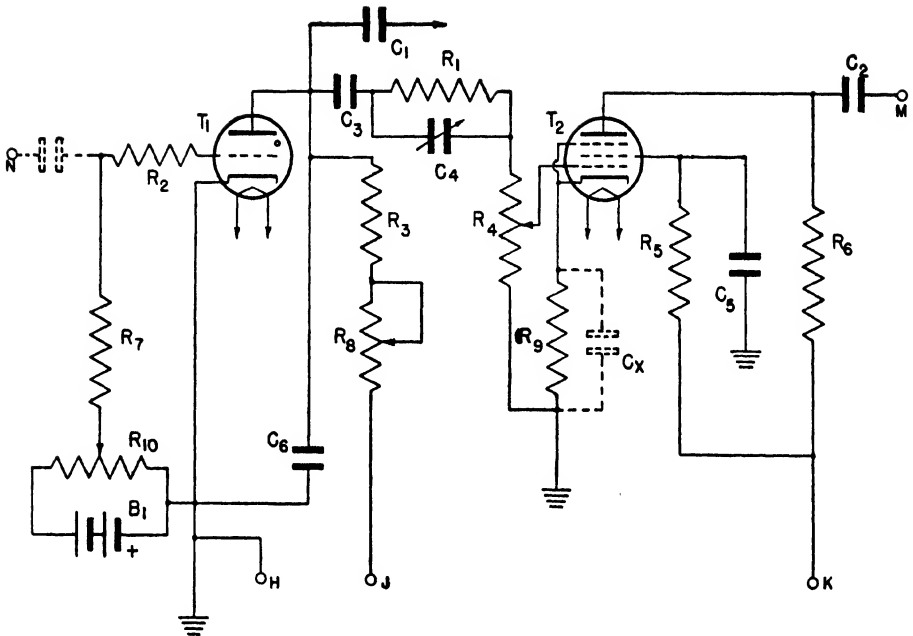
Fig. 12-16. Sawtooth Generator and Amplifier. $R_1 = 1.0$ megohm; R_2, $R_3 = .1$ megohm; $R_4 = .25$-megohm volume control; $R_5 = 1.0$ megohm; $R_6 = 50,000$ ohms; $R_7 = .1$ megohm; $R_8 = 2.0$ megohms; $R_9 = 1,000$ ohms; $R_{10} = 20,000$ ohms; H = B−; J, K = B+; M = deflection plate; $C_1 = .0001$ µf. or smaller; $C_2 = .05$ µf.; $C_3 = .05$ µf.; $C_4 = 5$–200 uf.; $C_5 = .5$ µf.; $C_6 = .0001$–1 µf.
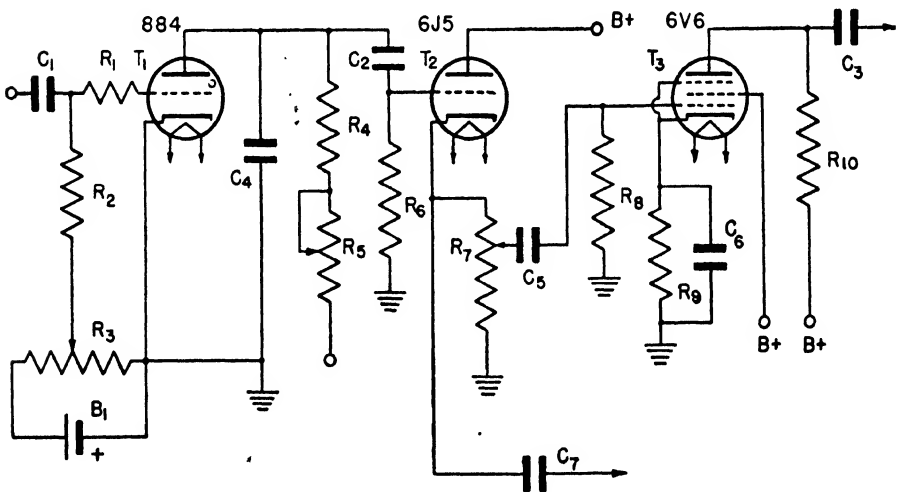
Fig. 12-17. Sawtooth Generator and Cathode Follower-amplifier. R_1, $R_2 = .1$ megohm; $R_3 = 20,000$-ohm potentiometer; $R_4 = .1$ megohm; $R_5 = 2.0$ megohm potentiometer; $R_6 = 5.0$ megohms; $R_7 = 2,500$ ohms; $R_8 = 1.0$ megohm; $R_9 = 750$ ohms; $R_{10} = 25,000$ ohms, 10 watts; $C_1 = .01$ µf.; $C_2 = .05$ µf.; $C_3 = .05$ µf.; $C_4 = .1$–$.0001$ µf.; $C_5 = .25$ µf.; $C_6 = 25$ µf.; $C_7 = .00001$ µf.

librium charge developed by C_2 will, therefore, be quite small. Similarly, the value of R_5 may also be quite large since signal division is achieved in the low-resistance potentiometer R_7. By properly choosing R_7, capacitor C_2 may be eliminated entirely.

EXPERIMENT 12-3

Purpose: To determine the characteristics of the sweep generators of Figure 12–16 or Figure 12–17.

Materials: Parts for Figure 12–16 or Figure 12–17

Procedure A. Wire the apparatus as shown in Figure 12–16, connecting the output directly to the vertical deflector plates of a commercial oscillograph or to the horizontal deflector plates of Figure 12–18. Adjust the grid voltage of the gaseous triode to approximately 5 v. with R_{10}. Use a value of .01-μf. for C_6 and adjust R_4 for full scale on the oscillograph screen. If the oscillograph deflection is less than full with R_4 fully on, increase the grid voltage of the 885 tube until full scale is obtained. On the other hand, if full scale is obtained with R_4 only partly on, decrease the same voltage with R_{10}. Analyze the sawtooth voltage so obtained as in Experiment 12–6, either by plotting with it a sine wave of comparable frequency or by plotting the output of the circuit with the linear time base of the commercial oscillograph. Adjust C_4 through its full range and observe the effect on the pattern. If the patterns are not stationary, synchronize them by applying the synchronizing signal to N.

If the circuit of Fig. 12–18 is used, connect a .1-megohm $\frac{1}{2}$-watt resistor in series with the grid. The plate of the 885 tube should also be connected to the grid of the cathode-ray tube through a 50-$\mu\mu$f., 1,000-v. mica condenser. Observe that the return trace is completely eliminated. Observe that as the setting of R_4 is changed the value of C_4 must also be changed in order to obtain a perfect sawtooth wave. Decrease the value of R_4 so to attenuate by a factor of .1 to 10, and again increase the pattern size to normal by increasing the grid voltage with R_3. Observe that the rise is no longer linear but that the charging rate decreases toward the end of the change.

Study the same effects as well as other variations at different frequencies by changing R_8 (fine frequency control) and C_6 (coarse frequency control). In a commercial oscillograph the value of C_6 is changed with a selector switch, so that steps covering the range from 1.0 to .000050 μf. are obtainable. With the circuit constants indicated the steps may be 1.0, 0.2, .04, and so on; dividing the value of the preceding capacitor by 5 gives the value of the next one and allows some overlap. (Change the value of C_5 to 10 μf. and note that the high-fre-

quency portion of the wave is more distorted than before but the amplitude of the signal is somewhat greater).

Procedure B. Connect the apparatus of Figure 12–17. Then set R_7 to maximum and adjust R_3 so that the pattern goes off the edge of the screen. Reduce the size of the pattern to a suitable value with R_7, and analyze the shape of the wave as before. Change the value of C_4 and
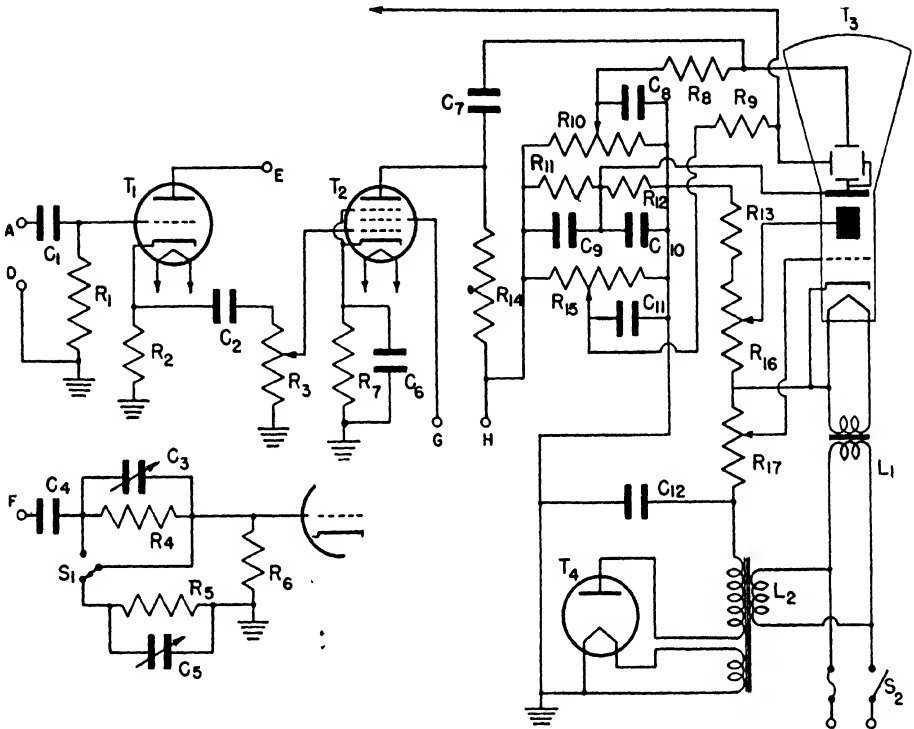
Fig. 12–18. Vertical Amplifier and Input Attenuator. $R_1 = 5.0$ megohms; $R_2 = 2,500$ ohms; $R_3 = .1$-megohm potentiometer; $R_4 = 5.0$ megohms; $R_5 = .5$ megohm; $R_6 = 5.0$ megohms; $R_7 = 1,000$ ohms; R_8, $R_9 = 5.0$ megohms; R_{10}, $R_{16} = 2.0$ megohms; R_{11}, $R_{12} = 250,000$ ohms; R_{13}, R_{16}, R_{17}, depend on the type of cathode-ray tube bleeder designed for 1,000 ohms per volt; C_1, C_4, .1 μf.; C_3, C_5, see text; $C_6 = .005$ μf.; $C_7 = .05$ μf.; C_8, C_9, C_{10}, $C_{11} = .25$ μf.; $C_{12} = .1$ μf. high voltage.

observe the effect at low frequency, that is, at large values of C_4. Replace the resistor R_7 with a 5,000-ohm variable resistor and a 0–10 milliammeter, leaving C_5 disconnected for the moment. Then, without disturbing R_3, short-circuit C_2 or remove it entirely, making a direct connection from the plate of the 885 tube to the 6J5 grid. Adjust the new resistor R_7 until the milliammeter reads approximately 6 ma. with the discharge tube working. Disconnect R_7 and measure its value. Reconnect a volume control of approximately the same total resistance just

determined for R_7, attaching C_5 as before. With this connection observe the linearity of the time base at low frequencies. Note that R_6 no longer serves a useful purpose and may be removed. An equivalent circuit of this type is used in some commercial instruments.

Procedure C. Single sweep.[17,18] Connect the plate of a 6H6 diode tube to the plate of the 885 tube and the 6H6 cathode to the arm of a 200,000-ohm volume control connected from B+ to ground. Set the volume control so that the 885 tube just reaches a voltage barely short of the discharge point. The diode begins to conduct, thus preventing C_2 from charging to a higher potential. Then apply a small positive voltage to synchronize input and note that the sweep makes a single excursion from the middle to one side of the screen and again comes to rest in the center. The rate of this single excursion is determined by the value of C_4 and R_5 as before. This arrangement is convenient in the study of transients, because the intermittent voltage sets off the sweep and the following phenomena will then be plotted and may be photographed as a single trace; that is, the sweep begins when the transient begins and the whole event or a portion may be observed by adjusting the value of R_5 and C_4. The entire screen may, of course, be used by adjusting the positioning controls and increasing the amplitude with R_7.

12–13. Vertical or signal amplifiers.

A good vertical or signal amplifier should be designed along the same lines as the sweep amplifier in order that it may amplify any wave shape without distortion. The circuit shown in Figure 12–18 includes an amplifier suitable for a 2- or 3-inch tube and includes the high voltage supply of the cathode-ray tube as well for the sake of completeness. If the sweep circuit of Figure 12–16 or Figure 12–17 is combined with the unit of this circuit, it will represent a complete oscillograph capable of producing square waves to several thousand cycles per second. The input tube operates at less than unity gain and serves to reduce the impedance so that the volume control in the grid of the 6J7 tube may have a low value and still allow a high input resistance. The input resistance at low frequencies is about 5 megohms.

This type of input, however, does not allow large signals at the input. If input signals higher than 20 v. are to be used the attenuator of Figure 12–18 may be used to replace R_1. With the switch in the up position the circuit is the same as before, while with the switch down the attenuation is about 1 to 11 and voltages as high as 220 v. may be used at the input. The value of C_3 must be correctly adjusted so that C_3 and C_5 (where C_5 also represents tube and wiring capacitance) are

[17] Haworth, L. K., *R.S.I. 12*, 478, 1941.
[18] Mezger, G. R., *Proc. I.R.E. 27*, 192, 1939.

in the ratio of 1 to 11. This adjustment may be accomplished quite easily with the aid of a square-wave generator by changing C_3 until the best high-frequency square wave is reproduced by the instrument. The 6J7 amplifier operates with inverse feedback at low frequencies, since C_6 is small. The effect of the capacitances in shunt with R_{14} is thus partially compensated. R_{17} determines the intensity of the beam current while R_{16} serves as a focusing control. It may be noted that the amplifier power supply is in series with the high-voltage supply and that the second anode is, therefore, at higher potential than ground by 150 v. This allows 150 v. of positioning voltage with R_{10} and R_{15} on either side of the center position. The positioning controls are thus adequate to move the spot completely off the screen. It may be noted that the secondary of transformer L_2 is 1,000 v. above ground potential. L_2 should therefore be a separate unit and should possess high insulation.

12–14. Beam switch.

In many cases it is advisable to turn off the beam current without disconnecting the apparatus from the mains. It may be accomplished by increasing the voltage across R_{17} until the grid cuts off the beam current. This method, although simple, makes it necessary to refocus the beam when it again is put to use. On the other hand, if a switch is placed so that it connects the grid either to the desired voltage from R_{17} or to the negative end, the difficulty is avoided. The insulation of the switch must, of course, be sufficient to withstand the high voltage. This switch may also be used as a wave-form or peak (Figure 12–14) selector switch if an electronic relay is substituted for it, so arranged as to put the beam on when a signal that is to be studied suddenly appears. A camera shutter may then be kept open continuously to photograph the phenomenon.

12–15. Time markings.

Since the linear time base using gaseous triodes does not have a high-order frequency stability, and moreover, since it tends to synchronize with the signal under measurement, it is never used as a frequency standard. If a certain signal is to be plotted against this linear time base and the actual signal duration measured accurately, the grid of the cathode-ray tube may be modulated with a signal of known frequency so that alternate segments of the trace will be dark and followed by normal portions. In order to limit the width of the dark portion to small values in relation to the light portions, so that no large amount of plotting data is lost, a special signal is required. If the output of a square-wave generator is differentiated with a small capacitor and applied to the grid of a cathode-ray tube, small serrations will appear in the pat-

tern and provide an excellent time base if the fundamental frequency of the square-wave generator is known.   .

12-16. Signal separators.

In cases where one part of a signal is to be studied to the exclusion of others, circuits may be arranged to isolate or clip the portions desired and exclude or minimize the remainder. If the highest amplitude of a wave is to be studied on a large scale it may be accomplished by arranging a diode circuit in a manner which will allow only amplitudes above the desired value to pass. The circuit shown in Figure 12–19a ac-

(a)   (b)
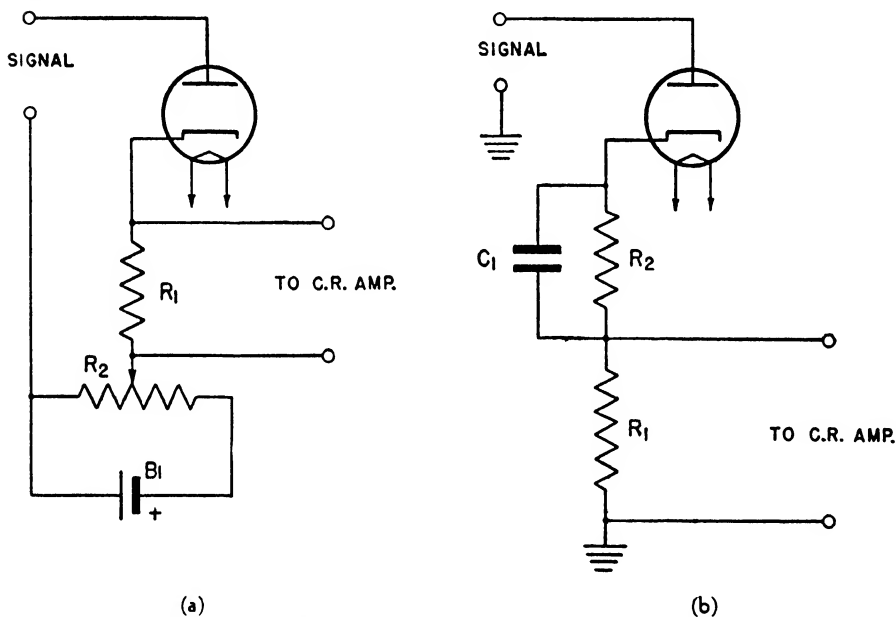
FIG. 12–19.   Clipper Circuits Using a Diode.

complishes this by placing a positive D.C. voltage on the cathode of a 6H6 tube. When the peak A.C. voltage reaches the value of this bias voltage, current begins to flow in R_1 in proportion to the A.C. voltage on the diode, and only voltages higher than the 6H6 bias will be passed to the next stage.

A self-bias arrangement for accomplishing the same effect is shown in Figure 12–19b. If a sine-wave signal is impressed on this network, capacitor C_1 is charged to a value approaching the maximum amplitude of the sine wave and only a small amount of current flows in R_1. If, however, one of the sine waves carries a small additional peak, current will flow in R_1 in proportion to the voltage of this peak. Small irregularities in the peak of the wave may then be studied in the presence of only small amplitudes of the main voltage. This circuit has the advantage

that it is self-adjusting, biasing the tube to the average value of the peak input voltage if the ratio of C_1 to R_1 is selected correctly.

If the low-amplitude portion of the wave is to be studied, the same circuits of Figure 12-19a may be used. The oscillograph amplifier is connected to the plate of the diode and the cathode. As soon as the diode conducts, the voltage becomes equal to the drop in the diode tube and input voltage above this value, as determined by the setting of R_2, is clipped. If both sides of the wave are to be included in any of the foregoing cases, the circuits must be duplicated in push-pull.

12-17. D.C. reinsertion.

When a photocell is illuminated from a modulated light source such as a neon bulb operated from the 110-v. A.C. mains, and the resulting
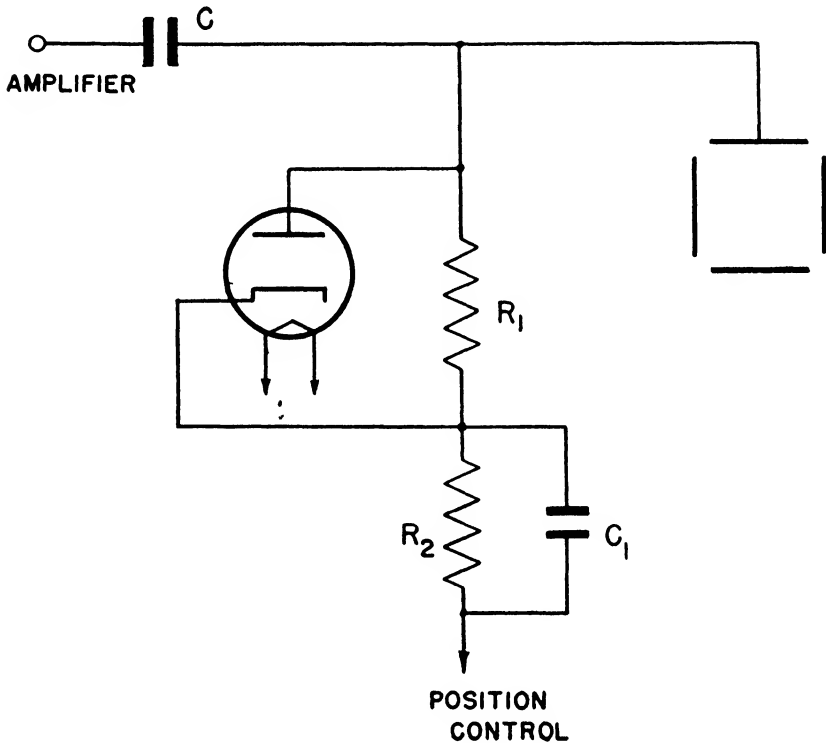
FIG. 12-20. D.C. Insertion Using a Diode.

photocurrent is amplified and applied to the deflector plates of a cathode-ray tube, a pattern is produced that approximates a sine wave uniformly distributed about the zero axis, that is, positive and negative portions. The original signal from the photocell consisted of D.C. pulses. If the intensity of the light is increased the patterns spread out

uniformly on both sides of the axis. A definite zero point may be maintained by a D.C. reinsertion network shown in Figure 12–20. This is essentially a rectifier so arranged that half of the wave is rectified and allowed to generate a voltage which is applied to one of the deflector plates. Either deflector plate may be used for this purpose, although the one connected to the amplifier is shown in the figure. The time constant should not be too large, otherwise the zero point will shift slowly as the input amplitude is decreased or increased.

12–18. D.C. signal amplifier.

If low-frequency A.C. voltages are to be plotted with an oscillograph, a D.C. or zero-frequency amplifier should be used. Many new difficulties are encountered in the design of a unit of this type. As has been indicated in former sections, D.C. coupling requires that the RI drop of the D.C. portion of the plate current be compensated for. This compensation may be accomplished by voltage elevation of successive stages such that the cathode of each stage is just more positive than its grid, which in turn must be at the plate potential of the preceding tube. This difficulty may be avoided by using two power supplies, as shown by Geohegan.[19]

12–19. Mechanical sweep generator.

Low sweep frequencies may be generated with the circuit described in Figure 12–17, but at frequencies lower than 1 c.p.s. the linearity becomes poor unless mountain-size capacitors are used. A simpler solution to this problem may be obtained by removing the stop from a General Radio type 314-A potentiometer and connecting its shaft to a motor revolving at a speed in revolutions per second equal to the desired frequency. The resistance of the potentiometer should be high in order to limit the power input to small values. If a 300-v. power supply is connected across this potentiometer, 300 v. of deflecting voltage is available as shown in Figure 12–21a. If push-pull deflection is desired, two 314A controls may be mounted on a common shaft but wired in opposite directions, with their sliders connected one to each deflector plate as shown in Figure 12–21b. In this manner, 600 v. of deflecting potential are produced. R_1 or R_3 may be used to control the amplitude of the linear sweep.

12–20. Electron-ray tubes—the design of electron-ray tubes.

When the function of a cathode-ray tube is only to measure voltage without plotting its variation with time, only one set of deflector plates is required, no particular focusing being necessary. A very simple cathode-ray tube may, therefore, be used in the measurement of volt-

[19] Geohegan, W. H., *Electronics*, Nov., 1940; p. 26.

age.[20],[21],[22] Devices produced commercially for this purpose are known as *electron-ray tubes and consist of a cathode, an electron collector cup* coated with a fluorescent material, and a deflector. The deflector is in the form of a vane so arranged that as it becomes progressively more negative electrons are repelled, casting a shadow of the deflector electrode on the fluorescing cup. Tubes of this type may combine two vanes in a single envelope, producing two shadows. The type 6AF6G is a typical example of this construction. Fairly large voltages are required to obtain large deflections; for this reason many electron-ray tubes combine a triode in the same envelope to amplify the deflecting voltages. Types 6U5 and 6N5 and similar types are examples of this construction. The

(a)   (b)
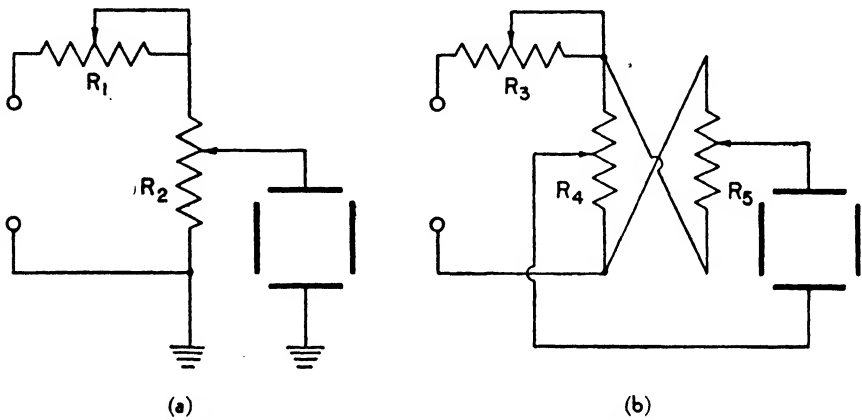
FIG. 12–21.   Mechanical Sweep Generators.

cathode-ray portion of these tubes may be studied separately from the triode section and this type will, therefore, be used in the following experiments.

EXPERIMENT 12–4

Purpose: To study the characteristics of an electron-ray tube.

Materials: 6N5 tube
1,000- and 10,000-ohm volume control
0-150 and 0-10 voltmeters
1-megohm $\frac{1}{2}$-watt resistor
7.5-v. battery
3 45-v. batteries
6.3-v. transformer

Procedure A. In order to study the cathode-ray portion of the electron-ray tube, wire the apparatus as shown in Figure 12–22. Adjust R_1

[20] Thompson, H. C., *Proc. I.R.E.* **24**, 1276, 1936.
[21] Waller, L. C., *R.C.A. Rev.* **1**, 111, 1937.
[22] Ridenour, L. H., *R.S.I.* **12**, 134, 1941.
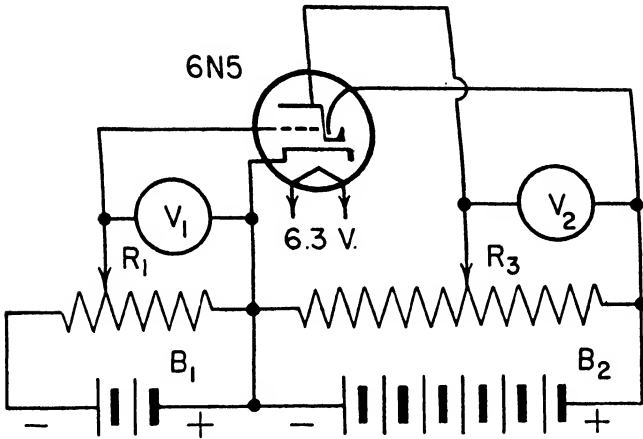
Fig. 12–22. Characteristics of an Electron-ray Tube. R_1 = 10,000-ohm potentiometer; R_3 = 25,000-ohm potentiometer; V_1 = 0–10 voltmeter; V_2 = 0–150 voltmeter; B_1 = 7.5 v.; B_2 = 90 v.
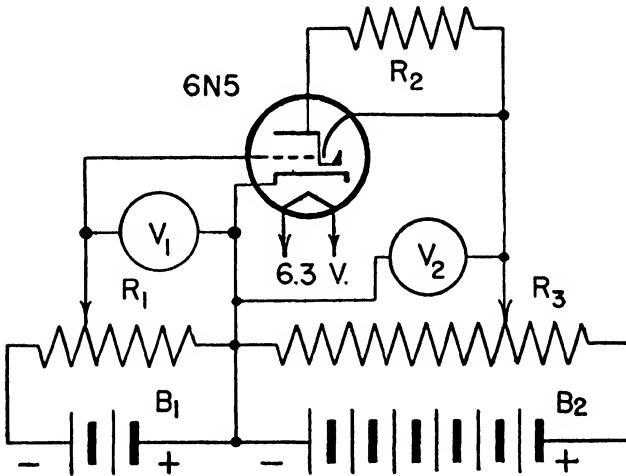
Fig. 12–23. Circuit for Determining the Characteristics of an Electron-ray Tube. R_1 = 10,000-ohm potentiometer; R_2 = .5 megohm; R_3 = 25,000-ohm potentiometer; B_1 = 7.5 v.; B_2 = 135 v.

to maximum voltage so that no plate current flows in the triode unit. Under these conditions the triode unit cannot affect the measurements. Since the deflector plate of the 6N5 tube is connected internally to the plate of the triode unit, the plate lead is made negative with respect to the target by R_3. Paste a divided scale around the top of the tube in order to read the deflection; then, with 45 v. across R_3, vary the voltage on the deflector electrode (plate connection) and read the deflection at various intervals. Repeat with 90 v. and 135 v. Note that as the voltage increases the fluorescence becomes brighter but the deflection sensitivity decreases. Plot these values as a function of accelerating voltage.

Procedure B. Connect the tube in the normal fashion as indicated in Figure 12–23, and determine the deflection sensitivity by changing the grid voltage with R_1. Use plate voltages of 45, 90, and 135 as before. Plot the deflection as a function of grid voltage. Repeat the experiment with different values of R_2. Note that the triode functions as a voltage amplifier so that when the plate current is at cutoff the deflector vane and plate are at the same potential as the target or fluorescing cup, but as the grid becomes less negative the plate current increases and the potential of the plate and deflector vane drop in relation to the voltage of the target.

SUPPLEMENTARY LITERATURE

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