RADIO RECEIVING AND TELEVISION TUBES

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JAMES A. MOYER

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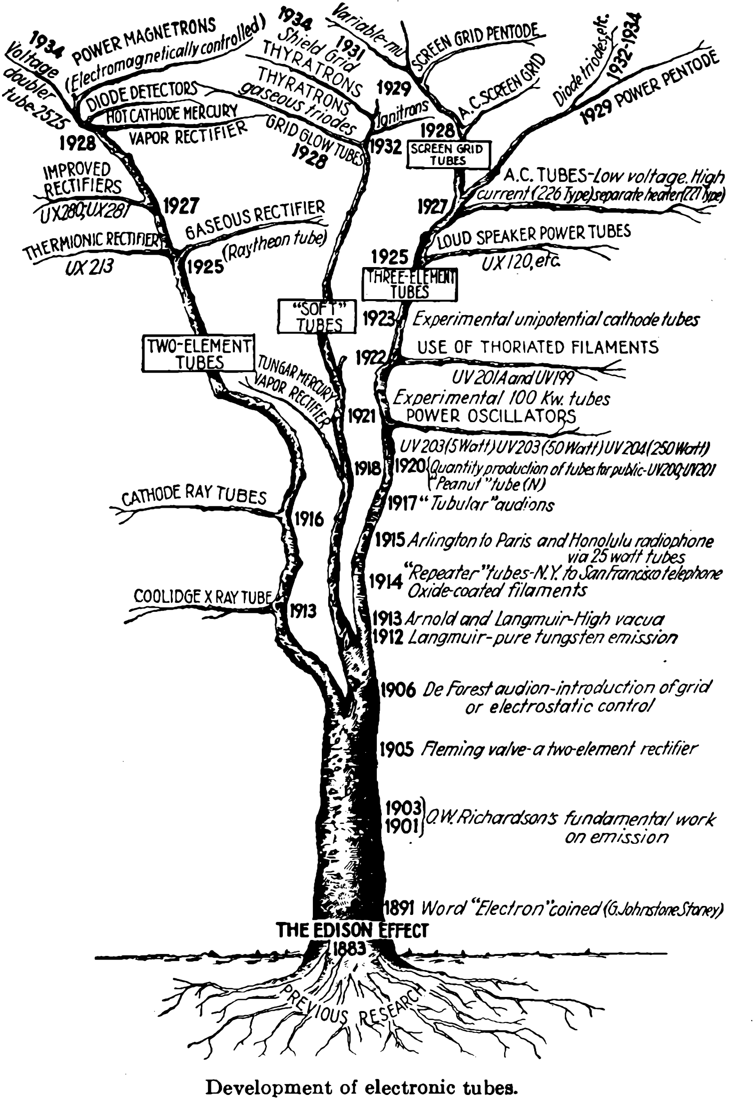

Development of electronic tubes.

RADIO RECEIVING

AND

TELEVISION TUBES

INCLUDING APPLICATIONS FOR DISTANT CONTROL OF INDUSTRIAL PROCESSES AND PRECISION MEASUREMENTS

BY

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THIRD EDITION

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PREFACE TO THE THIRD EDITION

Every year a seemingly new crop of radio tubes comes from the laboratories of the manufacturers. Although their bewildering technical names refer in most part to improvements rather than to fundamental changes, there have been in the last few years many really important developments which have had a significant influence on the application of all kinds of electronic equipment.

When the previous edition was published, the radio receiving tubes then in practical use had only two, three, or four elements. With the development and introduction into practical designing of tubes with five, six, or more elements, combining in one tube the functions that were formerly performed by two or more tubes, there were, of course, made available to the designer opportunities for obtaining results in radio reception that previously were economically impossible.

The introduction of all-metal tubes by which the glass bulb of radio receiving tubes is replaced by a much smaller thin metal cylinder has made it possible for engineers to make their new designs more compact and safer in transportation than before.

In this revision, the previous edition has been entirely rewritten and reset; information that is no longer of general usefulness to designers has been omitted, and emphasis has been given to the strictly modern types of tubes and their applications, not only in radio receiving and television equipment, but also in other practical uses.

Opportunities for employment in the radio and television fields, and, in fact, in the whole general field of electronics, may be said, in the words of a well-known and successful engineer, to lie "both forward and sidewise—forward into new types of applications, and sidewise into more extensive use in the services for which they have already demonstrated their value." Those having guidance responsibilities in universities, engineering colleges, and technical institutes may very well have in mind these facts, so that courses in engineering science may be arranged to include electronic theory and practice. Such employment possibilities, important as they are for the person recently graduated, are equally important, however, for the engineer who graduated before the modern electron tube was invented or before it emerged from the laboratory and entered into actual services. Those engineers of an earlier vintage in graduation who have not had the benefit of systematized instruction in the subject of electronic theory and practice while in college should somehow acquire a knowledge of the fundamental characteristics and applications of the new electronic tubes—whether or not they have permanent employment—or they are much in danger of dropping behind in their profession.

The authors are especially indebted in the preparation of this revision to M. J. Carrol of the R.C.A. Victor Corporation, Camden, New Jersey; Chester L. Dawes, Professor of Electrical Engineering, Harvard University, Cambridge, Massachusetts; C. Davis Belcher, Boston, Massachusetts; and also to the Raytheon Production Corporation, and the Hygrade-Sylvania Corporation, for important text material.

In the preparation of this revision, frequent references have been made to the current issues of *Electronics*, *Electrical Engineering*, *General Electric Review*, *Electric Journal*, *Proceedings of the Institute of Radio Engineers*, and the *Journal of the Franklin Institute*. The engineering departments of the Westinghouse Electric and Manufacturing Company, Radio Corporation of America, and Bell Telephone Laboratories have made valuable contributions.

THE AUTHORS.

STATE HOUSE, BOSTON, MASSACHUSETTS,
January, 1936.

PREFACE TO THE FIRST EDITION

Until the invention of printing, the communication of news and ideas was accomplished almost entirely by word of mouth. Thereafter, the avenues of communication were broadened enormously, and as a result the eye supplanted the ear as the principal external medium for the reception of ideas. With the present development of radio devices, the ear has come into its own again. Sound borne upon radio waves transcends space and transcontinental communication is commonplace. This remarkable accomplishment owes much to the vacuum tube, the most essential part of all radio apparatus.

In a comparatively short time, there has been a great increase in the use of vacuum tubes for radio purposes. Concurrently, popular interest in a practical knowledge of radio principles and radio operation has greatly increased.

In this book the essential principles underlying the operation of vacuum tubes are explained in a manner calculated to present a well defined picture to students and general readers. The vacuum tube possesses a remarkable variety of functions and, accordingly, this book includes, in addition to the use of two- and three-element vacuum tubes for radio reception and transmission, other applications that are of considerable practical significance. These additional applications include the remote control of airplanes and sea-going vessels by the use of instruments which employ vacuum tubes in essential capacities, as well as methods of applying vacuum tubes to the remote control of humidity and similar uses. The first chapter of the book is introductory; its purpose is to outline briefly some present theories concerning the flow of electrons from highly heated bodies to those which are relatively cool.

The authors wish to express their appreciation of the assistance they have received from Mr. Glenn H. Browning of the Browning-Drake Corporation and Mr. Horatio Lamson of the General Radio Company, and to acknowledge the contributions made by the Radio Corporation of America, the General Electric Company, the New England Telephone and Telegraph Company and E. T. Cunningham, Inc.

THE AUTHORS.

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February, 1929.

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RADIO RECEIVING AND TELEVISION TUBES

CHAPTER I

INTRODUCTION

Principles of Operation of Radio Vacuum Tubes.—For more than one hundred years the fundamental phenomena associated with the present use of radio vacuum tubes have been known to scientists.[1] These phenomena depend on the ability of very hot bodies to discharge electricity at moderate voltages through the surrounding air, which thus acquires electrical conductivity. A white-hot platinum wire, for example, when placed in an atmosphere where the pressure is very low will charge negatively an electrode which may be nearby. This phenomenon is due to the emission of negative *ions*[2] from the hot platinum wire.

The analogy of this phenomenon to the operation of a radio vacuum tube can be made clearer by studying the mutual effects of a highly heated filament and an enclosing cylindrical electrode made preferably of a metal which is a good conductor of electricity. The filament may, of course, be conveniently heated to incandescence by passing an electric current through it. Now, if this filament and the surrounding cylindrical electrode are in a glass tube or similar container in which a *high vacuum* is maintained, and provision is made by the use of suitable connections to apply to the electrode a high *positive* potential, the electrode will be heated moderately

[1] DuFay, "Mémoires de l'Académie," 1733.

[2] *Ions* are small charges of electricity which, according to our modern theories, are not supposed to be associated directly with matter. Negatively charged ions of electricity are called *electrons*.

merely by the "bombarding" action of the negative ions or *electrons* emitted from the incandescent filament. A glass tube containing a filament and an electrode in a rarefied atmosphere, as described, is called a *two-element vacuum tube.*

Reasons for the Use of Vacuum in Radio Vacuum Tubes.—The mutual action of a highly heated filament and a nearby positively charged electrode for producing electron emission is increased if the filament and electrode are in an enclosure from which the air and all other gases have been removed. The reason for this is that a gaseous atmosphere in the enclosure has a retarding influence on the emission of negative ions or electrons. Also, any effects due to the ionization of a gas by impact with the electrons are avoided.

Edison's Experiments.—Sometime before 1890, when Edison was engaged in experimental work with carbon-filament incandescent lamps, he observed, when a metal plate was sealed inside a lamp bulb so that it was between and separated the two sides of the carbon filament but was entirely insulated electrically from the filament itself, that a current of electricity flowed through a galvanometer when connected between the outside terminal of the metal plate and the *positive* terminal of the filament. On the other hand, when the connection was reversed, that is, when the galvanometer was connected between the *negative* terminal of the filament and the outside terminal of the plate, no current flowed through the galvanometer. At the time Edison made this experiment, there was no satisfactory explanation. It is now known, however, that this action is due to the flow of electrons from the heated filament to the plate inside the bulb when the outside terminal of the plate is made positive. In other words, when the outside terminal of the plate is *positive* by being connected electrically to the positive terminal of a source of electricity, the electrons which are evaporated from the heated filament are *attracted* to the plate and set up a flow of current. When, however, the insulated plate is connected to the negative end of the filament, it is made *negative* so that it *repels* the electrons which are being evaporated, and consequently there is no noticeable flow of current from the filament to the plate. There is no perceptible flow of electrons in the latter case because they cannot leave the insulated plate to flow to the filament, it being possible for only very small numbers of ions to escape from a cold body.

When stating the fact that ions can freely leave the surface of a hot body but cannot leave the surface of a cold body to an appreciable extent, the word "cold" is taken to mean that the temperature of the body is below that corresponding to a dull red heat.

When, therefore, an *alternating current* is applied to a heated filament surrounded by an electrode, both being in a rarefied atmosphere, it will be found that a current of electricity will flow in *only one direction;* that is, from the electrode to the hot filament instead of both ways as a normal alternating current does.

Two-element Vacuum Tubes for Rectifying Alternating Currents.—Practical application can be made of this phenomenon for the rectification of alternating current, and vacuum tubes made especially for this kind of service are called *rectifying tubes.* When used for this purpose, each of the two terminals from the alternating-current supply is connected to either of the lead-wires supplying the current required for heating the filament and also one of the terminals of the alternating-current supply is connected electrically to the electrode surrounding the filament.[1]

An arrangement of a filament *F* and an insulated plate *P* with galvanometer and battery connections is shown in Fig. 1. A so-called "A" battery may be used to heat the filament to

[1] At the moment when the field, due to the alternating current, acts in such a direction that the surrounding electrode is negative with reference to the hot filament, only positive ions can pass across, and the number of these is very small. On the other hand, when the alternating current reverses and produces a field in the other direction, there is a relatively free passage of electrons (negative ions) from the hot filament to the electrode.

The emission of negative electrons, unlike the positive ions, is quite steady, and varies in amount for different materials used for making the filament and with its temperature.

incandescence. As shown in the figure, a "B" battery is here in series with the negative terminal of the heated filament, the galvanometer, and the insulated plate. This is the condition when, as in the description of the Edison experiment, the negative terminal of the heated filament is connected through the galvanometer to the cold plate. Now, when the plate is made positive with respect to the heated filament, the electrons evaporating from the filament will be attracted to the plate,

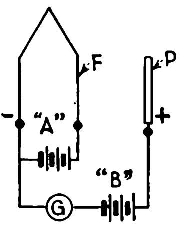

FIG. 1.—Circuit diagram in vacuum tube when the plate is positive.

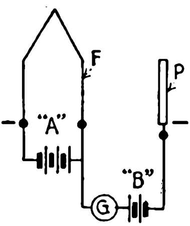

FIG. 2.—Circuit diagram in vacuum tube when the plate is negative.

entering the plate and flowing back to the negative terminal of the filament through the wires connecting the galvanometer and battery. The electrons will then pass from the negative terminal of the filament to the side connected to the positive terminal and again evaporate on that side and pass on by attraction to the cold plate. On the other hand, when the conditions shown in the figure are reversed so that the plate becomes negative with respect to the filament, as in Fig. 2, the electrons coming from the filament will be repelled by the plate and will reenter the filament. In this case, there is no current in the plate circuit. The two-electrode vacuum tube may, therefore, be used as a *rectifier of alternating electric currents* as it permits the flow of current in only one direction. In this respect, this kind of vacuum tube has similar characteristics to some mineral rectifiers of radio currents called "crystal detectors."[1] In fact, in the early years of radio

[1] MOYER and WOSTREL, "Practical Radio," 4th ed., pp. 36–38, McGraw-Hill Book Company, Inc., New York, 1931.

communication, two-electrode vacuum tubes were used to some extent in the place of crystals. It was in 1905 that Prof. J. A. Fleming suggested the use of a two-electrode vacuum tube as a rectifier for the detection of radio waves, while in 1907 deForest conceived the idea of introducing a third electrode into a tube of this kind from which practically all the air and gases had been removed. This third electrode was in the form of a metallic mesh through which the electrons must pass on their way from the filament to the surrounding electrode, which will now be called the *plate.* This original three-electrode vacuum tube, as first devised by deForest, is shown in Fig. 3. Because of its shape and appearance, deForest called this third electrode a *grid,* and he discovered that it served a very useful purpose in a vacuum tube, as it was a means of controlling the flow of electrons from the filament to the plate. The introduction of this grid into the vacuum tube made it possible to increase enormously the sensitiveness of the receiving apparatus used in radio work. By making the grid of a vacuum tube positive or negative, according to requirements, the amount of *current* flowing between the plate and the hot filament can be increased or decreased, as may be necessary. The grid in performing this function consumes practically no power for itself, serving merely as a sort of *valve* for controlling the amount of plate current.

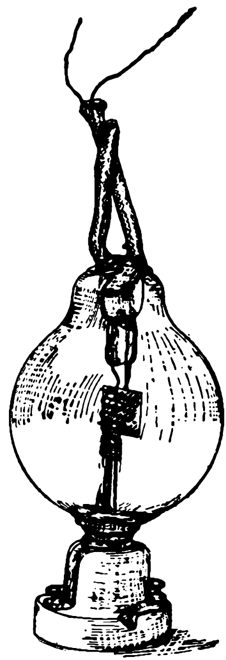

FIG. 3.—Three-element vacuum tube as constructed by deForest.

Since the grid in a vacuum tube is nearer the filament than the plate, any change of potential difference between it and the filament produces a greater change of field strength at the filament than when there is an equal change of the potential difference between the plate and the filament. Thus, a relatively small change of the potential difference between the grid and the filament causes a relatively large change of the current flowing between the plate and the filament. As the electrons constituting this current from the plate to the filament come near the wires of the grid, they are attracted both by the grid when it is *positive with respect to the filament* and *by the positively charged plate.* In this case, the attraction of the *strongly positive plate tends to predominate,* with the result that relatively few of the electrons actually reach the grid; consequently, nearly all are in the flow of electrons to the plate. On the other hand, in those cases which occur so frequently in practice, where the grid is *negative with respect to the filament,* the amount of current reaching the grid is so small that it may be considered a negligible quantity. Further, the action of the negative grid is to decrease the flow of electrons to the plate.

It will thus be seen that the grid provides a means of controlling the amount of current flowing from the plate to the filament, and that this control is obtained by the use of a small amount of current, and, also, by the expenditure of very little power (watts) for the reason that the voltage changes are very small.

Three-element Vacuum Tubes.—In this description of the action of vacuum tubes with three elements, that is, the filament, the plate, and the grid, it has been assumed in all cases that the atmosphere in the tube was very much rarefied and that, therefore, the gas, from whatever source, remaining in the tube had no effect on its action. In the so-called "hard" vacuum tubes (page 22), so little gas is present that this assumption is justified. A few types of vacuum tubes, however, usually called "soft" or gas tubes, contain a small amount of gas which was put into them during the process of manufacture. In the normal operation of these "soft" vacuum tubes, the stream of flying electrons from the heated filament to the positively charged plate has the effect of ionizing the gas contained in the tube and segregating from the gas some positive ions. These segregated positive ions, owing to their weight, move toward the filament quite slowly. In the space near the filament, these positive ions from the gas neutralize the negative electrons, which are farther away from the filament, thus permitting a greater current to be maintained with a given voltage difference between the fila-

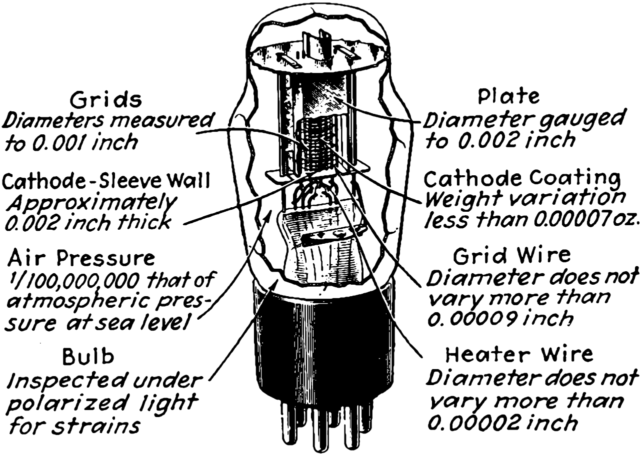

FIG. 4.—Materials used in typical radio receiving tubes.

Materials for Vacuum Tubes.—The complex nature of the structure of the modern vacuum tube, and of the manufacturing processes, is well illustrated by a consideration of the materials that are used.

Gases.—Argon, carbon dioxide, chlorine, helium, hydrogen, illuminating gas, neon, nitrogen, and oxygen.

Metals and Compounds.—Alumina, aluminum, ammonium chloride, arsenic trioxide, barium, barium carbonate, barium nitrate, borax, boron, caesium, calcium, calcium aluminum fluoride, calcium carbonate, calcium oxide, carbon, chromium, cobalt, cobalt oxide, copper, iridium, iron, lead, lead acetate, lead oxide, magnesia, magnesium, mercury, misch metal, molybdenum, monel, nickel, phosphorus, platinum, potassium, potassium carbonate, silica, silicon, silver, silver oxide, sodium, sodium carbonate, sodium nitrate, tantalum, thorium, thorium nitrate, tin, titanium, tungsten, zinc, zinc chloride, and zinc oxide.

Accessories.—Bakelite, ethyl alcohol, glass, glycerine, isolantite, lava, malachite green, marble dust, mica, nigrosine, petroleum jelly, porcelain, rosin, shellac, synthetic resin, and wood fiber.

ment and the plate than is possible in a so-called "hard" tube where there are practically no positive ions present from gases in the tube.

The materials commonly used at present for making the filaments of vacuum tubes will be discussed in later sections. The electrodes, both the plate and the grid, are usually made of nickel or molybdenum or other conductors of electricity having high melting points. The materials and tolerances used in the construction of RCA radio receiving tubes are shown in Fig. 4.

The early three-element vacuum tube as constructed by deForest was called an "*audion*" and proved to be a very sensitive detector of radio currents, but was rather erratic in its behavior, the difficulty being that the various gases remaining in the tube after the imperfect and incomplete removal of gases, as attempted at that time, left so much residue that the ionization of the gases was a variable and, consequently, troublesome factor.

In 1912, improved methods were developed for the manufacture of radio vacuum tubes of the three-element type, making possible the almost complete removal of all the air and other gases in the tube to suit the special requirements of any kind of work, including the removal of the gases which had been absorbed in the metal of the electrodes and in the glass walls of the tube. Following these improvements in manufacture, vacuum tubes became dependable and reproducible in their characteristics, so that it is now possible to calculate the proper proportions of a vacuum tube.

Briefly, the principle of operation of a three-element vacuum tube is that the flow of electrons from the hot filament to the cold plate is varied by applying variations of voltage to the grid. The circuit of the tube consists, therefore, of two branches: (1) the *output circuit*, or plate circuit, connecting the filament to the plate through some kind of "load" such as a resistance or an inductance coil, and (2) the *input circuit* connecting the filament to the grid through the secondary winding of a transformer or other means of supplying variations of potential to the grid.

Since small variations in the potential applied to the grid produce large variations in the plate current, it can reasonably be expected that more power is released in the *output or plate circuit* than is expended in the *input circuit*, and this is actually the case. Since the power in the output circuit of the three-element tube is greater than the power expended in the input, it is possible to increase the degree of sound amplification by *feeding back*[1] part of the energy in the output to the input. If the proportion of the energy thus returned to the input circuit is large enough and the phase relations of the currents in the output and input circuits are right, the tube can be made to produce the kind of sustained oscillations (page 147) that are needed for some radio circuits.

The addition of the grid as a part of the radio vacuum tube produced a device of enormous possibilities, giving the vacuum tube the same importance as the steam turbine, the Diesel engine, the dynamo, and the telephone.

Classification of Receiving Tubes.—Vacuum tubes may be classified in a number of ways depending on the subject under discussion. The radio-service expert, the amateur, and the student may find it useful to group them as tubes with two elements, tubes with three elements, tubes with more than three elements, and tubes that are gas-filled at low pressure for changing their operating behavior. Tubes are named according to the number of elements they possess—thus, a two-element tube is a *diode*, a three-element tube is a *triode*, a four-element tube is a *tetrode* (screen-grid), a five-element tube is a *pentode*, and so on. Tubes may be classified also according to the kind of service for which they are intended—under this heading there are *power amplifiers* or power-output tubes, *voltage amplifiers*, *frequency converters*, *detectors*, *mixer tubes*, *rectifiers*, *oscillators*, *current regulators*, and *voltage regulators*. The frontispiece illustration shows very clearly the various stages in tube development. A number of special types which are used in applications other than radio broadcasting and reception are the magnetron, the dynatron, the cold-electrode (general purpose), and the cathode-ray tubes.

[1] MOYER and WOSTREL, "Practical Radio," 4th ed., p. 67.

CHAPTER II

CONSTRUCTION OF VACUUM TUBES

The number of electrons emitted from a hot metal depends on the kind of material and its temperature. Tungsten emits electrons freely and can be heated to high temperatures. This metal is, therefore, suitable for use in making the filaments in many types of vacuum tubes. The emission of electrons from platinum is not free but is increased considerably, even at low temperatures, if the platinum is coated with certain oxides such as those of strontium, barium, and calcium. A filament made of tungsten and thorium oxide also emits electrons freely.

At the present time the most common types of electron emitters for radio receiving tubes are the heated cathode filament, the coated filament, and the thoriated tungsten filament.

Heater Filaments.—The type of filament known also as a unipotential cathode or as an indirectly heated cathode consists of a nickel sleeve which encloses a "heater" element carrying the heating current. The heater element, made of tungsten wire, is electrically insulated from the metal sleeve. The sleeve is coated with alkaline earth compounds, such as barium and strontium carbonates, with the addition of a small amount of carbonates of sodium or potassium. A difficulty experienced with the early type of cathode heater was the time required to reach the operating temperature, this being as high as 60 seconds for some types. Various types of construction are used to obtain a low heating time which in some tubes has been reduced to less than 10 seconds. Extreme care is needed to avoid a construction which is favorable to hum or to microphonic action in the attempt to reduce heating time. Several methods may be used for electrically insulating the heating element from the electron-emitting cylinder. In some types, particularly those intended for quick heating, the insulating material may be applied to the heating element with a spray gun; in others the insulating material is used in the shape of a core with suitable openings for the heating element. The tungsten wire comprising the heating element appears in many forms as shown in Fig. 5, some of which are the coil and the inverted V in a single-hole insulator, the wire loop in a double-hole insulator, and the wire loop in a single-hole insulator with end spacers. A recent form in

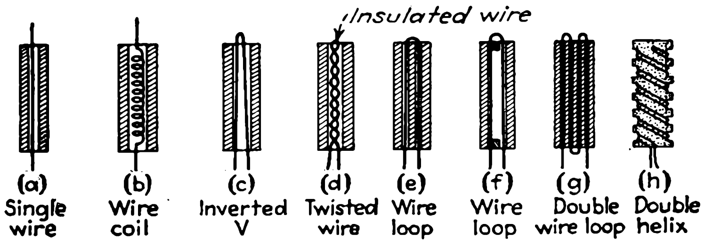

FIG. 5.—Tungsten heating elements.

which a reversed coil winding is baked in the insulator or threaded into it is intended not only to reduce the electromagnetic field responsible for the production of hum but also to reduce the heating time by placing the heater wire nearer to the cathode sleeve. The insulator also appears in various forms, such as the solid single-hole type, the solid double-hole type, and the perforated type; the materials used include porcelain, magnesia compounds, and alumina compounds.

Tubes utilizing the *heater-cathode construction* are well adapted for filament operation with alternating current since the heater element is insulated from the sleeve, and the sleeve has a shielding effect. Tubes of this type, because of their freedom from electrical interference which might enter through the filament supply line, because of their mechanical strength, and because of the electrical flexibility due to the single cathode connection, are suitable for any direct current and especially for automobile receiving sets. Heater cathodes have been used also in diode rectifiers. When the electron emission stops in either the heater type or the coated type of filament the usefulness of the vacuum tube is ended.

Oxide-coated Tube Filaments.—An ordinary oxide-coated filament of a vacuum tube is usually made of a thin strip of nickel, silicon-nickel, or cobalt-nickel alloy, with a *surface layer* of strontium and barium oxides. Compared with a filament made entirely of tungsten, one of the oxide-coated kind has a longer life and is capable of a given rate of electron emission at about one-tenth of the filament power (watts) that is required by a tungsten filament. The end of the normal life of this type of filament is indicated by an actual failure or burn-out and not by a previously marked decrease in filament emission. The resistance of the oxide-coated filament is constant throughout its life because the current flows mostly in the core and the evaporation takes place from the coating. The approach of the end of life of such a tube is accompanied by an increase in temperature in places on the filament, sometimes indicated by *bright spots.* At the rated operating temperature, an oxide-coated filament is dull red in appearance. The use of the oxide-coated filament is limited almost entirely to applications in which both the power requirements and the operating voltages are relatively low.

Thoriated-tungsten Filaments.—The type of filament which is made mainly of tungsten but contains a small percentage of thorium oxide is called a thoriated-tungsten filament. In the process of manufacture the oxide is dissolved in molten tungsten before it is drawn into threadlike filaments. When a filament of this kind is heated in the normal operation of a vacuum tube, part of the thorium oxide is changed to metallic thorium which accumulates on the outside of the filament and constitutes the active surface from which the emission of electrons takes place. At the specified temperature of operation the emission of electrons from the filament surface takes place at the same rate as the thorium emerges from the interior of the filament. This process continues throughout the life of the tube provided the temperature of the filament is not excessively high. If, however, the temperature of the filament is raised a few hundred degrees Fahrenheit above the normal value, that is, to a temperature corresponding to a voltage overload of about 10 per cent of the rated value, the balance between surface evaporation of the thorium oxide and the supply of this oxide from the interior of the filament is disturbed. After being subjected for a time to this excessive voltage, the active thorium layer on the filament is completely evaporated, leaving a clean tungsten surface. The filament emission then decreases rapidly because the electron emission of a tungsten filament even at this excessive temperature of operation is very small. At the excessive temperature, however, the rate of formation of the metal thorium from its oxide is increased, but the rate of surface evaporation is increased to a greater degree. If the filament voltage is still further increased, the overload on the tube is increased until finally no emission at all is obtained.

Under certain conditions, ionization[1] of gas in a vacuum tube will serve to dissipate the thorium on a filament or to neutralize its activity. On the other hand, if the temperature of operation is *below* the normal value (corresponding to an underload) the rate at which the surface layer of thorium is retained may be likewise retarded, with the result that the filament may be "paralyzed." The normal life of a thoriated-tungsten filament ends when the thorium supply is exhausted. The indication of the exhaustion of the thorium is a sudden decrease in filament emission, and not an actual failure or burn-out as in the oxide-coated filaments. At the rated operating temperature the thoriated-tungsten filament is yellowish in appearance.

At the present time the thoriated-tungsten filaments are used mostly in power tubes (page 22) rated at several hundred watts.

Pure-tungsten Filaments.—The pure-tungsten filament once much used in vacuum tubes has been replaced by the more efficient oxide-coated and thoriated filaments. The

[1] Ionization of the gas is explained on p. 21.

so-called "type UX-200" and "201" vacuum tubes which are no longer manufactured were made with this kind of filament. At the rated operating temperature a tungsten filament is whitish in appearance. Vacuum tubes used for heavy power work and operated at high plate voltages are still made with pure-tungsten filaments.

Filament Emission.—The available supply of electrons at the filament of a vacuum tube must always be greater than the "demand" produced by the plate current. Thus, the normal maximum plate current of a certain three-element vacuum tube (page 6) is 20 milliamperes. But at the full output of the tube the plate current varies from about 1 to about 40 milliamperes. Consequently, in order that the "peak" current may be satisfactorily "handled" by the tube, the minimum satisfactory electron emission for this type of vacuum tube is about 50 milliamperes, or two and a half times the normal maximum plate current.

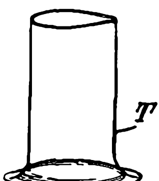

Fig. 6.—Glass support for vacuum tube.

Manufacture of Vacuum Tubes.—A step-by-step description of the assembly of the parts of a vacuum tube will illustrate its construction. The type of tube selected for this description is the 2A5, a power amplifier pentode (page 9), which is similar to type 42 (page 621), except for its heater rating. Figure 6 shows the glass tube *T* which serves as the main support of the elements of the vacuum tube, and Fig. 7 the kind of construction which is used to hold the supporting posts *R* and the lead-in wires *W* in the glass seal *S*. This glass seal is fused to the top of the flanged glass tube *T* and a long piece of thin glass tubing *E* is fused into the side of the glass tube *T*, as shown in Fig. 8. At the stage in manufacturing shown by these figures, both ends of the glass tube *E* are open because during the fusing process air is blown through the tube. The progress of construction after the supporting posts *R* are bent to the proper position is illustrated in Fig. 9. Each of the three wires *N* is connected to its terminal wire *W* and three of the four posts *R* are connected to wires *W*, but one post *R* serves merely as a support. In the next stage of manufacture the lower mica disk *M* is added. The principal purpose of this and the other mica disks is to maintain the alignment of the various elements of the tube and to provide rigidity. Next the cathode-heater cylinders *H*, illustrated in Fig. 10*a*, are located in holes in the mica disk. The filament wire *F* shown in Fig. 10*b*, which is in the form of an inverted *V* is covered with insulation except at the top and the ends. This filament wire fits snugly in

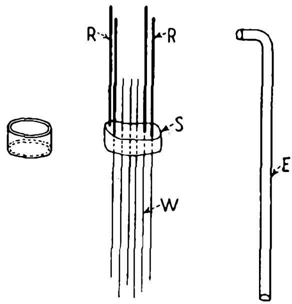

FIG. 7.—Construction of supporting posts and lead-in wires.

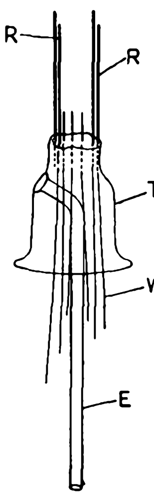

FIG. 8.—Method of fusing capillary tube into flanged glass bell.

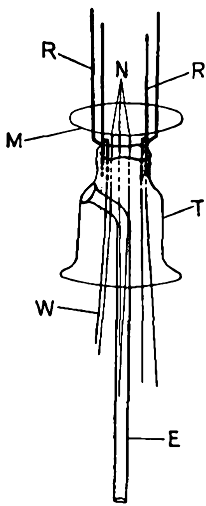

FIG. 9.—Method of bending and connecting supporting posts to wires connected to common terminals.

the cathode heater cylinder *H*. The complete filament consists of two sections connected in parallel as shown in Fig. 10*c*, and attached to two of the supporting wires *N* shown in Fig. 9, and consequently also to wires *W*.

In the type of *grid* illustrated in Figs. 11*a*, 11*b*, and 11*c*, the grid wires are pressed into the soft metal of the frame during the process of winding. The grid wire is made of molybdenum,

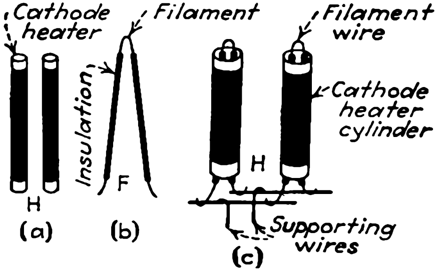

FIG. 10.—Construction of cathode heaters.

nichrome, nickel-iron alloy, or manganese-nickel. The grid frame wires fit into holes in the mica disk *M*. The smallest and innermost grid G_1 is connected through one of its frame wires to the supporting wire *N*, indicated in Fig. 9. This grid is known as the *control grid*. Grid G_2 is the *screen grid* which is connected to one of the supporting posts *R* by a metal strap joined beneath the lower mica disk, to one of the end frame wires of G_2. The *cathode* or *suppressor grid* G_3 is located

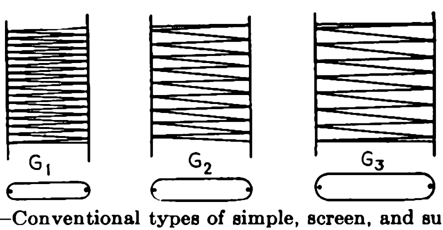

FIG. 11*a*, *b*, *c*.—Conventional types of simple, screen, and suppressor grids.

between the screen grid and the plate. The *plate P* (Fig. 12), in the form of a metal cylinder, fits over the two end posts and is welded to them. Various forms of plates are used, from a wire-winding to heavy sheet metal. The material is usually nickel or iron. After these parts have been attached the upper mica disk *M* is set in place. One of the frame posts of the grid G_3 is connected by a metal strap *L* (Fig. 13) placed above the upper mica disk to a supporting post *R*. This same post *R* is connected to the two cathode heater cylinders *H* by a metal strap *O* located beneath the lower mica disk. The heat radiator *K*, made of carbonized nickel, is connected above the upper mica disk to the frame posts of the control grid G_1 and serves not only to increase the radiation of heat but also to reduce the grid emission.

The *getter*, the action of which is described later (page 19), is contained in the receptacle *C* as in Fig. 12, or in some forms of construction is fastened directly to an element of the tube such as the plate *P*. In this tube the getter cup *C* is welded to one of the supporting posts *R*.

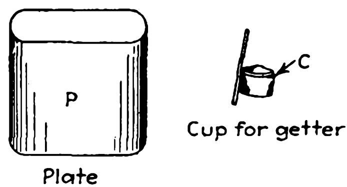

FIG. 12.—Typical plate and cup for getter.

A glass bulb *B* is placed over the assembled unit, as indicated in Fig. 14, and is fused to the flange on the large glass tube *T* (Fig. 13). The only connection between the inside of the bulb and the atmosphere is through the very small glass tube *E*.

Many of the glass-sealing processes used in the manufacture of vacuum tubes require careful annealing of the glass parts of the tube. This is accomplished by allowing the temperature to drop very slowly. Molten glass which is cooled quickly is subject to internal strains. When the cooling is rapid, the temperature at the surface drops quickly and the outside layer solidifies. The interior, however, tends to contract and exert an inward pressure on the outer layer. This may result in cracks. The air and other gases are exhausted from the glass bulb of the tube through the small glass tube *E*.

Care is required to get rid of the air and other gases, not only in the space inside the glass bulb, but, also, in the walls of the bulb and glass tubes and in the metal of the elements. Even if a bulb is thoroughly exhausted by a vacuum pump, it subsequently would give indications of the gases which gradually come out of the interior parts. At ordinary temperatures, these gases are released so slowly that the period of evacuation would have to be lengthened to a prohibitive extent before the vacuum is satisfactory. In order to drive out quickly these gases from the walls of the bulb and from the elements, the tube is kept hot during the process of exhaustion. For

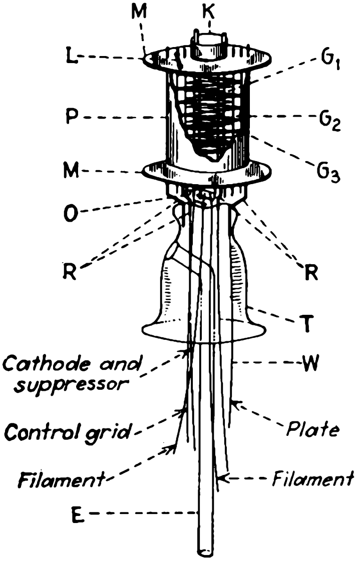

FIG. 13.—Assembly of grids, plate, mica disks, cathode heater cylinders, and heat radiator.

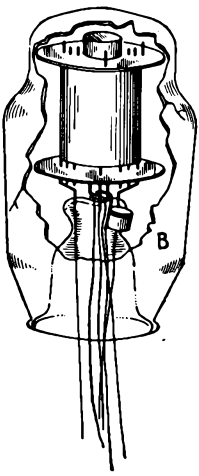

FIG. 14.—Glass bulb used to cover assembled unit.

a similar purpose, the filament may be heated by electric current and a positive voltage applied to the grid and plate so that they are heated by the impact of electrons from the filament. The evacuation is continued until the vacuum reaches a value corresponding to a pressure of 1/100,000 millimeter of mercury (1/100 micron[1]). When the desired

[1] The standard of atmospheric pressure is defined as that pressure which at sea level and at a temperature of 0°C. will support a column of mercury 760 millimeters high. Another unit used in the measurement of very low pressures is the *micron* of mercury, equal to one thousandth of a millimeter of mercury. One millimeter is equal to 0.0394 inch.

degree of vacuum is obtained, the small glass tube *E* is melted off and the bulb is thus permanently sealed.

During the operation of a vacuum tube in service a further release of gases takes place. To absorb these gases a small supply of a so-called "getter" is assembled with the tube elements. This consists of an alkali metal such as magnesium or such a substance as phosphorus, arsenic, and sulphur, each of which volatilizes readily. When the tube is sealed this "getter" is volatilized and then condenses in a silvery film on the inside of the glass bulb. This film not only attracts the gases as they are released but also tends to seal the gases in the walls of the bulb.

Finally, the glass bulb is cemented to an insulating base in the bottom of which are small hollow rods. The lead-in wires pass through these rods and are fastened to them by a drop of solder at the bottom of each rod. These rods form the contact prongs of the vacuum tube which is then made up as shown in Fig. 15.

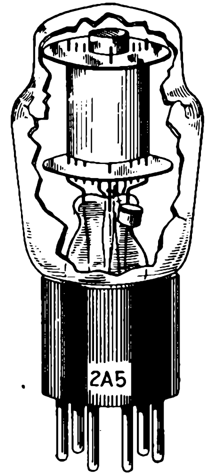

Fig. 15.—Attachment of contact prongs to glass-bulb radio tubes.

During manufacture the vacuum tubes are put through various factory tests and, in addition, production samples are taken for a test on characteristics. In this test a check is made of the filament current, electron emission, plate current, screen-grid current, grid current, grid emission, insulation, vacuum, amplifying properties, and plate resistance. These tubes then are given the life test in which they are operated at the maximum voltages for which they are designed; the filament types being operated continuously and the heater types intermittently. Mechanical tests may be given also to determine the effect of ordinary vibration and jarring on the tube structure.

Recent Changes in Tube Structure.—In the newer tubes, designs have been improved in a number of ways. For example, the dome-bulb type of construction is conducive to greater uniformity and mechanical stability than the former pear-shaped bulb. In many types the size of the glass bulb has been reduced. In others, new types of cathodes have been introduced to provide a greater surface area or to reduce hum. Reduction of grid emission permits a higher output from the tube; for this reason emission from the grid (page 5) has been decreased by the use of carbonized grid wire and heat radiators (page 17) on the grid structure.

Automatic Tube-making Machines.—In the manufacture of vacuum tubes high-speed automatic machines are largely replacing manual operations. The grid, formerly wound by hand, is now wound, welded, and cut to length automatically. The plate is made from strip metal by a machine which forms the shape in one piece or fastens two halves together either by stitching or by welding. Coated filaments are made by a continuous process in which the wire is heated, coated, and cut to length by a machine. The glass flares and stems likewise may be produced mechanically. The mounting of the tube elements is mostly performed by hand, but undoubtedly machines for this operation can be developed. The final steps such as the sealing of the glass envelope over the stem, the attachment of the base, and the tube tests, are performed automatically.

In a machine used to remove from a tube the air and other gases, the tube passes through a high-temperature furnace in which some of the gas held by the *metal* and *glass* elements of the tube is driven off at the same time that the exhausting action inside the bulb is taking place. In the next step in manufacture the filament is lighted to form its coating, while any gas still held by the metal elements is driven off by the heat formed in the metal from the induced currents produced by a high-frequency electron "bombarding" machine. When the required degree of vacuum is attained, the tube is sealed.

Ionization by Collision.—It is impossible to remove completely all traces of gas from a vacuum tube. In a rarefied gas some of the electrons are parts of atoms and some are free. These free electrons move with such velocity that if one hits an atom another electron may be knocked off. This "stray" electron comes under the influence of the plate voltage and moves in the same direction as the colliding electron, that is, toward the plate in the vacuum tube. The remainder of the atom, which is a positively charged *ion*, moves in an opposite direction toward the filament. Thus, both parts of the atom act to increase the flow of current through the gas. This action of an electron on an atom is called *ionization by collision* and corresponds to the "break-down" of any electric insulator at excessive voltage. In a vacuum tube which contains residual gas, some ionization will occur when the plate voltage exceeds 30 or 40 volts, although vacuum tubes having a high vacuum may not have their operation appreciably affected by ionization.

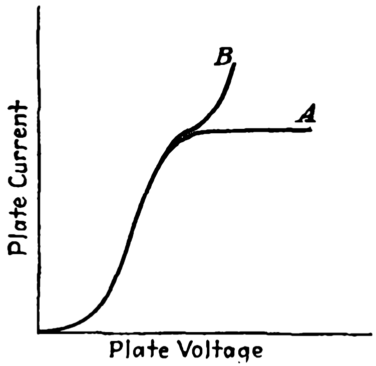

FIG. 16.—Curve showing relation between plate current and plate voltage with and without gas ionization.

Influence of Gas in a Vacuum Tube.—The relation between plate current and plate voltage for operation at rated filament voltage in a vacuum tube having no gas is shown by the curve *A* in Fig. 16. Under the action of ionization by collision the gas atoms are separated into free electrons and positively charged ions which move toward the plate and filament, respectively. This movement produces an increase of current as shown by curve *B*. It may be considered that ionization of the gas tends to neutralize the space charge and thus permits a larger current to pass through the tube.

There seems to be an apparent advantage in ionization by collision because the plate current is increased; but it happens that under this condition the filament deteriorates rapidly because the positively charged ions are attracted forcibly to the negatively charged filament, and, since they are much heavier than electrons, the impact breaks down the filament surface. Also, if a too high plate voltage is applied, a "blue-glow" discharge may result. In this condition, a tube is erratic in behavior and becomes insensitive because the plate current is so large that it is not affected by variations of the grid voltage. If a tube has a blue-glow discharge owing to excess gas or to abnormally high plate voltage, its characteristic curves do not repeat themselves and sharp breaks in the curves may appear. Further, such operation heats the tube elements and such heating may injure them.

There are, however, certain types of tubes in which gas is introduced deliberately to obtain changes in the operating characteristics. In a tube of this type, such as the mercury-vapor rectifier (page 98), the presence of the blue glow is an indication of normal behavior. Some pentode tubes (page 9) show a bluish glow when they are operating normally; in case there is any doubt about the condition of the tube a test should be made of the plate current.[1] In a tube which has become gassy the plate current is greater than normal.

Ionization in a Detector Tube.—To a certain extent ionization in a vacuum tube is of value in its use as a *detector*. "Soft" tubes are particularly useful as detectors and, if properly selected and operated, may be more satisfactory as detectors than "hard" tubes of similar construction. They are, however, quite critical of adjustment because the plate or grid voltage must be adjusted to a value just under that which produces ionization. The high-vacuum detector tubes used at the present time are less sensitive but much more dependable than the older tubes which did not have such good vacuums.

Ionization seldom takes place in a tube using the tungsten filament because the vacuum is high. It is more likely to occur in tubes using oxide-coated filaments because of the presence of occluded gas. A power tube[2] with an oxide-coated

[1] See Chap. VI.

[2] A *power tube* is a vacuum tube intended for the "last" audio-frequency stage of a receiving set. It takes its name from the fact that its power rating in watts is greater than for the usual types of tubes.

filament when once ionized cannot be used again at the usual high plate voltages unless it is reexhausted. It may, however, serve for use at lower plate voltages.

The rectifying property of a two-element tube is ineffective if the plate becomes heated to incandescence. This heating takes place when an excessively high plate voltage is applied. The high voltage increases the velocity of the electrons, which heat the plate by the force with which they impinge on it.

Testing a Vacuum Tube for Presence of Gas.—No considerable number of electrons will be given off from a *cold* element in a tube unless it is subjected to a strong electron bombardment. If, then, there is current flow in a tube in a direction which shows that electrons are emitted from a cold element, either the grid or the plate, it is proof of the presence of gas which is conducting the current.

One method of ascertaining the presence of gas in a tube is to apply the so-called *overvoltage test.* This consists of applying a plate voltage, higher than the normal operating value, for a few minutes and then testing the tube for performance. During the application of this excess voltage, some gas is released from the elements of a vacuum tube in which the vacuum is poor. If the tube performance is satisfactory, the amount of gas released is not enough to impair its action.

If a negative voltage is put on the grid of a vacuum tube in which there is no gas, the grid current does not reverse. It is found, however, that even in a tube having a high vacuum there is enough gas left so that the positive ions produce a minute reversed grid current when the grid is negative. The strength of this grid current increases with the strength of the plate current. This action in the flow of grid current can be made to serve as a test of the amount of gas present in a tube.

The presence of a large amount of gas in a tube may be detected during the final stages of manufacture by a simple test utilizing a source of high-frequency voltage which may be impressed across the tube elements. The color and distribution of the arc across the tube elements indicate the condition of the vacuum.

Relation between Tube Constants and Structure.—The two main factors that enter into the design of vacuum tubes are the degree of amplification (see page 9) and the plate resistance. The *amplification* increases with increasing distance between the plate and the grid and depends, also, on the spacing and size of the grid wires but not on the distance between the filament and the grid, for a tube with plane-surface electrodes. For a tube with a cylindrical arrangement of electrodes, the distance from filament to grid and the distance from filament to plate have an effect on amplification.

The *plate resistance* r_p is inversely proportional to the surface areas of the plate and filament. It depends, also, on the operating voltages. The value of r_p is further affected by the *amplification factor* u, which, as shown above with respect to amplification, depends almost entirely on the structure of the grid and its position with relation to the plate.

An amplifying tube gives best operation when its *plate resistance* is equal to the *impedance* into which the tube works. In cases where this is not possible the total plate resistance may be reduced by operating the vacuum tubes in parallel; or, by the use of an *output transformer*, the plate resistance of a tube may be matched to the impedance of the device with which it operates.

The mutual conductance G_m, being equal to u/r_p, depends on the factors which determine these terms. In some types of tubes it is necessary to make this ratio u/r_p as large as possible. Then, for a given value of u, r_p must be as small as possible. To make u large and r_p small, therefore, the grid must be close to the filament.

When a vacuum tube is to be used as a detector, it should have a low internal resistance which changes suddenly within narrow limits when the grid voltage is varied. Since the amplification factor depends on the ratio of the change in the plate voltage to the change in the grid voltage, the maximum action is obtained when, for a given change of the grid voltage, the necessary change of the plate voltage to provide the same current is a maximum. Thus, in a detector tube the resistance must drop suddenly from a maximum to a minimum for a small change in grid voltage. In an amplifying tube, on the other hand, a small change in grid voltage should tend to increase the resistance to a maximum. The nearer the grid is to the filament and the farther the grid is from the plate, the better are the detecting qualities of a tube. Conversely, the farther the grid is from the filament and the closer the grid is to the plate, the better are the amplifying qualities of a tube.

Limiting Operating Conditions.—Since some gas always remains in a vacuum tube, there are in every tube a large number of molecules of gas left even when the vacuum in the tube is as high as possible. Ionization of this gas will occur if the plate voltage applied to the tube is too high, or if both the filament voltage and plate voltage are high. The extent of the effect of ionization on the tube characteristics depends on the amount of gas present. Thus, one limiting condition of the operation of a tube at high voltages is due to ionization of the gases left in the tube. Tubes using oxide-coated filaments cannot be so completely evacuated as those having filaments consisting only of tungsten, hence ionization is more likely to occur in the former.

The other limiting condition is the deterioration of the elements of a vacuum tube from overheating. Thus, the heating of the plate is due to electron bombardment, the amount of power taken by this heating being the product of plate current and plate voltage. The electrons moving from the filament to the plate convert this power first into an increase in their velocity and then into heat which is released when they reach the plate. This heat, since the elements are in a vacuum, can be dissipated only by radiation. It may be mentioned here, again, that a tube may cease to function if its emission is impaired by the impact of positive ions on the surface of the filament.

The plate may get so hot that the glass bulb will give way by sagging. In high-power tubes this difficulty is avoided by changing the construction so that the outside of the tube comprises the plate. Then cooling water can be circulated around the plate to carry off the heat. The plates of high-power air-cooled tubes are sometimes blackened to increase their heat radiating capacity. Sand-blasting or even oxidizing the plates of low-power tubes produces somewhat the same effect.

The factor of *distortion* has a bearing on the possible output of a vacuum tube. Several operating conditions must be assumed if the distortion is to be below the value which is considered to be a minimum. The table on page 617 states these operating conditions and gives the maximum undistorted outputs of a number of tubes.

Life of a Tube Filament.—The life of a filament is shortened by excessive heating due to impact by positive ions produced by collision due to ionization, which occurs to some extent even in tubes having a high vacuum. The normal life of a filament depends, also, on the rate at which the substance volatilizes. As a metallic filament, for example, one of tungsten, volatilizes, its resistance increases. This causes a decrease in filament current, if operation is at constant voltage, and hence a decrease in electron emission. On the other hand, if the operation of the tube is with a constant current, the voltage is increased, and the filament temperature rises. The effect of this is to shorten the life of the filament.

In an oxide-coated filament only the surface volatilizes. The filament current flows mainly through the core, the resistance of which remains constant. With this kind of filament the impact of positive ions produces local heating which is cumulative and tends to burn out the filament at that place.

CHAPTER III

FUNDAMENTAL ELECTRICAL RELATIONS

It is well known that many common forms of matter can be made to show evidences of the phenomenon which we call "electricity." Thus, if a piece of hard wax is rubbed with a cloth which is then taken away, both bodies will attract light bits of paper. The wax is said to have a negative charge and the cloth a positive charge. It can be shown also that "like" charges repel each other while "unlike" charges attract. When equal "unlike" charges come into contact they combine and a neutral state results.

Electrostatic Field.—This mutual effect of one charge upon another exists even when there is a considerable distance between them. The space around the charged bodies is said to be under a strain which allows it to act upon another charged body. This space is called an "electrostatic field," which extends in all directions around a charged body. At any considerable distance from the body, however, the field intensity or strength is small because it varies inversely as the square of the distance from the body.

Theory of Electrons.—Every substance consists of a large number of atoms and molecules, which, for a given substance, are alike. In order to account for the presence and behavior of electricity in matter, it is considered that at the center of each atom there is a charge of *positive* electricity and that a number of charges of *negative* electricity rotate at great speeds around this center. Normally, the sum of the negative charges balances the positive charge. These negative charges, which are all equal, are called *electrons* and represent the smallest amounts of electricity which can be conceived. The arrangement and number of these moving electrons belonging to an atom determine whether the atom is copper, or silver, or hydrogen, and so on.

Some of the electrons, in moving about, may escape from one atom and get into the atomic system of another. If an atom loses an electron, the balance between positive and negative charges is destroyed and the atom is left *positively charged.* In the same way, a *negatively charged* body is one which has obtained more than the number of electrons needed for the electrical equilibrium of its atoms.

Electrons and Electric Current.—It is now a generally accepted fact that an electric current is nothing more than a series of moving electrons, but the amount of current set up by a single electron in motion is too small to be measured by the most delicate current-measuring instruments. For example, in order to have a flow of 1 ampere in a wire, (approximate current requirement for an ordinary 100-watt incandescent lamp) a flow of 10^{19}* electrons per second is required. Notwithstanding this large number of electrons in movement, their forward progress is slow. The average velocity of the electrons in forward movement in a copper wire 1 millimeter in diameter is about $1/1000$ centimeter per second, even when the current is so large that the copper wire is heated by the current to a red-hot temperature.

At times when there is *no current* flowing in a wire, or, in fact, in any other kind of conductor, the electrons will have a to-and-fro movement of which the velocity is about 20 miles per second. On the other hand, when a *current is flowing* as, for example, along a copper wire, the *progressive* movement of the electrons is, as already stated, only a very small fraction of a centimeter per second. Under other conditions, the forward movement of the electrons may be much greater and may actually attain a high value, if the usual collisions of the electrons are prevented.

Under some circumstances there are practically no collisions of electrons, and in that case, the electrons attain velocities of thousands of miles per second, as, for example, in the vacuum

* The symbol in this case means 10 followed by 18 zeros.

tubes used for either radio reception or transmission, where a hot filament in the tube gives off large quantities of electrons which flow freely in the vacuum inside the tube from the filament to the plate.

Direct or Continuous Current.—In some of the practical applications of electricity, as, for example, the charging of a storage battery, it is necessary that the electrons pass around a circuit continuously in the same direction, including the passage between the plates of the battery. A current of this kind, in which the electrons have a progressive motion which is always in the same direction, is called "direct" or "continuous." In the early development of vacuum tubes for radio services, only direct or continuous current was used, but at present, such current is used for the power supply in radio work only in special cases or where current from a power line is not available as in some rural districts.

Units of Current.—The intensity of electric current, that is, the unit quantity of electricity flowing in a wire during a unit of time, is called an *ampere*. This intensity has the same value at all points along the circuit.

One kind of vacuum tube commonly used in radio receiving sets requires for the current to heat the filament about 0.25 ampere; but the plate circuit of this tube uses only about 0.001 ampere, or 1 *milliampere*, this being the unit commonly used for the small currents in radio circuits. For brevity, instead of milliampere the word *mil*[1] is quite commonly used. In some cases, still smaller currents must be measured in radio work, and these smaller currents are usually expressed in terms of the *microampere*, which is one millionth of an ampere.

Direction of Flow of Current.—The flow of direct or continuous current has been defined arbitrarily as taking place from the positive to the negative end of a conductor; thus, in a wire connecting the terminals of a battery the direction of the flow of current is from the positive terminal of the battery to the negative. But it has been shown (page 4) that electrons, being negative charges, move from negative to

[1] In technical work the term *mil* generally refers to wire sizes (p. 33).

positive. Hence it must be remembered that the direction of electron flow is opposite to that of the usual representation of current flow, as shown in Fig. 17.

The amount and rate of flow of electricity can be detected by (1) chemical, (2) heating, and (3) magnetic effects which it produces. A familiar example of chemical action is the process of electrolysis used in electrotyping, electroplating, and in the refining of metals. The heating effect of electricity depends on the quantity of current flowing, and varies as the square of the current applied. In the incandescent lamp a filament is heated to incandescence by an electric current.

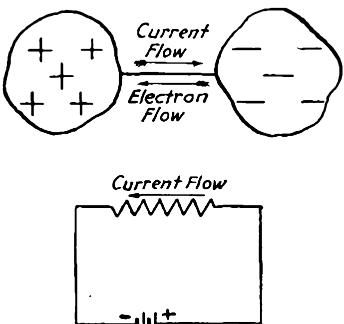

FIG. 17.—Electron flow opposite in direction to current flow.

The electrostatic field, which has already been described (page 27), is an effect of electricity at rest. Electricity that flows in a conductor sets up another kind of effect called a "magnetic strain" in the space surrounding the conductor. The space in which this field exists is called the "magnetic field." The magnetic field consists of imaginary lines of force which form closed circles around a conductor. The *direction* of the magnetic force[1] may be indicated by its effect on a compass needle held near the conductor.

Conductors and Insulators.—Matter may be regarded as belonging to two classes, one of which possesses free electrons, and the other does not. A substance having free electrons is called a "conductor" and is said to offer a low resistance (or opposition) to the flow of an electric current. A substance which does not have free electrons is an insulator and offers a high resistance to the flow of electric current.

All substances, however, contain some free electrons and, theoretically, will allow the passage of an electric current

[1] See MOYER and WOSTREL, "Industrial Electricity and Wiring," pp. 11–15, 165. McGraw-Hill Book Company, Inc., New York, 1930.

although the resistance of some may be so extremely high that the material is considered a good insulator. Further, the resistance of some materials is not constant, and may, for example, vary inversely as the temperature of the material. That is, the material may serve as an insulator at low temperatures and a conductor at high temperatures.

Examples of good conducting materials are the metals and that class of liquid conductors called the *electrolytes*. Examples of insulating materials are dry gases, glass, porcelain, hard rubber, and various waxes, resins, and oils. The minute current which will pass through an insulator under certain conditions is called a "leakage current."

Difference of Potential.—If one piece of a substance is charged positively and a piece of another substance is charged negatively, there is said to be a *difference of potential* between them. When these pieces are connected by a wire, as in Fig. 17, there is a flow of current through the wire while electrons pass through the wire from the negatively charged piece to neutralize the positive charge on the other piece. The electric charges which accumulate at the ends of the wire have the effect of neutralizing the original conditions of charge.

If the original difference of potential is maintained by removing the neutralizing charges as they accumulate, the flow of the electric current will be steady and continuous. Such a steady difference of potential or *electromotive force* may be provided by putting the charged bodies and their connecting wire into a closed circuit containing a device capable of developing an electromotive force.

Electromotive force may be developed by friction, by thermal means, by chemical action, and by induction as in an electric generator. Electricity may be produced by *frictional machines* at high voltages but with very small amounts of current. This method of producing electromotive force is not practical because of the difficulties encountered in connection with insulation, dampness, and variation in performance.

Electromotive force may be produced by heating the junction (*thermocouple*) of two unlike metals. Tables of the thermoelectric power of metals are given in most electrical handbooks.[1] The electromotive force developed at a junction of steel and constantan wires is about 30 microvolts.[2] Low voltages but fairly large currents are possible by this means.

The production of electromotive force by chemical action is exemplified by the *battery.* This action is due to the fact that a difference of potential exists between two different substances used in the battery, such as zinc and carbon when placed in certain chemical solutions. The efficiency of this method is high but the cost of producing electricity in this way for most purposes is prohibitive because of the expensive materials that are required.

The ability of an electric generator to produce an electromotive force and thus maintain a difference of potential is due to the condition which results when the wires on the armature of the generator pass through the magnetic field of magnets, called *poles.*

Resistance.—As the free electrons move along a conductor it is supposed that they hit the atoms of the substance which lie in their paths. The effect of this opposition is to reduce the velocity of the electrons. The extent of the opposition is proportional to the electrical resistance of the conductor. Resistance varies with the shape, substance, and temperature of the conductor. The unit of resistance is called an *ohm.* For very small resistances the millionth part of an ohm is used as a unit and is called a *microhm.*[3] For high resistances a million ohms is used as a unit and is called a *megohm.*

Unit of Electromotive Force.—The unit of electromotive force or voltage is called a *volt.* One volt is that voltage which will force a current of 1 ampere through a resistance of 1 ohm.

Conductance.—A circuit which offers but little resistance R to a current is said to have good conductance. If conductance

[1] Moyer and Wostrel, "Radio Handbook," p. 46, McGraw-Hill Book Company, Inc., New York, 1931.

[2] A microvolt is a millionth part of a volt.

[3] See Appendix for explanation and table of metric prefixes.

is represented by G, then $G = 1 \div R$ or $R = 1 \div G$. The unit of conductance is called a *mho*.

Resistance of a Wire.—If r is the *specific resistance* of a substance, that is, the resistance of a wire of unit length and cross-sectional area, then the resistance R of a conductor having a length of L feet, and a cross-sectional area of A circular mils (as defined below) is

$$R = \frac{rL}{A} \tag{1}$$

A unit wire is a round wire 1 foot long and 1 mil in diameter (or having an end area of 1 circular mil). A *mil* is equal to 0.001 inch. The area of a wire 1 mil in diameter is 1 *circular mil.* The area of a circle in circular mils equals the square of the diameter in mils.

To find the resistance in ohms of a length of any size of wire, multiply the specific resistance, that is, the resistance in ohms of one *circular mil-foot,* by the length in feet and divide by the square of the mil diameter (circular-mil area). Specific resistances for wire sizes in mils are given in Table I.

TABLE I.—RESISTANCE PROPERTIES OF METALS AND ALLOYS

Metal	Resistance, cir.-mil-ft. ohms	Temperature coefficient of resistance at 20°C.
Aluminum	17.0	0.0039
Antimony	251.0	0.0036
Bismuth	663.0	0.0040
Copper (drawn)	10.37	0.00393
Gold	14.7	0.0034
Iron:		
Electrolytic	60.0	
Cast	450 to 600	
Lead	125.0	0.0039
Mercury	565.0	0.00072
Nickel	41.7	0.0062
Platinum	66.0	0.0030
Silver	9.8	0.0038
Steel (soft)	96.0	0.0015

It is obvious that the resistance of a conductor varies directly with its length; that is, as length increases, the resistance increases. Also, the resistance varies inversely with the cross-sectional area; that is, as the area increases, the resistance decreases.

Variation of Resistance with Temperature.—The variation of the resistance of a pure metal with changes in temperature is given by the equation,

$$R_t = R_0(1 + a \times t) \tag{2}$$

in which R_t = resistance at $t°C$.
R_0 = resistance at 0°C.
t = temperature in degrees centigrade.
a = temperature resistance coefficient.

If it is assumed that $a = 0.004$* the equation may be stated thus: *for each 2.5°C. rise in temperature above 0°C. the resistance increases about 1 per cent.*

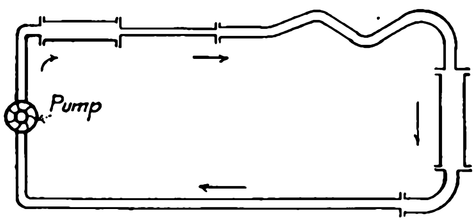

FIG. 18.—Water pipes connected in series.

The resistance of some substances does not follow this rule. Thus, carbon shows a decrease in resistance with increase in temperature; one alloy of nickel and copper shows no increase in resistance with ordinary increases in temperature.

Series and Parallel Circuits.—In radio work some units of apparatus are connected in series and others in parallel. If the various parts of a circuit are connected in such a way that the total current must flow through each part, the parts are said to be in *series*. If the analogy of the flow of electricity to the flow of water is used, this corresponds to the pipe line shown in Fig. 18 in which pipes of various sizes and lengths are

* Approximately correct for copper wires.

connected in series. If the various parts are connected in such a way that the total current is subdivided, the parts are said to be in *parallel.* The corresponding condition in the pipe line is shown in Fig. 19. If each of the four paths offers the same resistance to current flow, then the total current at A will be divided into four equal parts, which unite again at B. The equivalent resistance R of a group of resistances r_1, r_2, r_3, r_4, and so on *connected in series* is equal to the sum of the separate resistances; that is $R = r_1 + r_2 + r_3 + r_4 + \cdots$ The equivalent resistance R of a group of resistances r_1, r_2, r_3, r_4, and so on, *connected in parallel,* is equal to the reciprocal of the sum of the reciprocals of the separate resistances. That is,

$$R = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \frac{1}{r_4}} \qquad (3)$$

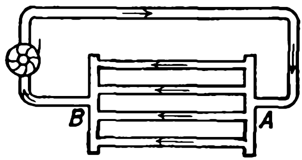

FIG. 19.—Water pipes connected in parallel.

Relation between Current, Voltage, and Resistance.—The opposition offered by the resistance R of a conductor to the flow of current reduces the effective velocity of the electrons and hence decreases the strength of current I. In order to compensate for this opposition, and, thus, to maintain a constant value of current flow, it is necessary to apply to the circuit an electromotive force or voltage E which is equal to RI. If R is the resistance in ohms and I is the current in amperes, then E is in volts. This relation is known as *Ohm's law* and may be expressed in the three forms below:

$$E = IR, \text{ or voltage} = \text{current} \times \text{resistance, or volts} = \text{amperes} \times \text{ohms.} \qquad (4)$$

$$I = \frac{E}{R}, \text{ or current} = \frac{\text{voltage}}{\text{resistance}}, \text{ or amperes} = \frac{\text{volts}}{\text{ohms}}. \qquad (5)$$

$$R = \frac{E}{I}, \text{ or resistance} = \frac{\text{voltage}}{\text{current}}, \text{ or ohms} = \frac{\text{volts}}{\text{amperes}}. \qquad (6)$$

Ohm's law holds true for any circuit or part of a circuit. When the equation is used for a *part* of a circuit the values of voltage, current, and resistance must apply to that part only.

Rheostats.—In radio work the need is constantly arising for adjusting a current to a specified value. This is usually done by varying the resistance of the circuit. Changes in the resistance of the circuit can be made by means of resistance devices called *resistors*, which are either variable or fixed in value. Variable resistors are called *rheostats*.

Power and Energy.—The work accomplished by the voltage E in moving an electron through a unit length D is equal to DE (since work = force × distance through which it acts). A current I flowing in a conductor corresponds to a transfer of N electrons per second through a unit length D.

Power being defined as the *rate* at which work is done, the total work performed per second or the power is then $W = NDE$ or IE. The unit of electrical power is called a *watt*. A watt is the power expended by a current of 1 ampere flowing through a resistance of 1 ohm. One *kilowatt* is equal to 1,000 watts.

Since $E = IR$ then by substitution $W = I^2R$, and since $I = E \div R$ by similar substitution $W = E^2 \div R$.

Thus there are three forms of the equation for power W,

$$W = EI, \text{ or power} = \text{voltage} \times \text{current, or watts} = \text{volts} \times \text{amperes.} \quad (7)$$

$$I = \frac{W}{E}, \text{ or current} = \frac{\text{power}}{\text{voltage}}, \text{ or amperes} = \frac{\text{watts}}{\text{volts}}. \quad (8)$$

$$E = \frac{W}{I}, \text{ or voltage} = \frac{\text{power}}{\text{current}}, \text{ or volts} = \frac{\text{watts}}{\text{amperes}}. \quad (9)$$

Each of the expressions $W = I^2R$, and $W = E^2 \div R$ can be stated in three forms in a similar manner.

Energy is expressed in the same units as work. The commercial unit of electrical energy is the *kilowatt-hour*. Electrical energy is measured by an instrument called the integrating *wattmeter* which automatically adds up the work done, though there may be a continual variation of power.[1]

[1] The energy which is required to maintain the velocity of the electrons is given up by them in the form of heat caused by their collisions with each other and with the atoms.

For example, if an electric motor requires for its operation 5 kilowatts of *power*, then it uses in each hour of its operation 5 kilowatt-hours of energy; and if this motor operates 8 hours a day for 5 days in the week, the energy expended or work done in this service is 5 × 8 × 5, or 200 kilowatt-hours per week. The electrical units of power are sometimes used as a means of measuring other forms of energy, as, for example, in radio work, sound may be conveniently expressed in these units. The sound of the average human voice expressed in power units is about 10 microwatts; a microwatt being one-millionth of a watt.

Joule or Watt-second of Work.—One watt of power exerted for one second is called a watt-second or one joule, which is a unit frequently used in calculations of very small powers, such as there are in radio work. An interesting example can be made of the stored energy and the lifting power of an ordinary 6-volt storage battery which, at a discharge rate of 10 amperes, will continue this rate for about 20 hours. The energy of total discharge in joules is therefore the product of the current in amperes × the voltage × the number of seconds, or energy = 10 × 6 × 60 × 60 × 20 = 432,000 joules (watt-seconds).

Now if the weight of the battery is 20 pounds and it is connected up by wires to an electric motor, of which the efficiency is 70 per cent, then at the above discharge rate the stored energy of the battery might be exerted through the motor to lift the battery. For these conditions, the lifting power of the battery is 10 (amperes) × 6 (volts) × 0.70 = 42 watts. Since 1 watt = 0.738 foot-pound per second,[1] the lifting power in foot-pounds is 42 × 0.738 = 30.0 foot-pounds. The distance the battery is lifted per second is 30.0 ÷ 20 = 1.5 feet.

Ampere-hours.—Any primary source of electric current will be depleted after being connected to the resistances of a circuit for a time, so that a *dry cell*, for example, must be

[1] One *horsepower* is equivalent to 746 watts and also 550 foot-pounds per second, so that one watt is 550 ÷ 746 or 0.738 foot-pound per second.

discarded after it has given out, as it cannot be successfully recharged. A *storage cell*, on the other hand, may be recharged. When cells of either of these kinds are used for supplying current for radio tubes, obviously the active life of the cells will be less in proportion to the number of tubes supplied. The term *ampere-hour* is used to designate the number of hours a battery can supply current at a given rate in terms of amperes and hours. Thus, if a battery has a rating of 80 ampere-hours, it can supply the tubes of a radio receiving set at the rate of 2 amperes for 40 hours. The average 6-inch dry cell, such as is commonly used for electric bell circuits and for the lighting of the filaments of "low-current" vacuum tubes, can be used for about 15 ampere-hours. The small cells used as dry "B" batteries (page 4) have a much smaller output. A $22\frac{1}{2}$-volt "B" battery of small dry cells weighing about 5 pounds can be used for about 2 ampere-hours under average conditions, while the smaller size of dry "B" battery weighing about 2 pounds is good for only about 0.8 ampere-hour. It should be noted, however, that the available ampere-hours of any battery are reduced in proportion to the rate at which current is taken out. For example, a 5-pound dry "B" battery, when delivering 5 milliamperes will be good for 4,000 milliampere-hours, while a similar fully charged battery when delivering 50 milliamperes will be good for only 1,000 milliampere-hours. This means that this battery with the 5-milliampere rate will last for 800 hours of average service, while at the 50-milliampere rate it will last only 20 hours.

Applications of Ohm's Law and Power Relations.—It is a simple matter to carry out the calculations for the action of a direct-current circuit. Thus, to determine the resistance of the filament of a vacuum tube it is necessary only to apply the relation $R = E \div I$ or ohms = volts ÷ amperes. A typical tube takes 0.25 ampere at 5 volts. Hence the resistance R equals $5 \div 0.25$ or 20 ohms. The *conductance* (page 32) being the reciprocal of resistance is equal to $\frac{1}{20}$ or 0.05 mho.

If a voltage of 45 volts is applied to the plate-to-filament circuit of a certain tube, the plate current will be 0.0017 ampere. Then the internal or direct-current resistance R of the tube in ohms from plate to filament is $R = E \div I =$ 45 volts $\div$ 0.0017 ampere = 26,470 ohms.

The *power input* W_f in watts of the filament circuit is $W_f = EI$ or 5 volts $\times$ 0.25 ampere = 1.25 watts. The *power output* W_p of the plate circuit is $W_p = EI$ or 45 volts $\times$ 0.0017 ampere = 0.077 watt.

The electrical energy taken by a device rated at 80 watts over a period of 10 hours is 80 $\times$ 10 or 800 watt-hours, which is equivalent to 0.8 kilowatt-hour. At a cost of 10 cents a kilowatt-hour the expense of operating the device for 10 hours is 0.8 $\times$ 10 or 8 cents.

Frequency, Kilocycle.—The current in a wire or other conductor, of which the electrons flow first in one direction and then in the other, is called alternating. The *alternating current* in most of the power-line circuits in America has 120 reversals of direction in a second, meaning that there are 60 complete cycles (see Fig. 21) per second. In a wire connected to such a line, the electrons flow first in one direction for $\frac{1}{120}$ second, then stop, flow in the opposite direction for $\frac{1}{120}$ second, then stop again, and start from this point on a repetition of the cycle. The number of complete cycles of current flow in a second is called the *frequency*. In the case just mentioned, the frequency is 60, and the current in the wire is called a 60-cycle current. The high-frequency electric currents used in radio circuits are usually measured in thousands of cycles, one thousand cycles being a *kilocycle*. For ordinary broadcasting, the frequencies mostly in use are between 550 kilocycles and 1,500 kilocycles, while for oceanic radio telegraphy, the frequencies most used are about 60,000 cycles per second or, in other words, about 60 kilocycles per second. Modern short-wave radio transmission is at such high frequencies that the kilocycle unit is too small for convenience so that the frequencies of short waves are expressed in a unit called a *megacycle* which is 1,000,000 cycles. Thus a frequency of 20,000,000 cycles per second is 20 megacycles per second.

The relation between cycles per second (frequency) and wave length can be very simply stated. The velocity of electric waves (including the radio kind) is 300,000,000 meters (186,000 miles) per second.[1] The ordinary power-line electric current makes 60 cycles per second. In other words, there are 60 cycles or electric waves in a distance of 300,000,000

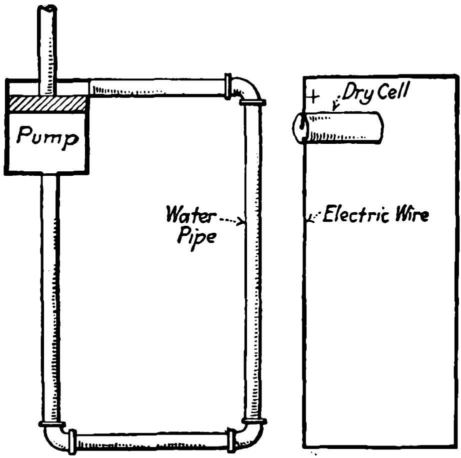

FIG. 20.—Pipe and pump line to illustrate analogy to electric circuit.

meters, or the wave length of each cycle is 300,000,000 ÷ 60 or 5,000,000 meters. Conversely, short waves of, say, 10 meters in length will have a frequency of 300,000,000 ÷ 10 or 30,000,000 cycles = 30 megacycles per second.

Alternating Radio Current.—When radio waves are changed into an alternating electric current in a conductor by means of a radio receiving apparatus, this current not only changes its direction at a definite rate but also varies in strength. If there is an alternating voltage in a circuit, the variations in both strength and direction of the electric current correspond to the variations of the voltage. The flow of an

[1] This is the same as the velocity of light.

alternating current is like the flow of water which would be produced in the pipe line in Fig. 20 when the water is agitated by a paddle moving back and forth rapidly over a short distance. In that case, the water simply surges, first in one direction, then in the other direction. It no sooner attains speed in one direction than it is compelled to slow up and then accelerate in speed in the opposite direction, and so on, over and over again. An object placed in the water will not travel around the pipe circuit, but will simply oscillate back and forth.

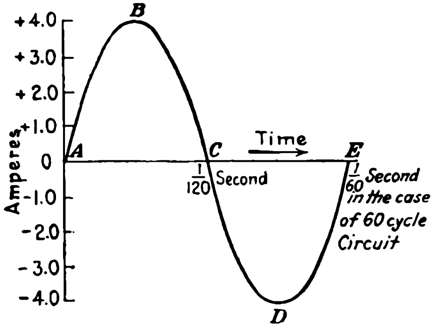

FIG. 21.—Diagram showing variations of alternating current with time (one cycle).

In order to distinguish the directions of flow, we call one direction the positive (+) and the other the negative (−) direction. During the flow in one direction, the strength of the current varies from zero to a maximum and back to zero again. Figure 21 shows a simple way of indicating the variations in strength, direction, and time when an alternating current is considered. The positive direction of flow is from *A* to *C*, the negative from *C* to *E*. During the flow from *A* to *C*, the strength of the current varies from zero to a maximum, and again to zero, as shown by the curve *ABC*.

Effective and Average Values of Alternating Current.—The shape of the curve in Fig. 22 indicates obviously that the values of the alternating current are continually changing; the change being in the figure from zero to a positive maximum, then again to zero and a negative maximum, and finally back again to zero. The value in amperes of such a flow of current which, for the present discussion, may be assumed to be a sine wave, might at first thought seem to be based on the average value. If the net value in amperes of the wave is considered for a complete cycle, its average value is zero, as there is in such a wave form as much negative as positive current. This fact would be shown by connecting into the circuit of such an alternating current a direct-current ammeter for the measurement of the current. The indication of the amount of current with such an instrument would be zero, for the reason that its indications or readings are of average value. Actually, an alternating current does not have zero value for the reason that the ampere value of an alternating supply is not determined by the average value but by the *heating value* of the current. In this respect, it is desirable to define quite clearly the alternating-current ampere. It is the current which, flowing through a given (ohmic or non-inductive) resistance (page 52), will produce *heat* at the same rate as a direct-current ampere.

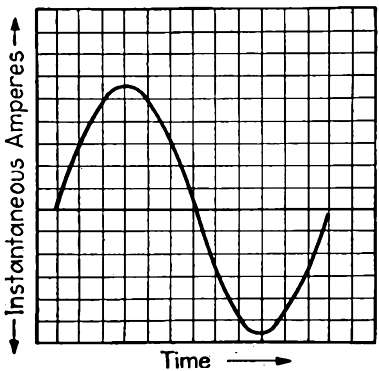

Fig. 22.—Typical sine wave of alternating current.

The production of heat by an alternating electric current is used, therefore, as a means of defining the value of such current. A practical example like the following may serve to make this clear. A lamp filament may be assumed to have its temperature raised 1 degree Fahrenheit in 5 minutes by a direct current of 1 ampere. If, then, the direct current is disconnected from the filament and an alternating current is supplied instead which raises the temperature of the coil also 1°F. in 5 minutes, then the value of the alternating current thus measured by its heating effect is also 1 ampere.

The heating effect of electric current in a filament or other conductor is not measured by a simple proportionality with respect to the increase or decrease of the current. Actually, the heating effect of any electric current is increased or decreased in proportion to the square of the current (I^2). The value, therefore, of the effective current in amperes represented by the wave of so-called *instantaneous* values of current in Fig. 22 cannot be read directly on the scale of

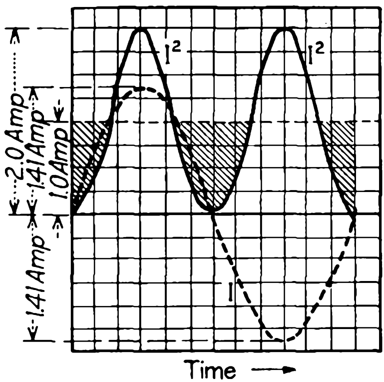

FIG. 23.—Effective or root-mean-square values of sine-wave alternating current.

ordinates (amperes) on the curve, but another curve like Fig. 23 based on *squared* values will have to be obtained. This figure shows the instantaneous values of current by a heavy dotted line which is the same as the instantaneous values of current shown in Fig. 22. Superimposed on the dotted curve is the one calculated from squared values, and this curve is marked I^2. This latter curve is obtained from the dotted curve by plotting the square of each of the ordinates in the I curve. As indicated in Fig. 23, the maximum value of the I curve, both positive and negative, is 1.41 amperes, and the square of this maximum value is the whole number 2.[1]

The squared curve (I^2), it will be noticed, lies entirely above the axis of zero value. This is because the square of any

[1] The value 1.41 is often represented by $\sqrt{2}$.

negative value is a positive number. It is interesting to notice also that the squared curve (I^2) has twice as many peaks as the original curve or curves, which means, of course, that the squared curve has a frequency that is twice as large as that of the curve of instantaneous value (I); and its horizontal axis of symmetry is, of course, halfway between its maximum value and the zero axis, which, in this case, is one ampere. This horizontal axis of symmetry of the squared curve (I^2) indicates also the average value of the effective current for the reason that the areas above this line of symmetry will just equal in area the shaded area below this line. The average of the squared values of the curve in Fig. 22 is therefore 1 ampere.

The values of current shown by the curve of squared values (I^2) in Fig. 23 represent, as already explained, heating values which, ampere for ampere, are equivalent to heating values due to direct current. The average value of this squared current representing heating values is indicated on the scale of ordinates by the line of symmetry, which corresponds to the average value of 1 ampere. This average value is called the *effective* current or the *r.m.s.* current, the latter meaning *root-mean-square* current (explanation on page 45).

The statement has been made that a *direct-current* ammeter, when used in an alternating-current circuit, registers zero even if a large current is flowing. On the other hand, an *alternating-current* ammeter is designed to indicate the *effective* value of the current, or, in other words, the r.m.s. value. The alternating current that varies in instantaneous value according to a sine-wave form and produces heat at the same rate as one direct-current ampere according to the calculations as explained in Fig. 23 has both positive and negative maximum values of 1.41 (or $\sqrt{2}$) amperes.

It should be plain, therefore, that for a sine-wave alternating current the ratio of a maximum to the effective (r.m.s.) value is 1.41, or $\sqrt{2}$. Similarly the ratio of the effective to a maximum value is $1 \div 1.41$ or 0.707. It should be noted here that the method of obtaining the effective value of a current from the instantaneous values as shown in Fig. 22 will be the same whether or not the curve of instantaneous values is an accurate sine wave. In fact, the method will be the same for an alternating current which varies in shape considerably from the wave shown in Figs. 22 and 23.

Explanation of Effective (R.M.S.) Current.—The curves in Fig. 24 are intended to illustrate the actual calculation of the effective value of the current shown by the positive half of the sine wave *ABCD*. As shown in the figure, the curve *ABC* is a sine wave of current, of which the maximum instantaneous value is 1.5 amperes. For the accurate representation of the curve of squared values, ordinates marked with the letters *HJK*, *MBE*, etc., are constructed on the base line *AD* at regular intervals. The ordinate *HJ* on the scale of instantaneous values is 1.3 amperes. This value when squared is 1.69 amperes, which is to be laid off to determine the point *K* on the ordinate *HK*. On the curve of instantaneous values, the ordinate *MB* is 1.5 and the square of this value is 2.25 amperes, the latter value determining the maximum ordinate at *E*. In the same way, ordinates of the curve of squared values can be determined at the points *N*, *P*, and *Q*, thus completing the curve *AKERC* of squared values.

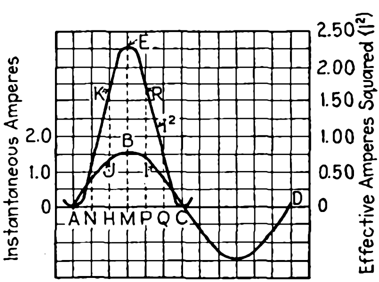

FIG. 24.—Method of calculating effective values of alternating current.

After constructing the curve of squared values of an alternating-current sine wave, in order to obtain a useful result, it is necessary to find the *average* value of the curve. One of the simplest ways to do this is to erect several equally spaced ordinates on the base line *AC* closer together than those shown in Fig. 24, and then take the sum of these ordinates as measured on the scale of squared current and divide this sum by the number of ordinates. This will give an average value of the current from the curve of squared values. Then the effective value is equal to the square root of the average value. The accuracy of the determination will depend on the number of ordinates that are used.

Another method of finding the average value of the squared current from the curve *AKERC* is to measure the area under the curve in square inches with a planimeter[1] and divide the area thus obtained by the length in inches of the base line *AC*. This division gives the *average height* of the curve of squared current in inches, and then to find the average value in amperes, it is necessary to multiply the average height thus obtained in inches by the scale of ordinates in amperes per inch. For example, in the figure, the area under the curve *AKERC* is 0.75 square inch and the length of the base line *AC* is approximately 1 inch. The average height of the curve of squared current is therefore 0.75 divided by 1.0 or 0.75 inch. The scale of ordinates of squared current is approximately 1.5 amperes per inch. The average squared value of the alternating current shown by the curve in Fig. 24 is therefore approximately 0.75×1.5 or nearly 1.13 amperes.

The average value of squared current as calculated above for a positive half cycle is, of course, the same in numerical value as that for the following negative half cycle, and the same also for the following positive half cycle, etc. The average squared current for any of these half cycles produces the same heating effect in a given resistance as a direct current whose squared value is 1.13 amperes, and therefore the *effective* alternating current represented by the curve is the square root of 1.13 or $\sqrt{1.13} = 1.06$ amperes.

It is a matter of interest to check after the construction of a curve of this kind the ratio of the maximum to the effective current which, for a sine wave, has been shown to be 1.41. In this case, the ratio 1.5 amperes $\div$ 1.06 is almost equal to 1.41, which is a fairly good check. As a rule, for the usual

[1] Detailed descriptions of various types of planimeters and the theory of their construction and operation are given in "Power Plant Testing," 4th ed., by James A. Moyer, McGraw-Hill Book Company, Inc., New York, 1934.

alternating currents to be dealt with in practice, the shape of the wave is not nearly sinusoidal, and the ratio of the maximum to the effective value is not so nearly 1.41 as in the case here illustrated.

Capacity.—A device which is so arranged that it has a large electrostatic capacity within a small space is called a *condenser*. Essentially, it consists of two groups of plates which are insulated from each other.

A condenser used with inductance (see page 50) can be made to tune the circuit to a definite wave length. A condenser may be inserted into a circuit to by-pass an alternating current around some other part of the circuit. It may be used also to prevent the flow of direct current in a circuit.

A steady voltage is not able to pass a steady current through a condenser. When the circuit is first closed, a charging current flows until the voltage between the plates of the condenser has risen to the same value as the applied voltage. If this applied voltage is then removed and the circuit completed by a wire, a discharge current flows out of the condenser in the opposite direction to the charging current.

For a given condenser, the charge Q is proportional to the applied voltage E. This relation may be written $Q = CE$ where C is a constant called the "capacity" of the condenser. The unit of capacity is the *farad*. A farad is the capacity of a condenser in which a voltage difference of 1 volt gives the condenser a charge of 1 *coulomb*[1] of electricity. The farad is a unit which is too large for practical purposes and it is usual to use the microfarad (one millionth of a farad) and the micromicrofarad (one millionth of a microfarad).

During the time the charge is accumulating in a condenser the voltage $Q \div C$ due to this charge is increasing. This voltage tends to oppose the charging voltage and when $Q \div C$ becomes equal to E the charging process comes to an end. It will be noticed that the equation $Q = CE$ does not contain a time factor; therefore, the same amount of charge is

[1] A coulomb is the quantity of electricity furnished by a current of 1 ampere in 1 second.

stored in a condenser whether it is built up slowly or quickly. However, the rate of building up the charge depends on the value of the capacity and resistance of the circuit. The larger the product of the factors C and R the greater is the time required to arrive at any given fraction of the applied voltage. This product $(C \times R)$ is called the *time constant* of the circuit.[1]

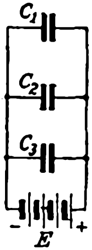

FIG. 25.—Condensers in parallel.

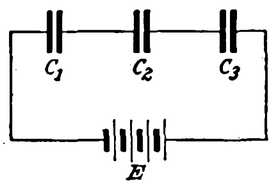

FIG. 26.—Condensers in series.

When $t = CR$, $I = 0.368E \div R$, that is, the charge reaches 63.2 per cent of its final value and the charging current drops to 36.8 per cent of its initial value in a time CR.

Condensers in Parallel and in Series.—A group of three condensers connected in parallel is shown in Fig. 25. All of these condensers are subjected to the same impressed voltage and each accumulates a charge proportional to its capacity. Since capacity is proportional to plate area, it is obvious that the method of connecting condensers in parallel has the effect of increasing the plate area of the condensers. A *parallel connection of condensers* gives a capacity which is larger than that of any one of the group. If C is the equivalent capacity

[1] The changing current I at any time after the circuit is closed is,

$$I = \frac{E}{R}\left(K\right)^{-\frac{t}{CR}} \qquad (10)$$

where C = capacity, farads.
E = applied voltage, volts.
R = total resistance of circuit, ohms.
t = time, seconds.
K = 2.7128.

of the group and c_1, c_2, c_3 the capacities of the condensers respectively, then

$$C = c_1 + c_2 + c_3. \tag{11}$$

A group of three *condensers connected in series* is shown in Fig. 26. *Each condenser accumulates the same charge Q*, and the total voltage is subdivided among the condensers in inverse ratio to their capacities. A *series connection of condensers* gives a capacity which is smaller than that of any of the group. If e_1, e_2, e_3 are the voltages across the condensers c_1, c_2, c_3 respectively then

$$E = e_1 + e_2 + e_3$$

and since $E = Q/C$ then

$$\frac{Q}{C} = \frac{Q}{c_1} + \frac{Q}{c_2} + \frac{Q}{c_3}.$$

It follows that

$$\frac{1}{C} = \frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3}$$

and

$$C = \frac{1}{\frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3}}. \tag{12}$$

Magnetic Field of a Wire Carrying Current.—A conductor carrying an electric current is surrounded by a magnetic field similar to that of the familiar magnet. The strength of this magnetic field is proportional to the current. The direction of the magnetic field is given by the direction in which the fingers point if it is imagined that the right hand is closed and the thumb points in the direction of current flow. These relations are shown in Fig. 27. The direction of the magnetic field reverses when the current reverses. An alternating current produces an alternating magnetic field which has the same frequency as the current and reverses with the current.

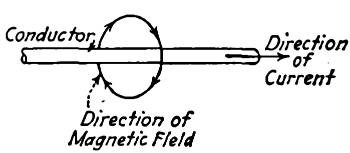

FIG. 27.—Diagram of relative directions of current and magnetic field.

Inductance.—The significant characteristic of a circuit *including a coil* and carrying an alternating current is that there is more interference with the flow of current than there would be with a direct or continuous current. In other words, when a coil carries a *direct or continuous current,* the amount of current that will flow through it is limited only by the ohmic (page 42) resistance. When, however, an *alternating* current flows through the same coil, there is much more interference with the flow. For example, if a coil which has 5 ohms of resistance is connected to a 10-volt battery (direct current), it will carry 2 amperes. On the other hand, if this same coil is connected to a supply line carrying alternating current, which is adjusted to give also 10 volts, the current then flowing in the coil will be very much less than 2 amperes; in fact, it may be only a fraction of 1 ampere. This example shows that there is something about this circuit when carrying an *alternating* current, called *inductance,* that makes the circuit different from what it is when carrying a direct or continuous current.

Induced Voltage.—It was stated in the preceding paragraphs that the strength of the magnetic field set up in either a straight wire or a coil is proportional to the amount of current which the conductor carries. Also, that if a coil is placed in a magnetic field, a voltage is induced in the coil when the strength of the magnetic field is varied. If the magnetic field in which the coil is located is produced by varying the amount of current in the coil, then the voltage that is *induced* in the coil by reason of varying the current acts in the opposite direction to that of the current producing the magnetic field. This means that when the current causing the magnetic field is decreasing, the *induced* voltage in the coil is in the direction that opposes the reduction of the current. The value of the induced voltage (usually represented by e) is then $N \times F$, where N is the number of loops or *turns* in the coil and F is the rate of change of the current in the magnetic field.[1]

[1] As usually expressed mathematically, the induced voltage equals $-N \times F$, the *negative sign* being used to show the relation between the

Coefficient of Self-induction.—In the preceding paragraph, the value of the induced voltage in a coil was expressed as the product of the number of loops or turns in the coil, and the rate of change of the magnetic field. It may also be expressed, however, in terms of the so-called *coefficient of self-induction.* If L is the coefficient of self-induction and F is the rate of change of the current in the magnetic field, then the induced voltage e, expressed with these symbols, is $L \times F$.

The coefficient of self-induction L is expressed by a standard unit called a *henry,* which is the self-induction produced in a coil by a change of current strength of 1 ampere per second that induces a voltage of 1 volt. For practical work, smaller parts of a henry are used, such as the *millihenry* (one thousandth henry) and the *microhenry* (one millionth henry).

The so-called filters (page 64) of radio receiving sets are designed for relatively large values of self-inductance, varying, usually, from 50 to 100 henrys. Each of the coils of a telephone receiver of the head-set type has usually an inductance of about one henry.

Mutual Induction.—If two coils are relatively near each other, and one of them carries a current but the other does not, the coils react on each other; and a so-called *mutual* (induced) voltage is produced in the coil that does not carry a current. This induced voltage is proportional to the rate of change of the current in the coil carrying it, and also to the mutual induction, expressed by the coefficient M, of the two coils. This relationship may be stated in symbols as $e = M \times F$, where e is, as before, the induced voltage in volts, and F is the rate of change of the current in the coil producing the self-induction in the other coil. Like the coefficient of self-induction, the *coefficient of mutual induction M* between coils is expressed in henrys. The coefficient of mutual induction *decreases* in value with a reduction in the number of loops or turns in either coil, and obviously also as the distance between the coils is increased.

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direction of induced voltage and the change in direction of the current producing the magnetic field.

Non-inductive and Inductive Circuits.—Comparative effects of induced currents in non-inductive and inductive circuits are shown in Figs. 28, 29, and 30. In the circuit shown in Fig. 28, there is a *non-inductive* resistance ($L = 0$), so that when the switch S is closed the current has immediately its maximum value. On the other hand, in the *inductive* resistance shown in Fig. 29, the current only gradually and slowly approaches its highest value. In fact, in this case it will take an infinite time for the current to reach its maximum value, although in a comparatively short time, it reaches very nearly its highest value, the rate of increase in current being, however, much more rapid immediately following the closing of the circuit than it is a little later. The rate of increase of current becomes less and less with elapsed time, until this *rate* becomes practically zero,[1] occurring in this case after 1/10 second.

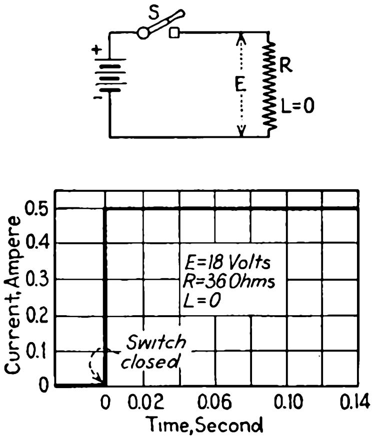


FIG. 28.—Curve of increase of current in non-inductive circuit after switch is closed.

The difference between the curves of current flow in Figs. 28 and 29 is due, of course, to the *inductance* which is zero in the first case and 0.9 henry in the second case, the voltage and resistance being the same in the two cases. The effect of inductance in delaying the increase of current in a circuit is the cause of the *time lag* that will be observed in the operation of the various types of relays that are used in many kinds of radio work.

[1] The equation of the rise of value of the current is as follows:

$$I = \frac{E}{R}\left(1 - e^{\frac{Rt}{L}}\right) \qquad (13)$$

where I is the current at a time represented by t in seconds, after the closing of the switch S, and e is the base of natural logarithms, which is 2.7128.

If a circuit like the one shown in the wiring diagram of Fig. 30 is short-circuited[1] by closing the switch *S*, as shown in the diagram, the current *I* through the coil does not stop immediately, as it would in a non-inductive circuit like Fig. 28, but continues to flow and does not become zero until an appreciable time after the short-circuiting switch has been

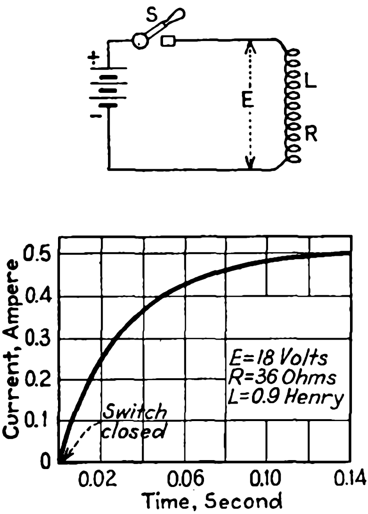


Fig. 29.—Curve of increase of current in inductive circuit when switch is closed.

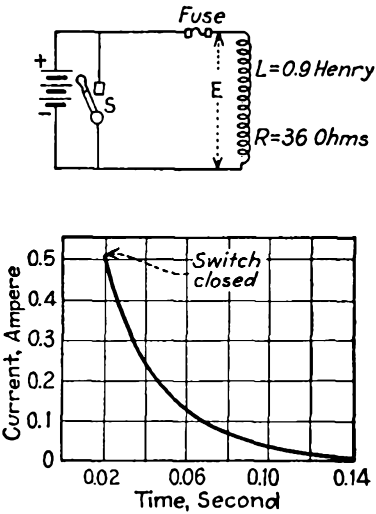


Fig. 30.—Curve of decrease of current in inductive circuit when switch is opened.

closed. This delay of the current in approaching a zero value, is shown by the current curve in the figure. The delay is caused by an induced voltage which, in this case, tends to slow down the rate at which the current is reduced.

In general, it may be said that inductance has the effect of opposing any change in the current. For example, if the current is increasing, the inductance has the effect of delaying

[1] Short-circuiting the part of the wiring including the inductance, as shown in Fig. 30, when the switch *S* is closed also short-circuits the battery, so that in order to prevent injury to it, a fuse should be inserted in the battery line.

that increase, and, on the other hand, if the current is decreasing the inductance tends to oppose the reducing rate of current flow. For these reasons, inductance may quite properly be called *electrical inertia.*

Arcing Effect Caused by Induction.—Quite different effects are produced at the blades of the switches, each marked S, in Figs. 28 and 29, when they are suddenly opened. As the switch bar is released from the blades in the circuit shown in Fig. 29, a relatively large flaming arc will be noticed at the switch; and, on the other hand, when the switch bar is removed from the blades in the circuit shown in Fig. 28, where there is no inductance, but only ordinary resistance, with exactly the same current and voltage as in the other case, the arc is very much smaller. This arcing at the switch is due to the voltage of induction, which in electric generators sometimes becomes so large that it punctures the insulation on the wire coils of the magnetic fields of a generator when a switch in the field coils is suddenly opened. In this and similar cases, the voltage due to induction may be many times the normal voltage in the coil through which the current has been flowing.

Calculation of Voltage in a Coil Caused by Induction.—The voltage generated in a coil by induction is proportional to the number of loops or turns in the coil (page 50) and also to the product of the inductance and the rate of change of current with respect to time. Briefly, then, if e is the voltage generated by induction, L is the inductance of the coil, and $I \div t$ is the rate of change of the current with respect to time, then for a circuit with a constant number of loops or turns,

$$e = L \times (I \div t). \qquad (14)$$

For example, if an induction coil has an inductance of 0.6 henry and the current through the coil is 12 amperes, which is interrupted after continuing for 0.05 second, then by the use of equation (14) the induced voltage in the coil is calculated thus:

$$e = 0.6 \times 12 \div 0.05 \text{ or } 144 \text{ volts.}$$

Energy of Magnetic Field.—In order to establish a magnetic field in a coil for radio or similar services, the expenditure of some energy is necessary. On the other hand, in order merely to maintain a magnetic field of a constant intensity; that is, a magnetic field that does not vary in its strength, no energy is required after the field has once been built up.[1]

In other words, the heat loss, owing to the current in a coil, is exactly the same with a direct or continuous current going through the coil as it is when the same kind of current passes through that same coil when it has an iron core (page 58). The energy in the magnetic field of a coil may be considered as potential or stored energy, somewhat similar, for example, to that of a suspended weight. Irrespective of the method, work is performed in raising the weight to greater heights, but no energy is expended in maintaining the weight in any position to which it has been elevated. Somewhat similarly, energy is stored in the magnetic field of an induction coil. The energy S expressed in watt-seconds or joules, stored in a magnetic field is

$$0.5LI^2 \tag{15}$$

where L is the inductance of the circuit in henrys and I is the current in amperes. This equation shows that for a given induction coil, the magnetic field is proportional to the square of the current in its winding. For this reason therefore, if the current in an induction coil is reduced to one half its initial value by placing a suitable resistance in the circuit, the energy of the arc caused by the opening of a switch in the circuit will be only one fourth as large as it would be without the resistance.

Example of Calculation of Energy and Power in an Induction Coil.—If an induction coil has an inductance of 0.06 henry and the current in the coil is 1.2 amperes, which is interrupted

[1] Energy lost in electromagnets, for example, because of the current passing through the resistances of the coils of the magnets is accounted for as heat in the wires of the coil, and is not, therefore, considered a loss in the magnetic circuit.

after a duration of 0.05 second, the *energy* S stored in the field of the induction coil is calculated by equation (15) as follows:

$$S = 0.5 \times 0.06 \times 1.2^2, \text{ or } 0.0432 \text{ joule.}$$

The *average power* P expended during the time that the circuit is being interrupted is $P = 0.0432 \div 0.05$, or 0.864 watt.

Coupling and Mutual Induction.—If two coils, like those marked C_1 and C_2 in Fig. 31 are set up so that they are near each other, as shown in the figure, and coil C_1 is supplied with current from a battery B or other source of direct or continuous electric current, then when the switch S is closed so that current flows in the coil C_1, a magnetic field will be established, as illustrated by the elliptical dotted lines in the figure. With the two coils located, as shown, some of the magnetic lines originating in the coil C_1 will also pass (as shown) through the coil C_2. Now, if the current in the coil C_1 is interrupted by opening the switch S, there will obviously be a change in the distribution of the magnetic lines in both of the coils, and this change will induce a voltage in the coil C_2. In other words, the coils C_1 and C_2 are so located with respect to each other that they are called *linked* or *coupled* coils, and because any change in the current flowing in the coil C_1 will produce an induced voltage in the coil C_2, the two coils have *mutual induction.* Even if the coil C_1 is brought very close to the coil C_2, it is impossible to have all of the magnetic lines established by the current in the coil C_1 circle or couple the coil C_2. The ratio of the number of magnetic lines from the coil C_1 that couple the coil C_2 to the total number of magnetic lines produced by the coil C_1 is called the *coefficient of coupling,* and is usually represented by the letter K. The extent to

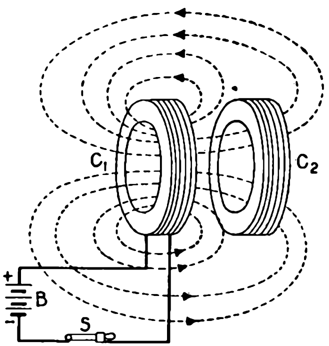


FIG. 31.—Mutual induction between two coupled coils.

which the magnetic field set up in a coil influences all the loops or turns in another coil is called the *coupling effect* of one coil on the other. The coefficient of coupling in terms of coefficients of mutual induction (page 51) and of self-induction (page 51) is expressed as

$$K = \frac{M}{\sqrt{L_1 \times L_2}} \tag{16}$$

where M = mutual induction between two coils, henrys.
L_1 = total self-induction of one coil, henrys.
L_2 = total self-induction of the other coil, henrys.

By definition, it should be added that when the current in one of two coupled coils is flowing at the rate of 1 ampere per second, and causes an induced voltage of 1 volt in a second coil, the two coils have a mutual inductance M of 1 henry (page 51).

A coil C_2 is the second of a coupled pair. The primary current in the first coil is I_m in amperes. If the duration of current is t in seconds, it is clear that the rate at which the current in the primary circuit (C_1) is changed is $I_m \div t$. Now, if, as before, the mutual inductance of the two coils with respect to each other is M in henrys, then the induced voltage e_2 in volts in the second coil is,

$$e_2 = M \times I_m \div t. \tag{17}$$

Similarly, if the current conditions in the coupled coils are reversed so that the coil C_2 receives the primary magnetizing current, then if I_n in amperes is the primary magnetizing current in the coil C_2, and this magnetizing current prevails for a time t in seconds, then the induced voltage in the coil C_1 is e_1 in volts, or

$$e_1 = M \times I_n \div t.$$

Example of Calculation of Induced Voltage in Coupled Coils.—A current of 0.4 ampere flows in one of two coupled coils, of which the mutual induction is 0.15 henry. The current flows through one of the coils for a duration of 0.04

second. Equation (17) can be used to calculate the induced voltage e_2 in the second coil, thus

$$e_2 = (0.15 \times 0.4) \div 0.04 \text{ or } 1.5 \text{ volts.}$$

Coupled Coils with Iron Core.—The insertion of an iron core, preferably of the kind having a complete magnetic circuit, as shown in Fig. 32, improves very much the mutual induction between two coupled coils, and consequently raises proportionately the coefficient of coupling. In fact, by this arrangement, the coefficient of coupling may be nearly unity.

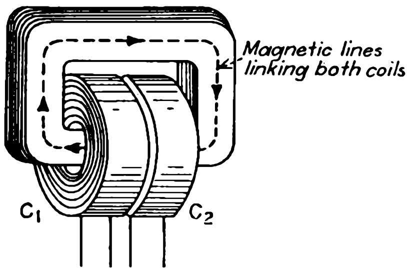


FIG. 32.—Closely coupled coils with iron core making magnetic circuit.

Types of Induction Coils.—When an iron core is placed in a coil of wire, it has the effect of increasing very much the inductance of the coil. Those coils of wire that have an iron core are called *iron-core coils* and those that have none are *air-core coils.* The air-core coils that are generally used in radio receiving sets which have relatively few loops or turns of wire without an iron core are comparatively low in inductance. On the other hand, a small iron-core coil of the kind that is used in a telephone receiver, for example, which has many thousands of loops or turns of fine wire has a much larger inductance than an air-core coil of coarse wire which is many times larger in diameter and in length.[1]

[1] Large air-core coils cannot be successfully used in radio receiving sets for the reason that at the high frequencies (p. 39) of the current used they have considerable condenser effect (p. 47); in fact, under such circumstances the condenser effect of a large-diameter air-core coil is much greater than its induction effect.

Induction-coil Calculations.—The inductance of coils that are in simple geometric shapes such as circles, cylinders, and spheres, can be calculated from theoretical formulas; but these are so complicated that their derivation cannot be taken up here. One of the most used of the simple-shaped air-core coils is the *solenoid* (Fig. 31), which is cylindrical with its loops or turns of wire wound in a continuous circuit.

Single Loop.—A single circular loop of wire is, of course, even a simpler geometric figure than the solenoid. The inductance L_0 in *microhenrys*[1] of such a single loop (with or without insulation covering) for *direct* or *continuous* current in the coil may be calculated with the following formula:

$$L_0 = 0.004\pi R\left[\left(1 + \frac{r^2}{8R^2}\right)\log_e \frac{8R}{r} + \frac{r^2}{24R^2} - 1.75\right] \quad (18)$$

where R is the radius of the loop or turn measured to the center of the wire in centimeters; r is the radius of the wire in centimeters; π is 3.1416; $\log_e$ is the logarithm to the base e or the natural logarithm (Table II, page 60).

The inductance L_a in *microhenrys* of a *single-layer solenoid* (with air core) for direct or continuous current is given approximately by the following equation:

$$L_a = 0.04kR^2n^2l \quad (19)$$

where R is the radius of the solenoid to the center of the wire in centimeters; l is the length of the coil in centimeters; n is the number of loops or turns per centimeter of length of the coil; k is a shape factor depending on the ratio of the diameter of the coil to its length. Values of this shape factor are given in Table III on page 61.

The inductance L_i in microhenrys of a solenoid with an iron core consisting of a bundle of soft-iron wires is expressed approximately by the following equation, where d_c is the diameter of the *core* in centimeters (assume in case of *single-layer* windings same as diameter of coil) and N is the total

[1] A microhenry is one millionth of a henry—the standard unit of inductance (p. 51).

TABLE II.—NAPIERIAN LOGARITHMS

$e = 2.7182818 \qquad \log e = 0.4342945$

	0	1	2	3	4	5	6	7	8	9
1.0	0.0000	0.00995	0.01980	0.02956	0.03922	0.04879	0.05827	0.06766	0.07696	0.08618
1.5	0.4055	0.4121	0.4187	0.4253	0.4318	0.4382	0.4447	0.4511	0.4574	0.4637
2.0	0.6931	0.6981	0.7031	0.7080	0.7129	0.7178	0.7227	0.7275	0.7324	0.7372
2.5	0.9163	0.9203	0.9243	0.9282	0.9322	0.9361	0.9400	0.9439	0.9478	0.9517
3.0	1.0986	1.1019	1.1053	1.1086	1.1119	1.1151	1.1184	1.1217	1.1249	1.1282
3.5	1.2528	1.2556	1.2585	1.2613	1.2641	1.2669	1.2698	1.2726	1.2754	1.2782
4.0	1.3863	1.3888	1.3913	1.3938	1.3962	1.3987	1.4012	1.4036	1.4061	1.4085
4.5	1.5041	1.5063	1.5085	1.5107	1.5129	1.5151	1.5173	1.5195	1.5217	1.5239
5.0	1.6094	1.6114	1.6134	1.6154	1.6174	1.6194	1.6214	1.6233	1.6253	1.6273
5.5	1.7047	1.7066	1.7884	1.7102	1.7120	1.7138	1.7156	1.7174	1.7192	1.7210
6.0	1.7918	1.7934	1.7951	1.7967	1.7984	1.8001	1.8017	1.8034	1.8050	1.8066
6.5	1.8718	1.8733	1.8749	1.8764	1.8779	1.8795	1.8810	1.8825	1.8840	1.8856
7.0	1.9459	1.9473	1.9488	1.9502	1.9516	1.9530	1.9544	1.9559	1.9573	1.9587
7.5	2.0149	2.0162	2.0176	2.0189	2.0202	2.0215	2.0229	2.0242	2.0255	2.0268
8.0	2.0794	2.0807	2.0819	2.0832	2.0844	2.0857	2.0869	2.0881	2.0894	2.0906
8.5	2.1401	2.1412	2.1424	2.1436	2.1448	2.1459	2.1471	2.1483	2.1494	2.1506
9.0	2.1972	2.1983	2.1994	2.2006	2.2017	2.2028	2.2039	2.2050	2.2061	2.2072
9.5	2.2513	2.2523	2.2534	2.2544	2.2555	2.2565	2.2576	2.2586	2.2597	2.2607
10.0	2.3026									

number of loops or turns in the coil for *direct-* or *continuous-*current conditions and for coils having ratios of diameter to length between 0.07 and 0.10:*

$$L_i = 0.08N^2d_c. \tag{20}$$

TABLE III.—SHAPE FACTORS FOR CALCULATING INDUCTANCE OF SOLENOIDS

Ratio of diameter to length	Shape factor k	Ratio of diameter to length	Shape factor k
0.00	1.000	0.95	0.700
0.05	0.979	1.00	0.688
0.10	0.959	1.10	0.667
0.15	0.939	1.20	0.648
0.20	0.920	1.40	0.611
0.25	0.902	1.60	0.580
0.30	0.884	1.80	0.551
0.35	0.867	2.00	0.526
0.40	0.850	2.50	0.472
0.45	0.834	3.00	0.429
0.50	0.818	3.50	0.394
0.55	0.803	4.00	0.365
0.60	0.789	4.50	0.341
0.65	0.775	5.00	0.320
0.70	0.761	6.00	0.285
0.75	0.748	7.00	0.258
0.80	0.735	8.00	0.237
0.85	0.723	9.00	0.219
0.90	0.711	10.00	0.203

Calculation of Inductance of Air-core and Iron-core Solenoids. *Example* 1.—The inductance of a wire coil is very much increased when a core made up of iron wires is inserted in its center. This may be shown by calculating the inductance of a solenoid with an air core 60 centimeters long, 6 centimeters

* "Standard Handbook for Electrical Engineering" (1933), Sec. 5, §§156 and 164, also H. Armagnat, "Induction Coils" (translated from French by O. A. Kenyon), McGraw-Hill Book Company, Inc., New York.

in outside diameter, and having 150 loops or turns, with equation (19), for direct- or continuous-current service thus,

$$L_a = 0.04kR^2n^2l \tag{21}$$

where k is a shape factor from Table III, which varies with the ratio of the diameter to the length of the coil. In this case, $d = 6$ centimeters, $l = 60$ centimeters and $d \div l = 0.10$, so that the corresponding shape factor k from the table is 0.959. The radius R of the coil is 3 centimeters, the number of loops or turns per centimeter of length of the coil n is $150 \div 60$, or 2.5, then

$$L_a = 0.04 \times 0.959 \times 3^2 \times 2.5^2 \times 60, \text{ or } 129.0 \text{ microhenrys.}$$

The inductance of the same solenoid, when it has a core of iron wires, can be similarly calculated approximately by the use of equation (20), in which $N = 150$ loops or turns and d_c is *approximately* 6 centimeters,

$$L_i = 0.08N^2 \times d_c \tag{22}$$
$$L_i = 0.08 \times 150^2 \times 6, \text{ or } 10{,}800 \text{ microhenrys.}$$

It will be noticed in the above examples that the inductance of the solenoid with an iron core is about 80 times as large as when the coil has an air core.

Example 2.—A solenoid (air-core coil) has a radius R of 2.54 centimeters (1 inch) and length l of 10.16 centimeters (4 inches). The number of turns n per centimeter of length is 8. Ratio of diameter to length of coil is $5.08 \div 10.16$, or 0.5, so that the form factor k is 0.818. Then the inductance L_a for direct or continuous current in microhenrys is calculated thus,

$$L_a = 0.04k \times (2.54)^2 \times 8^2 \times 10.16 = 0.04 \times 0.818 \times (2.54)^2 \times 64 \times 10.16, \text{ or } 137.0 \text{ microhenrys.}$$

Example 3.—A single-layer air-core solenoid, 4 inches (10.16 centimeters) in diameter and 8 inches (20.32 centimeters) long has 203 turns. Ratio of diameter to length is 0.5 so that the form factor k is 0.818. Number of turns n per centimeter of length is 203 ÷ 20.3 or 10. The inductance L_a in microhenrys for direct or continuous current is

$$L_a = 0.04 \times 0.818 \times (5.08)^2 \times 10^2 \times 20.32 = 0.04 \times 0.818 \times 25.806 \times 100 \times 20.32, \text{ or } 1{,}715 \text{ microhenrys.}$$

Example 4.—The diameter of an induction coil with an *iron* core is 0.15 as large as its length, which is 50.8 centimeters. The number of turns of wire in the coil is 200. Using equation (20), the diameter d_c of the iron core is nearly 50.8 × 0.15, or 7.62 centimeters and the inductance L_i of the induction coil for direct or continuous current is given approximately as follows:

$$L_i = 0.08 \times (200)^2 \times 7.62 = 24{,}380 \text{ microhenrys.}$$

The inductance of the same coil with an *air core* is interesting to calculate with equation (19), in which R is (50.8 × 0.15) ÷ 2, or 3.81 centimeters, l is 50.8 centimeters, and the form factor k from the Table III for $d \div l$ equals 0.15 is 0.939. The number of turns n per centimeter of length is 200 ÷ 50.8, or 3.94, so that the inductance L_a is

$$L_a = 0.04 \times 0.939 \times 3.81^2 \times 3.94^2 \times 50.8, \quad \text{or} \quad 430.5 \text{ microhenrys,}$$

meaning that the inductance of this coil with an iron core is about 60 times as large as it is without the core.

In the preceding paragraphs the formulas were used for the calculation of inductance of a single loop or turn of round wire and of solenoids, the latter being of the air-core and the iron-core types. When a wire loop or solenoid has an iron core its inductance depends a great deal on the magnetic qualities of the iron that is used for the wires of the core. If the manufacturer of the iron furnishes a curve showing the flux density of his product, the inductance of an iron-core coil can be calculated more accurately by the usual laboratory methods.[1]

[1] *Bureau of Standards Circular* 74 *and Bureau of Standards Scientific Paper* 169. Formulas for the calculation of edgewise-strip spirals, flat spirals, and multilayer coils are given in Moyer and Wostrel, "Radio Handbook," pp. 97–101.

Choke and Other Induction Coils for Alternating Current.—The inductance of a coil with an iron core and two windings of wire, intended for an *alternating current* (page 39) in one winding and a direct or continuous current in the other, decreases in value as its direct- or continuous-current magnetization current in one winding is increased. The action of these coils on each other is in this respect like that of the two circuits of the transformer of an audio-frequency amplifier (page 410). This fact is of considerable significance in the designing of *choke coils* for *filters* in radio receiving sets; the choke coils being intended to "choke out" or at least partially eliminate the alternating ripples in the rectified (page 4) alternating current.

The design of induction coils is largely empirical as there are many conditions for which available data are incomplete. The preceding equations, it will be noted are for the inductance of coils, with and without iron cores for direct or continuous current only. The corresponding values of inductance for alternating current are generally much less and must be determined by actual testing by laboratory methods.

Tuned Circuits.—By the method of using variable condensers (page 64) in series with induction coils, radio receiving sets are adjusted to receive broadcasting from one particular transmitting station, and to eliminate the broadcasting from other stations. This is called "tuning the circuit to a particular frequency," which is possible because the different broadcasting stations transmit at different, sufficiently separated frequencies.

Variable and Stationary Condenser Calculations.—Formulas are given on page 65 by which the capacity of simple types of condensers can be calculated. In these formulas the following symbols are used: C is the capacity of the condenser in micromicrofarads; A is the area in square centimeters of a side of one of a series of stationary plates; d is the distance in centimeters between a movable plate and a stationary plate in a variable condenser or between any two of a series of stationary plates; n is the number of movable plates in a variable condenser; A_m is the area in square centimeters of one side of a movable plate in a variable condenser; A_b is the area of one side of one sheet of a rolled by-pass condenser; t is the thickness in centimeters of the paper in a rolled by-pass condenser; π is 3.1416; and k is the specific inductive capacity of waxed paper (see page 614).

The capacity of a pair of *parallel flat plates* with air separation is

$$C = 0.884A \div d \text{ (in micromicrofarads).} \tag{23}$$

The maximum capacity of a *multiplate variable condenser* (with a number of movable plates one less than the stationary plates) is

$$C = 0.1768nA_m \div d \text{ (in micromicrofarads).} \tag{24}$$

The capacity of a rolled by-pass condenser (Fig. 33)

$$C = 0.1768kA_b \div t \text{ (in micromicrofarads).} \tag{25}$$

Practical Example of Calculation of Capacity of Variable Condenser.—By the use of the equations already given, the capacity of most condensers can be readily calculated. For example, the following calculation shows how the capacity of a typical variable condenser of the kind ordinarily used for tuning in radio receiving sets can be calculated. In this case, the variable condenser has five movable plates (and six stationary plates). Each movable plate has an area of 7.5 square inches (7.5 × 2.54 × 2.54),[1] or 48.37 square centimeters, and in the position for maximum capacity effect is equidistant from the stationary plate on each side. The distance in this position between a movable plate and a stationary plate is 0.05 inch or 0.05 × 2.54, or 0.127 centimeter. The capacity C in micromicrofarads of this con-

[1] Inches are changed to equivalent centimeters by multiplying by 2.54, and square inches to square centimeters by multiplying by 6.45 (2.54 × 2.54).

denser, when the plates are in a position for maximum effect, may then be calculated by the use of equation (24) as follows:

$$C = 0.1768 \times 5 \times 48.37 \div 0.127 = 336 \text{ micromicrofarads.}$$

Another interesting example to work out is the normal capacity of a rolled condenser (Fig. 33) made up of a plate of aluminum foil that is insulated on both sides by wax paper. This condenser is similar to the one shown in Fig. 33. The capacity of this condenser may be calculated by using equation (25). The specific inductive capacity of the waxed paper is 2.3. The aluminum foil used in making the condenser is

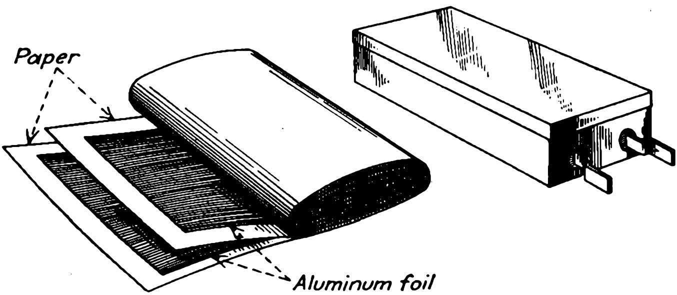


FIG. 33.—Method of making electric condenser from sheets of aluminum foil and waxed paper.

7.5 centimeters wide and 915 centimeters long. The wax paper is 0.0025 centimeter thick. Substituting these values in the equation, the capacity of the condenser C in micromicrofarads equals $0.1768 \times 2.3 \times 6{,}863 \div 0.0025$, or 1.12 microfarads.

Reactance of Condenser.—It is an interesting fact that if a condenser is connected to an alternating-current line, the charging current will be directly proportional to the impressed voltage and directly proportional also to the frequency of this voltage. It is also a fact that if a condenser having a capacity of 3 microfarads, for example, is used in a circuit in the place of one having a capacity of 1½ microfarads the charging current will be doubled. It is plain, then, that the charging current is proportional to the voltage, the frequency, and the capacity. The reactance of a condenser usually designated by the symbol X_c is the value obtained by dividing the voltage by the charging current. It is, therefore, inversely proportional to the charging current as well as inversely proportional to the frequency and the capacity of the condenser. Stated algebraically, the reactance of a condenser in ohms is

$$X_c = \frac{1}{2\pi fC} \tag{26}$$

where C is the capacity in farads, f is the frequency in cycles per second, and π is 3.1416.

Calculation of Current Flowing in Condenser.—In the same way that the current flowing in an inductive circuit is found by calculating the ratio of the impressed electromotive force or voltage E to the reactance X of the circuit, the current flowing in a condenser circuit can likewise be calculated by determining the ratio of the impressed electromotive force or voltage to the reactance X_c of the condenser. It was shown above, however, that the reactance of the condenser can be stated in terms of constants, frequency, and capacity, or that X_c in ohms equals $1 \div 2\pi fC$.

The current I in a condenser circuit in amperes is, then,

$$I = \frac{E}{X_c} = \frac{E}{1 \div 2\pi fC} = 2\pi fCE.^* \tag{27}$$

Example of Calculation of Current in Condenser Circuit.—By using the preceding equation, the current in a condenser circuit can be readily calculated. For example, the current I flowing in a condenser having a capacity of 5 microfarads, when connected in a 50-volt, 60-cycle distributing line is calculated as follows:

$I = 2 \times 3.1416 \times 60 \times 5 \times 50 \div 1{,}000{,}000$ or 0.0943 ampere.

* It will be noted in this equation that the current flowing in a condenser circuit is directly proportional to the frequency, while in an inductive circuit (p. 52) the current is *inversely* proportional to the frequency. If the capacity C is in microfarads the equation is $I = 2\pi fCE \div 1{,}000{,}000$.

An interesting example for calculation is the following, relating to the antenna of a radio broadcasting station. The antenna has a capacity effect of 0.0032 microfarad and is connected to a 400-volt circuit operating with a frequency of 1,000,000 cycles per second. The current flow in the antenna is then

$$I = 2 \times 3.1416 \times 1{,}000{,}000 \times 0.0032 \times 400 \div 1{,}000{,}000 = 8.04 \text{ amperes.}$$

Reactance of Coils with Alternating Current.—It can be shown experimentally as well as theoretically that any coil having a constant value of inductance (page 50) and ohmic resistance (page 42) will interfere more with the flow through it of a high-frequency current than it will with a current that has a much lower frequency. For example, if the current going through a coil from an ordinary alternating lighting circuit having a frequency of 60 cycles per second is 5 amperes, then the current that will go through the same coil when the frequency is 300 cycles per second will be only about one-fifth as much or about one ampere. The combined effect of both inductance and frequency is usually represented by the letter X and is called *reactance*. Its value is given in *ohms* in the following equation where L is the inductance in henrys, f is the frequency in cycles per second, and π is 3.1416:

$$X_L = 2\pi fL, \text{ or } 6.28fL. \qquad (28)$$

Some circuits have practically no inductance so that they are called *non-inductive*. An incandescent lamp, for example, is a typical example of a non-inductive circuit. It has no inductance and, therefore, also no reactance (obviously $X_L = 0$, when $L = 0$). In this case an alternating current is limited only to the *ohmic* or ordinary resistance R of the circuit.

Current in Inductive Circuit. Impedance.—In an inductive circuit, the flow of current is limited by the resistance and the reactance. The factor limiting the amount of current in an inductive circuit is not the arithmetical sum of the resistance and the reactance, but is the square root of the sum of the squares of these quantities.[1] The combined effect of resistance and inductive reactance is called the *impedance*, and is represented usually by the symbol Z. Then, if the ordinary resistance of a circuit is R and the reactance of that circuit is X,

$$Z = \sqrt{R^2 + X^2}. \qquad (29)$$

The relation of these quantities, as expressed by the above equation, applies to a coil or to a condenser, either of which may have a resistance in series with it.

Practical Example of Calculation of Current in Inductive Circuit.—In capacity circuits, in most cases, the losses other than the condenser reactance are usually so small that they need not be considered. In an inductive circuit, however, the resistance may be a large factor and must be considered along with the inductive reactance. In other words, the calculation of the impedance, expressed in *ohms*, of a coil requires the determination of both its resistance and its inductive reactance for use in the equation $Z = \sqrt{R^2 + X^2}$.

A useful example for calculation is the determination of the current in an inductive circuit in which the ordinary resistance R is 7½ ohms, the inductance L is 0.05 henry, and the circuit is connected to a supply line at 100 volts and 60 cycles per second. In this case, R equals 7½ ohms, L equals 0.05 henry, f equals 60, and π equals 3.1416. Substituting these values in the equation (28) for inductive reactance, where $X = 2\pi fL$, the value of X is $2 \times 3.1416 \times 60 \times 0.05$ or 18.8 ohms, or the impedance Z is then

$$\sqrt{7.5^2 + 18.8^2} = \sqrt{56.25 + 353.4},$$

or 20.23 ohms. Since, in an inductive circuit, the current flow I in amperes is obviously $E \div Z$, the current flow in this case is $I = 100 \div 20.23$, or 4.93 amperes.

An examination of the equation for impedance Z shows that if the frequency is very large, the ordinary resistance becomes negligible in relative value so that the current in that case

[1] See Moyer and Wostrel, "Radio Handbook," p. 75.

might be calculated by taking into account only the inductive reactance without the resistance.

Example of Calculation of Current in a Circuit Having Condenser and Resistance in Series.—When dealing with a circuit having a resistance and a condenser in series, the method of calculation is very much like the preceding example. An interesting problem is to find the current flowing through a circuit containing a condenser and a resistance supplied with alternating current at 220 volts and at a frequency of 60 cycles per second, the resistance in the circuit measuring 30 ohms and the capacity of the condenser being 75 microfarads. Using the formula on page 67, the condenser reactance X_c is

$$1 \div 2\pi fC \text{ or } 1 \div [2 \times 3.1416 \times 60 \times (75 \div 1{,}000{,}000)], \text{ or } 35.4 \text{ ohms.}$$

The impedance of the entire circuit is then

$$Z = \sqrt{30^2 + 35.4^2} = \sqrt{2153},$$

or 46.4 ohms; and the current flowing in the circuit is $E \div Z$, or $220 \div 46.4$, or 4.74 amperes.

Resistance, Inductance, and Capacity in Series.—Probably the circuit to which reference is made most often in the study of radio apparatus is the one which has resistance, inductance and capacity in series. Figure 34 shows diagrammatically a circuit taking current from an alternating supply. The ordinary resistance is represented by R, the inductance by L, and the condenser producing the capacity effect by C. In the radio circuits usually found in practice, the resistance to be dealt with is only that of an induction coil, as the series resistance of the condenser is negligibly small. If it happens that the condenser has an appreciable resistance, the circuit resistance R to be used in the calculations is the sum of the induction coil resistance and that of the condenser. In a

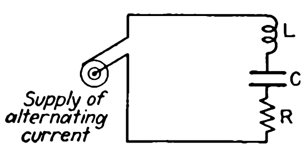


FIG. 34.—Alternating-current circuit with resistance, inductance, and capacity in series.

circuit of this type, the following items must be determined before the calculation of the net effect of resistance, inductance, and capacity can be worked out. In other words, the quantities to be considered are:

1. Ordinary resistance.
2. Inductive reactance.
3. Condenser reactance.

The inductive reactance and the condenser reactance tend to neutralize each other when they are in the same circuit. The total reactance of a circuit of this kind is therefore the difference between the two reactances instead of the sum. If X_t is the net or total circuit reactance, then $X_t = X_L - X_c$.

If the equation for impedance is changed in form for the two kinds of reactance, it is $Z = \sqrt{R^2 + (X_L - X_c)^2}$. On pages 67 and 68, inductive reactance and condenser reactance were written in terms of frequency f (cycles per second), inductance L (henrys), and capacity C (farads). Substituting these values in the preceding equation, we have for the impedance Z in ohms:

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2} \qquad (30)$$

also the current I in this circuit in amperes is,

$$I = E \div \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2} \qquad (31)$$

The equations that have just been derived are of the utmost importance in radio work. They are invaluable in the study of the principles underlying the tuning and selectivity of radio receiving sets. Assume that the current supply to a circuit containing resistance, inductance and capacity in series is at 110 volts and that the frequency of the supply is 60 cycles per second. It is desired to calculate the current in a circuit supplied by this line and containing an induction coil having an ordinary resistance of 15 ohms and an inductance of 0.15 henry, the capacity of the condenser being

15 microfarads with negligible resistance. Besides calculating the current in this circuit, it will be worth while to determine also the voltage across the coil, as well as the voltage across the condenser. The resistance R of the induction coil, as stated, is 15 ohms. The reactance X of the induction coil is $2\pi fL = 2 \times 3.1416 \times 60 \times 0.15$, or 56.52 ohms. The reactance X_c of the condenser is $1/2\pi fC = 1 \div [3.1416 \times 60 \times (15 \div 1{,}000{,}000)]$, or 177.0 ohms. Since the condenser reactance and the induction coil reactance tend to neutralize each other, the net or total circuit reactance is 56.52 ohms $-$ 177.0, or -120.5 ohms. In this algebraic addition, the minus sign before the result indicates merely that the capacity effect is larger than that of induction.

The impedance Z of the circuit is $\sqrt{15^2 + (120.5)^2}$ equals 121.4 ohms. The current I in the circuit is $E \div Z = 110 \div 121.4$, or 0.906 ampere.

In order to calculate the voltage across the coil, it is necessary to determine the impedance of the induction coil itself, which has not yet been done. This impedance

$$Z' = \sqrt{15^2 + 56.52^2},$$

or 58.5 ohms. The voltage across the induction coil ($I \times Z'$) $= 0.906 \times 58.5$, or 53.0 volts.

The voltage across the condenser $I \times X_c = 0.906 \times 177.0$, or 160.4 volts.

A more interesting example than the above with also a circuit including resistance, inductance and capacity in series is the following from Morecroft.[1]

This example deals with a radio circuit consisting of an induction coil having an inductance of 250 microhenrys and a resistance of 20 ohms. This induction coil is in a circuit in series with a condenser which has a capacity of 110 micromicrofarads. The current is to be calculated in this circuit when the electromotive force is 4 millivolts at a frequency of 1,000 kilocycles per second. After the current is calculated, the voltage drop across the condenser and also across the

[1] MORECROFT, JOHN H. "Elements of Radio Communication," p. 46.

induction coil are to be determined. The resistance of the induction coil is 20 ohms. The reactance X_L of the induction coil is then $2\pi fL = 2 \times 3.1416 \times 1{,}000{,}000 \times (250 \div 1{,}000{,}000)$, or 1,570 ohms. Reactance of the condenser is $1/2\pi fC = 1 \div (2 \times 3.1416 \times 1{,}000{,}000 \times 110 \div 1{,}000{,}000{,}000{,}000)$, or 1,450 ohms. Net or total reactance X_t of the circuit is $X_L - X_C = 1{,}570 - 1{,}450$, or 120 ohms. Impedance of the circuit $Z = \sqrt{R^2 + X_t^2}$, or $\sqrt{20^2 + 120^2}$, or 121.7 ohms. Current I in the circuit is $E \div Z$, or $0.004 \div 122$, or 0.000038 ampere. Voltage across the induction coil[1] is $I \times X_L$ equals $0.000038 \times 1{,}570$, or 0.06 volt. In this case it was stated that the voltage induced in the circuit is 4 millivolts, and the calculations show that the voltage drop across either the coil or the condenser is much greater than this value. In other words, the voltage drop across either the coil or the condenser is nearly 15 times as large as the induced voltage in the circuit.

Inductances in Parallel and in Series.—Inductances in series are added like resistances. If the coils are so far apart that mutual inductance is negligible, inductances in parallel combine like resistances in parallel (page 35). If mutual inductance is considered, the total value of inductances in series is

$$L = L_1 + L_2 + L_3 + \cdots + 2(M_{1-2} + M_{1-3} + M_{2-3} + \cdots).$$

Some or all of the mutual inductances may be negative. For two coils in parallel the total inductance is

$$L = \frac{L_1L_2 - M^2}{L_1 + L_2 - 2M}.$$

The term $2M$ changes sign if M is negative.

Examples of Calculation of Capacity of Condensers in Parallel and in Series.—As already stated, when condensers are connected in parallel, the resulting total capacity is the

[1] The resistance R is so small in comparison with the reactance of the induction coil that it is not included in this calculation. Voltage across condenser equals $I \times X_c = 0.000038 \times 1{,}450$, or 0.055 volt.

sum of the individual capacities. Thus, if the capacities of a group of three condensers are respectively c_1, c_2, c_3, then the capacity c_p of a single condenser that would replace the parallel group would be $c_1 + c_2 + c_3$. Now in a practical example, if the individual capacities of a group of three condensers are respectively 0.0005, 0.0010, and 0.00025 microfarad, then the equivalent capacity C_p of a single condenser in microfarads to replace the group when connected in parallel is 0.0005 + 0.0010 + 0.00025, or 0.00175 microfarad.

A somewhat similar statement applies to the equivalent capacity of a single condenser to replace a group of condensers that are connected in series. In the case of such series connection, the reciprocal of the equivalent capacity of a number of condensers in series is equal to the sum of the reciprocals of the capacities of the individual condensers. Thus, if in a group of condensers in series the individual capacities are represented by c_1, c_2, c_3 in microfarads, then the capacity C_s in microfarads is given by the following equation:

$$\frac{1}{C_s} = \frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3}.$$

Assuming the values of three condensers in a group, the same as in the last example, which are respectively 0.0005, 0.0010, and 0.00025 in microfarads, then $1/C_s$ is given by the following equation:

$$\frac{1}{C_s} = \frac{1}{0.0005} + \frac{1}{0.001} + \frac{1}{0.00025} = 2{,}000 + 1{,}000 + 4{,}000 = 7{,}000,$$

or $C_s = 1/7{,}000$ or 0.0001429 microfarad or 142.9 micromicrofarads. It will be noticed, therefore, that in the case of condensers in series, the equivalent single condenser has a much smaller capacity than any of the individual condensers.

Using the notation on page 47, the electrostatic charge Q in microcoulombs on a condenser is $C \times E$, where E is the potential in volts *across the condenser* and C is the capacity of the condensers in parallel connection in microfarads.

In the case of the three condensers in the preceding example, if the electric current charging the condensers is from a 110-volt line, the charge Q in microcoulombs is $C \times E$ or 0.0001429×110, which is 0.015719 microcoulomb.

If now the potential across the first condenser of the group is represented by e_1, that across the second by e_2, and that across the third by e_3, then, by reversing the method of calculation ($e = Q \div c$),

$$e_1 = \frac{0.0157}{0.0005}, \text{ or } 31.4 \text{ volts.}$$

$$e_2 = \frac{0.0157}{0.0010}, \text{ or } 15.7 \text{ volts.}$$

$$e_3 = \frac{0.0157}{0.00025}, \text{ or } 62.8 \text{ volts.}$$

Energy Stored in Condensers.—When there is a difference of potential between the positive and the negative plates of a condenser (as may be shown by the spark that results when its terminals are short-circuited), there is obviously stored energy in the condenser. The stored energy S in watt-seconds (page 37) or joules for a given condenser is $S = 0.5QE$ where Q is the charge on the condenser in coulombs and E is the potential across the condenser in volts. Then, since $Q = E \times C$ or $E = Q \div C$, the above equation for the stored energy may be stated thus, $S = 0.5CE^2$; or in another form

$$S = 0.5Q^2 \div C. \tag{32}$$

The next to the last of these equations shows that the energy stored in a condenser[1] is proportional to the square of the potential (voltage) E across the condenser.

Using again the group of three condensers considered in the preceding examples, the last equation (31) can be used to calculate the stored energy in *each* of the condensers in watt-seconds, or joules, as in the following equations:

[1] The energy S (watt-seconds or joules) stored in an electromagnetic field, is $S = 0.5LI^2$ (see p. 55).

$s_1 = 0.5(0.0157 \div 1{,}000{,}000)^2 \div (0.0005 \div 1{,}000{,}000) = 0.0000002466$ joule.

$s_2 = 0.5(0.157 \div 1{,}000{,}000)^2 \div (0.0010 \div 1{,}000{,}000) = 0.0000001233$ joule.

$s_3 = 0.5(0.0157 \div 1{,}000{,}000)^2 \div (0.00025 \div 1{,}000{,}000) = 0.0000004932$ joule.

Total energy S in the group of condensers is $0.5(0.0157 \div 1{,}000{,}000) \times 110 = 0.000000863$ joule.

Also for a check of the last result,

$$S = s_1 + s_2 + s_3 = 0.0000002466 + 0.0000001233 + 0.0000004932, \text{ or } 0.000000863 \text{ joule.}$$

Angle of Lag of Current in Induction Coil.—If the voltage impressed on an induction coil has a sine-wave form, the current will also follow a sine wave. There will be, however, a so-called "phase difference" between the voltage and the current for the reason that in an *inductive* circuit of any type, the current *lags* behind the voltage, meaning that the current does not reach its maximum values at the same time that the voltage does but lags behind the voltage. This "phase difference" between the current and voltage in an inductive circuit is usually represented by angular measure, the phase difference being called the *angle of lag*. The theoretical maximum angle of lag is 90 degrees or one quarter cycle. This theoretical maximum of angle of lag is, however, never attained as it would imply that the resistance of the coil is zero, which is, of course, an impractical condition. In well-made coils of the kind used in first-class radio receiving sets, the angle of lag may approach very close to 90 degrees and in fact the angle of lag in some radio-frequency circuits as used in radio construction may be as large as 88 or 89 degrees.[1]

The angle of lag of an inductive circuit cannot be simply determined by direct methods and is usually determined

[1] The angle of lag in inductive circuits as commonly found in power plant work varies usually from 50 to 70 degrees and is scarcely ever more than 75 degrees.

indirectly from the numerical ratio of the reactance of the circuit to the resistance of the circuit.[1]

Transformers for Alternating-current Radio Receiving Sets.—Transformers with iron cores are commonly used in radio receiving sets with the primary winding of the transformer joined up with the plate circuit of a vacuum tube. The iron core of the transformer is thus magnetized by both the direct or continuous *plate* current (page 4) and also the alternating plate current due to the applied signal voltage. The inductance due to the alternating current in the transformer winding decreases rapidly as the magnetization due to a direct or continuous current is increased. This fact is of importance in the designing of choke coils for filters (page 64), such coils being used to suppress the alternating components of a rectified (page 3) alternating current.

The reactance X_L (or $2\pi fL$, page 68) of a coil connected to a 110-volt 60-cycle line is 750 ohms. The current in the coil must therefore be $110 \div 750$, or 0.147 ampere.

Resonance Frequency.—The net or total reactance (page 71) of a circuit is the arithmetical difference between the inductive reactance X_L and the condenser reactance X_C. Obviously, then, a radio circuit can be constructed, in which the inductive reactance X_L and the condenser reactance X_c are equal and in which, consequently, the net or total reactance is zero. When this equality with respect to reactance occurs, there are larger values of current in a given circuit than under any other conditions; and when this condition exists a circuit is *resonant*. Since the inductive reactance X_L (measured by $2\pi fL$) and the condenser reactance X_c (measured by $1 \div 2\pi fC$) have both the factor f indicating frequency, the value of

[1] The angle of lag is determined numerically from the ratio of the circuit reactance to the circuit resistance, this ratio being the tangent of the angle. Thus, if the circuit reactance and the circuit resistance are equal, the value of the tangent is unity and the corresponding angle as determined by trigonometric relations is 45 degrees. In terms of the symbols already used the tangent of the angle of lag is $X_L \div R$; the sine (abbreviated "sin") of the angle of lag is then $X_L \div Z_L$; and the cosine (abbreviated "cos") of the angle of lag is $R \div Z_L$.

frequency at which the circuit will have resonance can be readily calculated by solving the following equation:

$$2\pi fL = 1 \div 2\pi fC,$$

so that

$$f_{res} = 1 \div 2\pi\sqrt{LC} \tag{33}$$

in which f_{res} is the resonance frequency of the circuit, L is the inductance in *henrys*, and C is the capacity in *farads*. In radio work, these units are, however, inconveniently large, so that for this kind of service, the following equation is preferred, in which L' is the inductance in *microhenrys* and C' is the capacity in *microfarads*:

$$f_{res} = 1{,}000{,}000 \div 2\pi\sqrt{L'C'}. \tag{34}$$

Example of Calculation of Resonance Circuit.—The following calculation shows the method of finding the resonance frequency of a circuit having an inductance L' of 200,000 *microhenrys* and a capacity C' of 20 *microfarads* in series. The inductance is that of an induction coil, of which the resistance R is 5 ohms. When the voltage E supplied to the circuit is 20 volts at the resonance frequency, determine the current I in the circuit, and also the voltage drop across the induction coil and across the condenser. The resonance frequency by equation (34) is

$$f_{res} = 1{,}000{,}000 \div 2\pi\sqrt{200{,}000 \times 20} = 1{,}000{,}000 \div 2 \times 3.1416\sqrt{4{,}000{,}000} = 1{,}000{,}000 \div (6.2832 \times 2{,}000) = 1{,}000{,}000 \div 12{,}566.4 = 79.6 \text{ cycles per second.}$$

Current I in circuit is $E \div R = 20 \div 5 = 4$ amperes.

Induction coil reactance X_L at 79.6 cycles per second is

$$2\pi f_{res}L = 2 \times 3.1416 \times 79.6 \times 200{,}000 \div 1{,}000{,}000 = 100.0 \text{ ohms.}$$

Condenser reactance X_c at 79.6 cycles per second is

$$1 \div 2\pi f_{res}C = 1 \div [2 \times 3.1416 \times 79.6 \times (20 \div 1{,}000{,}000)] = 1 \div 0.010005 = 100.0 \text{ ohms.}$$

Net circuit reactance = 100.0 − 100.0 (as it should be for resonance)

Impedance of induction coil $Z = \sqrt{R^2 + X_L{}^2} = \sqrt{5^2 + 100.0^2} = 100.1$ ohms.

Voltage drop across induction coil $= I \times Z = 4 \times 100.1 = 400.4$ volts.

Voltage drop across condenser $= I \times X_c = 4 \times 100.0 = 400.0$ volts.

Example of Resonance in Radio Antenna.—It is often important to know the frequency in kilocycles (per second) at which an antenna will deliver the maximum current to a receiving set to which it is connected. Assume that an antenna has a capacity effect of 0.0025 microfarad and that a coil having an inductance of 100 microhenrys is in series with it. Then by equation (34),

$$
\begin{aligned}
f_{res} &= 1{,}000{,}000 \div 2\pi\sqrt{0.0025 \times 100} \\
&= 1{,}000{,}000 \div 2 \times 3.1416 \times 0.5 = 318{,}180 \text{ cycles, or} \\
&\qquad 318.18 \text{ kilocycles per second.}
\end{aligned}
$$

By similar calculation, if the capacity of an antenna is known, a coil can be inserted in series with the antenna to make it resonant for a particular frequency. As an example of this, if the capacity of an antenna is as before 0.0025 microfarad, and it is desired to insert in series with the antenna an induction coil to give resonance at 500 kilocycles (500,000 cycles per second), then the amount of inductance L would be calculated as follows:

$$
\begin{aligned}
500{,}000 &= 1{,}000{,}000 \div 2\pi\sqrt{0.0025 \times L} \\
500{,}000 &= 1{,}000{,}000 \div (6.2832 \times 0.05 \times \sqrt{L}) \\
\sqrt{L} &= 2 \div 0.31416 = 6.36 \\
L &= 40.45 \text{ microhenrys.}
\end{aligned}
$$

Example of Calculation at Resonance of Tuned Radio Circuit.—A tuned circuit (page 64) in a radio receiving set includes an induction coil of 200 microhenrys (0.0002 henry) and it is desired to determine the capacity of a variable condenser which is in series with the induction coil, when it is set for maximum response (resonance) for broadcast reception at a frequency f of 700 kilocycles (700,000 cycles) per second. In this case, the capacity C in farads will be determined by the following equation derived from (33):

$$C = 1 \div [(2\pi f_{\text{res}})^2 \times L]$$
$$C = 1 \div [(2\pi)^2 \times 700{,}000^2 \times 0.0002]$$
$$C = 1 \div 3{,}870{,}000{,}000, \text{ or } \frac{1}{3{,}870} \text{ farad} = 0.00028 \text{ microfarad.}$$

Wave Meter.—An interesting application of the foregoing theory and numerical exercises is in an apparatus that is always needed for amateur radio broadcasting. It is called a *wave meter*, and is used for measuring the frequency of radio currents. This instrument consists merely of an induction coil which is in series with a variable condenser and a small ammeter, usually of the hot-wire type[1] to show the amount of current in the circuit. Attached at one end to the shaft carrying the movable plates of the variable condenser is an indicating device, usually a simple pointer, which moves over a calibrated scale graduated to be read in either *wave lengths* (page 40) in meters, or frequency in kilocycles per second. A single coil is adaptable to scale readings from 500 kilocycles to 1,500 kilocycles per second, but for a larger range of frequency, a set of inductance coils is required.

In the practical use of this instrument, when the induction coil of the wave meter is brought near to another induction coil, which is in series with the circuit in which the frequency is to be determined, and the capacity of the variable condenser of the wave meter is adjusted for the maximum current, as shown by its ammeter, there is the condition of resonance, and the frequency of the induced current in the wave meter is the same as that of the voltage in the circuit of which the frequency is to be determined.

[1] See MOYER and WOSTREL, "Radio Handbook," p. 108, McGraw-Hill Book Company, Inc., 1931.

Calculation of Frequency of Resonance of Antenna.—The resonant frequency of an antenna circuit may be calculated by the use of equation (34), assuming that its capacity is 0.012 microfarad and that there is connected in series with the antenna an inductance of 25 microhenrys. Then the frequency of resonance f_{res} is $1{,}000{,}000 \div 2\pi\sqrt{0.012 \times 25} = 285{,}000$ cycles, or 285 kilocycles.

Capacity of Variable Condenser for Circuit Resonance.—The setting of a variable condenser (in microfarads) for tuning a circuit of a radio receiver may be determined when, for example, this condenser is in series with an induction coil of which the inductance is 180 microhenrys; the frequency of the tuned circuit being 1,220 kilocycles (1,220,000 cycles). Using the same notation as in the preceding examples, f_{res} is 1,220,000 cycles and L' is 180 microhenrys. Then rearrangement of equation (34) gives in terms of capacity C' in *microfarads*

$$\sqrt{L'C'} = 1{,}000{,}000 \div 2\pi f_{res},$$

or

$$C' = 1{,}000{,}000{,}000{,}000 \div [(2\pi f_{res})^2 \times L']$$

then $C' = 1{,}000{,}000{,}000{,}000 \div [(2\pi \times 1{,}220{,}000)^2 \times 180]$, or 0.000094 *microfarad.*

Decrement as Related to Resonance.—A term used in radio which has a definite relation to the resonance of a circuit is called the *decrement.* It is the quantity that indicates how rapidly the reduction in value of oscillating currents set up in a circuit takes place. Information about the decrement of a circuit is useful because of its relation to selectivity (page 82). In general, it may be stated that the greater the selectivity of a circuit, the sharper its actual resonant point and also the lower the decrement will be. A typical curve of a resonant circuit is shown in Fig. 35, where the resonant frequency is marked for an ordinate corresponding to the maximum value I_{res} of current in the circuit. Two other frequencies marked f_1 and f_2, corresponding to a current, $I_{res} \div \sqrt{2}$ are points where the value of the current is $1/\sqrt{2}$ of the resonant value. An inspection of the resonance curve shows that the closer f_1 and f_2 are to each other, the sharper the resonance of the circuit will be, and for this reason it may be said that $(f_2 - f_1) \div f_{res}$ is a measure of selectivity.

Decrement of a circuit can also be written[1] as $R \div 2\pi f_{res}L$, where it has significance from an entirely different point of view from that being discussed now.

With this relationship in mind, we can write

$$(f_2 - f_1) \div f_{res} = R \div 2\pi f_{res}L \tag{35}$$

$$\pi(f_2 - f_1) \div f_{res} = R \div 2f_{res}L. \tag{36}$$

This last equation shows that the selectivity of a circuit is inversely proportional to the decrement. In this connection,

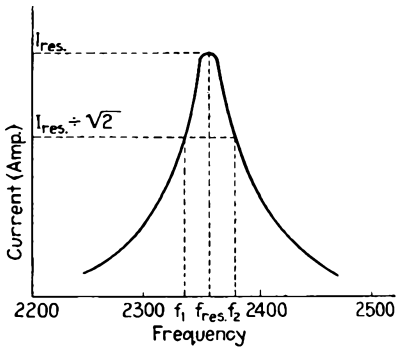


FIG. 35.—Typical resonance curve.

still another term called the *selectivity factor* is sometimes used, this being $f_{res} \div (f_2 - f_1)$, and since the reactance of an inductive circuit X_L is $2\pi f_{res}L$, we can express the selectivity factor as follows in terms of reactance and resistance as given in equation (35)

$$\frac{f_{res}}{f_2 - f_1} = \frac{2\pi f_{res}L}{R} = \frac{X_L}{R}. \tag{37}$$

This last equation shows that *selectivity* of a circuit is the ratio of the coil reactance X_L in ohms at the resonant frequency to the resistance R, and, further, that when the resistance R of a coil is small compared with its inductive reactance X_L,

[1] See MORECROFT, "Elements of Radio Communication," p. 54.

as it should be in all good radio equipment, then the impedance Z of the coil and its *reactance* X_L being practically equal, we may say that the selectivity of the circuit in which the coils are suitably selected and constructed is proportional to the ratio of the impedance Z to the resistance R.

Inductance, Capacity, and Resistance in Parallel.—The general treatment of the flow of alternating current in a parallel circuit is complicated beyond the requirements for the circuits ordinarily used in radio work when it includes both inductance and capacity in addition to resistance. For this reason, only special cases that have possible application in radio services will now be considered. The most common application of this kind is the shunting (by parallel connection) of an induction coil by a condenser. One problem for solution is then to determine for a given circuit the amount of current (taken, for example, from a generator G) as shown in Fig. 36. In a branched circuit of this kind the current received by each branch is exactly the same as it would be if there were not a second or third branch. For this reason the current in each branch of the circuit illustrated in the figure will be *calculated in the same way as for a simple circuit.* In that case, then, the current I_L (amperes) in the inductive part of the circuit may be written

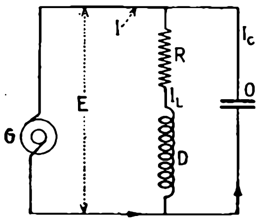


FIG. 36.—Parallel resonance of inductance and condenser.

$$I_L = \frac{E}{Z} = \frac{E}{\sqrt{R^2 + X_L^2}} \tag{38}$$

where the voltage across the terminals of the circuit E is in volts, the impedance Z is in ohms, the resistance R is in ohms, and the inductive reactance X_L is in henrys.

The current I_C (amperes) in the capacity part of the circuit is

$$I_C = 2\pi fCE \tag{39}$$

where f is the frequency in cycles per second, C is the capacity of the condenser in farads, E is the voltage across the terminals of the circuit in volts, and π is 3.1416.

These equations will now be used to calculate the current in the line and the current in parts of the circuit represented by Fig. 37 when the inductance L is 0.125 henry and the resistance R is 12.0 ohms. In parallel with this inductance and resistance is a condenser with a capacity of 14.25 micro-

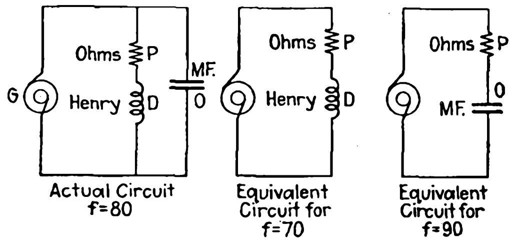


FIG. 37.—Inductance and condenser in parallel: (1) for frequency of resonance; (2) for frequency below resonance; (3) for frequency above resonance.

farads; the line voltage and frequency being respectively 100 volts and 60 cycles per second.

The coil impedance $Z = \sqrt{R^2 + (2\pi \times 60 \times 0.125)^2} =$

$$\sqrt{12^2 + (2\pi \times 60 \times 0.125)^2} =$$
$$\sqrt{144 + (47.12)^2} =$$
$$\sqrt{144 + 2{,}220}, \text{ or } 48.63 \text{ ohms.}$$

Coil current I_L is 100 ÷ 48.63, or 2.06 amperes.

$$\text{Active coil current } I_{LA} \text{ is } I_L \times R \div Z. \qquad (40)$$
$$I_{LA} = 2.06 \times 12.0 \div 48.63, \text{ or } 0.51 \text{ ampere.}$$

Reactive coil current $I_{LR} = \sqrt{I_L{}^2 - I_{LA}{}^2}$

$$(\text{or } = I_L \times X_L \div Z) \qquad (41)$$
$$I_{LR} = \sqrt{2.06^2 - 0.51^2}, \text{ or } 2.00 \text{ amperes.}$$

The condenser current I_C is $2\pi fCE$ (C in farads) $= 2\pi \times 60 \times (14.25 \div 1{,}000{,}000) \times 100$, or 0.537 ampere.

Active current, I_a supplied by line $= I_{LA}$, or 0.51 ampere. Reactive current supplied by line $I_r = I_{LR} - I_C$, or $2.00 - 0.537$, or 1.46 amperes.

Line current $I_{line} = \sqrt{I_a^2 + I_r^2} = \sqrt{0.51^2 + 1.46^2}$, or 1.55 amperes.

Line impedance $= E \div I_{line} = 100 \div 1.55$, or 64.5 ohms.

Response of Parallel Circuits.—A circuit with inductance, capacity, and resistance in any combination arranged in parallel can also be made resonant for the same conditions and under similar circumstances as a series circuit. Therefore, the frequency of resonance of a parallel circuit may be calculated by setting the reactive coil current I_{LR} equal to the condenser current and then solving for the resonant frequency. The following calculations would then be made. Coil *reactive* current I_{LR} is $I_L \times X_L \div Z$ [Equation (41)], and since $I_L = E \div Z$, $I_{LR} = (E \div Z) \times (X_L \div Z)$, or

$$I_{LR} = \frac{E}{\sqrt{R^2 + X_L^2}} \times \frac{X_L}{\sqrt{R^2 + X_L^2}}$$

$$= \frac{2\pi fLE}{R^2 + (2\pi fL)^2} \text{ (page 69), since } X_L = 2\pi fL \text{ (page 68).}$$

Condenser current I_C is $2\pi fCE$ (page 67).

Setting down then I_{LR} equal to I_C, since the two currents are equal when the circuit is *resonant*,

$$\frac{2\pi fLE}{R^2 + (2\pi fL)^2} = 2\pi fCE \tag{42}$$

and solving for the value of the *resonant* frequency f_{res}

$$f_{res}^2 = \frac{(L \div C) - R^2}{(2\pi L)^2}$$

$$f_{res} = \frac{0.5}{\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}. \tag{43}$$

Now it happens that in nearly all practical radio circuits the value of the term R^2/L^2 is negligibly small and may therefore be neglected. For ordinary practical conditions, therefore, we can write,

$$f_{res} = \frac{0.5}{\pi}\sqrt{\frac{1}{LC}} \tag{44}$$

Now it is interesting to know that this last approximate equation for resonance frequency in *parallel* circuits is the same as the equation for the resonance frequency in *series* circuits (page 78). This fact can often be made use of in designing radio equipment, knowing that a *coil and condenser will have practically the same resonance frequency when connected in parallel as when connected in series.*

Line Impedance at Resonant Frequency.—When the frequency of the current in a parallel circuit is that of resonance, the line current is the same as the active coil current, but the two reactive currents are equal and opposite so that they neutralize each other. In that case, the line impedance is exclusively line resistance and of high value. This resistance if represented by the symbol R_{line}, can be written

$$R_{\text{line}} = \frac{E}{\textit{Active coil current}} = \frac{E}{I_{LA}} \qquad (45)$$

and since $I_{LA} = I_L \times R''/Z$ [equation (41)] and $I_L = E \div Z$.

$$\frac{E}{I_{LA}} = \frac{E}{E/Z \times R''/Z} = Z^2 \div R'' =$$

$$[\sqrt{(R'')^2 + X_L{}^2}]^2 \div R'' = [(R'')^2 + X_L{}^2] \div R''$$

where R'' is the ordinary resistance in the circuit. However, in most cases R'' is negligibly small in comparison with X_L so that it may be stated *approximately* that

$$R_{\text{line}} = X_L{}^2 \div R''.$$

When there is *resonance* in the circuit $X_L = X_C$ and $R_{\text{line}} = (X_L \times X_c) \div R''$, or $2\pi fL \times 1/2\pi fC \div R''$, then equation (45) becomes

$$R_{\text{line}} = \frac{L}{CR''}. \qquad (45a)$$

In the preceding example at the *resonance* frequency, the line resistance R_{line} is in ohms,

$$R_{\text{line}} = \frac{0.125 \times 1{,}000{,}000}{14.25 \times 12}, \text{ or } 730 \text{ ohms.}$$

Method of Reducing Resistance in Resonant Parallel Circuit.—When an induction coil and a condenser are connected in parallel as shown in Fig. 38 and are adjusted to the frequency of resonance, the induction coil and the condenser thus connected in parallel act as though there was exclusively resistance in the circuit. This resistance may be too large for other requirements in the design of radio equipment. The value of the line resistance R_{line}, for this condition as shown by equation (46) is $R_{line} = L \div CR''$ where R'' is the actual resistance of the induction coil and the condenser in series (page 70) and L and C are respectively the inductance and capacity in the circuit.

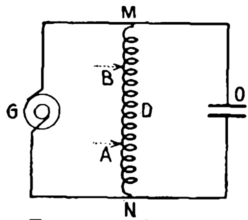


FIG. 38.—Resonance frequency impressed at points of circuit that are varying distances apart.

As a rule, this line resistance R_{line} is very large so that it may be excessive for the other elements of a complicated design. As an example, the induction coil D in Fig. 38 may be assumed to have an inductance L of 200 microhenrys and a resistance R'' of 7.5 ohms. The condenser O is of the variable type (page 64) and has been set for the resonant frequency of 750 kilocycles. Its capacity at this setting is 0.0001 microfarad. Under these conditions the apparent impedance across the points marked A and B (exclusively resistance) is $L \div CR''$, or

$$\frac{200 \div 1{,}000{,}000}{(0.0001 \div 1{,}000{,}000) \times 7.5}, \text{ or } 266{,}667 \text{ ohms.}$$

When the calculation of the resistance of a resonant circuit has large values it is usually advantageous to modify the circuit to obtain a lower resistance. For this purpose the circuit in Fig. 38 might be charged to have the line current delivered to the circuit at, for example, M and A or N and B, instead of at M and N as in the case calculated. When this charge is made, or in other words, when the line current is supplied at points closer together with respect to the induction coil than are M and N, the circuit resistance may be halved or quartered or even reduced as much as 90 per cent. By the method of using a variable contact on the winding of an induction coil like *D* in Fig. 38, such a parallel resonant circuit can be made use of as an adjustable resistance. This method, it will be found, has numerous applications in vacuum tube circuits where it is necessary to match the resistance of the circuit to the resistance of the vacuum tubes.

Selection of Resistances for Radio Circuits.—The general rule may be stated that the induction coils for a radio receiver should have low resistance for the reason that the lower the resistance of the coils used in radio-frequency circuits (page 505), the better the selectivity (page 82) is likely to be, and to some extent also the greater the amplification (page 24).

Selection of Inductance for Radio Circuits.—As stated in the preceding paragraph, low resistance of the induction coils in a radio circuit is a first consideration, but it is also important to have the right amount of inductance effect for the frequency range of the radio receiving set that is being designed. For each frequency for which a radio receiving set is to be used, there are corresponding values of inductance and capacity that will produce resonance. For example, for a frequency of 1,000 kilocycles per second, an induction coil of 200 microhenrys and a condenser rated at 125 micromicrofarads may be used.[1] Similarly, resonance at this frequency can be obtained with an induction coil of 1,000 microhenrys and a condenser of 26 microfarads. All of these combinations will, by calculation, satisfy the requirement of giving resonance at 1,000 kilocycles per second; but when using coils of ordinary construction, there is not this wide range of selection. If an induction coil of 1,000 microhenrys is used, the range over which the receiving set can be tuned is very narrow. A well-designed radio receiving set for standard broadcasting reception should give a useful frequency range of about three to one (for example, 500 kilocycles to 1,500 kilocycles), but if coils of 1,000 microhenrys are used, the range will be certainly

[1] This is derived from the equation $f = 1 \div (2\pi\sqrt{LC})$ (p. 78). See also table of f and LC in Moyer and Wostrel, "Radio Handbook," p. 17.

not more and possibly less than two to one. In addition to the capacity effect in a radio receiving set produced by condensers, there is always some stray capacity from the parts of the receiving set. Some of this additional capacity is caused by the wiring itself and some more by the vacuum tubes and their sockets. The coils also may have considerable extra capacity which interferes with the best tuning. The amount of stray capacity in the average radio receiving set is about 25 micromicrofarads which is a value that may be interesting for comparison with that of the ordinary variable condenser when set for its minimum value of capacity; that is, about 10 micromicrofarads. It is therefore obvious that even when the tuning condenser of a radio receiving set is set for its minimum value of capacity (with plates as far apart as possible) the capacity effect of an induction coil and variable condenser connected in series is at least 35 micromicrofarads.

If a radio receiving set is to be made so that it will "tune" as low as 500 kilocycles per second, the maximum capacity of the circuit having an induction coil of 1,000 microhenrys would have to be about 100 micromicrofarads. But when the variable condenser is set at its minimum value, the capacity of the circuit is about 35 micromicrofarads. The circuit with this value of capacity and the 1,000-microhenry coil is resonant at a frequency of about 850 kilocycles per second; the frequency range in that case being therefore from 500 kilocycles to 850 kilocycles per second or not even two to one.

Still another combination of inductance and capacity is interesting for study, this being the case where a small inductance and a large capacity are used. For example, if the induction coil has an inductance of 68 microhenrys and is used with a variable condenser with a capacity of 1,500 micromicrofarads, the circuit will have its resonant frequency at 500 kilocycles per second and will have a very wide range, probably between 500 kilocycles and 3,000 kilocycles per second. A condenser of such large capacity is, however, very expensive and it would be found that the selectivity of the set would not be satisfactory. The inductance of a coil that is well adapted to a frequency range between 500 and 1,500 kilocycles per second (the operating range for standard broadcasting) is between the two extremes which have been calculated and the best average results are obtained when the inductance of a coil is about 250 microhenrys. With this value of the inductance, a variable condenser of only moderate size will be required (about 400 micromicrofarads of capacity)

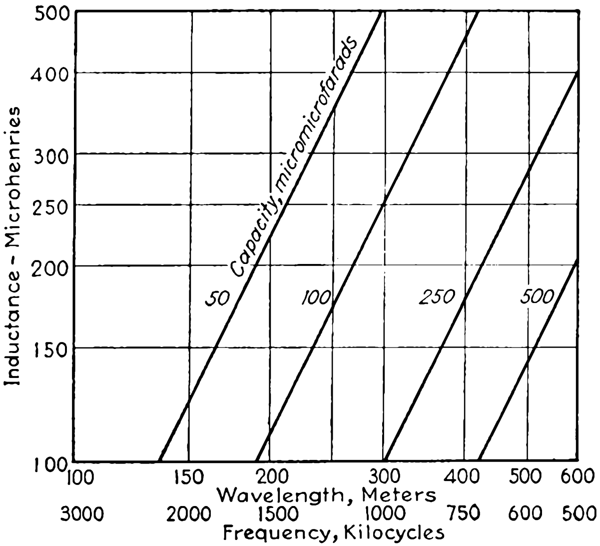


FIG. 39.—Relation between capacity and inductance of circuit for varying frequencies or wave lengths.

and the selectivity will be sufficiently good for ordinary services. The chart of Fig. 39 shows the values of inductance in microhenrys and capacity in micromicrofarads which are required for a given frequency in kilocycles or wave length in meters. For the range of frequencies of ordinary radio broadcasting, the reactance of the coil should be about 1,500 ohms for the highest frequency at which it is used. This value varies, however, from about 1,000 ohms to as much as 2,000 ohms, according to the construction of the coil.

An average value, however, of about 1,500 ohms will usually give the most satisfactory results.[1]

Circuit Having Resistance and Inductance in Series.—If i is the *instantaneous current*, the voltage required to force this current through a non-inductive resistance R is Ri, and the voltage required to overcome the induced voltage of the inductance is X_Li. Hence, the *instantaneous* value of the applied voltage e is $Ri + X_Li$. But these values of non-inductive and inductive voltage cannot be used to calculate the *effective* applied voltage, because the voltages Ri and X_Li are not in phase. When the voltage Ri is zero, the voltage X_Li is at a maximum. The sum of the two voltages may have a maximum value which is less than the sum of their individual maximum values.

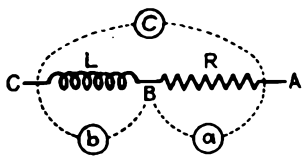


FIG. 40.—Voltage measurements across inductive and non-inductive resistances in series.

This may be shown by an experiment in which an alternating current is passed through a circuit containing non-inductive and inductive resistances connected in series as in Fig. 40. Three voltmeters marked a, b, and c are used to measure the voltages between the points A and B, B and C, and C and A, respectively. The *effective* voltages indicated by the voltmeters are such that the reading of instrument c is not equal to the reading of b plus that of a, as would be expected for direct current. The voltmeter a indicates now a reading of RI, and b a reading of X_LI where I is the *effective* value of current, such as would be obtained with an alternating-current ammeter. The voltmeter c indicates the *effective* value E of the applied voltage which is represented by the hypotenuse of a right triangle whose sides are RI

[1] If a coil for a radio receiving set is well designed, it will have a reactance which is from 100 to 200 times as much as its resistance. The resistance increases as the frequency of the circuit increases, owing to the fact that the losses are larger at high than at low frequencies. For this reason the ratio of reactance to resistance is practically the same for the frequencies in the usual broadcasting range.

and X_LI. The relation between the sides and hypotenuse of a right triangle is such that

$$E^2 = (RI)^2 + (X_LI)^2 = I^2(R^2 + X_L^2).$$

From this the effective value of the current produced by the effective applied voltage E is

$$I = \frac{E}{\sqrt{R^2 + X_L^2}}.$$

CHAPTER IV

VACUUM-TUBE ACTION

Electron Emission.—The tendency of a metal to evaporate, just as water evaporates at ordinary temperatures, is due to the tendency of the atoms of the metal to separate from each other at temperatures that are high enough to give them the necessary velocity.

The electrons associated with an atom are in motion at a rate which increases with increasing temperature. When a metallic filament is heated to incandescence, the atomic agitation of the substance is increased and the motion of its electrons becomes so rapid that some of them break away. The escape of electrons in this way from a metallic filament occurs at a temperature which is lower than that necessary to produce *atomic* evaporation, for the reason that the velocity of the electrons is greater than that of the atoms. At the surface of a metal, according to the theory of Richardson,[1] the electrons are restrained from leaving the metal by electric forces similar to the molecular forces which cause the surface tension of a liquid.

In the absence of any external electrical attraction most of the electrons return to their former position when cooled, because the filament is left *positively* charged and exerts therefore an attractive force on the electrons which are always *negatively* charged. At the same time the electrons already present in the space exert a repelling force on those leaving the filament. This setting free of electrons by a body when it is heated is called *electron emission.* The presence of such free electrons in the space surrounding a heated filament makes this space a good conductor of electricity.

[1] Richardson, A. W., "Theory of Thermionic Emission," *Philosophic Trans.*, Vol. 202, p. 516.

This kind of electron emission is called *thermionic.* There are, however, several other means by which electron emission may be produced. One of these other means, called *secondary electron emission,* refers to the bombardment of a body by positively charged ions (page 20), by electrons, and by atoms. The secondary electrons produced in this way have a very low velocity. The number produced depends on the material, the condition of the surface, and the velocity of bombardment. A metal surface coated with graphite tends to reduce the emission of secondary electrons. The action of secondary emission of electrons is utilized in the *dynatron tube* (page 94). In ordinary radio vacuum tubes the action of secondary electrons is injurious. For example, an oscillator tube (page 9) will "block" if the grid voltage becomes positive from the effect of secondary electrons. Another means, called *photoelectric electron emission* (page 212), refers to the emission of electrons when radiation such as light or X-rays strikes a surface. Electrons emitted by means of photoelectric effect have a velocity which depends on the frequency of the radiation; and the number emitted depends on the intensity of the radiation. Still another means, called *electrostatic electron emission,* depends on the application of a high voltage, and may be utilized in the cold-cathode tubes (page 190).

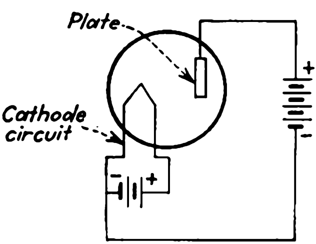


Fig. 41.—Diagram of circuits in typical radio receiving tube.

Emission Current.—When a suitable bulb, as shown in Fig. 41 from which the air has been removed to obtain a vacuum, contains a filament or cathode near the middle, with a flat metallic plate close to it, and the cathode is heated, a few electrons will leave the cathode with sufficient velocity to reach the plate. If this plate in the bulb is entirely insulated, the electrons which accumulate on it will soon build up a negative charge that is sufficient to prevent a further flow of electrons from the cathode. If, however, instead of being insulated, the plate is connected by a conductor to the cathode, large numbers of electrons will flow across the space between the cathode and the plate, and then back to the cathode through the connecting conductor. This current, thus produced by electron emission, is called the *plate current.* This current can be greatly increased if a battery or other source of electric current is connected into the circuit between the plate and the cathode so as to create a positive potential or voltage on the plate.

Characteristic Curves.—The performance of vacuum tubes in radio communication may be studied by the use of curves which show their characteristic properties. The performance of a simple electrical device incorporating an ordinary ohmic resistance can be determined from a knowledge of only two properties of the device—its ohmic resistance and its current rating. On the other hand, the performance of vacuum tubes is usually shown by diagrams from which a determination can be made of all the possible combinations of voltages and currents that may occur in practice. These diagrams, known as characteristic curves, are easily obtained by keeping constant the cathode voltage of a vacuum tube, varying the applied voltages, and then reading and plotting the resulting currents in the plate-to-cathode circuit.

Two-element (Diode) Vacuum Tubes.—A two-element tube consists of a metallic filament or cathode and a metallic plate both sealed in a glass or metal bulb in which there is a vacuum. The filament or cathode may be heated by the current from a battery or from some other source of current. The *plate is made positive* with respect to the cathode by connecting a battery or other current supply in the plate-to-cathode circuit. Under these conditions, as explained before (page 6), a flow of electrons takes place from the cathode to the plate. As the plate voltage is increased there is a value at which all the electrons emitted from the cathode are drawn to the plate, and after this value is reached, any additional increase in plate voltage is not accompanied by any increase in plate current. This maximum value of emission is called the *saturation current* and, because it is an indication of the total number of electrons emitted, it is also called the *emission current* or *cathode emission*. This condition is shown at point A in the curve of Fig. 42. The bend in the curve shows that when the plate voltage has been made large enough there is little further gain in the plate current. Under these conditions the *plate current can be increased*, however, in another way, and that is by increasing the cathode temperature. The explanation of this is that the number of electrons sent out by the cathode *increases with the temperature* approximately as the square of the excess of the cathode temperature above

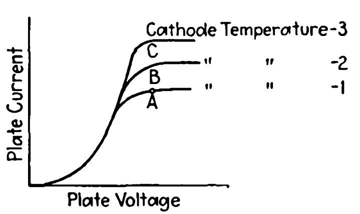


FIG. 42.—Relation of plate current to cathode temperature.

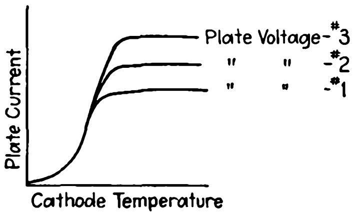


FIG. 43.—Relation of plate voltage to cathode temperature.

a red heat, and, thus, more electrons are available to be drawn over to the plate. For any temperature of the cathode there is, however, also a corresponding maximum value of plate current. This maximum is reached when the electrons are drawn over to the plate at the same rate as they are emitted from the cathode. The effect of varying the temperature of the cathode is shown by comparing the curves A, B, and C in Fig. 42.

On the other hand, if the plate voltage is kept constant, and the cathode temperature is raised by increasing the cathode current, the emission current or cathode emission will be increased. The plate current will increase up to a certain temperature, but beyond this temperature it will remain practically constant, even though more electrons are being given off. This means that for every value of plate voltage there is a corresponding value of cathode temperature beyond which no increase in plate current is obtained. This effect is shown by the curves of Fig. 43.

The explanation[1] of this behavior is that the stream of negative electrons flowing through the vacuum tube acts as a *space charge* of negative electricity which neutralizes the electrostatic field owing to the positive plate (page 27); that is, the effect of the negative "space" charge upon the electrons leaving the filament is opposite to that of the positive charge on the plate. In consequence, only a limited number of electrons can flow to the plate per second with a given plate voltage, and the remainder are compelled to return to the cathode. It is obvious, therefore, that the condition of either voltage or current under which the cathode of a vacuum tube is to be operated must be specified.

For given plate voltage the maximum possible value of plate current depends on the spacing, size, and shape of the elements of the tube.[2]

Commercial Types of Two-element Vacuum Tubes.—The ordinary commercial applications of two-element vacuum tubes are (1) for the rectification of alternating current, (2) for detection, and (3) for the production of x-rays. The applications of the diode detector are explained in Chap. VIII and the applications of rectifier tubes in Chap. IX. Vacuum-tube rectifiers of alternating current are divided into two general classes: (1) the high-vacuum type, and (2) the gas-filled and vapor-filled types.

High-vacuum rectifier tubes for radio applications include types 5Z3, 12Z3, 1-V, 80, 81, 83V, 84, and the metal tube type 5Z4. These types in general are similar in construction and action, but have different ratings as shown in the Tube Table, page 617. A point of difference is that some types, designated as *half-wave rectifiers*, are designed to rectify only half of the

[1] LANGMUIR, I., "Theory of Electron Tubes," *Physical Rev.*, Vol. 2, p. 450, 1913; and *Proc. Inst. Radio Eng.*, Vol. III, p. 261, 1915.

[2] The plate current of a high-vacuum tube when not limited by the space charge (p. 97) of the cathode of the heater type (p. 11) (unipotential, p. 10) is given theoretically by the equation $I_2 = KE^{3/2}$ where K is a constant depending on the structure and spacing of the elements of the tube and E is the plate voltage.

cycle of current, while *full-wave rectifiers* pass current during both halves of a current cycle.

Gas-filled and vapor-filled rectifier tubes for radio applications include the mercury-vapor types 82, 83, and such tubes as the Tungar, the Rectigon, and the Raytheon rectifiers. Other types of gaseous tubes having two or more electrodes and designed for radio applications or for industrial control devices are described later in this chapter under the heading of gaseous tubes.

High-vacuum Rectifier.—High-vacuum rectifier tubes such as types 1-V, 5Z3, 80, 81, 83V, 84, and so on, are of the filament type and depend on true thermionic action for their operation; meaning that the electrons can move from the cathode to the plate, but, since the plate is not a source of free electrons, when these electrons are once on the plate they are not released and cannot flow back to the cathode. Thus, a current flows from the cathode to the plate only when the plate is positive and the current stops flowing when the plate is negative. By the use of this kind of rectifier tube an alternating current may be changed into a pulsating direct current. Tubes of this type have a current capacity limit of several amperes and a high voltage drop. Their characteristics are affected by the spacing and structure of the tube elements. The operating characteristics are affected by the type of filter system that is used. Characteristic curves for several tubes of this type are given in Chap. IX.

Hot-cathode Mercury-vapor Rectifier.—This type of tube is essentially a gaseous rectifier containing mercury vapor.[1] Its principal characteristics are low and practically constant voltage drop for all values of current, ability to withstand high inverse voltages (page 101), and improved regulation of voltage output in comparison with other devices. The *filament* or cathode of this tube is coated with an oxide and the

[1] Gas at a pressure of 3 to 5 centimeters of mercury is used to neutralize the space charge in the Tungar rectifier (p. 102), which is designed for low voltages only.

plate area is made small for the reason that there is a low voltage drop in the tube and consequently a low plate-current loss. The tube is intended for operation at a low gas pressure[1] and at relatively high voltages. In the full-wave rectifier (page 98), which is designed to rectify both halves of an alternating-current cycle, there are two plates, each of which entirely surrounds its filament.

In the operation of a hot-cathode mercury-vapor rectifier the electrons are drawn from the heated filament (cathode) on the *positive* part (page 41) of the cycle of the alternating current being rectified. Some of these electrons thus withdrawn collide with the mercury-vapor molecules and free new electrons. As the mercury vapor becomes ionized a characteristic blue glow appears. On the *negative* or "inverse" part of each current cycle the *anode* or plate is negative with respect to the filament or cathode, so that the flow of current stops, and the blue glow disappears. Disintegration of the filament or cathode by positive-ion bombardment is prevented by maintaining the voltage drop in the tube below a definite critical value (22 volts for mercury vapor).[2]

The positive space charge (page 97) between the plate and the filament which is produced by the positive ions on the plate neutralizes the negative space charge caused by the electrons emitted from the cathode. Because of this neutralization of the space charge, the plate can attract the necessary supply of electrons from the cathode, even though the voltage difference between the two is relatively low. No appreciable current flows until the plate voltage reaches a certain value and then the current increases rapidly in a fraction of a second. A surge of current of this kind occurs each time the plate charge changes from negative to positive. This current surge may cause noise interference in reception because of the currents induced in adjacent circuits. This effect can be reduced by

[1] STEINER, H. C. and H. T. MASER, "Hot-cathode Mercury-vapor Rectifier Tubes," *Proc. Inst. Radio Eng.*, January, 1930.

[2] The voltage at which mercury vapor begins to ionize is 10.4 volts. The voltage drop in this rectifier tube is approximately 15 volts.

inserting a radio-frequency choke coil (page 64) having an inductance of at least one millihenry in the plate circuit, and by shielding (page 121) the tube. A high plate voltage is needed to produce the usual amount of plate current required for the operation of a high-vacuum tube, but in the mercury-vapor tube about the same value of plate current can be obtained with a constant voltage of 15 volts. The reason that the current can increase without an increase of plate voltage is that *space-charge neutralization*, increasing as the current increases, allows more and more electrons to travel from the cathode to the plate.

The operating temperature of the tube determines the required mercury-vapor pressure, there being a definite relation between this pressure and the temperature of saturated mercury vapor. The coolest part of the tube determines the vapor pressure to be used for the reason that the mercury vapor will condense at the part which is at the lowest temperature. The operating temperature of this tube should be held within certain limits. The voltage drop in this tube is affected by temperature, but does not depend on the spacing of the elements. At the lowest limit of voltage drop in the tube this voltage drop has a value greater than the critical value at which filament or cathode disintegration begins. At the high limit of voltage drop, the tube may break down or flash-back on the negative (inverse) part of the alternating-current cycle. A tube made with a coated filament or cathode may be operated for short periods when the voltage drop is above the limiting value, but the life of the tube will be shortened through filament or cathode disintegration. High temperature in the tube, on the other hand, reduces the voltage drop, and is conducive to longer filament or cathode life. If the room temperature is over about 120°F. the tube must be cooled by mechanical means. Usually this is accomplished by passing a current of air over the tube.

The ratings of this tube which determine its power output are: (1) maximum peak value of negative (inverse) voltage at which operation is possible without the occurrence of flash-back, and (2) maximum peak plate current consistent with long filament (cathode) life. The maximum peak negative (*inverse*) voltage is equal to the peak voltage of the power transformer that is used for supplying power to the tube minus the voltage drop in the tube. The rating of the filter condensers (page 363) used with this tube in a rectifier must be high enough to enable them to withstand the instantaneous peak voltage of the circuit. The rating of peak plate current depends on the type of circuit as well as the kind of load and the filter. If this value of peak current is exceeded, the voltage drop increases so much that it may exceed the value at which filament (cathode) disintegration begins. It is stated that wherever possible a small inductance coil should precede a condenser in the filter circuit used with this tube, or, if this cannot be done, the current may be limited by the use of a protective resistance.[1]

When flash-back occurs in this tube, its effect is practically the same as that of short-circuiting the rectifier output. The short-circuit current under these conditions depends on the resistance and leakage reactance (page 68) of the transformer used in the circuit. Since a power transformer has an impedance under short-circuit conditions which may be only a small percentage of its *rated* impedance, the short-circuit current may have very high values.

The cathode voltage must be kept at the rated value. A reduced cathode voltage caused by poor contacts results in an increased voltage drop which may cause injury to the cathode. The same effect is caused if a normal voltage is applied before the cathode is properly heated. Under normal operating conditions the cathode of this tube heats quickly when the current is turned on and it will supply full-load

[1] For the protection of the power transformer that is used in the rectifier unit, its primary winding should be rated at about 150 per cent of the normal current it will carry. With the condenser-input type of *filter* (p. 364), the peak current may be more than three times the value of the continuous or direct-current output. With the choke-coil type of filter (p. 361), the peak current may be considerably less.

current before the other tubes in the receiver require it. If, through the handling of a tube, the supply of mercury becomes distributed over the electrodes it may be necessary to light the cathode for a short time with no plate voltage on the tube.

The improved regulation that is obtained with this tube may be attributed to the fact that the voltage drop of the tube is practically constant. Hence any decrease in output voltage as the load is increased is caused by voltage drop in the transformer and filter windings used in the circuit.

The end of the useful life of this tube is indicated by a simple test. With a direct-current voltage applied to the plate, the voltage drop should not exceed 18 to 20 volts for normal operation, when the plate current has a value of twice its rating. Discoloration of the glass bulb is a normal condition, and is not an indication of the end of the life of the tube.

Tungar Rectifier.—A Tungar rectifier tube functions by reason of the unilateral (single-direction) conductivity in the space between the *hot cathode* and the cold plate of the tube. It is of the *half-wave* type of rectifier, and the spacing between the cathode and the plate is close, to keep at a low value the voltage drop in the tube. A tungsten cathode is the source of electrons and is maintained at the necessary high temperature by a current from some external source. The tube is filled with *argon* which is an inert gas easily ionized by electrons. In this type of tube the plate current is transferred mostly by this ionized gas. The Tungar tube is made in capacities up to about 8 amperes and up to an input of about 75 volts (root-mean-square).[1] Although this rectifier tube has been manufactured for use with greater current capacity and higher voltage input than these limits, the results at the higher ratings have not been uniformly satisfactory. Because of the rela-

[1] Root-mean-square (r.m.s.) value of voltage is the square root of the mean of the squares of the instantaneous values of voltage for one complete cycle of alternating current. Unless otherwise specified, the numerical values of alternating voltages or currents refer to r.m.s. values. (MOYER and WOSTREL, "Radio Handbook," p. 10, McGraw-Hill Book Company, Inc., New York, 1931.)

tively high gas pressure in this tube, the current tends to concentrate in spots where it may cause localized burning of the cathode.

Rectigon Rectifier.—Similar to the Tungar is the *Rectigon* rectifier tube, both being examples of the low-voltage type of rectifier tube in which the flow of plate current is aided by gaseous conduction. Under some conditions, such tubes can be used for charging batteries when the cathode is cold and unlighted. One type of the Rectigon tube has been used to supply a direct-current voltage of 100 volts. It is possible to make a filter for application with these rectifiers so that they may be used for heating the cathodes of radio receiving tubes designed for direct-current operation.

Glow-discharge Rectifier.—Gaseous-conductor vacuum tubes are represented by the *Raytheon* rectifier tube, and by other types of gas-filled rectifier tubes which do not have filaments. This type depends for its action entirely upon the effects of ionization by collision. The tube consists of two elements inside a glass bulb under a reduced pressure of *helium* gas. The elements of the tube are arranged in such a way that the electrons from one element move a relatively short distance and are absorbed before any ionization by collision with the gas particles can take place. The electrons from the other electrode must move a greater distance and have a path which is long enough so that ionization by collision can take place, and new electrons and positive ions can be produced. Consequently when a voltage is applied in one direction there will be only a very small current from the flow of free electrons. When, however, the voltage is reversed there is a much larger flow of current from the effect of ionization by collision in the longer path. The rectification is not perfect because some current flows in both directions, although the *reversed* current is nearly negligible in value. This type of tube passes current freely in one direction at about 150 volts, but requires about 700 volts to cause a flow of current in the opposite direction. A characteristic of this tube is the sudden increase in current when the glow discharge takes place. The relatively high voltage drop necessary to produce an initial current flow is reduced considerably after the conducting path is once established. Because of this variation in operation the tube produces voltage surges which may cause considerable noise.

Three-element (Triode) Tubes.—It has been shown that the plate current may be influenced by changes in either cathode temperature or plate voltage or both. Another factor which will influence the flow of plate current is the effect of an *electrostatic charge* on a *third element* in the tube.

The third element, which is placed between the cathode and plate, is usually a set of parallel wires or a perforated plate called a *grid*. The spacing between the wires of this third element depends upon the service for which the tube is designed. The conventional representation of a three-element tube is shown in Fig. 44. *For simplicity*, in this figure the source of electrons is shown as a wire filament, although most modern tubes have heater cathodes (page 11). The source of power is shown in the figure by batteries, instead of the usual power-supply unit.

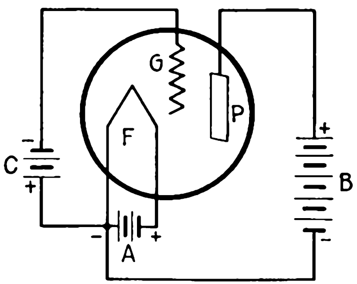


Fig. 44.—Conventional representation of three-element tube.

The third element or the *grid G* obtains an electrostatic charge from its connection to a battery or other source of voltage marked "C."

The cathode is nearer to the grid than it is to the plate so that a voltage applied to the grid exerts a greater attractive or repulsive force than the plate upon the cathode electrons. Usually, the grid is *charged* negatively with respect to the cathode. A negative potential may be applied to the grid by connecting the positive terminal of the battery "C" to the cathode and its negative terminal to the grid as shown in Fig. 44.

The negative charge of the grid tends to force the cathode electrons back to the cathode. This effect, together with that of the space charge (page 97) repels the electrons and, consequently, reduces the value of the plate current, because no appreciable number of electrons can reach the plate. If the negative voltage of the grid is reduced, the flow of electrons to the plate is increased. If, on the other hand, the negative voltage of the grid is increased, the flow of electrons to the plate is decreased. In fact, the plate current may be reduced to zero if the negative charge on the grid is large enough.

A *positive charge* on the grid will neutralize the repelling effect of the space charge on the flow of electrons, thus causing an increase in plate current. The greater the positive charge on the grid the more the plate current will increase until it reaches as a limit the saturation current corresponding to the temperature of the cathode.

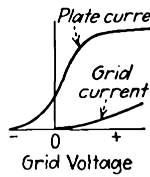


FIG. 45.

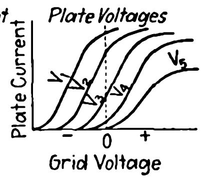


FIG. 46.

FIG. 45.—Relation of grid current and plate current to grid voltage.

FIG. 46.—Relation between plate current and grid voltage for series of values of plate voltage.

When the grid is positive, some of the cathode electrons will be attracted to it and produce in the grid circuit an electron flow from the grid to the cathode, through the battery or other source of current "C," and then back to the cathode. This effect is shown by the curve of grid current in Fig. 45.

The value of the grid current is relatively small so that it is usually measured in microamperes. The flow of current in the grid circuit may be controlled by using suitable values of the operating voltages. In the action of a vacuum tube as a *detector* (page 22), when a grid leak and grid condenser are used (page 134), the grid current becomes of importance.

The relation between plate current and grid voltage in a typical vacuum tube is shown by the curve in Fig. 45 for a given value of plate voltage and cathode temperature. If the cathode temperature is kept constant and a curve of plate current is drawn for each of a series of plate voltages a group of curves is obtained like Fig. 46. The relation between plate current and plate voltage for various grid voltages may be represented as in Fig. 47.

The electric power consumed in the input circuit of a three-element tube is very small because of the small electrostatic capacity of the grid with respect to the cathode. Ordinarily, there is no current in the grid circuit. A small change in grid voltage, however, produces as much effect on plate current as a much larger change in plate voltage. Thus, a small input of electric power, largely in the form of voltage on the

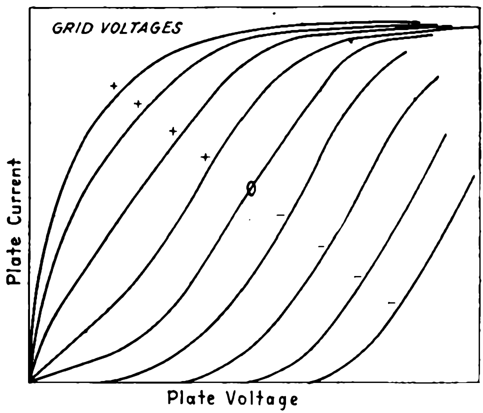


FIG. 47.—Relation of plate current to plate voltage for a series of values of grid voltage.

grid, controls a much larger amount of power in the plate circuit. This characteristic permits the amplification of voltage or power that may be obtained by the use of a three-element vacuum tube.

The insertion of the grid element gives the three-element vacuum tube the properties of amplification and oscillation which the two-element tube does not have. These properties give this kind of tube the important place which it occupies today in radio transmission and reception, and in numerous other applications.

Plate Current of Triode.—The electron current which flows from the cathode to the plate of a three-element vacuum tube depends on the grid and plate voltages, the spacing and size of the grid mesh, the distance between the elements (cathode, plate, and grid), and the area of the elements supplying current.

The equation for plate current is:

$$I_p = K(E_p + uE_g)^x \tag{45b}$$

where I_p = plate current of the tube, amperes.

K = constant depending on the type of tube.

E_p = plate voltage measured between the plate and the cathode, or the negative terminal of the filament, volts.

E_g = grid voltage measured between the grid and the cathode, or the negative terminal of the filament, volts.

u = amplifying ability of the tube, possibly variable.

x = exponent, approximately about 2, but variable, depending on grid and plate voltages.

The term E_p represents the "applied" voltage, being equal to the supply voltage minus the voltage lost in the resistance of the plate circuit. In radio-frequency amplifiers (page 88), the resistance in the plate circuit may be neglected, and the applied plate voltage becomes equal to the plate-supply voltage. With resistance coupling (page 346), the voltage loss in the plate resistance is at times large enough to consume more than one-half of the supply voltage. The effect of a voltage applied to the grid is given by the term uE_g, so that variations of grid voltage are u times as effective in causing changes in plate current as the same variations of plate *voltage*. Since the voltage which is applied to the grid is usually negative, the term uE_g lowers the "effective" plate voltage. Thus, if a type 30 tube has 90 volts on the plate, and the grid is connected to the negative terminal of the filament, then, at zero grid voltage ($E_g = 0$), the effective plate voltage E is $E_p + uE_g = 90 + 9.3^* \times 0 = 90$ volts, and the plate current I_p is 7.1 milliamperes. If now the value of the

* See Radio-tube Table, p. 617, for values of u.

voltage applied to the grid (*grid bias*)[1] is −4.5 volts, the effective plate voltage is decreased, although the actual supply voltage remains unchanged. Then $E = E_p + uE_g = 90 + 9.3(-4.5) = 90 - 41.9 = 48.1$ volts, and the plate current I_p now is reduced to 2.5 milliamperes, since the effective voltage is lower.

Curves showing the variation of plate current with plate voltage are needed only to show the plate current when the grid-bias voltage is zero. The relations for other conditions can be found by determining the effective plate voltage as in the example above and by applying this value to the curve to get the corresponding value of plate current.

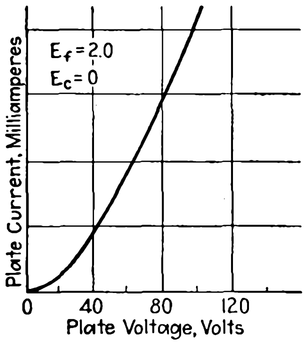


FIG. 48.—Relation of plate current to plate voltage for type 30 tube.

On the other hand, if the grid-bias voltage has a positive value, the effective plate voltage is higher than the applied voltage, since the term uE_g becomes positive and adds to the plate voltage E_p. Under such conditions, the grid current is large and the grid absorbs considerable power (wattage), so that the efficiency of the tube as an amplifier is reduced.

The curve of plate current plotted against applied plate voltage for the type 30 tube is given in Fig. 48. According to the notation on the drawing, the tube was operated at a cathode voltage (E_f) of 2.0 volts, and a grid-bias voltage (E_c) of 0 volts. An inspection of this curve shows that the plate current increases slowly at low plate voltages and more rapidly at higher voltages. This non-linear relation (due to the exponent x in the above equation) permits the use of the tube as a *detector*. This same relation makes special precautions necessary when a maximum amount of undistorted power output is required, as in power amplifiers.

[1] MOYER and WOSTREL, "Practical Radio," p. 79.

The normal plate current of tubes differs widely, ranging from 0.2 milliampere for the type 40 tube to 60 milliamperes for type 2A3, and up to 75 milliamperes for type 46 under certain conditions of class *B* amplification (page 130).

Plate Resistance.—The internal or *direct-current* resistance R of a vacuum tube permits a current I_p to flow from the plate to the cathode when the plate voltage is E_p. An estimate of this direct-current resistance of a vacuum tube may be obtained by observing the plate current corresponding to the plate voltage at which the resistance is desired. The relation between these factors may be expressed as $R = E_p \div I_p$.

The vacuum tube as generally used in radio reception operates with pulsating and not constant values of grid voltage, plate voltage, and plate current. Such a pulsating current, for example, is considered to be a combination of a direct-current portion and an alternating-current portion, each of which acts independently of the other. The resistance of the tube to alternating current differs from the resistance to direct current. Unless otherwise stated, the term *plate resistance* in connection with the description of vacuum tubes is the *resistance offered to the flow of alternating current* and is designated as r_p. The *alternating-current* resistance r_p of the plate circuit may be found from the relation,

$$r_p = \frac{E_p}{I_p} \qquad (46)$$

in which E_p is a *small* change in plate voltage which produces a corresponding *small* change I_p in plate current, when the *grid voltage is constant.* It may be seen from this that r_p is equal to the reciprocal of the slope of the plate current-plate voltage curve (Fig. 48, page 108) at the "point of operation." This slope (and, of course, the plate resistance) is approximately constant over the straight part of the curve but shows an increase at the lower and upper bends.

The expression for the alternating-current resistance may be given also as,

$$r_p = \frac{uE_g}{I_p} \tag{47}$$

in which E_g is a *small* change in grid voltage which produces a corresponding *small* change I_p in plate current. The term uE_g is, of course, equal to the term E_p from the preceding equation.

It is shown in Chap. VI that the plate resistance of the tube to alternating current is approximately equal to half the resistance of the tube to direct current. That is,

$$r_p = \frac{R}{2}. \tag{48}$$

The plate resistance is a measure of the effect of the plate voltage alone upon the plate current. It varies because of the non-linear relationship of plate current to plate voltage shown in Fig. 48. At low values of plate voltage the plate resistance is relatively high. As the plate voltage is raised, the plate resistance decreases rapidly and then more slowly as the normal operating voltage is reached. If the applied voltage is very high, the plate resistance may again increase. This critical value indicates that the saturation point is being reached; that is, practically the full emission current is flowing. This condition is apt to occur when vacuum tubes are subjected to voltages in excess of rated values, or when they are operated without a grid-bias voltage. If the cathode emission at high plate voltages limits the plate current, the plate resistance will increase. This decreases the efficiency of a vacuum tube as an amplifier. The plate resistance of commercial tubes, under rated operating conditions, ranges from 1,750 ohms for type 71A to more than 1,500,000 ohms for type 57. The plate resistance curve of a commercial tube is given on page 127.

A simple apparatus for volume control can be made to depend upon this increase in plate resistance which takes place when the emission current is near the value of the plate current. If the cathode current of one or more radio-frequency amplifying tubes is decreased, the reduced emission current increases the plate resistance and thus may be used to control amplification. The distortion thus introduced by the increased slope of the curve showing the variation of plate current with plate voltage may be neglected. The life of the tube is less, however, than if the control is accomplished by reducing the plate voltage by the method of using a series resistance in the plate circuit, or by the more common methods described on page 423.

Three-element Vacuum Tube Considered as a Variable Resistance.—An interesting conception of a vacuum tube is

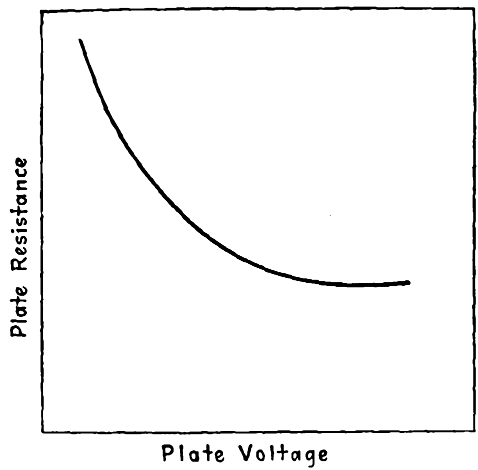


FIG. 49.—Relation of plate resistance to plate voltage at zero grid voltage.

that of a variable resistance. The curves of Fig. 47, showing the relation between plate current and plate voltage for various values of grid voltage, indicate that the three-element tube may be considered as a variable resistance, the value of which depends on the grid voltage; meaning that the higher the grid voltage, the less the tube resistance, and *vice versa*. As the grid voltage is varied from the negative to the positive direction, the value of plate current increases up to the saturation value. At this point, the resistance is a minimum for the given operating conditions. A curve showing the relation between the plate resistance r_p and the plate voltage E_p at zero grid voltage is given in Fig. 49. This conception of a tube is very helpful in a study of tube operation, especially for transmitting equipment.

The resistance of a vacuum tube causes a loss of power which cannot be avoided. The value of this loss of power is proportional to the value of the resistance. The tube resistance depends on certain factors of design such as the spacing between tube elements, the length and area of the cathode, the temperature and condition of the cathode, the efficiency of the emitting surface, the plate area, the amplification factor, and the applied voltages.

The performance of a tube may be improved if the plate resistance is reduced by changing the design factors mentioned before. The desirability of such a change, however, depends on some other conditions. It may happen that such a change may increase power consumption to an undesirable extent. It may affect the reliability, strength, and life of the tube, or the tube may not be suitable for the circuit in which it is used.

Amplification Factor.—The ratio of a *small* change in plate voltage E_p which is necessary to change the plate current I_p a given amount to the *small* change in grid voltage E_g which will produce the same change in plate current is called the *amplification factor* u, that is,

$$u = \frac{E_p}{E_g}. \tag{49}$$

The amplification factor depends on the spacing and size of the network of wires in the grid, that is, the closer the spacing the greater the screening effect of the grid on the electrostatic field of the plate and the greater the amplification factor. It also varies directly as the distances between the plate and the cathode, and between the grid and the cathode. The nearer the grid is to the cathode, the smaller will be the voltage which is needed to produce a field around the cathode equal to the field set up about it by the plate. Thus, a tube having a large amplification factor uses a fine grid mounted at a small distance from the cathode, as compared to the distance between plate and cathode.

The amplification factor may be described also as the ratio of the change in plate voltage to the change in control-electrode (grid) voltage in a direction such that there is no change in plate current. Thus, if the change in plate voltage E_p is 25 volts and if the change in grid voltage E_g necessary to maintain the plate current I_p at a constant value is 5 volts, the amplification factor is 25 ÷ 5, or 5.

The *theoretical formula* for the amplification factor in terms of the tube electrodes and structure indicates that its value is constant provided that the plate voltage is large compared with the grid voltage, and that certain assumptions are made as to construction. Calculated results agree with measured values to a reasonable degree. Mechanical requirements in the construction of tubes, however, introduce factors which result in the dependence of amplification factor on cathode, grid, and plate voltages. The variation is slight within the ordinary working range of voltages but becomes considerable for large changes in plate or grid voltages. The effect of electrode structure on amplification factor in the case of a tube having plane-surface electrodes is different from the effect of cylindrical electrodes.

The wire of the cathode of a tube is not at the same potential from end to end because there is a voltage variation along its length. Hence the voltage difference between the grid and various parts of the cathode is not constant. For example, if E is the voltage across the cathode and if the grid is connected to the negative end of the cathode, then the grid is at zero potential with respect to that end, but at a potential of $-E$ with respect to the positive end. Electrons can flow from the negative side of the cathode without being affected by the grid because there is no voltage difference between the grid and that side of the cathode. But the flow of electrons from the positive side of the cathode may be stopped entirely by the effect of the grid which, with respect to the positive side of the cathode has a negative voltage ($-E$). Consequently the amplification factor is affected because of the change in the relation between the grid and the cathode when various parts of the cathode are at different potentials. In the case of a tube with a unipotential heater cathode (page 10), the entire cathode has a uniform voltage with respect to the other electrodes.

The amplification factor is, however, practically constant in value over the straight portion of the characteristic curve (page 95) of a tube. The value of the amplification factor of a vacuum tube expresses the relative effects of grid voltage and plate voltage on the plate current, and so determines the plate resistance (page 109) of the tube. An increased amplification factor corresponds to an increased plate resistance and vice versa. A change in the amplification factor also affects the *mutual conductance* (page 115) to some extent even though the plate area, cathode length, and other such factors remain constant. A tube with a high amplification factor shows a lower mutual conductance than a tube of similar construction but with a lower amplification factor. This effect is shown in Fig. 50, for a number of tubes with different amplification factors but using the cathode and plate construction of a type 20 tube. It is evident from this drawing that a low value of the amplification factor should be used in order to gain the advantage due to improved mutual conductance, provided that the *load impedance* (page 8) can be adjusted to a suitable value. Such conditions are conducive to maximum power output. For voltage amplification in circuits in which high plate resistance is not important, as in resistance- or impedance-coupled amplification, a high value of u is desirable, because it allows an increase in voltage amplification to be obtained from each stage of the amplifier.

The amplification factor is a measure of the maximum voltage amplification obtainable from the tube alone. The grid-to-cathode voltage due to the reception of a radio signal appears in the plate circuit multiplied u times. The voltage developed across a high-impedance load placed in the plate circuit is very nearly equal to this value of uE_g. The amplification curve of a commercial tube is shown on page 127. The amplification factor of commercial tubes ranges from 3.0 for type 71A to more than 1,500 for type 57, but the practical maximum value which can be obtained is very much less than this.

Mutual Conductance.—Both the plate resistance and the amplification factor of a vacuum tube affect its performance as an amplifier. In comparing the merits of tubes it is convenient

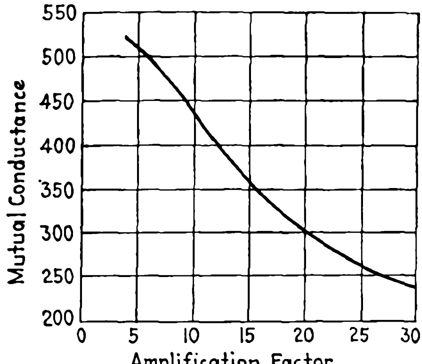


FIG. 50.—Relation of mutual conductance to amplification factor.

to use a term called "mutual conductance" or "control grid-plate transconductance" which takes both of these factors into consideration. *Mutual conductance* G_m is the ratio of the amplification factor to the plate resistance. The usual unit of mutual conductance is the *micromho*. This characteristic of a tube frequently is stated as *control grid-plate transconductance* S_m. Its value may be given in terms of milliamperes per volt (equation 50). It has been shown in equations (49) and (45*a*) that

$$u = \frac{E_p}{E_g}, \qquad \text{and} \qquad r_p = \frac{E_p}{I_p},$$

hence the ratio of the first of these two equations to the second gives the mutual conductance, thus,

$$G_m = \frac{E_p}{E_g} \div \frac{E_p}{I_p} = \frac{I_p}{E_g} \text{ (in mhos, or in amperes per volt of grid voltage).} \quad (50)$$

Or

$$G_m = \frac{u}{r_p} \text{ (mhos)} = \frac{u}{r_p} \times 10^6 \text{ (in micromhos).} \quad (51)$$

That is, mutual conductance may be expressed as the ratio of a small change in plate current to the change in grid voltage required to produce the same change in plate current. This expression also represents the slope of the curve showing the variation of plate current with grid voltage (Fig. 45, page 105) at the "point of operation." The slope of the curve is greatest, of course, at the point at which the curve is steepest. In other words, at the point of largest value of the slope, a given change of grid voltage produces the maximum change in plate current.

The expressions developed for the values of amplification factor, plate resistance, and mutual conductance show that these three factors are interdependent according to the following relations:

$$r_p = \frac{u}{G_m}, \qquad u = r_p \times G_m, \qquad \text{and} \qquad G_m = \frac{u}{r_p}.$$

Tubes having high values of mutual conductance are more efficient amplifiers than those having lower values, but the comparison must be made between tubes *designed for the same service* and having similar characteristics. The value of mutual conductance for commercial tubes ranges from 425 for type 99 tube to 2,500 for type 47. A relatively large change in mutual conductance causes only a small change in tube performance as judged by the ear in radio reception.

Effects of Interelectrode Capacity.—The elements of a vacuum tube form an *electrostatic system*, each element acting as one plate of a small condenser. The three direct capacities which exist in a triode are the grid-to-filament or grid-to-cathode capacity C_{gk}, the grid-to-plate capacity C_{gp}, and the plate-to-cathode capacity C_{pk}, as shown in Figs. 51 and 52.

The total capacity of a tube is made up of the capacity of the electrodes of the tube, of the lead-in wires, and of the base. The total capacity of a type 01A tube between the grid and the filament, and between the plate and the filament, is about 5 micromicrofarads, but the capacity between the grid and plate is larger, being approximately 10 micromicrofarads.

It is necessary to remember that the interelectrode capacities of a tube, as measured when the elements are free, are not the same as when the elements are connected. Thus the "direct" capacity between the grid and the plate is increased by the mutual capacity from the grid to the cathode and from the cathode to the plate. The direct capacity between the grid and the plate of a type 01A tube, when the cathode has been removed, averages 8 micromicrofarads, while the capacity as measured between these two elements in a complete tube is 10.1 micromicrofarads. The effective value of this capacity is further increased by the capacity of the wiring of the tube socket, the tube base, and also by the amplification action of the tube.

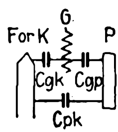


FIG. 51.

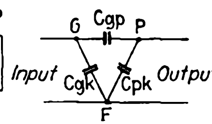


FIG. 52.

FIG. 51.—Elements of triode showing direct-interelectrode capacity.

FIG. 52.—Diagram of direct-interelectrode capacities of triode.

Input and Output Circuits.—When a tube is in use its *input circuit* is from the grid to the cathode, and its *output circuit* from the plate to the cathode through a source of power and some external load. Thus the capacity of the input circuit may be considered as that of a condenser which has the grid for one plate and the plate and cathode connected together for the other. The grid-cathode capacity shunts the impedance in the input circuit, and the plate-cathode capacity shunts the impedance in the output circuit; these capacities therefore affect the frequency characteristics of the circuits. If an alternating voltage is applied to the grid-to-cathode circuit of a tube, an alternating current will flow in the grid circuit because of the grid-to-cathode capacity. Whether the cathode is lighted or not, this grid voltage will set up a current in the plate circuit due to electrostatic induction through the capacity of the tube from the grid to the plate.

While the grid-to-cathode capacity and the plate-to-cathode capacity do not affect the performance of a tube at audio frequencies and have only a small effect at *radio* frequencies, the grid-to-plate capacity has a very marked effect in a radio-frequency amplifier. As far as the tube itself is concerned, the capacities between the elements of a tube introduce a reactance (page 66) effect.

When amplification is given in terms of the applied grid voltage, the cathode-to-plate capacity has only a small effect, so that the amplification is not affected by frequency for values up to several thousand kilocycles per second. Usually, however, the amplification is given as the ratio of the output power to the input power, and the effect of the reactance due to electrode capacities depends on the kind of circuit that is used. If the reactance of the output circuit has the effect of capacity, or if the output circuit consists of a resistance, the input resistance is positive. Under such conditions, power is taken by the tube from the input circuit. The value of this power which is used is so small at ordinary frequencies that it may be neglected. At high frequencies no power is taken by the grid circuit, but the electrode capacities offer a path to the input current and thus reduce the amplification.

The increase in effective interelectrode capacity may become so large under certain load conditions as to affect the performance of the tube at high audio frequencies. Thus, in a resistance-coupled amplifier the effective capacity reaches a value of 250 to 300 micromicrofarads, which is high enough to cause a decrease in amplification at frequencies over 5,000 cycles per second.

In general, then, it may be said that the effect of interelectrode capacity is to produce a coupling between the input and output circuits. Consequently the tube does not have a true unilateral or single-direction characteristic. The extent of the coupling depends upon the circuit constants. This coupling may cause a feed-back of energy to the input circuit, or with certain circuit adjustments, an absorption of energy from the input circuit. The effect of inter-electrode capacity is to reduce amplification at high frequencies. Several schemes for decreasing this effect in circuits using three-element tubes are given in a later section (page 444).

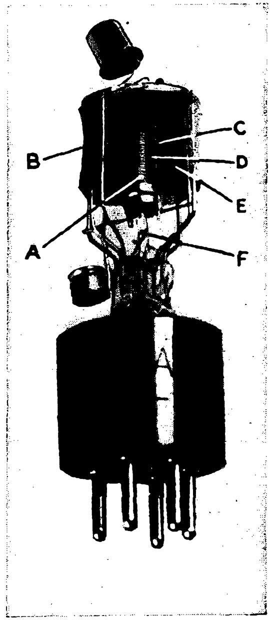


FIG. 53.—Typical screen-grid tube.

Four-element Tube (Tetrode).—A tube having four electrodes is called a tetrode. The screen-grid or shield-grid tube which has a cathode, plate, and two grids is one type of tetrode. Other forms of tetrodes are the space-charge grid tube, the dual-grid tube, and the variable-mu tetrode.

Screen-grid Tube.—The screen-grid tube as illustrated in Fig. 53 shows how the plate is separated from the control grid by the screen grid. The conventional method of indicating this type of tube and of connecting the four electrodes is shown in Fig. 54. The screen grid may be connected to a tap for positive voltage on the power supply unit; the plate voltage must be higher in value than the screen voltage. The presence of the screen grid reduces the effective capacity between plate and grid to the very low value of a few hundredths of a micromicrofarad. The screen grid is shunted to the ground through a condenser of large capacity (1.0 microfarad) to provide a path of low impedance to the

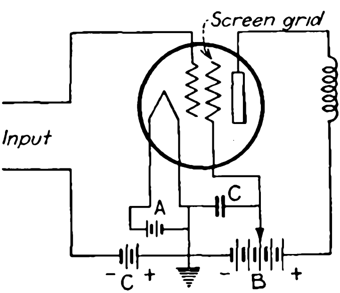


FIG. 54.—Connection of electrodes of screen-grid tube.

ground for radio-frequency currents. Thus the screen grid is, in effect, at ground potential with respect to radio-frequency currents, and is not affected by voltage variations of the plate. Consequently the control grid is shielded from plate voltage variations, and feed-back (page 9) is eliminated.

The direct electrode capacities of the screen-grid tube may be shown as in Figs. 55 and 56. Since the screen grid G_2 is in effect grounded, the diagram of Fig. 56 can be reduced to that of Fig. 57. Then the two capacities between the control grid and the cathode are in parallel, and those between the plate and the cathode are also in parallel. The electrode capacities

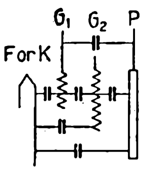


FIG. 55.

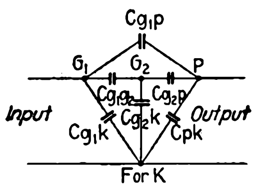


FIG. 56.

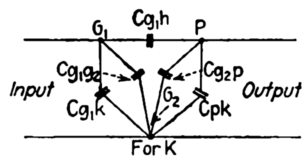


FIG. 57.

FIG. 55.—Elements of tetrode showing direct-interelectrode capacity.
FIG. 56.—Diagram of direct-interelectrode capacities of tetrode.
FIG. 57.—Equivalent capacity of tetrode.

of the screen-grid tube ordinarily given are the grid-plate capacity, the input capacity, and the output capacity.

It has been shown (page 119) that the grid-plate capacity may interfere with the proper operation of a tube by producing a feed-back of energy from the output circuit to the input circuit, particularly in radio-frequency amplifiers. Several circuit arrangements have been devised to be used with three-element tubes to counteract or neutralize this effect. The low grid-plate capacity of the screen-grid tube makes such circuit arrangements unnecessary.[1]

[1] Although the internal capacity between the control grid and the plate is small, it has been found that neutralization of the radio-frequency amplifying tubes seems necessary when a screen-grid tube is used in the radio-frequency stages of a circuit using regeneration applied to the radio-frequency transformer.

The plate resistance of the screen-grid tube is high because the plate current does not depend on the plate voltage. The mutual conductance depends principally on the screen-grid voltage and on the control-grid voltage. Thus the tube can be designed for high values of both plate resistance and mutual conductance, with a resulting high amplification factor.

Because of the high plate resistance it is difficult to design an external circuit which is matched properly to this tube. This difficulty is due partly to the high plate-to-screen-grid capacity which, being in parallel with the plate circuit, acts as a short-circuit at high frequencies. Thus at 1,000 kilocycles a capacity of 20 micromicrofarads has a reactance of 8,000 ohms. Even if the external impedance does not match the tube, a high voltage-amplification is possible because of the very high amplification factor.

Shielding of Screen-grid Circuits.—The internal shield of a screen-grid tube prevents or greatly minimizes feed-back through the interelectrode capacities of the tube. This, however, is only one form of coupling between stages. If there is any magnetic feed-back from one tuning circuit to the preceding one, oscillatory currents may be set up in the circuit. Hence, it is necessary, also, to shield the input from the output circuit. The amount of shielding depends on the voltage amplification per stage and the design of the circuit. A metallic shield for each tuned stage usually is sufficient. If the voltage amplification is high, it may be necessary to use on the tube a grounded metal covering extending to the base. The connection to the control grid is brought out to a cap on the top of the tube. The circuit wire connected to this cap should be shielded with a grounded covering.

Characteristic Curves of Screen-grid Tube.—The curves of plate and screen current against plate voltage for the screen-grid type 24A tube are shown in Fig. 58. The heavy line at 90 volts on the plate-voltage scale indicates the positive voltage on the screen grid. When the plate voltage is higher than the screen voltage, it is clear that plate-voltage changes do not have much effect on the plate current. When the plate voltage is lower than the screen voltage, the plate current decreases as the plate voltage is increased. This effect is caused by secondary emission (page 94). The screen grid, being in this case at a higher potential than the plate, has a greater attraction for electrons. Under this condition an electron may reach the plate and knock off another electron, both of which are then drawn to the screen grid. The *total* space current, that is, the plate current plus the screen-grid current, is practically unaffected by plate voltage. To the

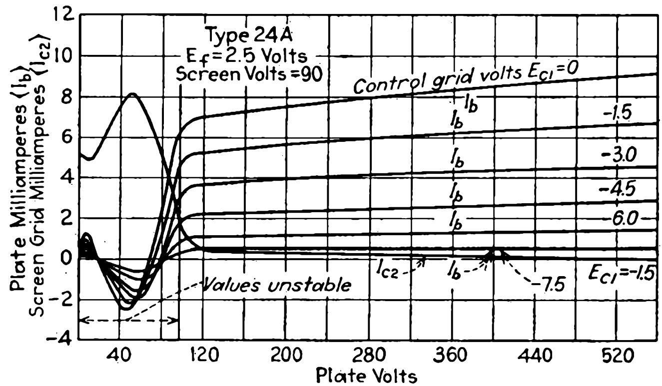


FIG. 58.—Average plate characteristics of type 24A screen-grid tube.

left of the line at 90 volts the secondary electrons are attracted to the screen grid; and to the right of the line at 90 volts they are attracted to the plate. Under normal conditions, the tube is operated on the portion of the curve which is nearly parallel to the plate-voltage scale. Usually the plate voltage is about twice the screen-grid voltage.

Power Limitation of Screen-grid Tube.—The capacity of a tube for power output depends on the value of plate current and the allowable swing of plate voltage. The screen-grid tube is limited in this respect for a number of reasons. Inspection of the curves in Fig. 58 (type 24A tube) shows that the plate current can be increased by making the control grid positive; but this will introduce distortion and reduce selectivity. The plate current can also be increased by making the screen-grid more positive. This change, however, reduces the allowable swing or variation of plate voltage. When the plate voltage becomes nearly equal to the screen-grid voltage the secondary emission from the plate causes a marked decrease in plate current. This limitation is overcome by the use of an additional electrode as in the pentode (page 127), to suppress secondary electron emission from the plate.

Space-charge Grid Tubes.—When a tetrode is used as a space-charge grid tube the outer grid serves as the control grid, and a positive voltage is applied to the inner grid to decrease the space charge around the cathode. The value of the positive voltage on the inner grid must not be so high that the space charge is entirely neutralized, because then the control grid would become ineffective. The performance of a tube connected in this manner, as compared with that of a screen-grid tube, shows a lower plate resistance, a higher amplification factor, higher interelectrode capacities, and a higher mutual conductance. The plate resistance depends on the voltages applied to the control grid and to the plate. The amplification factor depends to some extent on the values of the operating voltages but principally on the shape of the grid. The effect of control-grid and plate voltages on the plate current is the same as in a three-element tube.

A screen-grid tube operated with a space-charge grid connection does not give satisfactory service as an audio- or radio-frequency amplifier because of the high-amplification factor and the high interelectrode capacities. Tubes designed for operation with a space-charge grid have the characteristics of high interelectrode capacities, and a high amplification factor with low operating voltages.

Variable-mu or Super-control Tubes.—The distinguishing feature of a variable-mu or super-control tube; that is, a tube with a *variable amplification factor,* is the type of grid construction. A variable amplification factor can be obtained with a grid in the form of a tapered helix, or one in which the spacing between the turns of wire is variable, or one in which openings are provided in the grid structure. With this type of grid construction the amplification can be controlled by varying the voltage on the control grid. Grids of this kind

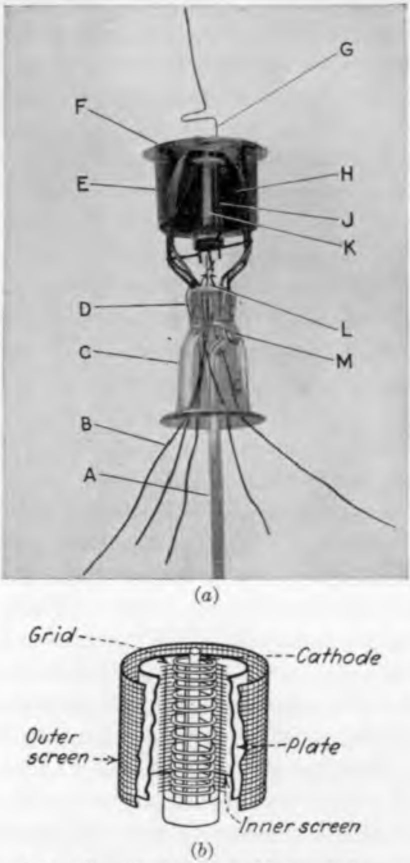


FIG. 59.—Typical variable-mu tube.

are used in tubes designated as types 34, 35, 39/44, 58, and 78. Cut-away views of type 35 tube are shown in Figs. 59*a* and in 59*b*. The latter illustrates the construction of the grid. These tubes are designed for service as radio-frequency and intermediate-frequency amplifiers, and also as mixers (page 9) in superheterodyne circuits.

The chief difference between the performance of a screen-grid tube and that of a variable-mu tube is shown in Fig. 60 by the curve of plate current against grid-bias voltage. The plate current of a screen-grid tube reaches the cut-off value when a moderate value of negative voltage is applied to the grid. The plate current of a variable-mu tube reaches the cut-off value at a high negative-grid-bias voltage. This effect is obtained because a very small plate current can flow, even though a very high negative-grid-bias voltage is applied. The amplification factor on moderate signal strength is the same as that of an ordinary screen-grid tube, but on strong signals it is reduced and the tube continues to operate on a straight portion of the plate current-grid voltage curve so that no distortion is introduced.

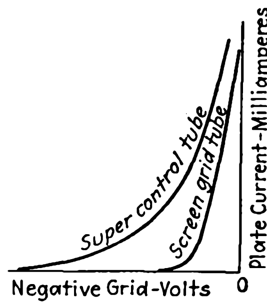


FIG. 60.—Relation of plate current to grid-bias voltage in super-control and screen-grid tubes.

A variable-mu tube is necessary in a radio receiver in which volume is controlled by varying the amplification in the radio-frequency stages in order to get a wide range of control with a minimum of signal distortion. Two kinds of signal distortion which may occur in the radio-frequency stages of a receiver are known as *cross-modulation* and *modulation distortion.* Modulation distortion, which usually takes place in the last intermediate-frequency stage of a superheterodyne receiver, is a distortion of the modulated *carrier wave* (page 324) and produces a distorted audio-frequency output; this effect is produced when a radio-frequency stage is operated so that the peak value of signal voltage causes a swing which is greater than that corresponding to plate-current cut-off, or when operation is on an excessively curved portion of the mutual conductance characteristic curve at high values of negative-grid-bias voltage. Cross-modulation, which usually occurs in the first radio-frequency stage, is the distortion due to an interfering signal which combines with the carrier wave of the desired signal; this effect is produced when operation is on an excessively curved portion of the mutual-conductance characteristic curve. These effects are reduced by the use of a tube in which the cut-off value of plate current is reached gradually and in which the curvature of the mutual-conductance characteristic curve is relatively flat. Tubes of this kind, because they are equally satisfactory for either strong or weak signals, are especially suitable for use in receiving sets provided with automatic volume control.

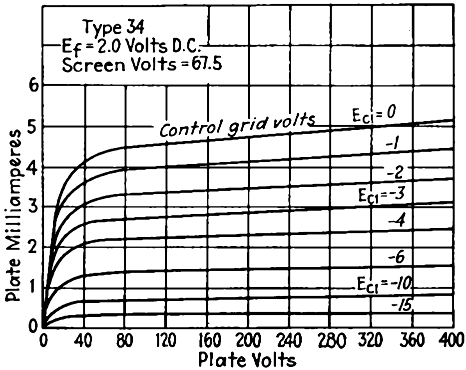


FIG. 61.—Average plate characteristics for type 34 tube.

Curves showing plate current plotted against plate voltage at various values of control-grid voltage for a type 34 tube are given in Fig. 61. These curves were taken with a screen voltage of 67.5 volts. It is clear that when the plate voltage is higher than the screen-grid voltage, the plate current is not affected to any considerable extent by changes in plate voltage. The relation between mutual conductance and control-grid voltage, and also the variation of amplification factor with control-grid voltage, are shown in Fig. 62. The shape of these curves is characteristic of typical variable-mu tubes. A variable-mu tube such as type 51 has a control grid-bias voltage range which is at least double that of type 24A tube, and it can be used in place of this type if the grid-bias voltage is changed. Type 35 tube cannot be used in place of type 24A because its plate current is higher and its plate resistance is lower.

Pentode or Five-element Vacuum Tube.—In the development of the screen-grid tube it was found that the plate current was reduced, and the permissible variation of plate current was limited by the effect of *secondary emission*, meaning the electron emission from the plate. This action occurs when an electron strikes the plate with enough force to dislodge other electrons. In a diode (page 95) or a triode (page 104) type of tube such loose electrons will travel back to the plate because there is no other positive electrode to attract them. But in a screen-grid tube the positive screen draws the loose electrons with an attraction which increases if the plate voltage becomes less than the screen voltage. Consequently the flow of plate current is hampered. This effect is shown by the dip in the plate current curve of a type 24A tube shown in Fig. 58.

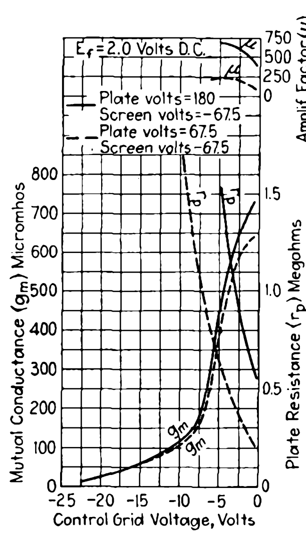


FIG. 62.—Relation of mutual conductance to control-grid voltage of type 34 tube.

To remove this limitation the *pentode type* of tube was designed, having a fifth electrode, known as a *suppressor*, located between the screen and the plate. The conventional representation is shown in Fig. 63. The suppressor by its connection to the cathode is negative with respect to the plate. Thus any loose electrons are barred from the screen by the suppressor and are diverted back to the plate.

The advantages inherent in this pentode construction are utilized in two different ways; namely, for increased power output, as in tubes represented by types 33, 38, 41, 43, 47, 2A5, and 6A4,[1] and for increased voltage amplification in radio-frequency amplifiers at plate voltages of moderate value, as in types 34 and 39/44.

Special control features through voltage variation on the suppressor electrode are available if the suppressor is provided with a base terminal. Examples of this type of tube are the triple-grid detector-amplifier type 57, and the triple-grid super-control amplifier, type 58.

The construction of the type 2A5 power-output pentode was described in Chap. II. The power-output pentode has the advantages of both a high amplification factor and a high power capacity, as compared with a triode or tetrode. Such a tube can deliver a higher power output on a smaller signal voltage input than a three-element tube having the same output rating. With the use of a pentode output tube one stage of audio-frequency amplification can be omitted, the output tube being driven by the detector tube, or the amplification in other parts of the radio receiver can be reduced. The increased power efficiency of a pentode as compared with a triode having the same output rating is an advantage as regards the use of the pentode in all battery and especially automobile receivers. The output pentode produces a small amount of harmonic distortion which can be tolerated if the load and operating conditions are correct but which may become objectionable if the output coupling unit is incorrectly designed. Curves in which plate current was plotted against plate voltage with various control-grid voltages for the type 47 power-output pentode are shown in Fig. 64. These curves were taken with a screen-grid voltage of 250 volts. In operation the voltages applied to the plate and screen grid

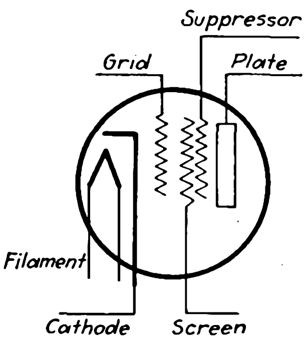


FIG. 63.—Conventional representation of pentode.

[1] Types 2A5 and 42 are similar except for the cathode rating.

are equal. A comparison of such curves for a pentode with those for a tetrode, for example type 24A, shows a similarity in that for both tubes the plate current depends principally on the voltages of the screen grid and control grid, being relatively unaffected by plate-voltage changes except at low values of plate voltage. When the plate voltage is low, a space charge is formed near the cathode, the plate current is reduced, and is no longer under the control of the control-grid voltage. A point of difference, however, is that the plate

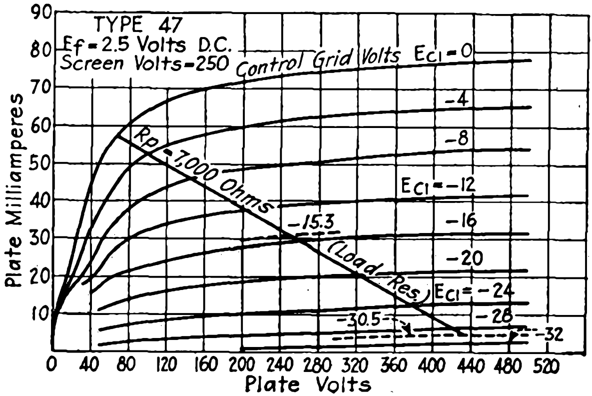


FIG. 64.—Average plate characteristics of type 47 power-output pentode.

current of the pentode does not decrease sharply when the plate voltage approaches a value which is less than the screen-grid voltage.

A radio-frequency amplifier pentode, for example type 39/44, is not affected by the limited permissible voltage variation which restricts the operating range of a tetrode at low plate voltages, when the value of plate voltage approaches that of the screen grid. For the pentode type the screen-grid and plate voltages may be the same, and yet satisfactory operation obtained for values as low as 90 volts. Another advantage of the pentode is that the use of the suppressor grid reduces the coupling effect of the tube between the input and output circuits.

Multi-electrode and Multi-unit Tubes.—Special types of tubes have been designed for particular applications, or to combine in one unit the services formerly available from two or more tubes. Tubes of the first kind generally need a number of extra electrodes in order to provide the required special characteristics, and may thus be classified as multi-electrode tubes. A tube with six electrodes may be termed a *hexode;* one with seven electrodes, a *heptode;* and one with eight, an *octode.* A variety of applications is possible with a multi-electrode tube because the electrodes can be connected in different ways for different requirements—for instance, a dual-grid power amplifier can be connected for service as either a class *A* or class *B* output amplifier[1] triode; or, a triple-grid power amplifier can be connected not only as a class *A* or class *B* output amplifier triode but also as a class *A* amplifier pentode.

Where two or more separate tubes are combined in a single unit, the combination is given a compound name such as the *duplex-diode triode*, the *duplex-diode pentode*, the *twin amplifier*, and the *triode-pentode.*

Another type consists of a combination of the multi-electrode tube and the multi-unit tube. For instance, the pentagrid converter type has seven electrodes in addition to the heater, which are so arranged that the tube can operate as an oscillator (page 9) and a mixer (page 9) at the same time.

[1] At this point only a brief outline of class *A*, *B*, and *C* amplifiers is needed. A full description is given in Chap. X. A class *A* amplifier is one in which the grid bias and the exciting grid voltage are such that the plate current through the tube flows at all times. A class *B* amplifier is one in which the grid-bias voltage is approximately equal to the cut-off (p. 149) value, so that the plate current is approximately zero when no exciting grid voltage is applied, and so that the plate current in each tube flows during approximately one-half of each cycle when an exciting grid current is present. A class *C* amplifier is one in which the grid-bias voltage is appreciably beyond the cut-off value so that the plate current in each tube is zero when no exciting grid voltage is present, and so that the plate current flows in each tube for appreciably less than one-half of each cycle when an exciting grid voltage is present.

The conventional representations of these types are shown in Fig. 65.

Dual-grid Tube.—An amplifier tube in a *class B* or *positive-grid swing system* is operated with a control-grid-bias voltage of such value that the plate current flows only when the signal voltage is in its positive half cycle. Harmonics are eliminated by the use of two tubes in push-pull connection (page 317). An amplifier tube suitable for class *B* operation should have a steep characteristic curve of plate current against grid voltage,

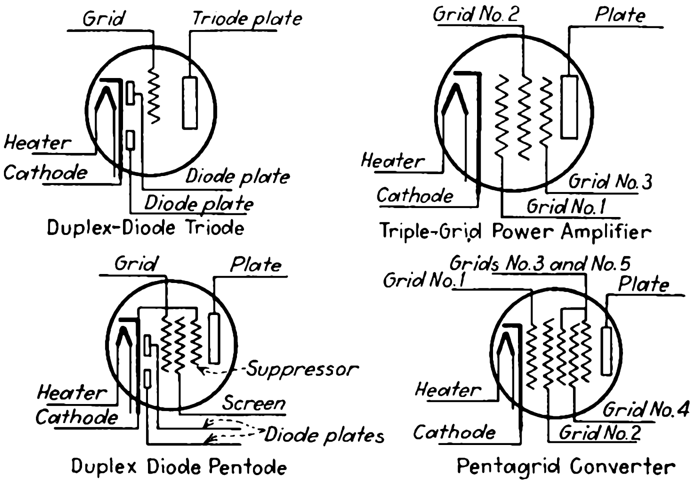


FIG. 65.—Usual representations of multi-electrode and multi-unit tubes.

with a sharp cut-off (page 149). Also, the load on the driving circuit should be light and as uniform as possible. For such requirements the tube must be capable of operation at zero grid-bias voltage and must have a high value of amplification factor. These features are obtained by a construction utilizing two grids, one inside the other, joined to one another, and acting as a control grid. Each grid is provided with its own terminal base pin. Type 46 tube, a dual-grid *power amplifier*, as shown in Fig. 66, illustrates this kind of construction, which is used also in tube type 49. In class *B* service at the maximum voltage the nominal power output of two tubes is 20 watts. The characteristic curve of plate current against plate voltage for tube type 46 in class *B* operation is a factor that favors this type of tube; because for equal dissipation of heat from the plate, the tube can be operated at relatively low plate voltages, thus decreasing the cost not only of the tube but also of the power supply unit. With a plate voltage of 400 volts and zero grid-bias voltage the static plate current[1] is low, being only 6 milliamperes. The amplification factor is so high that a negative grid-bias voltage is not required.

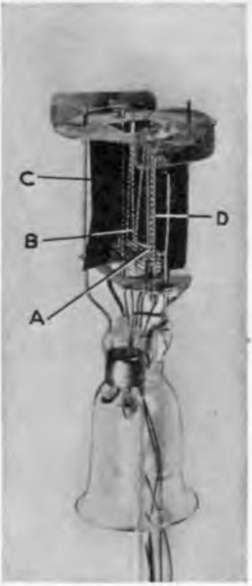


Fig. 66.—Typical dual-grid power amplifier.

When two tubes of type 46 are operated in a class *B* system the *driver* (meaning the tube in the previous stage) can be a single type 46 tube, operated as a class *A* amplifier, with the second grid connected to the plate in order that the tube may have a low amplification factor. The tube then is in effect a triode, and the grid next to the filament serves as the control grid. The characteristic curve of plate and grid current against plate voltage of a type 46 tube as a class *A* amplifier is shown in Fig. 67. With a plate voltage of 250 volts and a grid-bias voltage of minus 33 volts the amplification factor is about 5, and the plate current is 22 milliamperes. The average plate characteristics for class *B* operation are shown in Fig. 68, and the operation characteristics are shown in Fig. 69.

Another type of dual-grid tube, known as the *Wunderlich*, is shown in Fig. 70. The two grids of this tube are located in the same plane around the cathode. Each grid is provided

[1] This term designates the plate current which flows when there is no signal voltage.

with a separate support. The tube is designed for use as a detector, and also as a power amplifier. In the detector

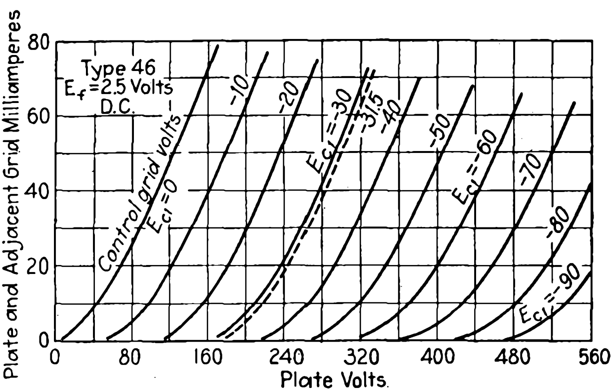


FIG. 67.—Average plate characteristics of type 46 tube used as class *A* amplifier.

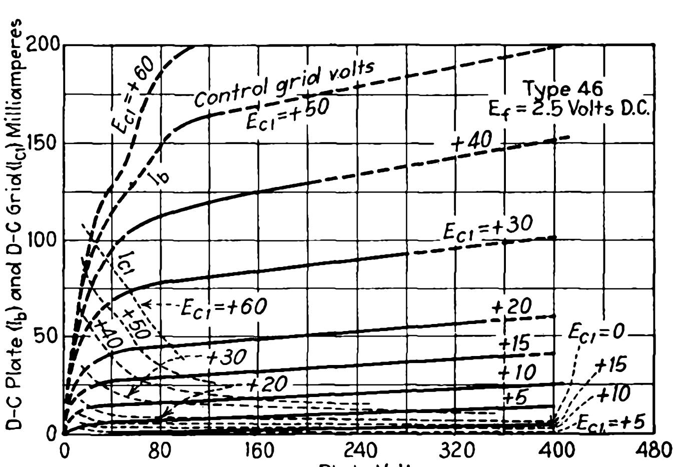


FIG. 68.—Average plate characteristics of type 46 tube used as class *B* amplifier.

circuit for this tube shown in Fig. 71 the radio signal voltage across the resistance *R* is applied to the two grids and the midpoint of the resistance is connected through a grid leak and a grid condenser (page 105) to the cathode. With this

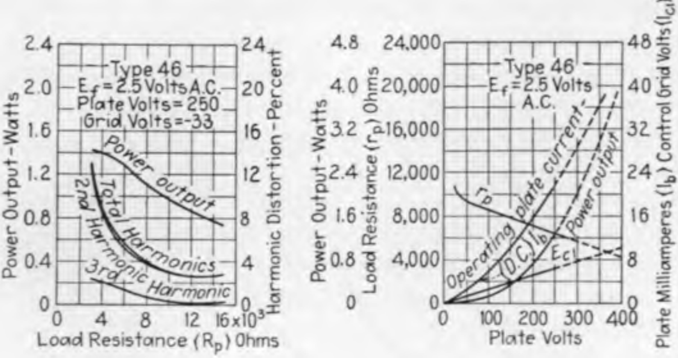


FIG. 69.—Operation characteristics of type 46 tube.

divided input circuit a much higher value of signal voltage is needed to operate the detector than with the usual grid-input circuit. Because of the rectifying action of this arrangement the rectified signal current flows from the grid to the cathode in the tube when the grid becomes positive. The voltage produced across the grid leak and the grid-condenser unit by the flow of rectified current is impressed on both grids at the same time, and acts to control the flow of current in the plate circuit. Since the radio-frequency effects (page 117) of the

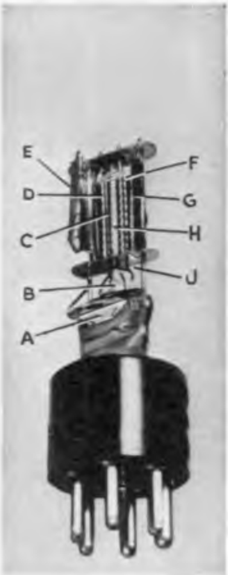


FIG. 70.—Wunderlich dual-grid tube.

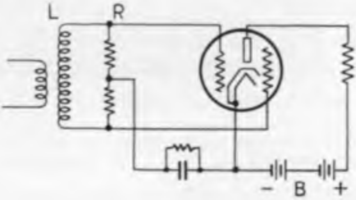


FIG. 71.—Detector circuit for Wunderlich tube.

two grids on the plate current are equal and opposite, there is no radio-frequency current in the plate circuit. Consequently the tube has a high output rating as a power-detector tube with low distortion. The characteristic curve of the detector action of this tube is linear (straight-line relation) over the operating range. The rectified voltage across the resistance R can be utilized for automatic volume-control purposes.

Triple-grid Tube.—The triple-grid tube was introduced because of the successful application of the suppressor-grid tube (page 127). Two examples of this construction are type 57, a triple-grid detector amplifier tube with a sharp cut-off (like that of type 24A), and type 58 which is a triple-grid super-control radio-frequency amplifier like the variable-mu (page 123) type 35. Types 58 and 6D6 are identical except for their heater ratings and their *interelectrode capacities* (page 141). A cut-away view of type 58 tube is shown in Fig. 72. Types 57 and 6C6 are identical except for their heater ratings and their interelectrode capacities.

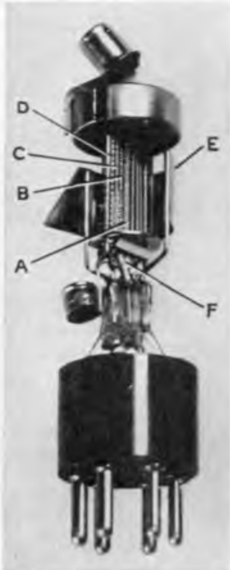


Fig. 72.—Section of typical triple-grid tube (type 58).

As a grid-biased detector tube, type 57 is capable of delivering a large audio-frequency (page 413) output voltage with a relatively small input voltage. The characteristic curves of plate current plotted against plate voltage for types 24 and 57 are shown for comparison in Fig. 73, and the curves of plate current and control-grid voltage for the same tubes are shown in Fig. 74. The curves of plate current plotted against plate voltage for types 58 and 35 are shown for comparison in Fig. 75 and the curves of transconductance (page 115) and control-grid voltage for the same tubes in Fig. 76.

In these types the suppressor connection (page 127) is made to a separate terminal pin on the base. When the suppressor grid is at the same voltage as the cathode there is

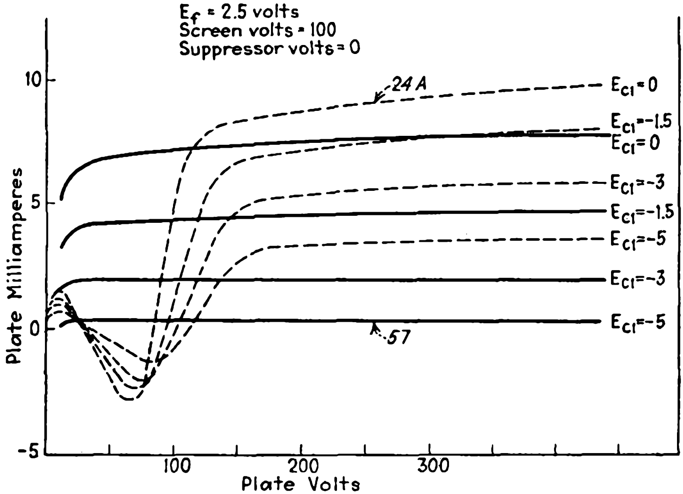


FIG. 73.—Average characteristics of grid-biased detector tubes (types 24 and 57).

practically no space charge between the suppressor grid and the screen grid. If a negative voltage is applied to the suppressor grid a space charge is set up between the suppressor grid and the screen grid. Under the effect of this space charge the tube characteristics are like those of a triode with the suppressor grid acting as a control grid. As a result of the presence of this space charge, electrons are attracted to the plate from the suppressor grid alone more readily than through the three grids. The effect of the control obtained by means of the triple-grid construction on the mutual conductance of the type 58 tube is shown in Fig. 77, and the effect on plate resistance in Fig. 78. Types 57 and 58 are

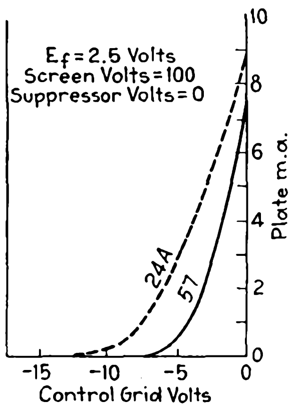


FIG. 74.—Relation of plate current to control-grid voltage in grid-biased detector tubes (types 24 and 57).

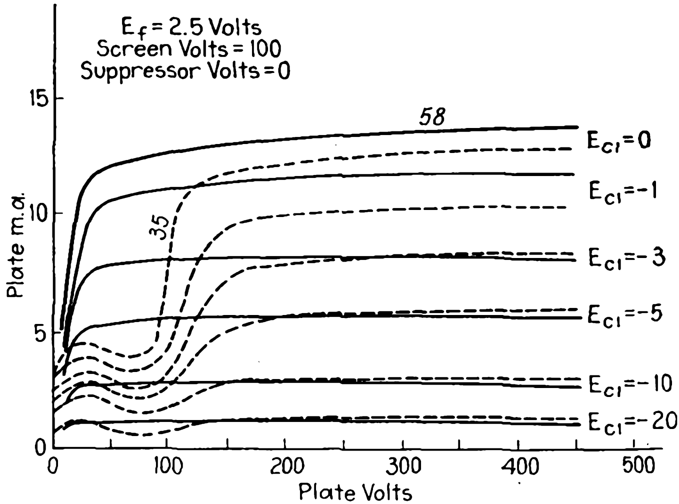


FIG. 75.—Average characteristics of grid-biased detector tubes (types 35 and 58).

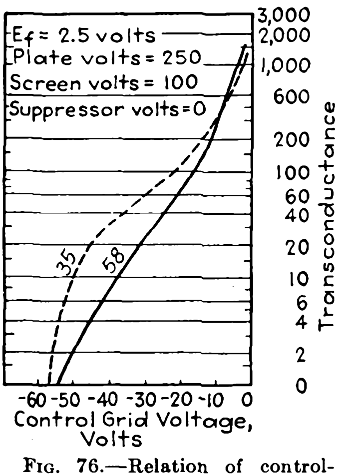


FIG. 76.—Relation of control-grid voltage to transconductance in grid-biased detector tubes (types 35 and 58).

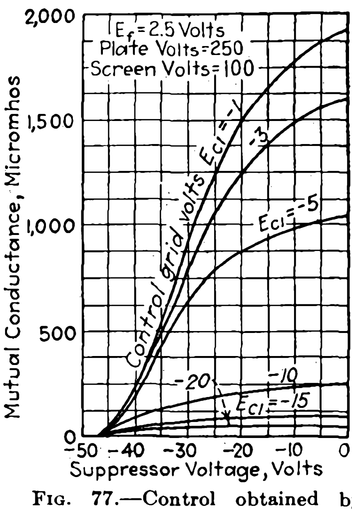


FIG. 77.—Control obtained by triple-grid construction on mutual conductance of type 58 tube.

constructed with an internal shield that is connected to the cathode within the tube. This shielding reduces the tube capacity from the plate to the ground, and also the capacity between the plate and the screen grid. An external shield of the can type should be used with these tubes in order to keep the various capacities of the tubes at a minimum.

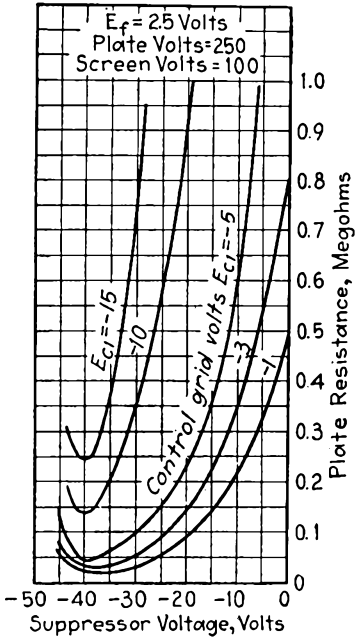


FIG. 78.—Control obtained by means of triple-grid construction on plate resistance of type 58 tube.

These types illustrate the application of the improved cathode design by which the usual rating of 1.75 amperes at 2.5 volts has been reduced to 1.0 ampere.

Type 59 tube is a triple-grid power amplifier. Each grid is provided with an external connection. Because of this construction the tube can be used as a class *A* (page 130) power-amplifier triode, a class *A* power-output pentode, or a class *B* power-output triode. When, however, the tube is to serve as a class *A* power-output triode, the second and third grids which are adjacent to the plate are connected to the plate, and the first grid is utilized for control purposes. Under these conditions the operation of the tube is similar to that of any class *A* power-output triode. When the tube is to serve as a class *A* power-output pentode the third grid is connected to the cathode, thus acting as a suppressor grid (page 127), the second grid is employed as a screen grid, and the first grid becomes the control grid. Under these conditions the operation of the tube is similar to that of *any* class *A* power-output pentode. When the tube is to serve as a class *B* power-output triode the third grid adjacent to the plate is connected to the plate while the first and second grids which are connected together act as a control grid. With such a connection no grid-bias voltage is needed.

Other triple-grid tubes are the type 77 triple-grid detector amplifier, the type 78 triple-grid super-control amplifier, and the type 89 triple-grid power amplifier.

Triple-twin Tube.—This tube, illustrated in Fig. 79, consists of two triode units (page 104) in one bulb. The first of these units consisting of elements similar to those in a heater-type general-purpose tube (page 184) is connected through its cathode to the grid of the second unit which is similar to a power-output triode. The two units are mounted on one stem. The conventional representation is shown in Fig. 80.

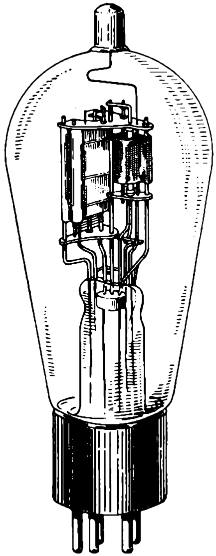


FIG. 79.—Triple-twin tube.

The input unit is operated in a manner similar to that of the ordinary detector or amplifier tube. The output unit is connected so that it operates on the *positive* as well as the negative portion of the curve of plate current plotted against grid voltage. The combination therefore can be used as an audio-frequency amplifier, or as a detector and amplifier. It is claimed that the tube is capable of a relatively high power output with low distortion.

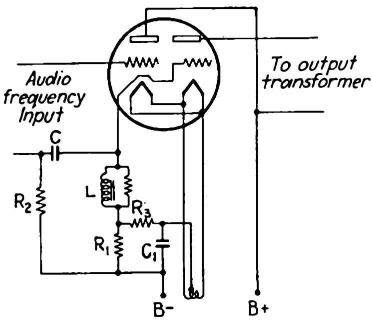


FIG. 80.—Conventional circuit for triple-twin tube.

The circuit in Fig. 80 shows how the tube is used in an amplifier. It should be noted that the cathode on the input side is not at the ground potential. The signal voltage is applied between the cathode and the grid through a low-impedance condenser C. The negative grid-bias voltage for the grid on the input side is obtained from the resistance R_1. The resistance R_2 provides a return path to the grid for direct current. The inductance L provides a path of low resistance for the grid and plate return currents. The grid on the output side is provided with a negative grid-bias voltage by the resistance R_3. Both the grid-bias voltage and the grid signal voltage for the grid in the output section of the tube are obtained from the cathode of the tube unit in the input section.

Plate rectification only is used because of the marked curvature of the curve of plate current when plotted against grid voltage. The grid current of the first section of the tube must be of the proper magnitude in the operation of the tube or the detector will be overloaded. The output voltage is in direct proportion (linear relation) to the input voltage.

Maximum power and minimum distortion are obtained with a load of about 4,000 ohms, but with a load of 8,000 ohms the second-harmonic distortion[1] is more than 2 per cent. With a signal voltage of 5 volts and a plate voltage of 250 volts the power output is 4.5 volts. In a push-pull connection with the same plate voltage and an applied voltage of 5.5 volts the power output is 10 watts and the distortion is about 2 per cent.

The operating values of voltages and tube characteristics are as follows:

TABLE IV.—TRIPLE-TWIN TYPE 295—DETECTOR-AMPLIFIER

Voltage and characteristic values	Input section	Output section
Plate volts	250 max	250 max
Grid-bias volts	16	3
Plate current, milliamperes	2.0	52.0
Amplification factor	14.4	13.0
Plate resistance, ohms	12,000	3,000
Mutual conductance, micromhos	1,200	4,350
Power output, watts		
Signal volts, r.m.s. (p. 44)	5.0	4.5
Load impedance, ohms	12,500	4,000

[1] Second-harmonic distortion is caused by a current which has a frequency twice that of the signal frequency.

Improvements in Triode Design.—Type 56 tube, a super-triode amplifier and detector, is an improvement on type 27 (Fig. 81) and has a new design of grid together with a high efficiency cathode. The result of the change in construction is obvious when the operating characteristics of the two tubes are compared. For example, the characteristics of the two tubes at the same plate voltage are similar except for mutual conductance and amplification factor; the mutual conductance for type 56 tube is 1,450, and its amplification factor is 13.8, both values being about 50 per cent greater than those for type 27 tube. The curves of plate current against control-grid voltage for the two types are given in Fig. 81. Types 56 and 76 are identical, except for their heater rating and their interelectrode capacities.

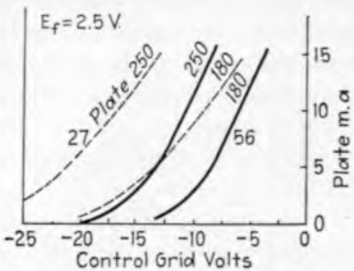


FIG. 81.—Relation of plate current to control-grid voltage in typical triode tube (types 27 and 56).

Duplex-diode Triode.—A combination unit consisting of two diodes and a triode in a single bulb is shown in Fig. 82. This combination is represented by the tube types 2A6, 75, 55, and 85. Types 2A6 and 75 are similar except for their heater ratings. Types 55 and 85 are also alike except for their heater ratings.

FIG. 82.—Duplex-diode triode.

The design of tube types 55 and 85 is the same as that of types 2A6 and 75, except that the triode unit of types 2A6 and 75 has an amplification factor of 100, while that of types 55 and 85 is 8.3.

The two diode units are independent of each other and of the triode unit, but a common cathode sleeve is used which has separate emitting surfaces for each of the diodes and also for the triode. Because of the flexibility of the circuit arrangement made possible by this type of electrode assembly, such combination tubes can be used for several services at the same time. Thus the diode units when used independently can provide (1) detection, (2) automatic volume control with

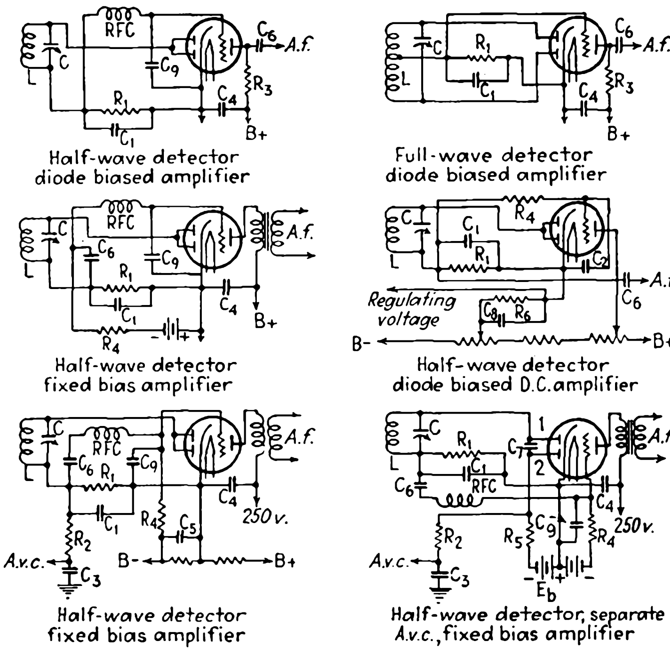


FIG. 83.—Typical duplex-diode triode in circuits (types 85 or 55).

sensitivity control, and (3) time-delay action restricted to the automatic volume control circuit. On the other hand, they may be used together either in parallel or in a full-wave rectifier circuit (page 98). At the same time the triode unit can be used as an amplifier. A number of typical circuits for the application of the duplex-diode triode are shown in Fig. 83. A curve of direct-current *voltage* developed by the diode plotted against the rectified *current* is shown in Fig. 84 for a *single* diode unit in a half-wave rectification circuit. The detector characteristics are the same for the four types mentioned above as well as the tube types 2B7 and 6B7. The plate characteristic curves of the high-mu triode unit when compared with those of the low-mu triode show several differences. The curves for type 75 are given in Fig. 85 and those for type 85 in Fig. 86. The type 85 tube has a much higher plate current and range of grid voltage than the others of this kind.

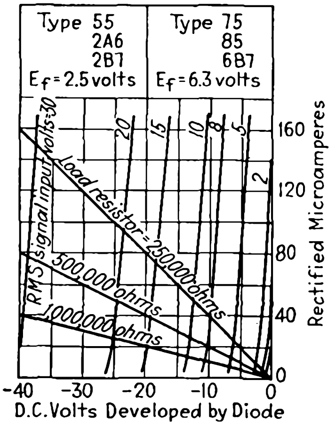


FIG. 84.—Relation of direct-current voltage to rectified current for single diode unit in half-wave rectification.

Duplex-diode Pentode.—The construction of this combination tube as shown in Fig. 87 is in general similar to that of the duplex-diode triode (page 141), except that the triode unit is replaced by a pentode unit. It is represented by types 2B7 and 6B7 which are identical except for the ratings of their heaters. The duplex-diode pentode is

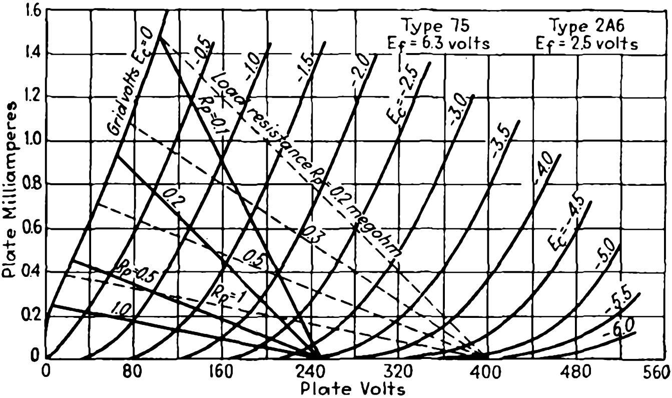


FIG. 85.—Plate characteristics of triode units (tube types 75 and 2A6).

used for the same general type of service as the duplex-diode triode.

The detection characteristics of this type of tube are the same as those of the duplex-diode triode type. The curves of plate current plotted against plate voltage for the pentode unit are shown in Fig. 88. These curves are somewhat similar to those for type 39/44 tube (page 124), but the curvature of the mutual conductance characteristic of the pentode unit is opposite to that of type 39/44 tube. The cut-off point of the pentode unit is extended somewhat so as to allow a moderate gain control (page 151) by the variation of the grid-bias voltage without distortion that might be caused by cross-modula-

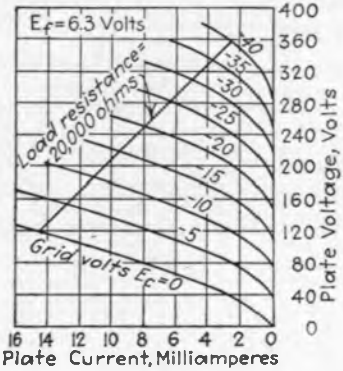


FIG. 86.—Plate characteristics of triode unit (tube type 85).

FIG. 87.—Duplex-diode pentode.

tion. When operated at the maximum values of plate and screen voltages, the pentode unit has an amplification factor of 730, which is more than seven times that of the triode unit of a duplex-diode high-mu triode (page 141). Typical circuit diagrams for the application of the duplex-diode pentode are shown in Fig. 89.

Twin Triode.—The twin triode, also known as a complete class *B* amplifier tube, contains two sets of triode elements in a single bulb, as shown in Fig. 90. The triode sections are provided with separate base prongs for all electrodes except the cathodes. It is represented by tube types 19, 53, 6A6, and 79. Types 53 and 6A6 are identical except for the ratings of their heaters.

A circuit for the use of a twin triode type 19 as a class *B* power-amplifier tube is shown in Fig. 91. The design of this circuit is essentially the same as that of a class *B* amplifier stage using individual output tubes. Figure 91 also shows the

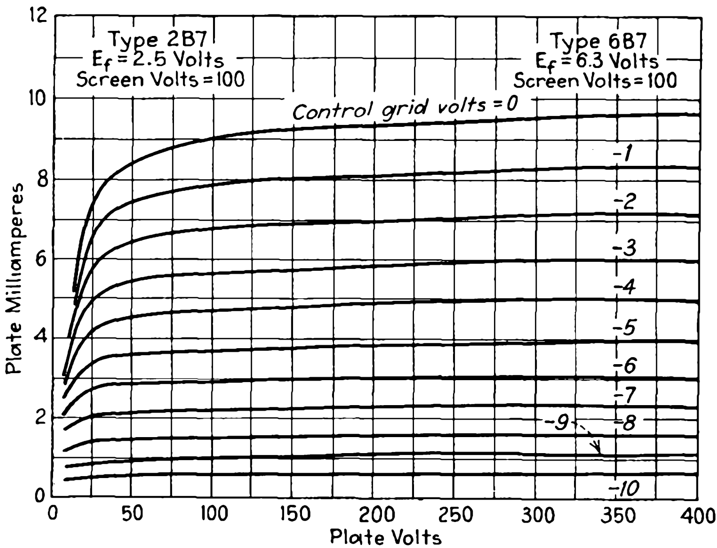


FIG. 88.—Average characteristics of duplex-diode pentode (type 6B7).

performance characteristics of type 19 as a class *B* amplifier tube under stated operating conditions. With this arrangement an additional stage of audio-frequency amplification would be needed to drive the output tube to a high value of output.

Type 53 (also 6A6) is a twin triode with a coated unipotential heater. This type is like type 79 except that it has a different heater rating and has a higher power output. At a plate voltage of 300 volts a power output up to 10 watts may be obtained. No grid-bias voltage is needed and the distortion is relatively low. If the two triode units of this tube are *placed in parallel;* that is, with the grids connected together and the plates connected together, the tube can be used as a class *A* amplifier to drive another type 53 tube as a class *B* amplifier in the output stage. This circuit arrangement as

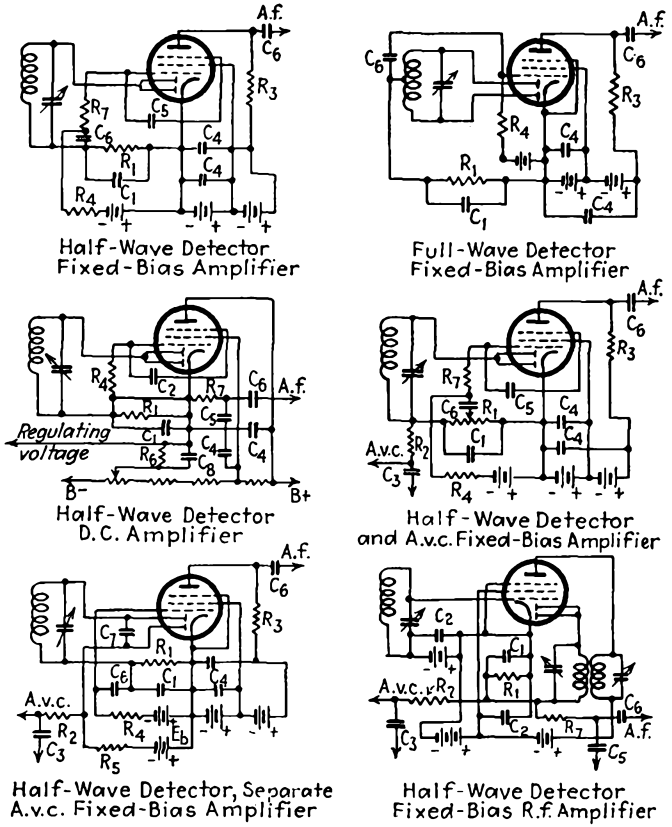


FIG. 89.—Typical circuit diagrams of duplex-diode pentode.

shown in Fig. 92 gives a high power output with low distortion. This tube can be used also (1) as a "biased" detector (page 108) and an audio-frequency amplifier, (2) as a two-stage audio-frequency amplifier, (3) as a two-tube oscillator, (4) as an oscillator and amplifier, and (5) as a combination voltage amplifier and phase inverter to supply by means of resistance coupling an output stage of tubes in push-pull connection. Type 79 can be used for the same applications as type 53 within the limitation of its lower rating of power output.

Pentagrid Converter Tube.—In a superheterodyne receiver (page 125) the desired signal frequency is generally converted to a new lower frequency which is then amplified, detected, and delivered to the audio-frequency-amplifier stages of the set. This lower or intermediate frequency is obtained by "mixing" the signal frequency with a locally generated frequency. The value of the local frequency is adjusted so that the intermediate frequency, which is the difference between the signal and local frequencies, is constant. This frequency conversion is accomplished in the first detector or *mixer tube*, both the signal and local frequencies being applied to its grid. The local frequency is generated either by a separate oscillator tube or in the detector tube itself. When the tube functions as a combined detector and oscillator, a reactive coupling (page 68) is used to connect the detector circuit to the oscillator (page 9). When a pentagrid converter tube is used the connection between the oscillator and detector circuits is made through *electron coupling*,[1] by utilizing the stream of electrons in the tube. The advantages of this system are (1) the simplification of circuit design, (2) elimination of undesirable intercoupling among the parts of the radio-frequency oscillator-mixer circuits, (3) increased stability of the oscillator, (4) improved translation gain (page 152), (5) provision for automatic volume control with the number of tubes

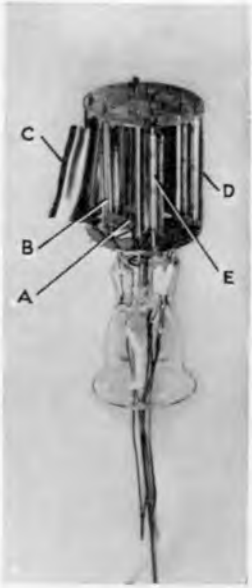


FIG. 90.—Twin triode (complete class *B* amplifier).

[1] Electron-coupled circuits are described in Chap. XI (Oscillators).

kept to a minimum, and (6) decrease of radiation at the local frequency.

The pentagrid converter tube is represented by types **1A6, 1C6, 2A7** and **6A7**. Types 2A7 and 6A7 are identical except

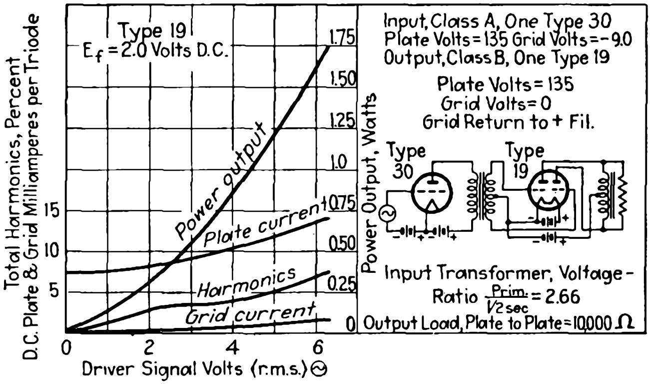


FIG. 91.—Circuit and performance characteristics of type of twin triode used as class *B* power amplifier (type 19).

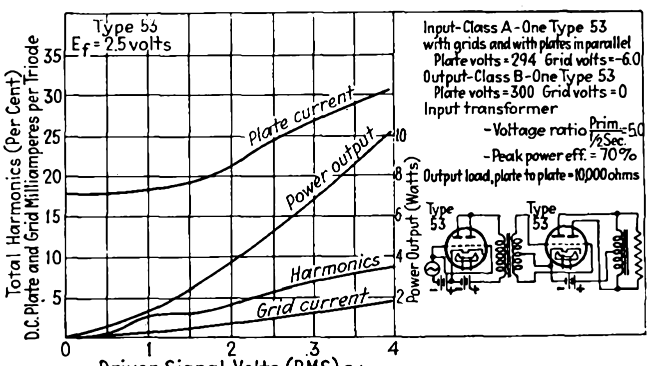


FIG. 92.—Circuit and performance characteristics of type of twin triode used as class *B* power amplifier (type 53).

for the ratings of their heaters. Types 1A6 and 1C6 are provided with cathodes intended for battery operation. Type 1C6 is similar to 1A6 except that it was designed for an increased emission rating and a higher mutual conductance in the oscillator section to give improved performance at high frequencies up to 20 to 24 megacycles.[1]

The extended cut-off action (page 130) of type 1A6 tube can be utilized to provide control of the sensitivity of the receiver. The electrode capacity between the plate and the modulator grid (page 150) is higher than in the ordinary screen-grid tube, and hence precautions must be taken to avoid reaction effects when the difference between the values of the intermediate frequency and the radio frequency is small. If the intermediate frequency is less than the radio frequency there is a degenerative effect which increases in magnitude when the plate-tuning condenser (page 47) is small; *neutralization* (page 120) can be used to compensate for this effect but overneutralization will cause regeneration. If the intermediate frequency is greater than the radio frequency there is a regenerative effect which may cause instability. The general precaution, under either condition, is to use in the plate circuit a capacity of more than 50 micromicrofarads.

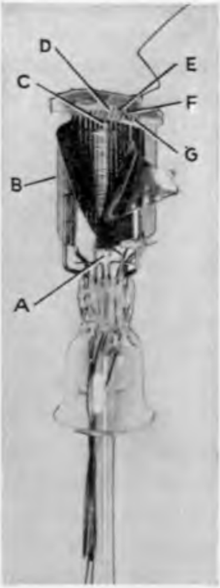


FIG. 93.—Pentagrid converter.

In the operation of a tube for purposes of frequency conversion it is necessary to modulate the cathode current. In the pentagrid converter tube, as shown in Fig. 93, this effect is accomplished by the interaction between supplementary electrodes and the cathode. The supplementary electrodes consist of an additional grid and an *anode grid*[2] which are located between the cathode and the control grid. The action can be explained by a description of the flow of electrons, with the help of Fig. 94 which is for tube type 2A7 or 6A7. The first grid (from the cathode) known as the *oscillator grid*, is

[1] One *megacycle* is 1,000,000 cycles.

[2] The *anode grid* is used as an anode for the oscillator.

the control grid for that part of the tube which acts as an oscillator. The second grid is the anode grid which serves as an anode for the oscillator. The third and fifth grids, connected together inside the tube, known as *screen grids*, are provided to accelerate the electrons coming from the cathode. These screen grids are positive with respect to the cathode. The fourth grid serves as the *modulator* or signal-control grid, and is shielded from the other electrodes by the combination of the third and fifth grids. The effect of this shielding action is to increase the output impedance of the tube which is desirable so far as "gain" (page 151) is concerned. The screen grid near the cathode is used to reduce radiation of the local frequency.

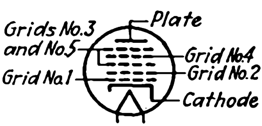


FIG. 94.—Diagram of electrodes in pentagrid converter.

Electrons from the cathode, after acceleration by the effect of the positive anode grid and the screen grids, are drawn through the oscillator grid. Because of the high velocity which these electrons acquire they pass through the anode grid and for the most part through the screen grid. The modulator grid, however, is negative and therefore retards the stream of electrons which approaches it. This region, between the screen grid and the modulator grid, which is filled with retarded electrons, acts as a virtual cathode for the modulator section of the tube. The modulator section may be regarded as a *tetrode modulator tube* consisting of a modulator grid, a screen grid, a plate, and a *virtual* cathode. The plate is connected to the intermediate-frequency output circuit.

The oscillator section of the tube consists of the cathode, the oscillator grid, and the anode grid. The oscillator-grid circuit is designed so that it can be made to oscillate at any desired frequency. Consequently the stream of electrons flowing through the oscillator grid is modulated at that particular frequency.

The electron stream, which has been modulated at the oscillator frequency, now comes under the influence of the modulator or signal-control grid to which the incoming signal voltage is applied. As a result of this influence a plate current is formed which consists of several components having frequencies corresponding to the various combinations of signal frequency and oscillator frequency. But only the intermediate frequency which is equal to the difference between the signal and oscillator frequencies can appear in the secondary of the intermediate-frequency (page 149) transformer because the primary circuit of that stage is designed for resonance at the intermediate frequency.

The modulator grid cannot cause *cut-off* (zero plate current) in the oscillator section because the current needed for sustained oscillations is controlled by the oscillator grid. Consequently it is possible to obtain control of the *gain* (voltage amplification) of the modulator by means of a variable negative grid-bias voltage on the modulator grid without any appreciable effect on the oscillator section. If the grid-bias voltage for the modulator grid is obtained from a variable resistance in the cathode circuit, the oscillator-grid return connection must be made to the cathode. If this connection is not used, the action of the oscillator will be affected by changes in the grid-bias voltage applied to the modulator grid. The modulator grid is designed to afford a gradually extended cut-off which is similar to that obtained in the operation of type 58 tube, but the conversion gain is higher.

Circuit Connections.—The circuit connections for the oscillator section of tube types 2A7 and 6A7 are similar to those for a triode type of oscillator. Likewise, the circuit connections for the detector section are similar to those for a separate variable-mu detector (page 123). Difficulty may be experienced from undesired audio-frequency oscillations if the grid leak and condenser unit allow an excessive amount of feed-back (page 9). The remedy is to decrease the coupling (page 56) between the coils in the oscillator grid and anode circuits, or to use a grid leak with a lower resistance.

The capacity in the plate circuit of the tube should be at least 50 micromicrofarads to limit the value of the radio-frequency voltage across the load. If this voltage is too high it may cause feed-back between the oscillator grid and the plate, producing degeneration and loss of "gain." A diagram of a typical pentagrid converter circuit for the filament type of tube is shown in Fig. 95. For the heater-cathode type of tube the cathode is grounded through a self-biasing resistance in parallel with a by-pass condenser.

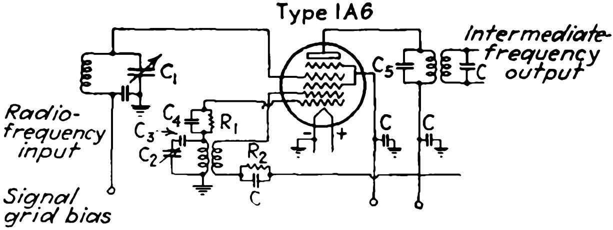


FIG. 95.—Diagram of typical pentagrid converter circuit for filament type of tube.

Circuit Efficiency.—The efficiency of this circuit is given by the term *conversion transconductance* or *conversion conductance.* This term is defined as a ratio of which the numerator is the value of the alternating current at intermediate frequency in the output circuit of the mixer (page 147), and the denominator is the radio-frequency voltage of the signal applied to the fourth grid. *Translation gain* is the ratio of the intermediate-frequency output voltage to the signal voltage applied to the fourth grid. A translation gain curve for type 6A7 tube is shown in Fig. 96.

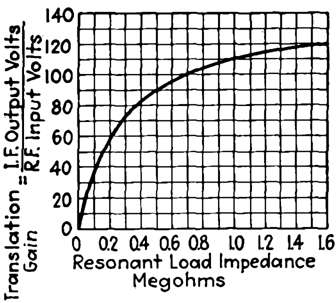


FIG. 96.—Translation gain curve for pentagrid converter (type 6A7).

As a frequency-converter device the present type of pentagrid converter tube is suitable for use at medium radio frequencies only. At frequencies higher than 15 or 20 megacycles the pentagrid converter has two undesirable characteristics—namely, a reduced conversion conductance, and a shift in oscillator frequency which occurs when the signal-grid bias voltage is varied.

The decrease in conversion conductance takes place even though the oscillator voltage is maintained at the proper level corresponding to a given section of the frequency range of the receiver, and becomes more noticeable as the ratio of signal frequency to intermediate frequency is increased. This effect is caused by the space-charge coupling which exists between the oscillator grid and the signal grid. When the intermediate frequency is low compared with the signal frequency, the signal circuit may have a value of impedance that is appreciable at the oscillator frequency. Under this condition a voltage at the oscillator frequency is produced in the signal circuit. This generated voltage and the oscillator grid voltage combine to reduce the conversion conductance of the tube. The reduction in conversion conductance becomes greater as the frequency increases for two reasons: (1) because the ratio of signal frequency to intermediate frequency becomes greater, and (2) because the ratio of the inductance L to the capacity C increases toward the high-frequency end of a band. This space-charge effect is inherent and cannot be eliminated by coupling a separate oscillator tube to the oscillator grid of the pentagrid converter.

In the operation of this type of pentagrid converter at high radio frequencies the oscillator frequency shifts when the grid-bias voltage on the signal grid is changed. This effect is caused by the transconductance between the oscillator anode and the signal grid. It can be eliminated by the use of a separate oscillator tube coupled to the oscillator grid of the pentagrid converter.

The pentagrid mixer amplifier metal tube type 6L7 (page 165) is designed to overcome these disadvantages.

Diode Tetrode.—In some cases it is desirable to use a diode-tetrode combination for detection, automatic volume control, and fixed grid-biased audio-frequency amplification service. Type 1A6 tube may be used for such service by connecting the first grid to the positive side of the cathode, using the second grid as a diode, and the fourth grid for audio-frequency control. The plate is connected to the next tube in the set by means of a resistance coupling. A circuit diagram for this use is shown in Fig. 97. Still another possible application

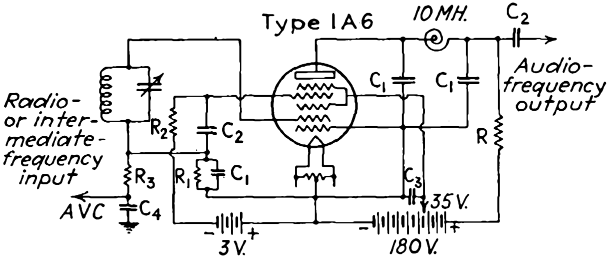


FIG. 97.—Circuit of diode tetrode for half-wave detection, automatic volume control, and fixed grid-biased audio-frequency amplification.

is given in Fig. 98 which shows the tube as a diode tetrode serving as a radio-frequency amplifier and half-wave detector, with automatic volume control.

Triode Pentode.—This is a heater cathode tube consisting of a triode and a pentode of the remote cut-off type. The two sections are served by a common cathode and are mounted

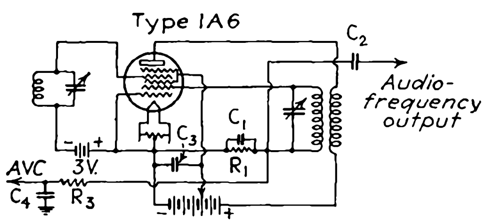


FIG. 98.—Circuit of diode tetrode for half-wave detection, automatic volume control, and radio-frequency amplification.

in a single bulb, the pentode being on top, as shown in Fig. 99. This combination is represented by the type 6F7 tube. The two sections, being independent of each other, can be used for the services obtained from single-unit types of tubes with similar characteristics. The conventional representation of a triode pentode is shown in Fig. 100. The curves of plate current plotted against plate voltage for the triode section are shown in Fig. 101 and those for the pentode section in Fig. 102.

The type 6F7 tube is intended for use as a frequency converter in a superheterodyne receiver. In this connection the triode section serves as the oscillator, and the pentode section as the mixer. One form of circuit diagram for this purpose is shown in Fig. 103. Here the "mixing" is accomplished by means of the coil in the cathode return wire. Because of the variable-mu characteristics (page 123) of the pentode section, it can be connected to the circuit for automatic volume control. The curve of conversion transconductance (page 152) plotted against the control-grid voltage in the pentode section is shown in Fig. 104 for the stated conditions.

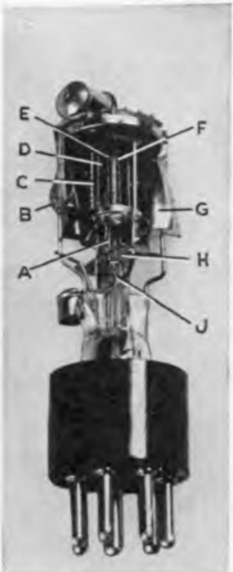


FIG. 99.—Triode-pentode tube.

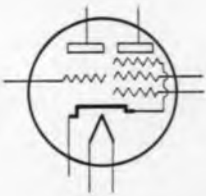


FIG. 100.—Conventional representation of triode-pentode tube (type 6F7).

In addition to its use as a detector and oscillator, the tube can be utilized for other purposes where a triode and pentode are suitable. For example, the pentode section of the tube can serve as an intermediate-frequency amplifier and the triode section as a detector of the fixed grid-bias, grid-leak, or diode type. Similarly, the pentode section can be used as an audio-frequency amplifier and the triode section as a second detector; or, the pentode section can be connected as either a detector or as an amplifier, using then the triode for automatic volume control or for noise suppression.

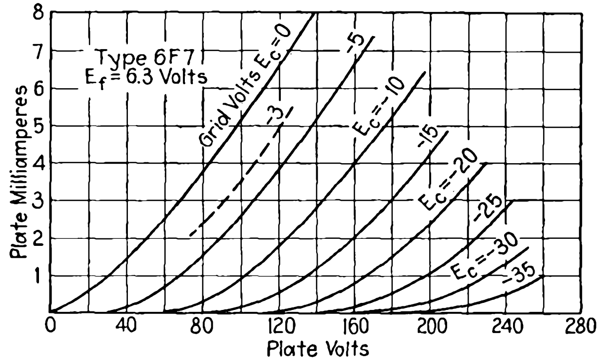


FIG. 101.—Characteristic curves of triode section of triode-pentode tube.

Spray-shield Tube.[1]—The distinguishing feature of this tube is that it has a shield consisting of a semiporous coating of a zinc alloy. This coating is applied to the outside of the

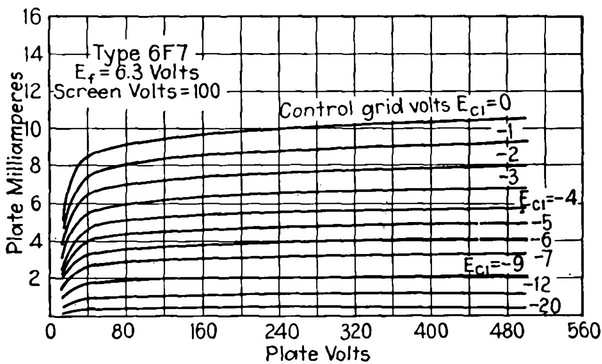


FIG. 102.—Characteristic curves of pentode section of triode-pentode tube.

glass bulb and to the shell of the base by successive operations of sand blasting and spraying the alloy with an oxy-acetylene blow torch. The coating is grounded to the chassis of a radio

[1] PARKER and FOX, "The Spray-shield Tube," *Proc. Inst. Radio Eng.*, May, 1933.

receiver by the use of contact clips. With this arrangement it is possible to apply a negative grid-bias voltage to the sprayed shield. The sprayed shield prevents the accumulation of electric charges on the inner wall of the glass bulb, thereby eliminating tube noise due to secondary emission of electrons from the glass wall, and prevents localized heating of the glass. Because of this external coating the tube elements are electrostatically shielded from adjacent circuits.

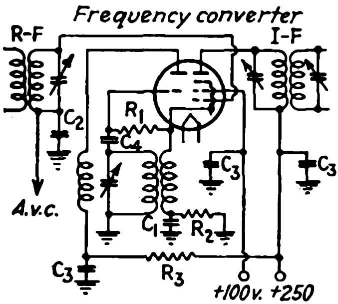


FIG. 103.—Circuit using triode-pentode (type 6F7) as frequency converter in superheterodyne receiver.

In multi-grid tubes the value of direct feed-back capacity can

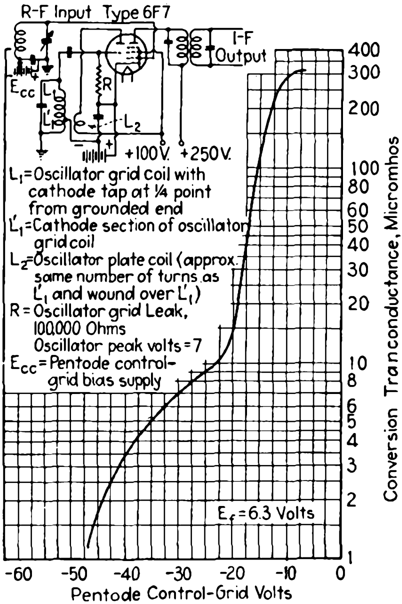


FIG. 104.—Relation between conversion transconductance and control-grid voltage in pentode section of triode-pentode (type 6F7).

be made very low if the tube structure is designed for use with a sprayed shield. By the use of this shield, tube structure can be simplified in manufacture. It is claimed that when the tubes are in operation the temperature of a bulb with a sprayed shield is less than that of a clear glass bulb enclosed in a shielding can. A sprayed shield is not used with tubes of the gaseous conduction type (page 97) because in such tubes a shield of this kind would cause an excessive flow of positive-ion current (page 94) to the glass walls of the bulb and produce electrolysis.

Summary of Development of New Tubes.—The fundamental applications of vacuum tubes in radio receiving sets have not changed—they are still used for obtaining amplification at radio and audio frequencies, oscillation, detection, rectification, and power output. The improved tubes now available are not intended for new uses, but they have made possible better performance through changes in design.

Recent changes in design can be illustrated by a comparison of familiar tube types. The well-known UV-201, a general-purpose tube, was rated at 5 volts on the tungsten cathode with a cathode current of 1 ampere. With 60 volts on the plate, the plate resistance was 18,000 ohms, the mutual conductance 410 micromhos, and the amplification factor was 7.5. In the type 01A tube the change from a thoriated-tungsten cathode brought about a reduction in cathode current to 0.25 ampere. This tube, at the maximum plate voltage of 135 volts has a mutual conductance of 800.

The older tube types in the power-output group started with type 20, then came in succession types 71 and 71A. The type 20 has an amplification factor of 3.3 and an undistorted power-output rating of 110 milliwatts at its maximum plate voltage of 135 volts and grid-bias voltage of 22.5 volts. The type 71A tube has an amplification factor of 3 and an undistorted power-output rating of 790 milliwatts at a maximum plate voltage of 180 volts and a grid-bias voltage of 40.5 volts.

Of the tubes designed for operation with alternating current, the type 26, an amplifier tube, has a coated low-voltage cathode with a current rating of 1.05 amperes at 1.5 volts. The type 27, a detector-amplifier tube, has an indirectly heated cathode for either alternating or direct-current operation with a current rating of 1.75 amperes at 2.5 volts. Both tubes have an amplification factor of about 9 and a mutual conductance of about 1,000 at 180 volts on the plate.

The next new type to be introduced was a four-element or *screen-grid tube* which eliminated much of the difficulty due to feed-back (page 9) by the use of an additional tube element, and made possible a greater stage amplification. The type 22, a screen-grid radio-frequency amplifier for battery operation, has an amplification factor of 270, a plate resistance of 725,000 ohms, and a mutual conductance of 375 at plate and screen-grid voltages of 135 and 45 volts, respectively. The type 24A, a screen-grid radio-frequency amplifier tube with an indirectly heated cathode for either alternating- or direct-current operation, has an amplification factor of 400, a plate resistance of 400,000 ohms, and a mutual conductance of 1,000 at plate and screen-grid voltages of 180 and 90 volts, respectively.

Then the development turned to *power-output tubes.* Type 45 with an undistorted power-output rating of 1,600 milliwatts with 250 volts on the plate and a grid-bias voltage of 50 volts was a decided improvement. Type 50, although it brought a maximum undistorted power output of 4.6 watts, has a high plate current of 55 milliamperes which limits its use. An entirely new design in the power-amplifier group is the *pentode* type 47 tube, which has a maximum output of 2.7 watts but has difficulties in application because of the low grid swing (limited range of variation), the production of odd harmonics, and the necessity for a high value of load impedance to match its plate resistance of 60,000 ohms.

The development of the radio receiver for battery operation and for use in automobiles brought the entire line of 2-volt tubes designed for operation on dry batteries, as well as the 6-volt tubes with indirectly heated cathode designed for operation on storage batteries.

The next advance brought the *variable-mu type* of tube. This was designed to overcome certain difficulties introduced by the screen-grid tube due to its low grid swing. The use of the variable-mu tube reduces the effects of modulation distortion and cross-modulation which are troublesome when a strong signal voltage is applied to the radio-frequency stages. This type of tube is being manufactured with various cathode ratings.

The *triple-grid type* came about as a result of the success attending the general application of the suppressor grid (page 127), as in the output pentode type 47 and in the super-control radio-frequency amplifier pentode type 39/44. In both of these types the suppressor grid is connected inside the tube to the cathode. The advantages of this kind of construction may be summarized briefly as follows: (1) the value of the voltage applied to the screen may be selected independently of the plate voltage; (2) the swing of plate voltage can be increased as compared with that of a screen-grid tube; (3) the reduction of secondary emission current between the plate and screen grid results in more even performance and in the elimination of the tube hiss occurring in screen-grid types because of the screen-plate secondary emission current; and finally (4) an increased plate resistance.

Two examples of the triple-grid construction are types 57, an amplifier-detector tube, and type 58, a super-control amplifier. Type 57 is of the sharp cut-off type similar to type 24, and type 58 is a variable-mu tube like type 35. Then came the *multi-electrode*, *multi-unit*, and combination tubes such as the *duplex-diode triodes*, *duplex-diode pentodes*, *twin amplifiers*, *pentagrid converters*, and *triode pentodes*.

The rectifier tube also required development to meet the conditions imposed by the application of other new tubes. The various requirements resulted in the introduction of the mercury-vapor rectifier tube (page 98) the rectifier-doubler tube (page 371), and the heavy-duty, high-vacuum rectifier tube.

All-metal Radio Receiving Tubes.—An important improvement in radio receiving tubes has been brought about by the manufacture of the *shells* of such tubes of a suitable alloy instead of glass. The object of this change in manufacturing is, of course, to obtain a sturdier construction with a smaller space requirement. In the process of manufacture, each lead-in wire is made to pass through a small glass bead, as

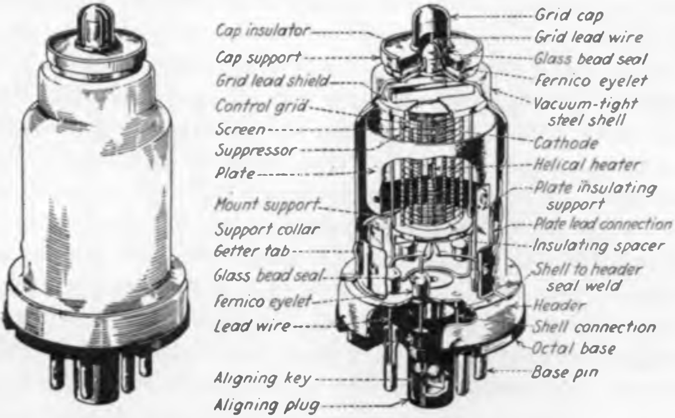


FIG. 105.—Triple-grid super-control device.

shown in Fig. 105. This glass bead is placed in an eyelet made of a special alloy of iron, nickel, and cobalt. This alloy has the same coefficient of expansion as the glass bead. The eyelet is welded to the metal container, and, in this process, the glass bead is fused. By reason of surface tension, the glass tends to center the lead-in wire, and fills the hole in the metal container so as to make an airtight seal. The bead is the only part of this new type of tube that is made of glass.

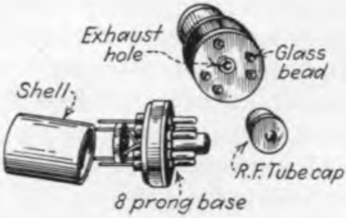


FIG. 106.—Parts of all-metal radio receiving tube.

By this method of manufacture, the vacuum in the tube can be made uniformly good, and it is stated that this vacuum is not only permanent, but actually improves with age. The operating parts of this type of vacuum tube are assembled on a steel base plate (Fig. 106) and when all the parts are in place, the shell is attached to the base plate and is welded to the latter around its circumference. By the use of this new type of base plate it is possible to utilize very efficiently short and direct lead-in wires which enter the base plate at the exact points where they will be closest to the tube elements to which they belong. The use of these short direct lead-in wires makes it possible to obtain, especially for short wave lengths, a greater amplification than is possible with glass-shell tubes. This is, of course, an important consideration at present because of the very great demand for all-wave radio receivers. Screen-grid tubes made by this method have only one-third of the plate-grid capacity of tubes with glass shells.

The all-metal tubes are much smaller, in both height and diameter, than the types of radio tubes that have glass shells. There is also the advantage in manufacturing that results from the abandonment of the now commonly used method of electron bombardment of the tubes (page 20). When the all-metal tubes are on the vacuum pump, they are heated by gas flames.

The use of metal shells for all kinds of radio tubes has special significance in the industrial field, as, by this method of manufacture, the objection is overcome that the tubes are too fragile for use in heavy industrial service. In spite of the increasing applications in the industrial field, many engineers are still hesitant about their use in *power-plant work*. The development of all-metal tubes has removed the mental hazards that have been associated with tubes with glass shells, so that they are now placed in the same category with other electrical equipment such as contactors, rheostats, and induction coils.

The Catkin metal vacuum tube made by the Marconi Osram Valve Company introduces new methods of design and manufacture for radio receiving tubes. A set of the parts for a screen-grid tube intended for alternating-current operation is shown in Fig. 107. After the copper-clad nickel-steel wires are welded to the electrodes below the steel clamp, the entire group is ready for insertion into the screen.

The screen, as shown, is hexagonal, with solid sides to keep the value of grid-plate capacity at a minimum.

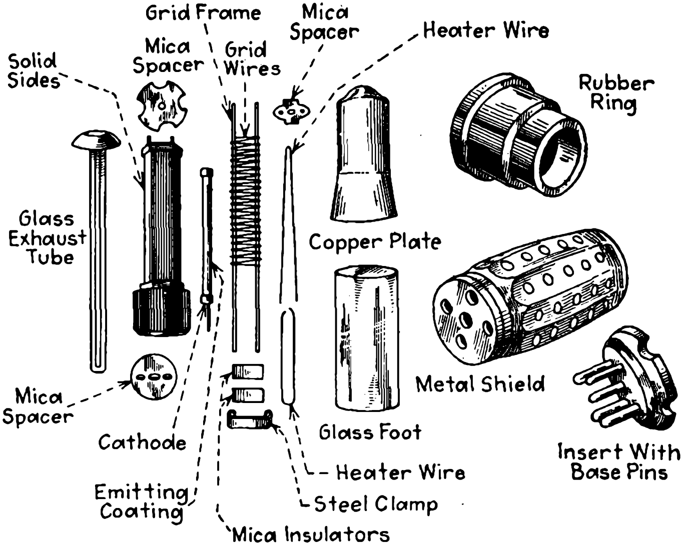


FIG. 107.—Parts of Catkin metal screen-grid tube.

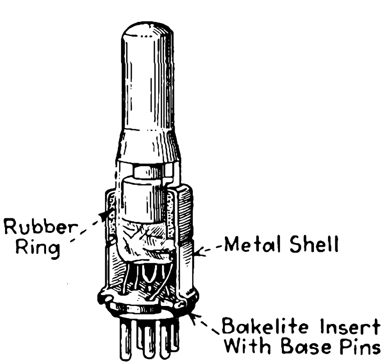


FIG. 108.—Method of attaching to the tube the base of Catkin metal vacuum tube.

The method of attaching the base *B* to the tube is shown in Fig. 108. The metal shell contains a thin rubber ring which fits against the flanged top of the shell. The tube is pressed into the rubber ring and is thus protected to some extent against mechanical vibration. The other end of the metal shell is then flanged over a bakelite insert which carries the base or terminal pins of the tube. When a terminal pin is provided for the plate, the connection to the plate is made by means of a wire brought down inside the rubber ring from a metal sleeve attached to the plate. In the screen-grid tube of this design the plate terminal is at the top of the tube and consists of a brass cup in direct contact with the plate. Finally a metal shield is fastened over the entire tube.

Characteristics of Metal Tubes.—The use of metal tubes does not require any change in methods of operation as compared with the arrangements that apply to glass tubes. The types of metal tubes available include the sharp and remote cut-off high-frequency amplifier tubes 6J7 and 6K7; a medium-mu triode 6C5; a high-mu triode 6F5; a pentagrid converter 6A8; a pentagrid mixer amplifier 6L7; a twin diode with separate cathodes 6H6; a power-amplifier triode 6D5; a power-amplifier pentode 6F6; and a full-wave rectifier tube 5Z4. Values of the operating characteristics of these types are given in the Tube Table on page 617.

Types 6J7 and 6K7.—The characteristics of the metal tube type 6J7 and the glass tube type 57 are identical except for their heater ratings and electrode capacities. The metal tube type 6K7 and the glass-tube type 77 are identical except for heater ratings and electrode capacities. These metal tubes are operated in the same manner as the corresponding glass tubes. Although no extra shielding is required for the tubes, the top-cap terminals and the leads to the top-grid caps may require an additional shield especially in the case of very sensitive receivers in which careful alignment of the tuning circuits is essential.

Types 6C5, 6D5, and 6F5.—The detector-amplifier triode 6C5 has a higher value of mutual conductance than the corresponding type of glass tube and consequently can be made to oscillate with a smaller value of coupling. Type 6D5 is a low-mu power triode with characteristics which resemble those of tube type 45. It may be used as an output tube or as a driver tube. The high-mu triode type 6F5 is similar to the triode section of type 75. Type 6F5 used together with the twin diode type 6H6 will give practically the same results as type 75 with the advantages that the cathode sections of the triode and diode units are separate, and that the two anodes of the diode unit are shielded. The combination of type 6F5 and type 6H6 will give better results than have been obtained with the duplex-diode triode type 55 or 85.

Type 6A8.—The pentagrid converter tube type 6A8 corresponds to the glass tube type 6A7 and is used under the same conditions of operation. Its characteristics are essentially the same as those of type 6A7.

Type 6F6.—The power-amplifier pentode type 6F6 has essentially the same characteristics as the glass tube type 42 (and type 2A5 except for heater ratings), and is used under the same operating conditions.

Type 5Z4.—The full-wave high-vacuum rectifier type 5Z4 resembles the glass tube type 83V except that it has a lower rating for output current.

Type 6L7.—The pentagrid mixer amplifier type 6L7 represents a new type. Its action resembles that of a radio-frequency pentode glass tube with suppressor grid "injection" from an external oscillator. Such an arrangement would minimize the undesirable characteristics of reduced conversion conduction, and of oscillator frequency shift, which occur at high frequencies (see pentagrid converter, page 152). This combination, however, cannot be used in certain types of receivers because the plate impedance is low and because a high value of oscillator voltage is required. Changes in the structure of the radio-frequency pentode type of tube can be made in order to overcome these disadvantages. Thus, a screen can be inserted between the suppressor and the plate to keep the plate resistance at the required value, and a grounded suppressor can be inserted between the plate and the oscillator screen. From such design changes the type 6L7 tube has been developed. The relative positions of the electrodes are shown in Fig. 108*a*. These electrodes are the heater, the cathode, the five concentric grids, and the plate. The first grid, nearest the cathode, is a control grid to which the signal voltage is applied as shown in Fig. 108*b*. This grid

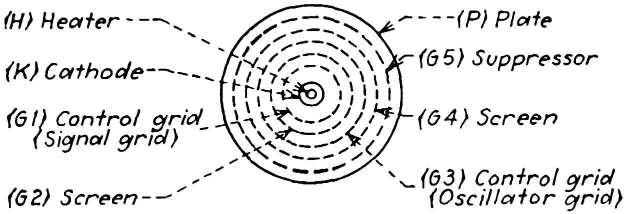


FIG. 108*a*.—Electrodes in type 6L7 tube.

is designed for a remote cut-off characteristic in order that radio-frequency distortion and cross-modulation effects may be minimized when the grid-bias voltage is obtained from an automatic volume-control system. The second grid acts like the screen in a tetrode tube, accelerating the movement of electrons toward the plate, and reducing the capacity between the first and third grids. The third grid, designed to have a sharp cut-off characteristic, is used as a second control grid to

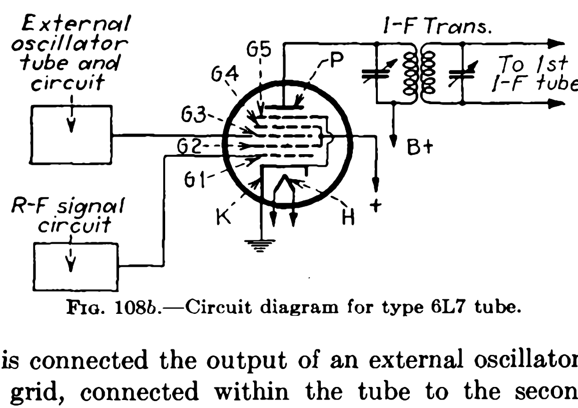


FIG. 108*b*.—Circuit diagram for type 6L7 tube.

which is connected the output of an external oscillator. The fourth grid, connected within the tube to the second grid, acts as a screen, increasing the plate resistance of the tube, and reducing the capacity between the third grid and the plate. The fifth grid, used as a suppressor, is connected within the tube to the cathode, and serves to limit the effects of secondary emission from the plate.

In one method of operation, as shown in Fig. 108*c*, the third (injection) grid is connected to the control grid of the oscillator

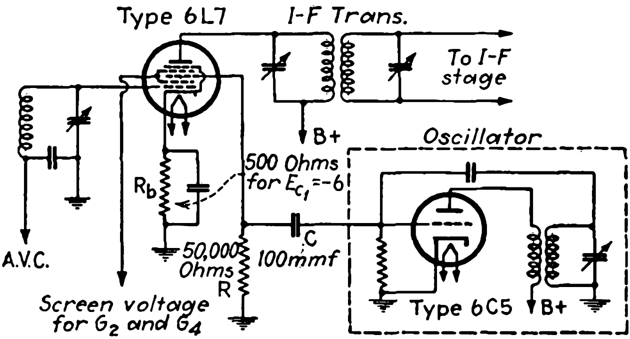


FIG. 108*c*.—Operating diagram for type 6L7 tube (first method).

tube through a coupling condenser *C*. The voltage which exists across the grid leak of the oscillator tube is applied across *R* and is used to modulate the electron stream in order to produce an intermediate-frequency component of plate

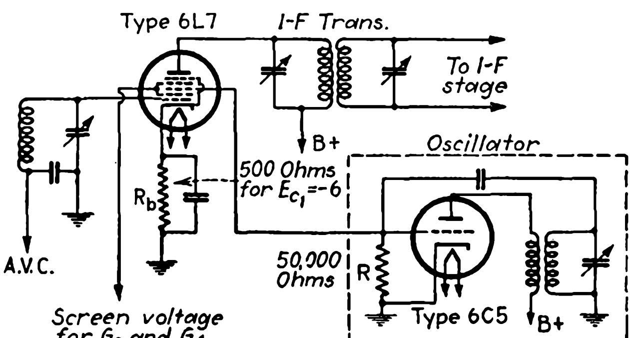


FIG. 108*d*.—Operating diagram for type 6L7 tube (second method).

current. With this arrangement the total grid-bias voltage for the third grid consists of the fixed grid-bias voltage obtained from R_b, and of a voltage which depends on the value of the oscillator voltage. If the applied oscillator voltage is high, rectification takes place in the circuit of the third grid, and a rectified current flows through R. The direct component of this current produces across R a voltage which contributes to the grid-bias voltage obtained from R_b.

In another method of operation, as shown in Fig. 108*d*, the third (injection) grid is connected directly to the control grid of the oscillator tube. Here the direct and the alternating components of the voltage across R are applied to the third grid of the mixer tube. The total bias voltage on the third grid is equal to the fixed grid-bias voltage obtained from R_b plus the direct component of the voltage across R. If the alternating component of the oscillator voltage has a peak value which exceeds the total grid-bias voltage on the third grid of the mixer tube, rectification will take place in the third grid circuit and the total grid-bias voltage will be increased. This arrangement has the advantage that the gain is practically independent of the oscillator voltage over a wide range.

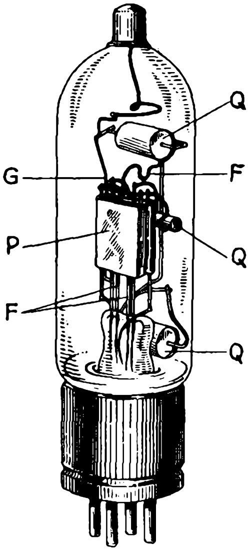


Fig. 109.—Pliotron detector tube (FP-54).

Tube with Low Grid Current.—The tube,[1] Pliotron FP-54, shown in Fig. 109, at present has no practical application, being used entirely for scientific measurements. In size it is like the ordinary receiving tube with a thoriated-tungsten filament and in appearance it differs mainly in the use of the quartz rods above and below the plate, which support the grid, and in the use of an extra space-charge grid. The purpose of this type of construction is to reduce insulation leakage. The action of the tube is like that of any high-vacuum electron tube with grid control, but its operating characteristics are different. The tube is operated with a plate voltage of

[1] Hull, A. W., "New Vacuum Valves and Their Applications," *Gen. Elec. Rev.*, December, 1932.

6 volts, a grid-bias voltage of 3 volts, a space-charge grid voltage of 3 volts positive with respect to the filament, a filament temperature of 1,700°K.,[1] and a plate current of 40 microamperes. These conditions are necessary to prevent the flow of a grid current. The sensitivity of this tube—that is, the smallest current that can be measured with it—is 1/1,000,000,000,000,000,000 ampere which is a smaller current than can be measured by the most sensitive electrometer. This sensitivity in terms of the electron, which is the smallest unit known, is about 6 *electrons per second.* The tube is used for such purposes as counting cosmic rays, measuring in connection with a phototube the light from stars, and recording the pieces (neutrons, protons, and alpha particles) of atomic groups broken apart by the impact of high-speed ions.

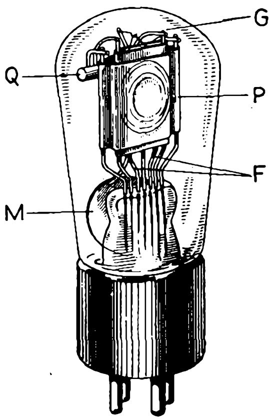


FIG. 110.—Low-noise Pliotron tube for measuring small voltages.

Low-noise Tube.—The appearance of this tube, Pliotron PJ-11, as shown in Fig. 110, is like that of an ordinary three-element tube in size and construction. Its special feature is its very high vacuum. A consideration of the action of this tube is helpful because it leads to a better understanding of the behavior of the electrons comprising the current flow. With free filament emission the electron current in a tube with the ordinary vacuum is limited by the mutual repulsion of electrons in the space between the electrodes. This effect is called *space-charge limitation.* Because of it the electrons travel at a considerable distance apart, approximately about one hundredth of a millimeter in an ordinary receiving tube. The factor that is of importance with regard to this space charge is the electron-attracting effect of the presence of positive ions and is not the current that they carry. If the

[1] Temperature in absolute or Kelvin degrees is equal to Fahrenheit degrees plus 460.

vacuum is high, the positive ion current may be only a fraction of a per cent of the electron current, yet there may be as many ions present as there are electrons. The electrons move several hundred times as rapidly as the ions. Under these conditions the space-charge limitation due to electron repulsion is practically eliminated.

The limiting value of the smallest signal that can be amplified by a vacuum tube is the tube noise caused by "shot effect" which is equivalent to an input signal of about 1 microvolt. Other tube noises, many times larger than that caused by "shot effect," are due to poor vacuum and are most noticeable at frequencies below 1,000 cycles per second. The input noise level of the PJ-11 tube at low frequencies is less than ½ microvolt. The tube can be used to measure voltages ten times smaller than those which could be detected previously. Uses that have been suggested are in the field of physiology for measuring heart beats and nerve impulses.

Midget Vacuum Tubes for Use at High Frequencies (Short Wave Lengths).—Experimental work in the field of radio transmission and reception with short waves has shown that the types of tubes and circuits developed for use with longer waves are not satisfactory. Improvements in tube design brought types that were effective at wave lengths of from 3 to 5 meters. Changes in circuit design have improved short-wave receiving apparatus (either tuned radio-frequency types or superheterodyne types with a detector stage using a triode tube) so that satisfactory *reception* is now possible with wave lengths as short as 5 meters.

Attempts have been made to depart from the usual types of receivers in the effort to find reception apparatus that would operate satisfactorily with wave lengths as short as 30 centimeters.[1] Types of circuits that have been tried include the super-regenerative detector, the heterodyne detector, and many others that cannot readily be classified. In most of these circuits the high-frequency current is handled in one stage only, and amplification is obtained at an intermediate

[1] Thompson and Rose, *Proc. Inst. Radio Eng.*, December, 1933.

or at a low frequency. From a practical point of view these circuits have a number of disadvantages; namely, inefficiency in the use of plate power; lack of sensitivity, or if sensitivity is acceptable, the stability is poor; broad tuning; and radiation from the oscillator stage.

The purpose of the investigation to be described was to design a tube that could be operated effectively at a wave length as low as 60 centimeters. The first step was to analyze the difficulties encountered in reception at low wave lengths with receiving apparatus, for example, of the tuned radio-frequency type. Trouble was experienced because the inter-electrode capacity (page 118) of a vacuum tube was so great that when a tuning condenser was added, the ratio of inductance to capacity (page 47) was too low to allow for adequate amplification. A vacuum tube of the ordinary type, when used at high frequencies, has so much inductance in its terminal wiring that a large portion of the output voltage cannot be utilized because of the inductance in the tube. Also, the combination of this inductance of the terminal wiring of the tube with the interelectrode capacities results in a circuit that has a wave length higher than that at which operation is required. Again, at very high frequencies, the time taken by an electron in crossing the space between the electrodes becomes a factor that must be recognized because it may cause a decrease in amplification.

In studies made of tube action and design it has been shown that the mutual conductance (page 115), amplification factor, and plate current are not affected by any change in the *size* of the linear dimensions of the tube electrodes and of the circuit, provided the linear dimensions are maintained in a fixed relation to each other. But the interelectrode capacities, the inductance of the tube wiring, and the time interval required for the passage of electrons between electrodes, are proportional to the size of the linear dimensions. The general principle deduced from these relations is that the *linear dimensions of a tube and circuit designed for any wave length should be proportional to that wave length.* In practice, however, this proportionality is not applied at long wave lengths because the resulting large dimensions would not bring any decided advantages. If it is assumed that an ordinary tube is not effective below a wave length of 5 meters, then according to this principle a tube suitable for use with 50-centimeter wave lengths should have linear dimensions which are one-tenth the size of those in an ordinary tube.

A photograph of a three-element and a four-element tube constructed according to the proportions stated previously is

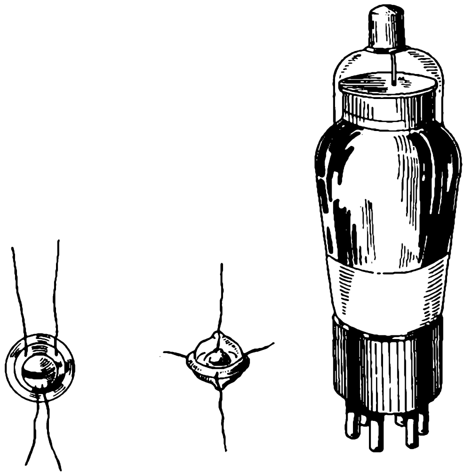


FIG. 111.—Midget three-element and four-element tubes shown with type 57 triode tube for comparison.

shown in Fig. 111, with a type 57 tube for comparison. The construction is of the parallel-plane type and indirectly heated cathodes are used. The largest dimension is less than ¾ inch.

A cross-section view of the triode (three-element tube) is shown in Fig. 112. The plate and cathode are made of metal cups. The grid is made of wire mesh placed over a holding ring and is located between the plate and the cathode. The outside of the cathode cup is coated with electron-emitting material, and the heater is placed inside the cup. The electrodes are spaced a few thousandths of an inch apart and are so light that they can be supported by their terminal wires. This type of construction does away with the capacities that exist between electrodes and their supports in the usual vacuum tube.

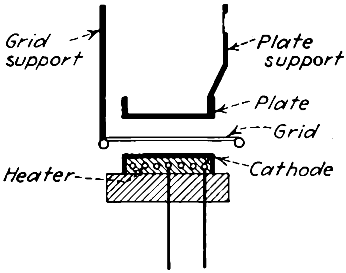


FIG. 112.—Cross section of midget triode tube to show construction.

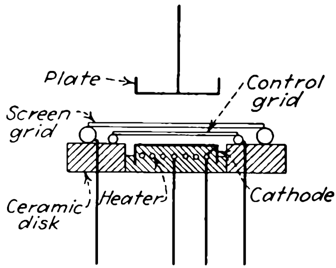


FIG. 113.—Cross section of midget tetrode tube to show construction.

A cross-section view of the tetrode (four-element tube) is shown in Fig. 113. The parts in size and shape are like those of the triode; the screen grid, also made of wire mesh, is larger than the control grid. The spacing between electrodes is only a few thousandths of an inch as in the triode. To obtain the necessary support and rigidity the grids and cathode are mounted on a ceramic disk, and the spacing between these elements is determined by their distance from the disk. The plate is supported by its terminal wire.

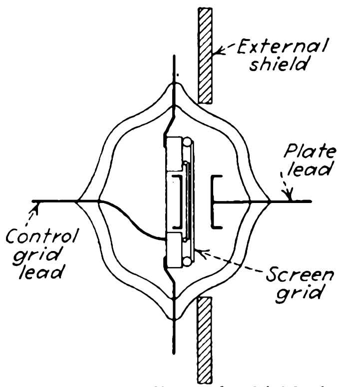


FIG. 114.—Bulb and shield for midget tetrode tube.

The glass bulb is made in two parts, round in shape, which are sealed at the joint. The terminal wires of the triode are brought out through this seal. The terminal wires of the tetrode, except the plate and control-grid wires, are brought out through the seal; the plate and control-grid wires are sealed in at opposite ends of the bulb as shown in Fig. 114.

The external shield used with the tetrode serves to isolate or shield the external plate circuit from the control-grid circuit. All the terminal wires are short, the screen-grid terminal wire leaving the bulb near the external shield where it can be grounded. Under these conditions the screen-grid impedance can be made low in value.

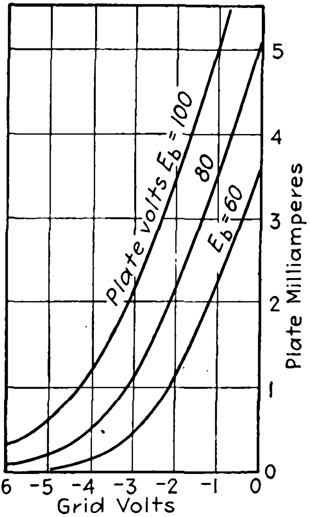


Fig. 115.—Relation of plate current plotted against grid voltage for short-wave triode tube.

The curves of plate current plotted against grid voltage for the short-wave triode are shown in Fig. 115, and the curves showing the relation between plate current and plate voltage in Fig. 116. It is evident that these curves are similar in value and shape to those of an ordinary triode. When the tube is operated with 67.5 volts on the plate and with a grid-bias voltage of −2 volts, the plate current is 4 milliamperes, the plate resistance is 9,500 ohms, the transconductance (page 115) is 1,550 microamperes per volt, and the amplification factor is 14.7. The measured values of interelectrode capacities in micromicrofarads are 0.7 between the grid and the cathode, 0.07 between the plate and the cathode, and 0.8 between the plate and the grid.

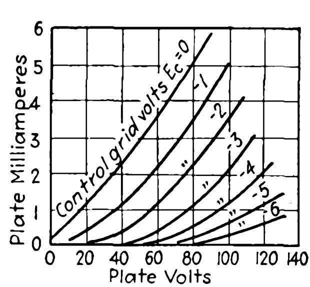


Fig. 116.—Relation of plate current and plate voltage for short-wave triode tube.

The curves of plate current plotted against control-grid voltage for the tetrode are shown in Fig. 117 and the relation between the plate current and the plate voltage is shown by the curves in Fig. 118. The curves in Fig. 118 end at 40 volts for the reason that as the plate voltage is reduced beyond that value the screen-grid current increases excessively. The

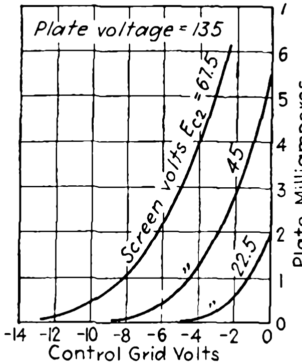


FIG. 117.—Relation of plate current to grid voltage for short-wave tetrode tube.

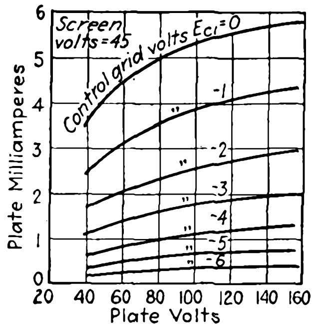


FIG. 118.—Relation of plate current to plate voltage for short-wave tetrode tube.

curves for this tube show similarity to those of the ordinary tetrode. When the tube is operated with 135 volts on the plate, 67.5 volts on the screen grid, and a grid-bias voltage of −0.5 volt on the control grid, the plate current is 4.0 milliamperes, the plate resistance is 360,000 ohms, the transconductance is 1,100 microamperes per volt, and the amplification factor is 400. For the same conditions, the input capacity is 2.5 micromicrofarads, the output capacity is 0.5 micromicrofarad, and the capacity between the plate and the grid is 0.015 micromicrofarad.

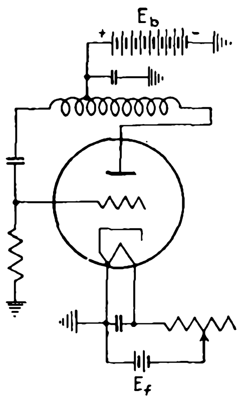


FIG. 119.—Circuit of small triode oscillator.

The comparison of this triode with ordinary tubes was made on the basis of the lowest wave length at which it would generate stable oscillations. The circuit of an ultra-high-frequency oscillator using this tube is shown in Fig. 119. The circuit is of the inductive feed-back type (page 9), the inductance being a coil of wire wound in solenoid form 1/8 inch in diameter. The interelectrode capacities of the tube are utilized for tuning the circuit. Stable oscillations at a wave length of 65 centimeters can be obtained with a plate voltage as low as 45 volts and a coil of six turns. The limit of stable oscillations is reached at a wave length of 30 centimeters with a plate voltage of 115 volts, and a coil of one turn, the plate current having a value of about 3 milliamperes.

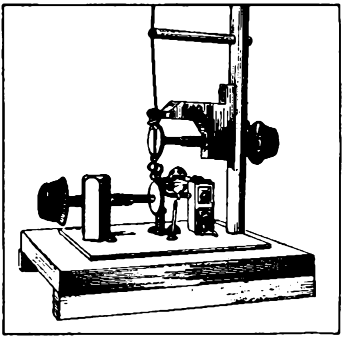


FIG. 120.—Oscillator for 100-centimeter wave lengths.

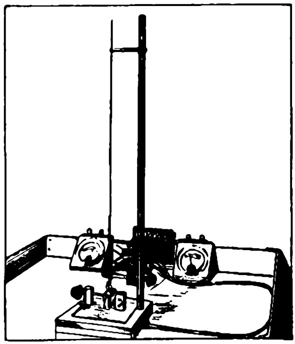


FIG. 121.—Transmitter for 100-centimeter wave lengths.

The radio-frequency amplification produced by the tetrode was determined by its operation in a receiving set because quantitative measurements at such short wave lengths present serious difficulties. One receiving set is made with two stages of tuned radio-frequency amplification using the tetrode tubes, a detector stage using the triode, and one stage of audio-frequency amplification using the triode. Small coils, similar to those used in the oscillator, and small condensers are in the tuned circuits. Metal shielding is provided for the batteries and for all outside wiring to prevent the pick-up of signals by any portion of the apparatus except its antenna, and to minimize the possibility of oscillation. Such a receiver has a tuning range of about 95 to 110 centimeters. A half-wave receiving antenna (page 79) is used.

The signal voltage for testing the receiving set is produced by an oscillator operating at a wave length of 100 centimeters. The oscillator and transmitter are shown in Figs. 120 and 121. The tube used in this oscillator is a small triode and modulation is obtained with a broadcasting receiver. The oscillator circuit is coupled loosely to a half-wave radiating antenna; the plate power required is 68 milliwatts.

When the receiving antenna was coupled to the detector stage of the receiving set, with the transmitter 200 feet away, no signals were received, but with the antenna coupled to the input circuit of the first radio-frequency stage a voltage amplification or gain per stage of about four was estimated.

Experiments with this apparatus indicate that a receiver for wave lengths shorter than 1 meter might utilize the superheterodyne circuit with one stage of radio-frequency amplification to prevent radiation from the oscillator. The tubes show good amplification in the range from 2 to 5 meters and could be used in that range for intermediate-frequency amplification. The success of this experimental work on tubes for operation at ultra short-wave lengths shows new possibilities in the *field of television*—for it is practically certain that television transmission must be carried on in the ultra short-wave region.

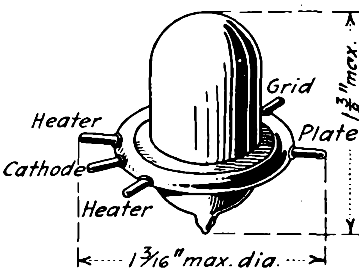


FIG. 122.—Acorn-type triode for use on wave lengths between 0.5 and 5 meters.

Acorn-type Tubes.—The midget triode described before appears in its commercial form as R.C.A. type 955. This tube is designed for use on wave lengths between 0.5 and 5 meters. It is provided with a heater-type cathode intended for operation on either direct or alternating current. The interelectrode capacities are low, being 1.4 micromicrofarads between grid and plate, 1.0 micromicrofarad between grid and cathode, and 0.6 micromicrofarad between plate and cathode.

The small size of the tube is apparent from the dimensions of the outline drawing in Fig. 122.

The type of construction is shown clearly in Fig. 123. The most noticeable change from the usual construction is the method of connecting the tube elements to the leads and of using these leads as the base pins. Special directions are given for mounting the tube in order that leakage losses may be kept at a minimum. Connections should be made to the terminal leads by means of clips—the heat of soldering might crack the bulb seal.

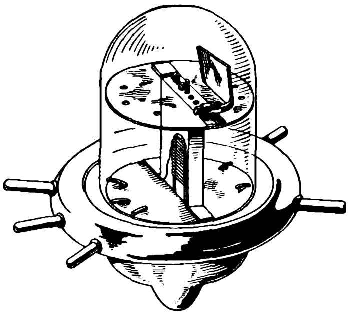


FIG. 123.—Midget triode tube (type 955).

Adequate radio-frequency grounding is necessary if the full capability of the tube is to be realized. The usual methods for by-passing and for grounding as provided in radio receivers

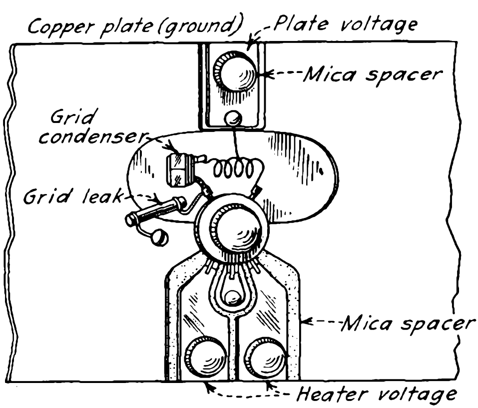


FIG. 124.—Typical mounting assembly for midget triode (type 955).

for broadcasting are not satisfactory with this type of tube. A suggested arrangement is shown in Fig. 124. The grounding plate of the chassis is a thick copper sheet. The leads to the terminal pins of the tube are made of metal in thin ribbon form and are insulated from the grounding plate by spacers of mica. The condenser action of the combination of metal ribbon and grounding plate separated by the mica spacers provides a radio-frequency by-pass condenser close to the tube terminals.

The tube characteristics are given in Tube Table, page 617. As a detector the tube may be used to give either

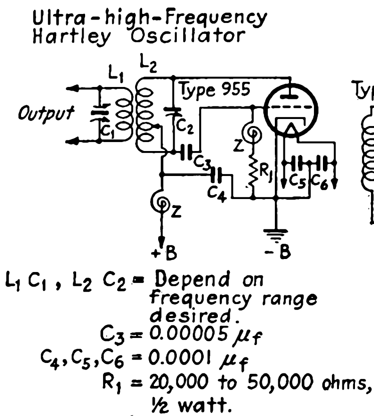


FIG. 125.—Circuit for the use of midget triode (type 955) as a radio-frequency amplifier for class C service.

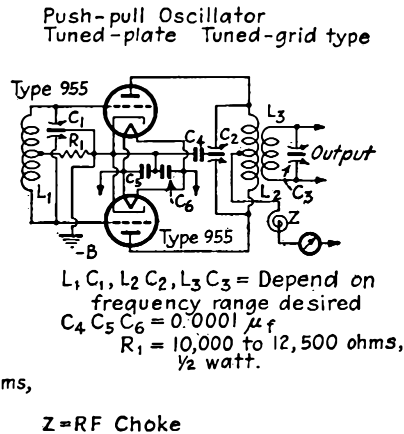


FIG. 126.—Circuit for the use of midget triode (type 955) as a push-pull oscillator.

grid-circuit detection, or plate-circuit detection. As an amplifier the tube may be used in the radio-frequency stages of short-wave receivers, or in audio-frequency amplifiers including those utilizing resistance coupling. As an oscillator, or as a radio-frequency power amplifier for class C service (page 130), the tube may be used as shown in Figs. 125 and 126. The choke coil Z shown in the single-tube oscillator circuit in series with the grid-bias resistance R_1 is needed to increase the radio-frequency impedance of the input circuit. This choke coil is not necessary in an oscillator circuit which uses the tubes in a push-pull connection. If suitable provision is made for short terminal connections, adequate insulation, and effective radio-frequency by-passing, this type of tube can

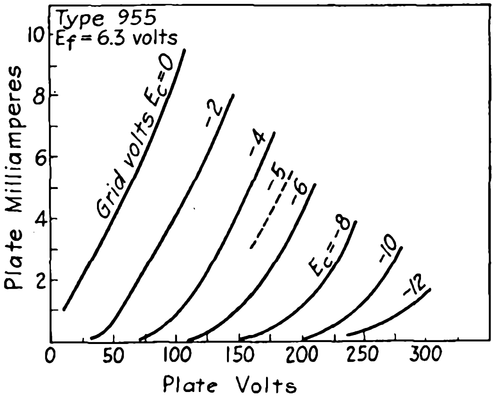


FIG. 127.—Relation of plate current to plate voltage in midget triode (type 955).

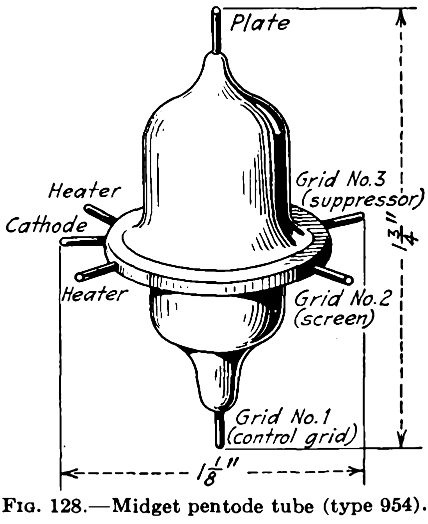


FIG. 128.—Midget pentode tube (type 954).

be used in any conventional circuit at frequencies much higher than the limit for standard types of tubes.

The curves of plate current against plate voltage for various grid-bias voltages are given in Fig. 127.

It is likely that for applications in amplifiers at high frequencies a new series of multi-element tubes will be developed, each rated for a definite frequency range in a manner similar to that used for high-frequency oscillator tubes (page 513).

Pentode.—A midget or acorn pentode is available commercially as RCA type 954. The general construction is similar to that of type 955, and the same precautions apply with regard to installation, mounting, shielding, heater operation, and grounding. In some applications it may be necessary to supplement the grounding effect of by-pass condensers by the use of radio-frequency choke coils mounted near the condensers in the supply wire for each electrode. The connections for the cathode and the screen-grid circuit follow conventional practice.

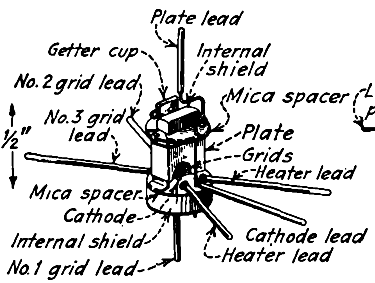


FIG. 129.—Details of construction of midget pentode tube (type 954).

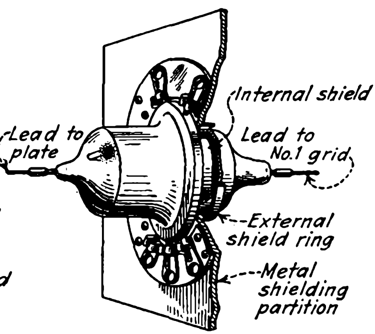


FIG. 130.—Method of shielding midget pentode tube (type 954).

The external appearance and size of this tube are indicated in Fig. 128, and the type of construction in Fig. 129. A suggested method for shielding is shown in Fig. 130.

The general characteristics of the tube are given in the table on page 617. The tube may be used for either audio-frequency or radio-frequency amplification in short-wave receivers, or as a grid-bias detector. A circuit for a radio-frequency amplifier is shown in Fig. 131, using the circuit constants given below. The wire used for the inductance coils is bare. The choke coil is wound with a single layer.

TABLE V.—CIRCUIT CONSTANTS OF ACORN-TYPE TUBE (R.C.A.-955)

	Circuit constants	Wave-length range, meters		
		2.75 to 5.3	1 to 3	0.8
L_1 and L_2	Turns	10	4	5
	Wire size	16	16	30
	Outside diameter, inches	3/8	3/8	1/8
	Length, inches	3/4	5/16	1/8
C_1 and C_2	Variable capacity, micromicrofarads	3 to 25	3 to 25	3 to 4
C	Fixed capacity, micromicrofarads	100 to 500	100 to 500	100 to 500
Z	Turns	15	15	15
	Wire size	30	30	30
	Outside diameter, inches	1/4	1/4	1/4

The curves of plate current against plate voltage for various control-grid voltages are given in Fig. 132, and the average characteristics in Fig. 133.

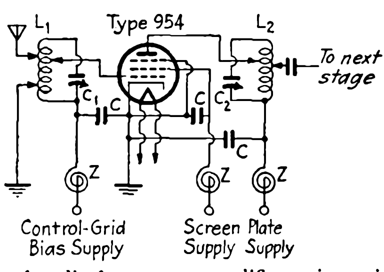


FIG. 131.—Circuit of radio-frequency amplifier using midget pentode tube (type 954).

High-vacuum Industrial Tubes.—Tubes of the high-vacuum type in industrial applications do not differ essentially in any respect from the types of tubes used in radio applications. They perform the same general services in amplification, oscillation, grid-controlled rectification, and detection. These tubes are rated and classified according to the amplifica-

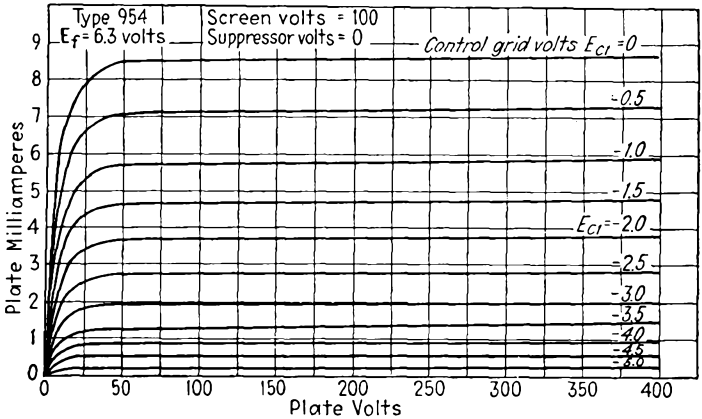


FIG. 132.—Relation of plate current to plate voltage of midget pentode (type 954).

tion factor, the plate resistance, the mutual conductance, and in special cases, the grid resistance.

Operating Characteristics.—The characteristic of a vacuum tube expresses the relations between electrode voltages and currents when the tube is operating. These relations are not constant and must therefore be shown in the form of curves. Information of this kind is needed in the design of circuits and in the calculation of tube performance. Three sets of curves generally are provided, namely, (1) the mutual characteristic showing the relation between grid voltage and plate current, (2) the plate characteristic showing the relation between plate current and plate voltage for different values of grid-bias voltage, and (3) the average characteristics showing the variation in amplification factor, plate resistance, and

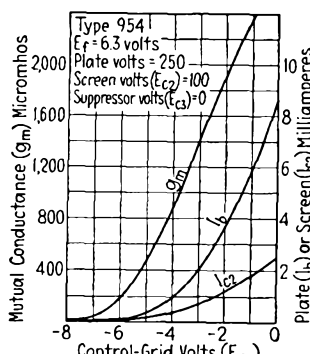


FIG. 133.—Average characteristics of midget pentode tube (type 954).

mutual conductance with grid-bias voltage for different values of plate voltage.

Classification of Amplifier Tubes.—Amplifier tubes may be classified in four main groups,[1] according to their application, namely, (1) voltage amplifiers, (2) current amplifiers, (3) power amplifiers, and (4) general-purpose amplifiers.

A *voltage-amplifier* tube has a relatively high amplification factor and is used where maximum voltage output is desired. An example of such service is when the output of the tube is applied to a circuit having a high impedance such as the grid circuit of another tube. A *current-amplifier* tube is designed to provide a relatively high plate current and to give a large change of plate current for a small change of grid voltage. This type of tube is applied where the load has a low resistance, and the current variations are so slow that a transformer cannot be used. A *power-amplifier* tube has a relatively low amplification factor, a low plate resistance, and is designed for operation at high plate voltages. The load impedance should be matched properly to the plate resistance. This type of tube is used where a maximum amount of undistorted power is required.

The operation of amplifier tubes is classified into classes *A*, *B*, and *C*. This classification is concerned with the relation between the tube output and the exciting grid voltage or the plate voltage. A detailed treatment is given in Chap. X. General types of amplifier circuits for industrial services are described in Chap. X, and specific applications in Chap. XIII.

Gaseous Industrial Tubes.—The gaseous grid-controlled tube, as illustrated in Fig. 134 is similar in construction to the triode vacuum tube in that it consists of an anode, cathode, and grid, mounted in an evacuated glass bulb, and filled with an inert gas, or with mercury vapor at a pressure of a few milli-

[1] In the classification system of the General Electric Company a *kenotron* is a high-vacuum tube regardless of the number of elements. A pliotron tube is a kenotron having grid control. A phanotron is a gas-filled or vapor-filled tube regardless of the number of elements. A *thyratron* is a *phanotron* tube having grid control.

meters. In its commercial form it has many names, such as the grid-glow tube of the General Electric Company, the thyratron of the Westinghouse Electric and Manufacturing Company, and so on. Commercial types having four electrodes are available. In a high-vacuum tube the flow of current is due mainly to the travel of electrons emitted at the cathode. In the gaseous tube the current is in the form of a glow or arc discharge[1] through the gas or vapor and consists of electrons moving toward the anode, as well as positive ions moving toward the cathode. The positive ions act to *neutralize* the space charge which in high-vacuum tubes causes a high tube resistance. Because of this neutralizing effect, the voltage drop of a hot-cathode gaseous tube is low, being about 15 volts for mercury vapor, and practically independent of current.

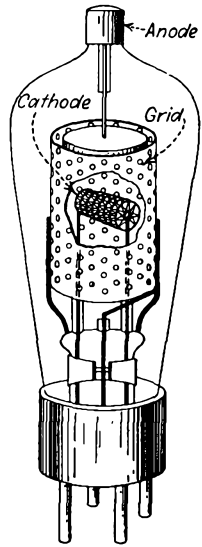


FIG. 134.—Gaseous grid-controlled tube.

A negative grid in a vacuum tube does not carry a current because it repels electrons. But the grid in a gaseous tube always carries a current except at that voltage which allows electrons and positive ions to arrive at the grid in equal numbers. In this type of tube the grid controls the *breakdown* of the tube, meaning the point at which current starts to flow. Current flow begins when the grid voltage has the proper value with respect to the anode-cathode voltage. After breakdown occurs, the flow of current is in the form of a glow or arc discharge limited by the circuit and tube characteristics and is not under the control of the grid. When the discharge begins, the voltage drop in the tube falls to a low value practically independent of the current. The discharge is stopped when the anode voltage is interrupted. Thus when the tube is operated with alternating current, the

[1] A more detailed description of discharge in gaseous tubes is given in Sec. XIII of "Radio Handbook" by Moyer and Wostrel.

discharge is stopped periodically, and the grid control is effective again upon reversal of the anode-cathode voltage.

The breakdown time, meaning the interval during which the conductivity is built up, is of the order of microseconds. The deionization time, meaning the interval before breakdown voltage is effective after current interruption, is of the order of thousandths of a second.

Gas- and vapor-filled tubes may be classified according to the kind of cathode into the following groups; the cold-cathode, the hot-cathode or thermionic, and the mercury-pool-cathode types. In the cold-cathode type, electron emission from the cathode is obtained by positive-ion bombardment, some ionized gas being present at all times. Because of its relatively high voltage drop and power loss this type of tube is used principally for the control of small amounts of power in sensitive relay applications. The hot-cathode and pool-cathode types have a low voltage drop between anode and cathode and are used mainly for power services. One important difference between these two types is that in the case of the hot-cathode tube the emission rating cannot be exceeded without danger of cathode deterioration, while the pool-cathode tube has a high overload capacity limited only by excessive heating.

Other tubes which may be classed in this group are gaseous-discharge rectifiers and glow lamps. Gaseous-discharge rectifiers are very similar in all respects to grid-controlled gaseous tubes except that they do not have a grid. Glow lamps are those types of gaseous tubes which are utilized for their light-emitting qualities. Glow lamps may have hot or cold cathodes, with or without grid control, but are generally of the cold-cathode two-electrode type. These types, also, have a constant voltage drop independent of the current, and will be injured unless a series current-limiting resistance is used.

Gaseous-tube Characteristics.—Gaseous tubes also may be classified according to the type of control, namely, positive control and negative control. The characteristic curves which follow are taken with grid voltage referred either to the anode or to the cathode, depending on the application, which is a departure from standard vacuum-tube practice. The definition of the polarity of grid voltage depends on the point of reference. Thus a positive grid, referred to the anode, means that the grid is positive when the anode is positive and the cathode negative. A negative grid, referred to the anode, means that the applied grid voltage is negative to the anode when the anode is positive. Similarly, a negative grid, referred to the cathode, means that the grid is negative when the cathode is negative. A positive grid, referred to the cathode, means that the grid is positive when the cathode is negative. In general, the polarity of the grid-bias voltage is that polarity which exists under *forward* voltage conditions on the tube.

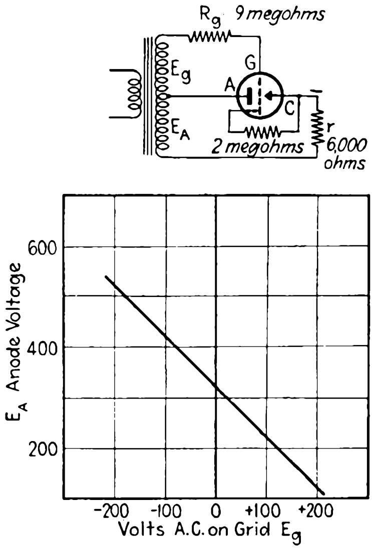


FIG. 135.—Relation of breakdown voltage to grid voltage in gaseous tube (type KU-618).

A control characteristic curve showing the relation between breakdown and grid voltages for a type KU-618 tube is given in Fig. 135. The unit *r* is a limiting resistance relay coil having a value of about 6,000 ohms. In this arrangement the grid voltage is referred to the anode. The use of the anode-grid resistance unit has some effect on the characteristics even with a high resistance, but is recommended for stabilization of the control characteristic. The fourth electrode, forming a shield around the anode and connected to the cathode through a resistance of at least 2 megohms, serves not as a control electrode but to provide more uniform and stable action.

A resistance characteristic curve showing the relation between breakdown voltage (alternating) and anode-to-grid resistance is given in Fig. 136 for the type KU-618 tube. Breakdown voltage curves show the minimum anode voltage at which ionization takes place and a flow of current begins, at a given grid-bias voltage. The voltages expressed in root-mean-square values indicate that the tube breaks down at the peak of each positive half cycle.

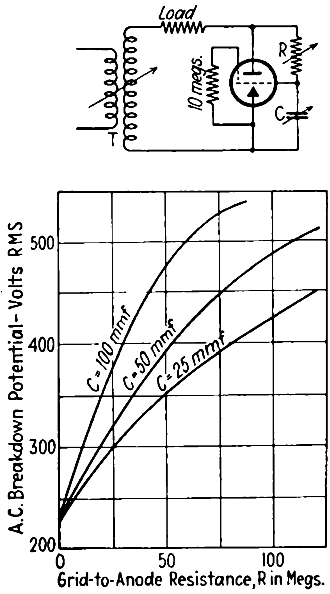


FIG. 136.—Relation of breakdown voltage to anode-to-grid resistance of gaseous tube (type KU-618).

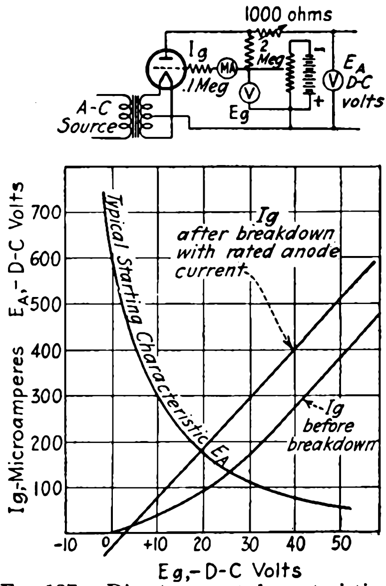


FIG. 137.—Direct-current characteristics of gaseous tube (type KU-610).

A direct-current characteristic curve showing the values of grid current before and after breakdown is given in Fig. 137 for the type KU-610 tube with rated load. From such curves the amount of power used in the grid circuit may be calculated. It should be noted that the curves show the direct-current values of the voltages. The alternating-current root-mean-square values may be obtained by dividing the direct-current values by 1.4 if the voltage wave has a sine form free from harmonics, and if the anode and grid voltages are 180 degrees out of phase. If the anode and grid voltages are not in proper phase, the direct-current characteristic may be considered as instantaneous points on the alternating-current wave and the condition for discharge thus predicted.

A control characteristic curve showing the relation between breakdown and grid voltages, using their direct-current values, is given in Fig. 138 for a type KU-628 tube. In this circuit negative control is used. One difference between the positive and the negative breakdown characteristic is that the grid-bias voltage under positive control is positive throughout the major part of the characteristic, while under negative control the grid-bias voltage is negative. This means that less grid current flows when a tube is used under negative control, because the grid is negative with respect to the cathode. The negative type of control is generally applied to mercury-vapor tubes.

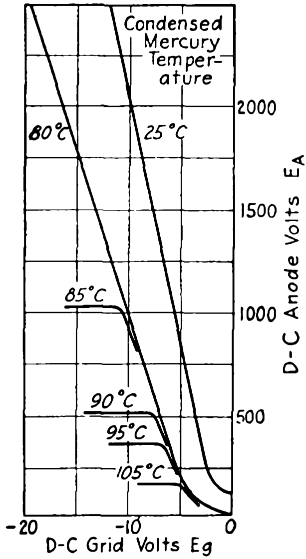


FIG. 138.—Relation of breakdown voltage to grid voltage of gaseous tube (type KU-628).

The control characteristic curve shows that a flow of current will take place at any condition represented by values at the right of and above the curve, but not at values at the left of and below the curve. That is, at a given grid-bias voltage E_g, current will not flow unless the anode voltage E_A is equal to or greater than the value of E_A corresponding to E_g on the control curve. To take care of possible variations in individual tubes or in a group of tubes, the grid voltage should exceed the amount needed, and the phase-shift (page 76) method of control should be used.

Tube Ratings.—A tube may be rated on the basis of maximum voltage, maximum current, load time, tube-voltage drop, cathode voltage, cathode current, and cathode heating time.

The voltage rating is given as the maximum crest voltage which is the highest instantaneous voltage that a tube can safely withstand in either the forward or inverse direction. This rating depends on the factors of grid control, flash-back, and insulation. The maximum crest forward-anode voltage is the maximum instantaneous voltage that can be held back by a suitable grid voltage. The maximum crest *inverse-anode voltage* is the highest instantaneous voltage that a tube can withstand in the direction opposite to that of normal current flow.

The maximum crest current is the highest instantaneous current that can be obtained without damaging the tube. This value usually is not equal to 1.4 times the root-mean-square value.

Maximum average current is that current, regardless of wave form, averaged over a certain number of consecutive seconds, that does not cause overheating of the tube. The maximum continuous average current on commercial frequencies is that value which is indicated by a direct-current ammeter.

Typical Circuits for Cold-cathode Gaseous Tubes.—The cold-cathode types of gaseous tubes generally are represented by the small sensitive tubes taking very minute grid currents. Tubes of this type are used where a relay is to be operated by sensitive means such as a change in resistance of the order of a few megohms, or a change in capacity of the order of a few micromicrofarads, or where the tube output current is sufficient to meet the requirements.

The various types of circuits used to control the tube depend on varying the grid voltage from one value to another between the anode and cathode voltages. This is accomplished by the use of a very high variable impedance, of the order of megohms, placed between grid and anode and the controlling element. The tube will break down when the anode impedance is decreased or when the cathode impedance is increased. If the grid is left floating electrically, it assumes a negative voltage, the breakdown voltage is increased, and breakdown occurs when a grid voltage of the proper value is applied.

The source E is generally an alternating voltage, but direct voltage may be used if the circuit does not have any capacity

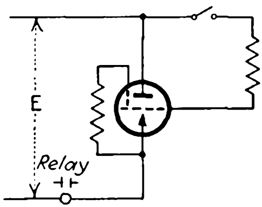


FIG. 139.—Circuit for cold-cathode gaseous tube with variable-resistance control.

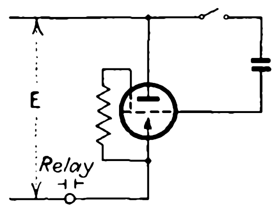


FIG. 140.—Circuit for cold-cathode gaseous tube with variable-capacity control.

units. With direct-current operation a "lock-in" characteristic is obtained, and the anode-cathode voltage must be reduced to zero to stop the anode current and to allow the grid to regain control. In the circuit of Fig. 139 the control is obtained with a variable resistance, and in Fig. 140 with a variable capacity. In Fig. 141 the control is obtained with a

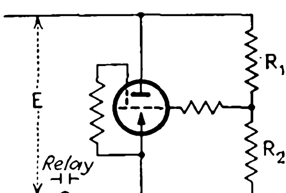


FIG. 141.—Circuit for cold-cathode gaseous tube with resistance-potentiometer units for control.

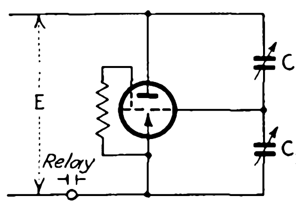


FIG. 142.—Circuit for cold-cathode gaseous tube with condenser-potentiometer units for control.

resistance potentiometer consisting of the units R_1 and R_2 which may be such elements as phototubes. In Fig. 142 the control is obtained with a condenser potentiometer consisting of units C_1 and C_2 which may be metal objects in a production line chute and metal plates built into the chute, the human hand, and so on. In Fig. 143 the control is obtained with the application from an external source of a grid-bias voltage such as a battery voltage, a surge-voltage, and so on.

Some of these circuits, with suitable modifications, may be used with hot-cathode gaseous tubes of the power type. Conversely, cold-cathode tubes may be used in some of the circuits for hot-cathode gaseous tubes, as in phase-shift control.

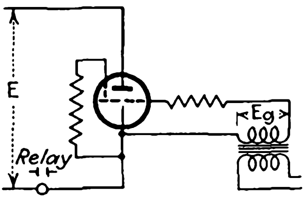


FIG. 143.—Circuit for cold-cathode gaseous tube with external source of grid-bias voltage for control.

Circuits for Hot-cathode Gaseous Power Tubes.—The hot-cathode gaseous tube for power service is made in two types. The tubes with low ratings have oxide-coated filament cathodes, and those with high ratings have mercury-pool cathodes. The filament-type tubes are filled with some inert gas such as neon, argon, or helium. The voltage drop in a hot-cathode tube depends on cathode emission, tube design, kind of gas, and gas pressure. The grid voltage may be either positive or negative, accelerating or retarding the electron flow and thus controlling the anode-cathode voltage at which ionization and breakdown occur. Tube performance depends not only on tube constants but also on circuit constants. There are two general methods of operation with regard to control characteristics: namely, positive-grid control, and negative-grid control.

In positive-grid control a positive-grid voltage is needed to start the tube. This method is used where a short deionization time is wanted, or where a characteristic is desired which is free from temperature effects. The disadvantage is the increase in grid current flow. The grid-bias voltage may be obtained from a battery or from the voltage drop across a resistance connected between anode and grid. Positive-grid control usually is applied to gas rather than mercury tubes.

Negative-grid control was used first on mercury-vapor tubes. The disadvantage of such operation is the resulting high temperature coefficient. Recently, gas-filled tubes have been designed for negative-grid operation with the control characteristics of the mercury-type tube but having less current capacity for a given size. This type has a negligible temperature coefficient.

The curves in Fig. 144 give a comparison of the characteristics of the neon-filled tube and the mercury-vapor tube. These curves are taken from Figs. 137 and 138.

The hot-cathode power gaseous tube is useful for services requiring a relay action with large current carrying capacity.

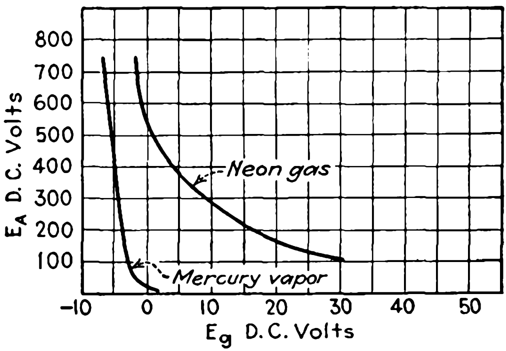


FIG. 144.—Comparison of operating characteristics of neon-filled tube and mercury-vapor tube.

Also, it possesses a high-speed *lock-in* characteristic when operated with direct current.

Phase-shift Control.—By means of this method of control a direct-current voltage that is continuously variable can be supplied from an alternating-current circuit, even though the tube itself has a non-continuous control characteristic. The tube, however, acts as a rectifier and can be made conducting at any point of the cycle through the grid control. The variable-voltage feature is obtained by selecting the desired portion (indicated by the shaded area) of each positive half wave during which the tube passes current, as shown in Fig. 145. The instantaneous-voltage curves of Fig. 146 show the action in detail. The curve E_A represents a cycle of line voltage. The corresponding grid-bias voltage at which the tube will break down is represented by the curve V. The values for curve V may be obtained from characteristics such as those shown in Figs. 135, 137 or 138 for various tubes. The tube will break down, at a given value of E_A, when the grid-bias voltage with respect to cathode is more positive than

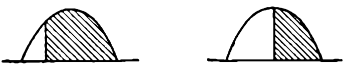


FIG. 145.—Portion of voltage wave during which the tube passes current.

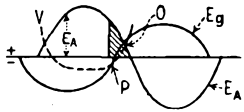


FIG. 146.—Instantaneous values of grid-bias voltage at which hot-cathode gaseous power tube breaks down.

the value V, and current will flow until E_A becomes smaller than the normal voltage drop of the tube, as at point O. If the grid-bias voltage curve E_g of line frequency is drawn, the point P can be located, at which point the grid voltage becomes more positive than the critical value. At this point the tube breaks down, and current flows during the remainder of the

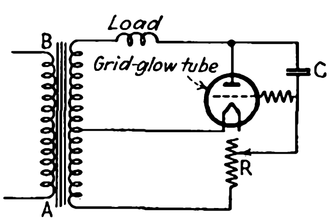


FIG. 147.—Circuit of half-wave rectifier using hot-cathode gaseous power tube.

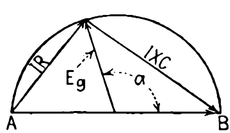


FIG. 148.—Vector diagram of voltage relations in half-wave rectifier using hot-cathode gaseous power tube.

voltage wave. Thus all or none of the wave may be used by properly shifting the grid-bias voltage.

A simple half-wave rectifier circuit for producing this grid-voltage shift, which can be arranged for either manual or automatic control, is shown in Fig. 147. In this circuit a resistance R, or an inductance L substituted for C, is used to control the phase shift. The voltage relations are shown in the *vector diagram* of Fig. 148. The voltage AB of the primary winding of the transformer is represented by vector AB, the grid voltage by E_g, the resistance-voltage drop by IR,

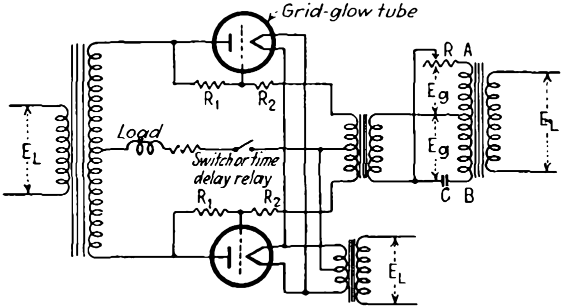


FIG. 149.—Full-wave rectifier circuit for producing phase shift with hot-cathode gaseous power tube.

and the condenser voltage by IXC. The phase shift between grid and anode voltages is represented by the angle a.

A full-wave rectifier circuit for producing phase shift is shown in Fig. 149.

Contact-control Tubes (Relay Action).—Tubes of this type may be used also as simple relay devices. The closing of contacts carrying very small amounts of power may be used to control the tubes which in turn either operate power contactors or act directly. The power controlled by the tubes may be either alternating or direct current. In relay operation the speed of the action is so high that the duration of power application may be reduced to a fraction of a cycle.

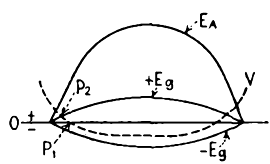


FIG. 150.—Relation of critical grid voltage to applied grid-bias voltage in contact-control tubes.

The grid-bias voltage, in this or any other form of control, must be sufficiently negative during the interval when no current is desired. This can be shown as in Fig. 150 in which V represents the critical grid voltage, and E_g the applied alternating grid-bias voltage. If the critical grid voltage is exceeded, in the positive sense, the tube becomes conducting. Then when a negative alternating grid voltage, $-E_g$, is applied, no current flows, but if zero grid-bias or a positive voltage, $+E_g$, is applied, the current starts to flow at point P_1 or P_2, respectively.

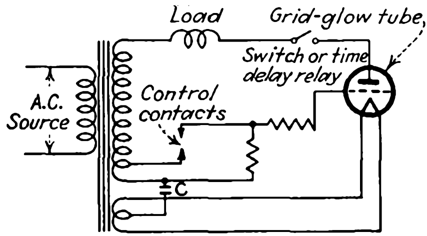


FIG. 151.—Circuit using contact-control tube for relay action by delicate contact.

The type of circuit shown in Fig. 151 may be used for tube control by delicate contacts. In such applications the voltage across the contacts before they close, and the contact current after they close, must be as low as possible to avoid damage to the contact surfaces.

A circuit suitable for spot welding and similar loads is shown in Fig. 152. The tubes are in parallel, but in inverse

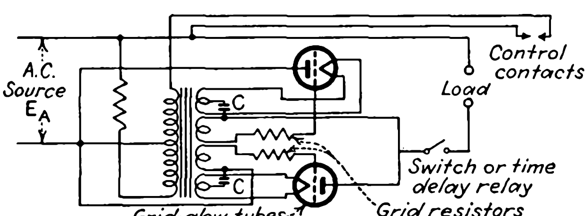


FIG. 152.—Circuit including contact-control tubes for relay action for spot welding.

relation in order to provide control on alternating current. The control action is such that before the control contacts are closed, the grid of each tube is negative with respect to its cathode while the anode is positive. After the contacts are closed, the grid voltage is reversed or made positive, and the tube becomes conducting. The diagram in Fig. 153 shows the relations between instantaneous values of current and voltage.

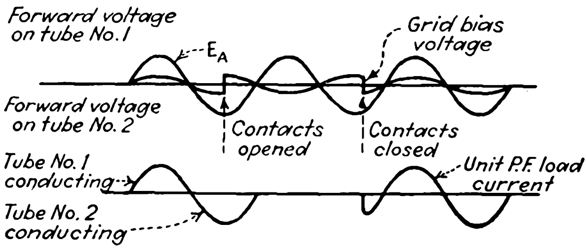


FIG. 153.—Relation of instantaneous values of current and voltage in contact-control tube.

Mercury-arc Rectifier.—This is a type of gaseous rectifier, controlled or uncontrolled, in which the cathode consists of a pool of mercury. It meets the requirements in traction and

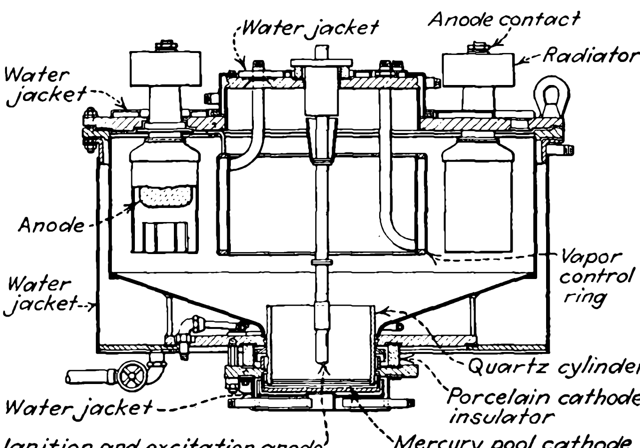


FIG. 154.—Construction details of typical Westinghouse mercury-arc rectifier.

electrochemical service because of its ability to withstand heavy momentary overloads without deterioration. On power applications for voltages below about 250 volts, rotating or other forms of conversion equipment are used. This type of rectifier is generally enclosed within a steel tank cooled by water. The vacuum is maintained by an evacuating system that is in continuous operation. The pressure of foreign gases should be not more than about one-tenth of one micron. The construction of a Westinghouse 750-kw., 600-volt mercury-arc rectifier is shown in Fig. 154.

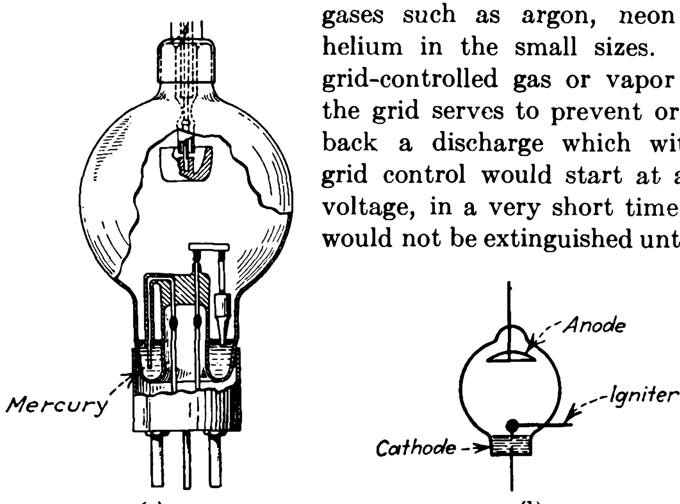
The rectifier will not operate until electrons are provided artificially at the cathode in a quantity sufficient to form an initial discharge or arc. The formation of such a discharge involves ionization by collision. The arc is maintained by a low voltage and can carry a very heavy current. In one type the cathode spot is formed by the use of a starting electrode. This electrode is made positive, pushed into the mercury pool by magnetic action, and then is withdrawn. As it leaves the pool an arc is formed. When the main anodes receive voltage and become positive, the arc shifts to them. Generally, separate exciting anodes are provided to maintain the arc.

The greatest difficulty encountered in operation is the failure caused by *arc-back,* which is a breakdown similar to the flashing of a commutator. The rating of a rectifier may be limited by this action, or by local heating. The formation of an arc during a period of back voltage can be caused if a cathode spot appears accidentally on an anode. The tendency to arc-back is eliminated by surrounding the anodes with shields and grids to protect them from mercury drops and from blasts of mercury vapor.

Controlled Rectifier.—A controlled mercury-arc rectifier is one in which a grid is placed in each arc stream. A voltage is applied to each grid so that it may build up a space charge to control the time of ignition or the beginning of conductivity in the arc path it affects. Thus there is provided a means for the control of output voltage and current.

Ignitrons.—The ignitron is a controlled rectifier of the gaseous type intended for use mainly in power service applications. In this type conductivity is established by igniting an arc in somewhat the same manner that an explosion is produced in an automobile engine cylinder.

Gas and vapor tubes of the hot-cathode, grid-controlled type, as represented by grid-glow tubes, thyratron tubes, and other makes, have certain limitations for power service. One of these is the time delay in starting to enable the cathode to reach its operating temperature before the flow of current begins. Another is the lack of adequate overload capacity due to the fact that the emission limit of the cathode cannot be exceeded without causing cathode deterioration. Mercury is used in the larger sizes of gas and vapor tubes, and other gases such as argon, neon and helium in the small sizes. In a grid-controlled gas or vapor tube the grid serves to prevent or hold back a discharge which without grid control would start at a low voltage, in a very short time, and would not be extinguished until the voltage was removed at least temporarily. The ignitron tube combines the overload capacity of the mercury-arc rectifier with the control characteristics of a grid-controlled gas or vapor tube. An additional advantage is that the ignitron as compared with the mercury-arc rectifier has a lower arc loss due to the closer spacing of its electrodes.



(a) (b)
FIG. 155.—Essential parts of ignitron tube.

The ignitron has a control electrode called an igniter consisting of a rod of suitable material which projects into the mercury pool. When the rod is positive with respect to the pool, a flow of current produces a spark at the junction of rod and pool. Under proper voltage conditions this spark expands in a few microseconds to an arc which moves to the anode if the anode is positive. Thus the ignitron starts at the beginning of each conducting half cycle. An ignitron tube is illustrated in Fig. 155 together with the conventional representation. The ignitron, in small sizes, is made with a glass envelope and does not require continuous evacuation. The larger sizes are enclosed in steel tanks and are provided with pumping systems.

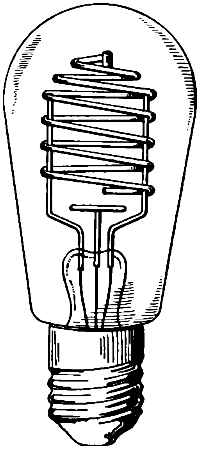


FIG. 156.—Glow lamp with spiral cathode.

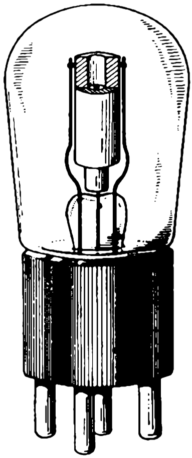


FIG. 157.—Glow lamp with crater type of cathode.

There is no arc-back difficulty with the ignitron tube because no back current is present when the anode is negative, and no ionization can occur. When means are provided for controlling the time of ignition the device acts as a controlled rectifier.

Glow Lamps.—A glow lamp is commonly of the cold-cathode two-electrode gaseous discharge type, designed primarily for producing light. In some cases glow lamps are made with control grids and also with hot cathodes as in the *stroboglow* tubes. Commercial types have usually one large and one small electrode so that the flash occurring on alternate half cycles is somewhat brighter. Tubes can be constructed, however, which pass current equally in either direction.

One type of glow lamp using a spiral cathode is shown in Fig. 156. In the *crater* type shown in Fig. 157 the glow is located in a crater in order to produce a concentrated beam which can be easily focused.

Action of Glow Discharge.—When a suitable voltage is first applied to the tube, the field between anode and cathode is uniform. The movement of electrons and ions to the electrodes, together with the ionizing effect and with emission from the cathode due to positive-ion bombardment and photoelectric action, represents the flow of an electric current which increases to a value depending on the operating conditions. With the flow of current the discharge becomes visible. But in a short time the field is non-uniform, being confined to the cathode where a positive space charge is built up.

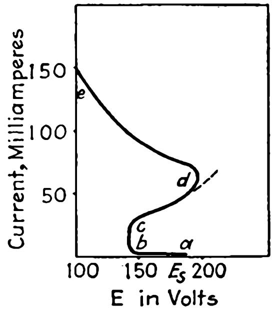


FIG. 158.—Relation of voltage to current in cold-cathode glow lamp.

The discharge when fully developed consists of several parts each of which is different in color and form. In the direction from cathode to anode there is first the cathode glow, covering the cathode. Next is the *cathode dark space* the extent of which depends on the pressure of the gas. On the anode side of the dark space is a region which at low gas pressure shows light called the *negative glow*. Following this is the Faraday dark space, which may be a hundred times as long as the cathode dark space. In the last part extending to the anode is the positive column which appears as the region of greatest luminosity.

Characteristics of Glow Lamp.—One type of a cold-cathode neon gas-filled glow lamp connected in series with a high resistance has the voltage-current characteristic shown in Fig. 158. There is practically no current flow as the applied voltage is increased until the breakdown or striking voltage E_s is reached. At this point a small current flows and the tube becomes faintly luminous. If the applied voltage is held constant and the series resistance is decreased, the tube current and voltage vary as shown from point *a* to *b*. During this period the luminosity increases and spreads toward the cathode. If the resistance is decreased further, the tube voltage remains constant, the current increases as shown from point *b* to *c*, and the flow spreads over the cathode. This portion *b-c* of the characteristic is called the *normal* cathode fall of voltage.

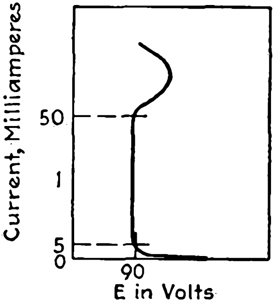


FIG. 159.—Relation of voltage to current of glow lamp as used in small-unit voltage regulation.

If the resistance is still further decreased, the tube voltage and current increase as shown from point *c* to *d*, owing to the voltage increase across the cathode dark space. This voltage is called the *abnormal* cathode fall of voltage. The current now is high enough to heat the cathode sufficiently to produce electron emission. The discharge assumes the form of an arc having a negative characteristic as shown between points *d* and *e*. The current at this stage is limited by the series resistance only.

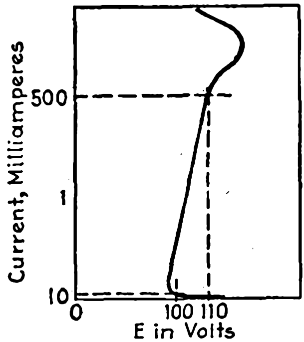


FIG. 160.—Relation of voltage to current in glow lamp in large-unit voltage regulation.

Operation of the tube as a glow lamp is carried out on the portion of the characteristic curve from *b* to *c*. The length of the operating portion *b-c* can be varied by changing the tube design and the operating conditions. For example, the type of glow lamp used in voltage regulation has a characteristic like that shown in Fig. 159. The characteristic of another tube having a larger capacity is shown in Fig. 160.

Tube Ratings.—The ratings generally given for glow lamps are the average and crest currents, the applied voltage, and the type of cathode. A tube of this type has a practically constant voltage drop independent of current. A current-limiting resistance must be used in series with the tube in order that the tube ratings may not be exceeded.

General Applications.—A glow lamp emits light during current flow only and the amount of light is proportional to the current. Because of this action the tube is suitable for use in stroboscope applications, television, and so on. The breakdown voltage being higher than the maintaining voltage, the tube may be used in any application in which a current flow is desired when the voltage exceeds a given value. Such applications include polarity indicators, ground or open-circuit indicators, voltage indicators, low-power surge arresters, and overvoltage relays. The lock-in characteristic, due to the difference between the breakdown and maintaining voltages, is valuable in certain applications.

Negative Glow Lamps as Illuminants.—Tubes of this kind are used as low-power illuminants and indicators to show whether a circuit is live or dead. These tubes generally are filled with neon gas because of its low striking voltage and comparatively high luminous efficiency. The color of the light is orange-red and the luminous efficiency is about 1.2 lumens per watt corresponding to about 10 watts per candle. On an operating voltage of 200 to 250 volts the striking voltage is about 180 volts and the extinguishing voltage about 140 volts.

The electrodes are close together, the light coming mostly from the negative glow. Under normal conditions of discharge the cathode is not completely covered by the discharge so that the area of glow and hence the light output are directly proportional to the current. Under abnormal conditions of discharge when the cathode is completely covered by the discharge, the glow increases with the current and again is proportional to it. Over a considerable part of the range of abnormal cathode voltage drop the relation between discharge current and applied voltage is linear.

Positive Glow Lamp as Illuminants.—These lamps are called *neon tubes* and are used extensively in signs. The operating voltage depends on the length of the tubes and is as high as 15,000 volts in some installations.

The electrodes are placed wide apart and operate in neon gas. There is a small glow area at the negative column followed by a narrow dark band but practically all the light comes from the glow of the positive column.

Discharge Tubes as Protective Devices.—A tube of this type can be used as a protective device in circuits of various kinds because the tube is non-conducting until the applied voltage reaches the *striking* value. As a protective device the tube is connected across a coil or transformer winding. In this application the insulation of the winding is protected from high voltages because the tube flashes over when a dangerous surge occurs. In a similar manner the tube can be used to protect a low-voltage line from damage by accidental contact with a high-voltage line. If the line voltage increases to the striking value of the tube, a current will flow in the tube and can operate a relay that grounds the line.

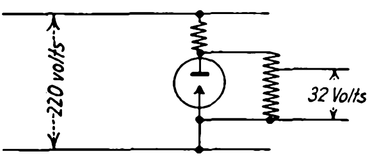


Fig. 161.—Glow lamp used for constant low-voltage supply from higher voltage source.

Glow Lamp as Voltage Regulator.—If a glow lamp and a resistance are connected in series as shown in Fig. 161 across a circuit with varying voltage, a practically constant voltage can be taken from the terminals of the tube. The reason for this is that the current in the range *b-c* of the characteristic shown in Fig. 158 can vary considerably without affecting the voltage. An application of this kind is on locomotive head-lights where the generator speed varies with the axle speed and serves to provide constant voltage for the lamp. The performance of lamps used as voltage regulators is shown in Figs. 159 and 160.

Cold-electrode Gas-filled Voltage-limiting Tube.—This tube is of the glow-discharge type (page 201), made with two electrodes placed in a rare gas, such as argon or helium, and designed so that breakdown takes place (current flows) at a definite high value of voltage, with a large current flow at a much lower voltage after breakdown occurs. A diagram of such tube types is shown in Fig. 162. The cylindrical electrode *C* is the cathode and the vertical wire *A* is the anode. The commercial type of this tube (R.C.A.-UX-874) has a breakdown voltage of 90 volts and a rating of safe continuous current of 50 milliamperes. The resistance which must be connected in series with this tube should be sufficient to produce a voltage drop with a current flow of 50 milliamperes of about 20 volts (for example, a line voltage of 110 volts minus an operating voltage of 90). The regulation curve showing operating voltage plotted against operating current, and the operation characteristics, are shown in Figs. 163 and 164. This voltage-limiting tube is used to prevent injury to

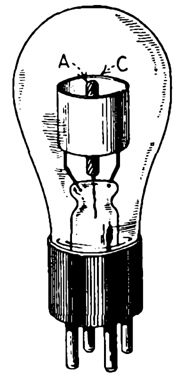


FIG. 162.—Cold-electrode gas-filled, voltage-limiting tube.

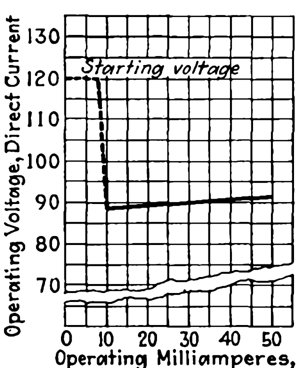


FIG. 163.—Regulation characteristics of UX-874 tube.

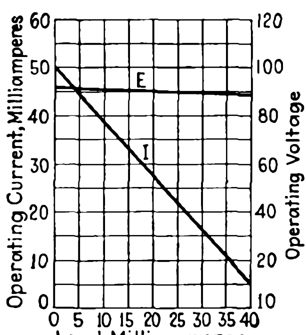


FIG. 164.—Operation characteristics of UX-874 tube.

electrical equipment from a surge of high voltage in the supply circuit. It is used also in connection with a rectifier unit (page 361) to maintain a constant direct-current output for varying load currents. In this application the tube maintains an approximately constant direct-current voltage of 90 volts for a current change of 10 to 50 milliamperes.

Ballast or Current-regulator Tube.—The ballast tube is essentially a *resistance unit* designed so that when a variable voltage is applied to it the variations in resistance maintain a constant value of current. This type of tube known also as a *current-regulator tube* appears in its commercial form as UV-876. It is designed to maintain a constant current of 1.7 amperes for a voltage drop in the tube of from 40 to 60 volts. When connected in series with the primary winding of a power transformer (page 242), the tube will absorb slight voltage variations in the alternating-current supply. A larger size is manufactured which requires an operating current of 2.05 amperes. If the current in the primary winding of the transformer is less than the values specified above an adjustment may be made by means of a resistance in parallel with the primary winding. If the primary current is too large for one ballast tube it is necessary to use two or more of these tubes in parallel. When the tube is connected in the primary circuit, the voltage on the primary winding of the transformer is equal to the line voltage minus a drop of about 50 volts in the tube.

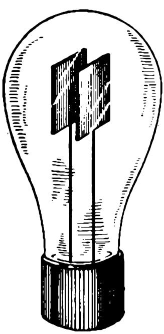


Fig. 165.—Neon tube.

Neon Glow Bulb.—The neon glow bulb belongs to the cold-electrode gas-filled group, known as *glow tubes*. Two plates of metal about 2 inches square are placed parallel to each other and spaced a few hundredths of an inch apart, as shown in Fig. 165. The plates are mounted in a glass bulb filled with neon gas. When a direct-current voltage of the proper value is applied across the plates, a discharge takes place and a reddish glow appears on one of the plates. In this condition of discharge the resistance of the tube is much less than the cold resistance. The flow of current stops if the applied voltage is reduced below a certain value.

Cold-electrode General-purpose Tube.—This tube with a cold cathode is used for *amplification, detection, and generation.* Patent rights in Great Britain have been allowed for this type of tube which was developed in Germany by Seibt. The main advantages of this tube are (1) that the cathode does not require heating so that the noise produced by the direct heating of the cathode from an alternating-current circuit is avoided, and (2) that the tube is superior to heated-cathode types for equal power consumption and voltage with regard to the slope of the characteristic curve (page 95) and the output. The tube is filled with neon gas at a pressure of about 6 millimeters of mercury. The leads to the electrodes must be insulated, preferably with glass tubes to prevent discharges between them.

In the operation of the tube a glow discharge is produced between the cathode and the first or discharge anode. The second anode is necessary for amplification. An intermediate electrode is provided for the usual control action. Not all the electrons in a gas-filled tube follow a straight path; some collide with gas molecules and are deflected by the impact. It is these deflected electrons that are utilized for an *amplification current.* In other words, the glow-discharge region serves as a source of electrons. The spacing and voltages of the electrodes, the size and shape of the electrodes, and the nature of the gas as well as the gas pressure, are so chosen that the luminous glow discharge occurs only between the cathode and the first or discharge anode. The electric field between the glow-discharge electrodes and the second or amplifying anode is not a continuation of the discharge field but is due to the electron discharge from the region surrounding the path of the glow discharge. It is assumed that the electrons are drawn by the second or amplifying anode from the discharge space between the cathode and the discharge anode *along the edges* so that the action can be considered as a kind of *edge effect.* The electrons of the amplification current should not have a speed dependent on the field of the glow discharge at the points where the electrons coming from the discharge field reach the amplification field. The voltage of the second or amplifying anode must be so low with respect to the discharge anode, and the gas pressure must be such that the amplification field cannot form a glow discharge. The shape of the electrodes must be such that the electrons produced in the glow-discharge field when moving at high velocities cannot reach the second or amplifying anode. Without this precaution a strong current would flow toward the amplifying anode, but its dependence on the voltage of the latter would be small because the acceleration of the electrons in this current is due mainly to the voltage between the discharge electrodes and less to the voltage of the second or amplifying anode.

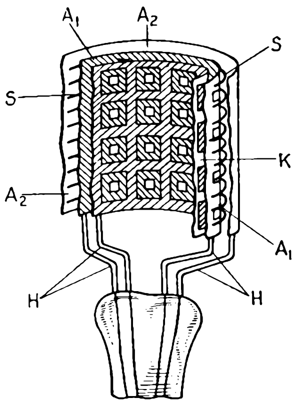


FIG. 166.—Cold-electrode tube with cylindrical electrodes.

One type of this tube using cylindrical electrodes is shown in Fig. 166. The discharge cathode K consists of a sheet-metal cylinder provided with a large number of rectangular holes or openings. The cathode is surrounded by a discharge anode A_1 which has an equal number of holes located opposite those in the cathode but has sides which are half the length of those in the cathode. The outer edges of the discharge anode A_1 project beyond those of the cathode. The openings in the discharge electrodes are so spaced that the screening effect of the discharge anode is maintained, and yet there are a large number of sources for the amplifying current. The next electrode is the intermediate or control electrode S which in the tube illustrated in the figure is constructed in the form of a helical grid, but it may be a network cylinder having a large mesh. The outermost electrode is the second or amplifying anode A_2 which is preferably a cylinder without perforations. The electrodes are secured by means of the supporting wires *H* on a glass foot. The individual electrodes have a height of a few centimeters and their diameters range from 0.5 to 2.5 centimeters. To maintain the screening effect the control electrode *S* and the amplifying anode A_2 should be placed very close to the discharge electrodes *K* and A_1, usually at a distance of 3 to 5 millimeters. The supporting wires *H* should be provided with insulating sleeves so that no discharge can take place between these wires. Amplification is increased by decreasing the open area of the control electrode *S* and by reducing the distance between the parts of the solid area and the openings in the discharge anode and locating them radially opposite.

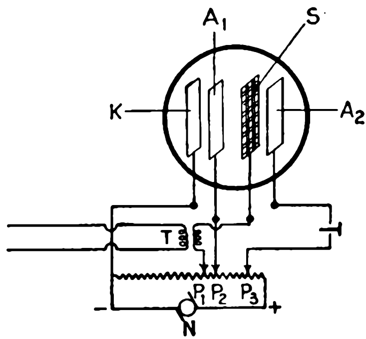


FIG. 167.—Typical circuit for application of cold-electrode tube.

A diagram of fundamental circuit connections in which this tube is used is given in Fig. 167. A source of current *N* of 220 volts is shunted by a potentiometer. The negative terminal of this current source is connected to the cathode *K*. The lead to the discharge anode A_1 is connected to a tap at P_2 to obtain about 200 volts. The lead to the amplifying anode A_2 is connected to a tap at P_3 to obtain about 210 volts, and a telephone headset is inserted in this circuit. The lead to the control electrode *S* is connected to a tap at P_1, giving a voltage which is negative by a few volts with respect to P_2. The primary winding of the transformer *T* receives the current to be amplified, and the secondary winding is connected into the control-electrode circuit.

The type of construction shown in Fig. 168, when used with a voltage of 200 volts and a current of 16 milliamperes between the discharge cathode *K* and the discharge anode A_1 and with a voltage on the amplifying anode A_2 which is about 10 volts higher than that on A_1, will have a *mutual* alternating-current *conductance* (page 114) of about 2.5 milliamperes per volt and an amplification factor of 6. The electron current between the discharge anode A_1 and the amplifying anode A_2 reaches the saturation value at about 10 milliamperes with a voltage difference of 1 volt, the current-voltage characteristic being very steep.

A cold-electrode, gas-filled tube which depends for its operation on the ionization of a gas has a characteristic curve of anode current plotted against voltage that shows three well-defined regions. In the first region, which is utilized in the action of the *Seibt tube,* the current increases slowly and uniformly for low values of voltage as the voltage is increased, the amount of current available from this source being small. In the second region the current increases sharply for small increases in voltage. In the third region the current change corresponding to voltage changes is similar to the current-voltage characteristic of a thermionic tube (page 94). The cold-electrode tube[1] developed by Hund utilizes this third region. Tubes of this type have been designed for a plate resistance of 7,000 ohms, a mutual conductance of 3,000 micromhos, and an input impedance of about ⅓ megohm. The efficiency and amount of heat dissipated are approximately the same as in thermionic tubes (page 94). Such a tube can be designed for various services in audio-frequency, radio-frequency and ultra high-frequency applications. The tube is intended for use in radio receivers for which a minimum expense for service is a requisite. Such receivers are to be utilized in a plan for providing radio-broadcast programs to the home through the medium of electric-power-line systems on a rental basis, the renting company being responsible for the servicing of the radio receiver.

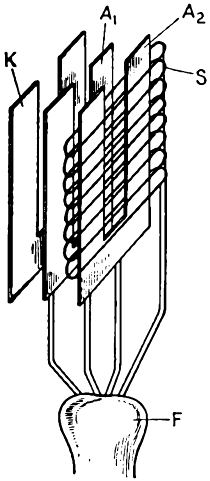


FIG. 168.—Construction details of typical cold-electrode tube.

[1] "Tubes with Cold Cathodes," *Electronics*, January, 1933.

In still another type[1] of cold-electrode tube a special grid construction is used to afford complete control of the current. This control is obtained because of the effect of the space charge around the grid on the discharge current. When there is a voltage difference between the grid and the adjacent body of ionized gas, a space charge having a polarity opposite to that of the grid is formed. This space charge acts to shield the grid in such a way that a change of grid voltage produces a change in the magnitude and direction of the grid current, and a change in the depth of the space-charge region. The grid current affects the anode current if the total cathode current is limited by a ballast resistance (page 206), but no amplification is possible. In this tube the design is such that the individual space charges around the wires of the grid can be made to spread until they combine into a single space charge to cut off the discharge current. A cross section of one form of this tube is shown in Fig. 169. The electrodes are mounted in a glass envelope filled with an inert gas such as helium at a pressure of 3 to 4 centimeters of mercury. The electrodes are spaced so that the discharge between the anode and cathode travels through the cylindrical grid. The voltage applied to the grid is positive with respect to the cathode and has a value intermediate between that of the cathode and the anode. The characteristic curves for this tube as shown in Fig. 170 were obtained under the indicated conditions of operation. It can be seen from these curves that the anode current is extinguished when the grid voltage is reduced to the proper value. The grid current may be decreased by changes

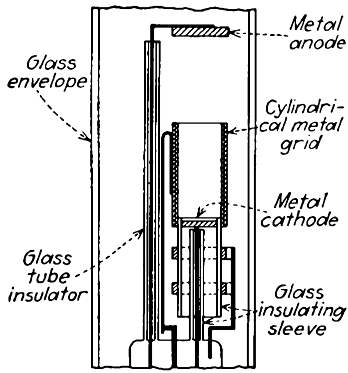


FIG. 169.—Reich and Hesselberth's cold-electrode glow-discharge tube.

[1] REICH and HESSELBERTH, "A Cold-cathode Amplifier Tube," *Electronics*, October, 1933.

in the design of parts of the tube and of gas pressure. The tube has a mutual conductance of about 100 micromhos and an amplification factor of 4. At present this type of tube is not suitable for radio-frequency amplification but may be used as an audio-frequency amplifier and as a control tube operated by photocells.

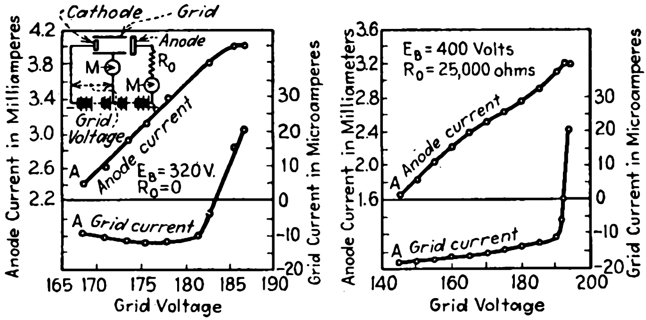


FIG. 170.—Operating characteristics of Reich and Hesselberth's glow tube. Curves for static conditions at left; for dynamic conditions, at right.

PHOTOSENSITIVE DEVICES

Classes of Photosensitive Devices.—A photosensitive device is made of materials which emit electrons under the influence of light in a manner called the photoelectric effect. The *rate* at which electrons are emitted is directly proportional to the light intensity, and the *number* emitted is proportional to the light frequency.

Three general classes of the photoelectric effect are known, namely, (1) photoconductive, (2) photovoltaic, and (3) photoemissive.

A photoconductive cell is made of material such as selenium which has a natural "dark" ohmic resistance that changes under the influence of light in a manner depending on light intensity and color. Another photoconductive material is thallium oxysulphide, used in the thalofide cell. In one form of construction the photoconductive material is applied in a thin layer to a glass plate which is mounted in a glass bulb filled with an inert gas. The current passed by a cell of this class is so small that the device is generally used in connection with a vacuum-tube amplifier.

A photovoltaic cell is one in which a voltage is developed under the action of light, two common types being the electrolytic and the electronic. The electrolytic type consists of two electrodes, for example, a copper cathode coated with cuprous oxide, and a lead anode, both being immersed in an electrolyte of dilute lead nitrate solution. In the electronic type which consists of two electrodes in dry contact, electrons are displaced from one electrode into the other under the influence of light. There are several commercial forms, such as the Weston photronic cell of iron and selenium, and the Westinghouse photox cell consisting of a copper disk, one side of which is oxidized and then coated with a transparent metallic film. In the photox cell the electrons pass between the oxide and the film. The accuracy of the photovoltaic cell is not seriously affected by normal temperature changes, its sensitivity is reasonably lasting, and its power output is appreciable.

Photoemissive effect describes that action by which electrons are actually emitted from a surface under the influence of light. A commercial device utilizing this effect is the phototube. In this section, we are concerned only with the phototube types.

Operation of Phototubes.—The operation of a phototube depends on the emission of electrons when light strikes a light-sensitive cathode.

As illustrated in Figs. 171 and 172, the phototube consists essentially of an anode and a cathode, these being sealed into a suitable bulb from which the air has been removed to produce an almost perfect vacuum, or else the bulb has been filled with an inert gas like argon at a low pressure (usually 0.04 to 0.02 millimeter of mercury). The effect of the argon is to increase greatly the flow of current due to the ions produced by the collision of the normal electrons with the gas molecules. The phototube operates very much like a two-element vacuum tube. In the most successful designs, the anode is a wire extending out from the bottom of the bulb into its central portion, the wire being "capped" in some designs by a small disk. The cathode is a material, usually caesium, which has

FIG. 171.—Typical photoelectric tube.

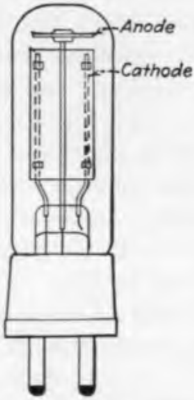


FIG. 172.—Elements of photoelectric tube.

the property of emitting large numbers of electrons when its surface is illuminated. The coating of caesium on the inside of the bulb is, in many cases, deposited on a "backing of metallic magnesium." After the electrons have been emitted from the cathode, their passage toward the anode may be hastened if a voltage of the right polarity and of suitable magnitude is applied between the cathode and the anode. A simple circuit including a phototube, an ammeter, and a battery is shown in Fig. 173. With these arrangements, a current flows through the tube and its circuit as shown, when its cathode is illuminated. A phototube must, obviously, have some provision for admitting light; and for this purpose, a small *window* is left in the magnesium backing.

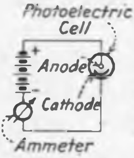


FIG. 173.—Simple photoelectric circuit.

The control of electric current by the action of light falling on a coating of caesium in a phototube may take place very rapidly. In fact, if a source of light is cut off from the cell several thousand times per second, the electric current will be affected the same number of times, following quite accurately the variation in light intensity.

Types of Photoelectric Cells.—There are two general types of photoelectric cells: (1) high-vacuum type, and (2) gas-filled; and each of these general groups has many kinds of special designs for use, particularly with different wave lengths of light.

There are many variable factors entering into the design of a phototube, these factors having important influences on the operating characteristics of the tube. Thus, certain phototubes have their greatest sensitivity for visible light rays, that is, for the visible part of the spectrum. Other designs of phototubes can be made to have their greatest sensitivity for ultraviolet rays, and still others for infrared rays.

Characteristics of Phototubes.—The behavior of a phototube may be represented by curves showing the relation between certain factors such as current, intensity of light, voltage, color of light, power output, and external resistance. The relations generally given are the current-illumination characteristic, the current-voltage characteristic, the current-color characteristic, the voltage-illumination characteristic, and the power-resistance characteristic.

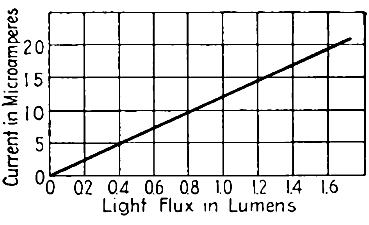


FIG. 174.—High-vacuum photoelectric tube (type SR-50).

Current-light Characteristic.—For a given illumination the current flowing between the anode and cathode of a phototube depends on the value of the voltage applied between anode and cathode. When the applied voltage reaches the saturation value of the tube, the current is proportional to the intensity of the applied light. The characteristic curve of current against light intensity for a high-vacuum photoelectric tube such as type SR-50 is shown in Fig. 174. The relation is linear and the current is small.

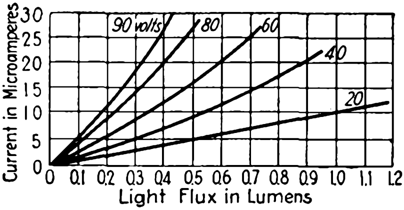


FIG. 175.—Operating characteristics of gas-filled photoelectric tube (type SK-60).

For greater emission, the gas-filled phototube may be used. The increased emission in this type depends on ionization by collision. The current-light characteristic of a gas-filled photoelectric tube such as type SK-60 is shown in Fig. 175. The curves show that, in the low range of illuminations and voltages, the flow of current is directly proportional to the light intensity. But in the higher ranges the relation is not in direct proportion. The linear relation can be approximated by variation of the load resistance.

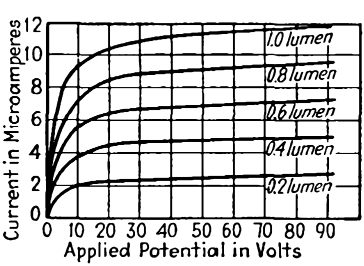


FIG. 176.—Relation of current and applied voltage at different light intensities for high-vaccum photoelectric tube (SR-50).

Current-voltage Characteristic.—Curves of the relation between current and applied voltage at different light intensities for the type SR-50 are shown in Fig. 176. For a given light intensity the current-voltage curve indicates saturation at a relatively low anode voltage.

The current-voltage characteristic for the type SR-50 high-vacuum tube is shown by the upper curve in Fig. 177 for a constant illumination. A saturation effect is indicated at the bend of the curve, but the current continues to increase as the voltage increases. In fact, if the voltage exceeds the maximum recommended for normal operating conditions, a glow discharge may take place in the tube and may cause injury to the cathode.

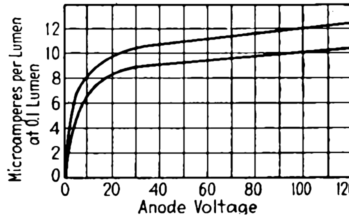


FIG. 177.—Relation of current to applied voltage at constant illumination for high-vacuum photoelectric tube (SR-50).

Current-color Characteristic. The current-color curve gives the relative response of the photoelectric tube at different values of the wave length of the light, when the applied voltage is constant and when the energy of the illumination is constant. The color sensitivity of a tube depends on the design. Commercial types of tubes are made to be sensitive near the red end of the spectrum because the ordinary lamp bulb used for photoelectric-tube illumination has maximum radiation in that range. The current-color curve *A* in Fig. 178 is for a vacuum-type photoelectric tube designed tc give

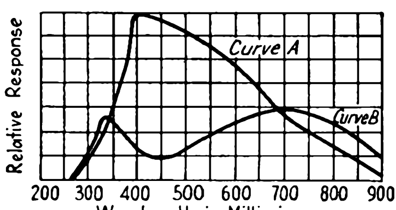


FIG. 178.—Relation of current to color in vacuum-type photoelectric tube. Curve *A* is for maximum response in violet region of spectrum. Curve *B* for deep red and ultraviolet region.

maximum response in the violet region of the spectrum. Curve *B* is for a vacuum photoelectric tube having maximum response in the deep red and ultraviolet region.

The sensitivity of a vacuum phototube is increased by the addition of gas, but the shape of the curve of response to color is not affected. The current-color curves when gas is added to the phototubes of the type used for Fig. 178, may be obtained by multiplying by 5 the response values shown.

Photo-glow Tube.—One type of gas-filled cell is intended for operation with an applied voltage having a value just below that at which the gas is ionized and breakdown occurs. When such a tube known as the photo-glow tube is illuminated the breakdown point is lowered because of electron emission from the cathode, and discharge occurs. The gas pressure in this type of tube is considerably higher than that in a gas-filled phototube. The glow discharge is sufficiently large (usually several milliamperes) to operate sturdy relays. The photo-glow tube is a half-wave rectifier and, consequently, direct-current relays may be operated by the current passed through it.

Voltage-light Characteristic.—The variation in voltage with changes in light for a typical photo-glow tube is shown in Fig. 179. The breakdown and break-off voltages are given by two sets of curves: one for alternating current and the other for direct current. The *breakdown voltage* is the value at which the glow starts, and the *break-off* voltage is the value at which the glow ceases. Under the influence of a direct voltage the discharge continues independent of the light and ceases when the voltage is reduced to the break-off value or when the circuit is opened. Under the influence of an alternating voltage the discharge starts and stops at points in the cycle which correspond to the breakdown and break-off values, respectively. Thus the curves show the limits within which a glow discharge can be maintained during small changes in illumination.

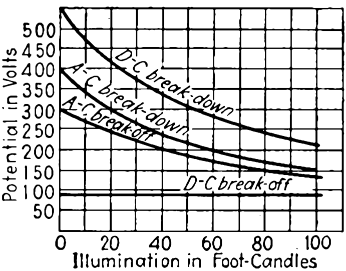


Fig. 179.—Relation of voltage to light changes in typical photo-glow tube.

Photoelectric Response of Radio Tubes.[1]—The degree of photoelectric response from radio tubes is affected by the

[1] Koechel, "Radio Tubes Used as Photocells," *Electronics*, December, 1932.

type of tube, the operating voltages, and the way in which the light is applied. Best results are obtained from tubes having black, not shiny plates. Four kinds of tubes which are suitable are types 38, 39, 45, and 50; of these the type 45 is the most sensitive. The grid is left free or floating, and for best sensitivity the grid prong (page 19) should be removed at the base of the tube to reduce leakage in the socket.

The cathode voltage must be kept within certain limits, but the working value is best determined by experiment. The

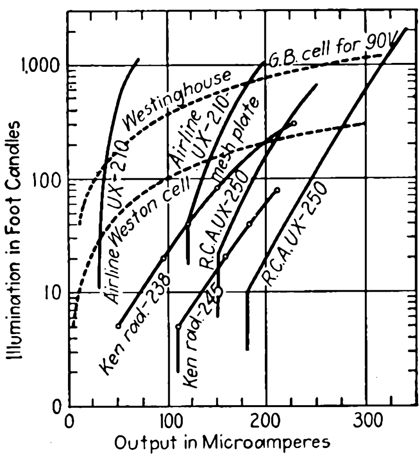


Fig. 180.—Photoelectric response for various tubes (floating grid).

values given in Fig. 180 may be taken as a guide. The cathode voltage must be high enough to provide the plate current needed when the tube is illuminated by the light source but not so high that the light from the cathode affects the photoelectric response. On the other hand, the cathode voltage should not be so low that sufficient emission is not obtained. The plate voltage must be obtained from a continuous- or direct-current source and its value depends on the application of the tube. If the tube is to be used as an indicator of light intensity, a plate voltage of 4 to 10 volts is adequate. If the tube is to operate a relay, a plate voltage of 22 volts or more is necessary. As shown in Fig. 181, the photoelectric response is very critical for relatively small changes in plate voltage.

The "*eye" of the tube is the grid;* therefore, the light must be directed to strike the grid. The glass at the top of the bulb must be clear so that light can enter. To avoid body capacity effects, which may be very noticeable, the tube should be

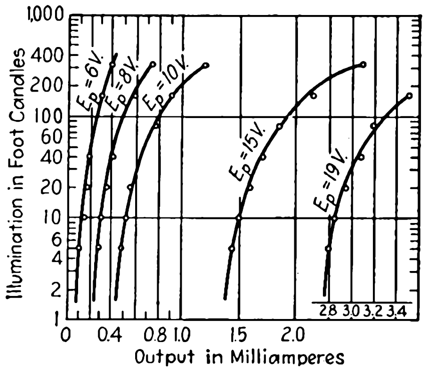


FIG. 181.—Photoelectric response for UX-245 tube (filament voltage 1.5, floating grid).

shielded; and the shield should be grounded to the cathode of the tube.

Tests made on the tubes in Fig. 180 gave the results indicated. The chart shows the photoelectric response in microamperes as the illumination in foot candles is varied. It is seen that the output response is very nearly in direct proportion to the logarithm of the light intensity.

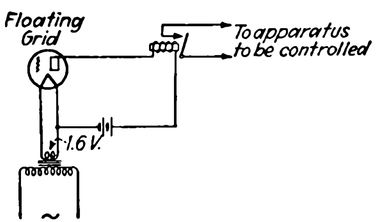


FIG. 182.—Circuit for using UX-245 as a photoelectric tube.

A circuit diagram to illustrate the use of a type 45 tube for the operation of a relay is given in Fig. 182. The value of the plate voltage needed to produce a current suitable for relay operation may be selected from the curves in Fig. 181. Thus, a Western Electric type B-40 relay having a resistance of 400 ohms will operate on a current of 1.5 milliamperes. At a plate voltage of 15 volts with no illumination, the plate current is 1.4 milliamperes. With an illumination of 80 foot-candles the plate current increases to about 1.8 milliamperes and operates the relay. A higher plate voltage can be used for the operation of a relay which responds to a stronger current.

TABLE VI.—OPERATING VOLTAGES FOR PHOTOELECTRIC EMISSION
(*See Fig.* 180)

Type of tube	Plate, volts	Cathode, volts	Screen grid, volts
Airline 210	10	6	
Kenrad 238	120	5	6
Kenrad 239	120	5	6
Airline 210*	30	6	
RCA 250†	6	6	
Kenrad 245	6	1.6	
RCA 250	8	6	

* Mesh plate. † Black plate.

MISCELLANEOUS TUBES

Cathode-ray Tube.—The cathode-ray vacuum tube is a device which utilizes a controlled beam of electrons (cathode ray) to produce light on a fluorescent screen. The direction of the beam is controlled by the effect of a magnetic or an electrostatic field, the amount of deflection being proportional to the field voltage or current. The movement of the beam is made visible on the screen.

A diagram of a cathode-ray tube of the low-voltage high-vacuum type is shown in Fig. 183. The assembly of electrodes, called an *electron gun*, is mounted in the stem of the tube. This gun consists of an oxide-coated indirectly heated cathode from which the electrons are emitted, and an anode by which the electrons are accelerated and made to emerge in the form of a diverging beam from a small opening. A second anode is used to produce further acceleration and to narrow the beam so that it appears at the screen with a very small diameter. The bulb of the tube is enlarged to make space for a screen of suitable size. The second anode consists of a metallic coating on the inside surface of the enlarged portion of the bulb. The control electrode, placed between the cathode and first anode, is used to start and stop the beam, to control its intensity, and to assist in obtaining a sharp spot on the screen. The electrons which appear on the screen are allowed to leak off to the second anode.

The electron beam, being in effect an electric current, can be influenced by a magnetic field. If the beam is arranged to be deflected by electromagnetic means it can be used to

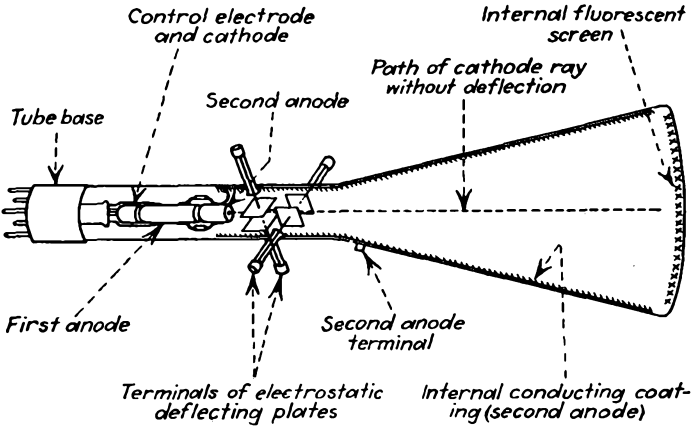


FIG. 183.—Typical cathode-ray tube.

indicate current. This effect may be obtained with two sets of coils at right angles to each other, placed outside the tube at a point beyond the forward end of the gun. The two coils in a set are mounted one on each side with their axes perpendicular to the axis of the beam, and with their magnetic fields aiding so as to produce a more uniform effect. The beam is deflected in a direction perpendicular to the axes of the deflecting coils, and the deflection can be determined by the left-hand rule. By this means the beam can be made to move in such a manner as to produce patterns corresponding to the phase relations between the deflecting fields. Deflection with a magnetic field is satisfactory for frequencies up to a few thousand cycles per second, but over that value difficulties may be encountered due to the inductance of the coils.

In the device described here the deflection system depends on electrostatic action. Two sets of deflecting plates at right angles to each other are mounted in the stem of the tube just beyond the electron gun. When a voltage is applied to these plates the beam is deflected toward the positive plate, the deflection being proportional to the voltage. The use of an electrostatic field for deflection is not limited by high frequencies. The effect of the plates is somewhat similar to that of a vacuum-tube grid when it is negatively "biased." The similarity is that the electrostatic plates take a negligible current, and have a very small input capacity.

A diagram of a rectifier circuit to supply the power required by a cathode-ray tube is given on page 381.

The cathode-ray tube is used in circuit investigations to trace oscillograms or wave forms of rapidly varying electrical phenomena. The visual image produced on the screen can be recorded on a photograph. A new electrical system for television transmission and reception is based on the use of the cathode-ray tube.

X-ray Tubes.—The x-ray tube is a type of electronic tube in which the velocity of the emitted electrons is first highly accelerated and then suddenly altered. This change in motion is accompanied by the formation of electromagnetic radiations of very short wave length, known commonly as x-rays, which pass outside the tube.

The cross section in Fig. 184 shows the construction of a Westinghouse radiographic x-ray tube. The electrons are emitted from a hot cathode of the filament type the temperature of which is adjusted to produce the desired current flow from the anode. The x-rays are produced when the stream of electrons is made to bombard a target, and this action to be effective must take place in a vacuum. The electrodes therefore are sealed in an evacuated tube, made of pyrex glass which has the necessary heat-resisting properties, mechanical strength, and transparency to x-rays. The anode, made of tungsten, serves as the target. A metal shield around the cathode directs the stream of electrons to the target. In the larger sizes of tubes some means must be provided for cooling to take care of the heat which is generated at the target. The frequency of the x-ray wave, and consequently its penetrating ability, depends on the voltage applied to the electrodes. The higher the voltage between the anode and cathode, the higher is the frequency of the wave and the greater is its penetrating ability.

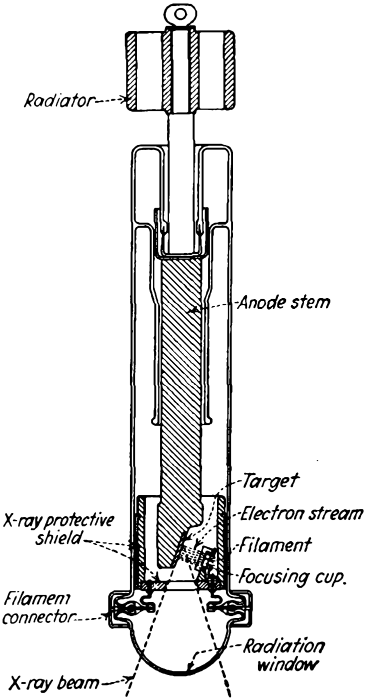


FIG. 184.—Construction details of typical radiographic x-ray tube.

The electrical energy for heating the cathode is supplied from a transformer having a suitable low-voltage secondary winding. The anode voltage, which may have a crest value of 200 kilovolts or more, is supplied by a high-tension transformer with the center point of the winding grounded. Some means must be provided for varying the voltage applied to the primary winding of the high-tension transformer. This control is obtained with an autotransformer by means of which the voltage applied to the low-voltage winding may be changed from the line voltage to any desired lower value. Since the x-ray tube passes current in one direction only, from anode to cathode, it is desirable to rectify the high-tension current supplied by the transformer. A rectifier circuit for this purpose, using one or more tubes, is described on page 382.

X-rays are able to penetrate metals, living tissue, and other objects. For this reason they are used in the medical and dental fields, and for the examination of the internal structure of various materials and substances. A few of such uses are: the examination of welded joints in pipes and boilers, the detection of flaws in metal castings, the fitting of shoes, and the detection of metal particles in food. The degree of penetration varies with the density or character of the objects so that shadows are formed. Such shadows can be observed on a fluorescent screen or they can be recorded photographically.

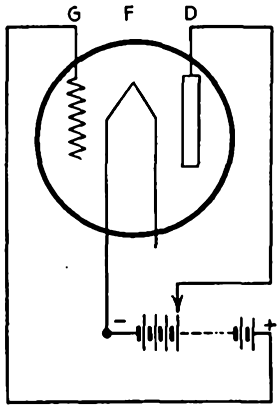


FIG. 185.—Dynatron connection for a three-element tube.

Dynatron.—A vacuum tube with the dynatron connection[1] utilizes the effect of secondary electron emission (page 122) so that the plate-cathode resistance of the tube is negative over a certain range of plate-voltage values. Performance of this kind is similar to that of a three-element tube connected to provide feed-back of energy from the output to the input circuit.

The dynatron connection for a three-element tube is shown in Fig. 185 with a grid voltage that is more positive than the plate voltage. If the grid voltage is fixed and the plate voltage is varied, the relation between plate current and plate voltage is shown by the curve in Fig. 186. Electrons due to secondary emission from the plate are attracted in general to that electrode which has the highest positive voltage. Thus when the grid is more positive than the plate, the secondary electrons are attracted to the grid and cause a reduction of plate current. In the region where the plate current decreases as the plate voltage decreases the resistance of the plate circuit of the tube is negative.

[1] HULL, A. W., "The Dynatron," *Proc. Inst. Radio Eng.*, February, 1918.

The control produced by the action of a normal control grid may be obtained with the dynatron connection of a *four-element tube* in which the plate voltage is less than the screen-grid voltage, and the control grid is used in the usual manner. The characteristics of dynatron operation are illustrated in the curves for the type 24A tube in Fig. 58 over the range of plate voltage from zero to the values on the curves at 90 volts.

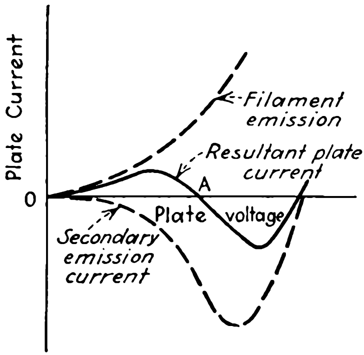


FIG. 186.—Relation of plate current to plate voltage in typical dynatron connection for three-element tube.

The dynatron connection can be applied in several ways to utilize the negative resistance characteristic of a tube. In one application a high-voltage amplification is obtained. This is accomplished by connecting an external resistance in the plate circuit of the tube and adjusting the operating conditions until the positive external resistance is nearly neutralized by the negative resistance of the tube, so that the resultant resistance is very low. Then the current flowing in the plate circuit is large and the voltage drop across the external resistance is also large. With this arrangement a voltage drop of several hundred times the applied voltage in the plate circuit can be obtained.

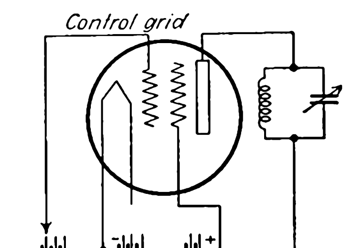


FIG. 187.—Dynatron connection of screen-grid tube to serve as oscillator.

In another application a *screen-grid tube* with the dynatron connection can be used as an *oscillator*. The arrangement is shown in Fig. 187. The tuned circuit connected to the plate of the tube will oscillate when its impedance is equal to, or greater than, the negative resistance of the tube. This action of the screen-grid tube as a dynatron oscillator can be utilized in a *wave meter*.

Magnetron.—The magnetron is a vacuum tube of the diode (page 95) type in which the movement of electrons from the cathode to the anode is controlled by a magnetic field. As shown in Fig. 188, the cathode is placed along the axis of the glass envelope and surrounded by a cylindrical plate or anode which is split so that it will not short-circuit the magnetic field. The coil provides a uniform magnetic field having a direction parallel to the cathode.

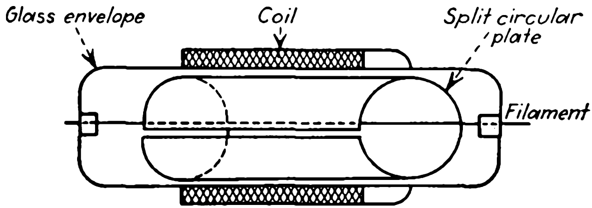


Fig. 188.—Diagram of magnetron.

When no magnetic field is present, an electron travels directly from the cathode to the plate. The effect of a magnetic field is to pull the electron in a direction at right angles to its motion and to the direction of the field. Under the action of a magnetic field *below the critical value* the electrons are forced to move around the cathode with a travel somewhat similar to a widening spiral, but they eventually reach the plate and consequently the plate current does not change. When the magnetic field is *above a critical value* the electrons are gradually pulled back to the cathode and the plate current is lowered to zero. This property of a magnetron tube can be utilized for amplification purposes because the power required for magnetization is much less than that which is present in the plate circuit. The tube is not suitable, however, for the control of high-frequency currents because an extremely strong magnetic field is required.

A magnetron in which the magnetic field is due entirely to a heavy alternating current in the cathode produces a continuous or direct pulsating plate current. This plate current has peaks which occur at a frequency twice that of the cathode current. The reason for this is that when the cathode current reaches its maximum value in one direction, the plate current is reduced to zero by the effect of the magnetic field; and the plate current is again reduced to zero when the cathode current reaches its maximum value in the opposite direction. When the cathode current is low, the control of the anode is stronger than that of the magnetic field and the plate current increases to a maximum.

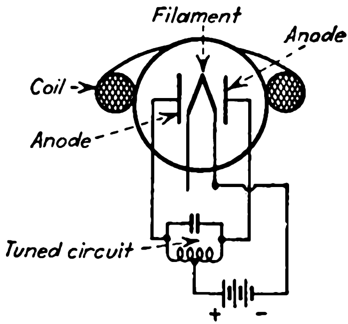


FIG. 189.—Magnetron for generation of high-frequency power.

One application of the magnetron is for the production of relatively large amounts of power at very high frequencies, although low frequencies can be obtained if the inductances and capacities are large enough. The circuit used for this purpose is shown in Fig. 189. In the tubes used for heavy power generation the anodes are water-cooled. The frequency is determined by the values of inductance and capacity in the tuned circuit. For the extreme limit of frequency the condenser is omitted and the external inductance consists merely of the connection between the anodes. The coil producing the magnetic field is supplied with continuous or direct current and the field strength must be sufficient to produce plate-current cut-off (page 130). With tubes of this type[1] power outputs of several kilowatts can be generated up to frequencies of 400,000 kilocycles, but the power output falls off rapidly at higher frequencies. The advantage of the magnetron over the triode in this connection is that its interelectrode capacities are much smaller.

[1] WHITE, W. C., *Electronics*, April, 1930.

CHAPTER V

RADIO METERS AND MEASUREMENTS

Types of Meters.—Practical tests of a vacuum tube and its associated circuits involve measurements of the value of current, voltage, resistance, inductance, and capacity. The magnitudes of the quantities to be measured should be kept in mind because they have a bearing on the type of instrument that may be utilized. Thus current measurements fall within the range from microamperes to several amperes, voltage measurements range from microvolts to hundreds of volts, resistance values range from fractions of an ohm to megohms, inductances range from microhenrys to millihenrys, and capacities range from micromicrofarads to microfarads. Both direct and alternating currents and voltages are encountered; and the alternating-current quantities may be of low or of high frequency. For example, the alternating current obtained from the usual house lighting circuit has a frequency of 60 cycles per second. On the other hand, the frequency of a radio signal having a wave length of 20,000 meters is 15,000 cycles per second, while the frequency corresponding to the wave length of short-wave radio broadcasting at 5 meters is 60,000,000 cycles per second. The current and voltage measurements to be considered deal as a rule both with direct-current and with alternating-current quantities.

The meters used for measurements of this kind include voltmeters, ammeters, ohmmeters, output meters, galvanometers, capacity meters, audio-frequency oscillators, and telephone receivers. . A Wheatstone bridge is also a necessary part of an adequate equipment. Several types of practical and commercial devices intended for testing vacuum tubes are described in Chap. VI.

Meter Accuracy.—Commercial types of voltmeters and ammeters using the moving-coil, permanent-magnet construction are said to have an accuracy of 2 per cent, and meters provided with a rectifier have usually an accuracy of 5 per cent; meaning that the accuracy at any point on the scale of one of these meters is equal to the given percentage of the full-scale reading. For example, assume a voltmeter having a scale range of 100 volts and an accuracy of 2 per cent. The accuracy at any point then should be 100 × 0.02, or plus or minus 2 volts. It should be noted that an error of 2 volts at a low position on the scale means a different *percentage* of accuracy from an error of the same number of volts at a high position on the scale. For instance, at 20 volts on the scale an error of 2 volts corresponds to a percentage of 10, while an error of 2 volts at a scale reading of 400 volts corresponds to an error of ½ per cent.

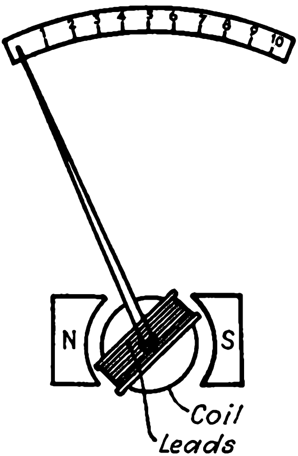


FIG. 190.—Direct-current voltmeter.

Direct-current Voltmeters.—A diagram of a typical voltmeter is shown in Fig. 190. This type, called a *moving-coil meter*, consists of a stationary magnet and a movable coil. A pointer attached to the coil passes over the scale which is graduated to indicate voltage values. A spring attached to the shaft of the pointer resists the movement of the coil and brings the pointer back to zero when no current is flowing through the instrument. By Ohm's law[1] the current flowing through the voltmeter is directly proportional to the applied voltage and consequently the meter scale may be marked to indicate *volts*.

A voltmeter must be connected *across* the voltage which is to be measured. On this account a high-resistance coil is

[1] MOYER and WOSTREL, "Industrial Electricity and Wiring," p. 62, McGraw-Hill Book Company, Inc., New York.

placed within the instrument in series with the moving coil to prevent a short circuit. The positive terminal of a voltmeter (marked +) should be attached to the positive side of the circuit. The range of voltage over which the meter can be used depends on its design and on the amount of the series resistance. Thus a millivoltmeter has a small resistance and can be used to measure small fractions of a volt.

An external resistance called a *multiplier* may be used with a voltmeter to increase its range. In the use of the multiplier the meter reading is multiplied by a constant which depends on the resistance of the multiplier.

The magnetic type of meter designed for use in direct-current circuits will not operate in an alternating-current circuit. If an alternating current flows through the moving coil, the magnetic field due to the current must alternate in direction at a rate corresponding to the alternation of the current. This rate of alternation, 120 per second for a 60-cycle current, is so rapid that the moving coil and the pointer attached to it cannot respond. Consequently meters of the moving coil and permanent-magnet type are designated generally only as direct-current instruments.

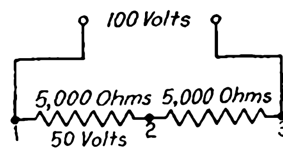


FIG. 191.—Simple electric circuit including two equal resistances.

Sensitivity of Voltmeters.—A voltmeter generally is rated by the range for which it is designed and by its sensitivity in terms of resistance per volt. Thus a voltmeter with a range of 200 volts and a total resistance of 200,000 ohms has a sensitivity of 1,000 ohms per volt. A low-resistance voltmeter connected across a high-resistance device such as a plate-supply unit for a vacuum tube will not give a true reading of the voltage because the current taken by the meter may be large enough to lower the voltage of the source of supply. This is shown clearly by the following example in which the use of a low-resistance meter is compared with that of a high-resistance meter. It is clear from the circuit shown in Fig. 191, that the voltage from point 1 to point 2 is 50 volts, when the voltmeter is not connected. A low-resistance voltmeter with a 100-volt range has a resistance of 200 ohms per volt, meaning a *total* resistance of 20,000 ohms. When such a meter is connected across points 1 and 2 to measure the voltage, the electrical circuit is shown in Fig. 192. The resistance of the circuit between points 1 and 2 is now 4,000 ohms, and the resistance between points 1 and 3 is 9,000 ohms. The current flowing is 100 ÷ 9,000 = 0.0111 ampere. The voltage drop in the branch between points 2 and 3 is

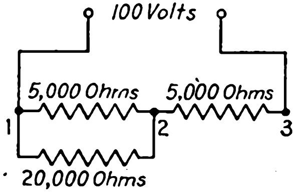


FIG. 192.—Circuit shown in Fig. 191 with the addition of a low-resistance voltmeter.

$$0.0111 \times 5{,}000 = 55.5 \text{ volts.}$$

Then the voltage drop between points 1 and 2 is 100 − 55.5, or 44.5 volts. The voltmeter, therefore, will indicate 44.5 volts.

Now for comparison a high-resistance voltmeter having a resistance of 1,000 ohms per volt is used. When this meter is connected across points 1 and 2 the electrical circuit is shown in Fig. 193. The resistance of the circuit between points 1 and 2 is now 4,762 ohms, and the resistance between points 1 and 3 is 9,762 ohms. The current flowing is 100 ÷ 9,762, or 0.0102 ampere. The voltage drop in the branch between points 2 and 3 is 0.0102 × 5,000, or 51 volts. Then the voltage drop between points 1 and 2 is 100 − 51, or 49 volts. The voltmeter will indicate 49 volts. It is obvious that a high-resistance voltmeter is more accurate than a low-resistance voltmeter.

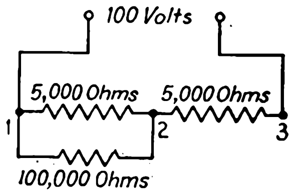


FIG. 193.—Circuit shown in Fig. 191 with the addition of a high-resistance voltmeter.

Commercial types of voltmeters for use with direct current may be obtained for various degrees of sensitivity—thus, 125, 200, or 1,000 ohms per volt. The sensitivity may also be designated in terms of resistance in ohms over a certain range of voltage—thus, 200 ohms for a range of 50 to 150 volts.

Direct-current Ammeter.—The action of an ammeter is the same as that of a voltmeter. Its construction is different because an ammeter is a device of low resistance which is connected in *series* in a circuit to measure the current. For this reason the series resistance used in a voltmeter is omitted in an ammeter. Ammeters of this simple type are made for small currents only, usually not over 50 milliamperes. For large currents the instrument is provided with a resistance, called a *shunt*, connected *across* the terminals as shown in Fig. 194. This shunt diverts to the coil a portion, usually one-tenth, of the main current. The meter is actuated by the small current which passes through its coil, but the scale is calibrated to indicate values of the total current. The meter may be utilized for several different ranges by the use of a number of different shunts each to be connected for a definite range. Equations for calculating the shunt resistances needed to extend the range of instruments may be obtained from the data sheets of meter manufacturers.

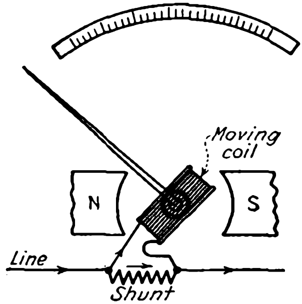


FIG. 194.—Direct-current ammeter with shunt connection.

The scales of voltmeters and ammeters of the electromagnetic type used for direct-current measurements are calibrated in equal divisions with each unit having the same space value as the next. The scale of an alternating-current meter has space divisions which are not equal but which increase as the square of the value.

Resistance of Ammeters.—The resistance of commercial types of ammeters as given by the manufacturers is stated in terms of the voltage drop across the meter at full-scale current. Direct-current milliammeters in models 301 and 506 by Weston, and in types MX and NX by Westinghouse, have a voltage drop of approximately 100 millivolts for ranges over

30 milliamperes. Direct-current ammeters in the above models by Weston, and in panel types by Triplett, have a voltage drop of approximately 50 millivolts for ranges up to 50 amperes.

Alternating-current Meters.—For alternating-current measurements a modified form of the magnetic-type instrument becomes necessary. Two kinds of devices for the measurement of low-frequency alternating quantities are available: the moving-vane type, and the inclined-coil type. The action of the moving-vane type, shown in Fig. 195, depends on the repelling effect between two magnetized iron vanes or plates *A* and *B*. Plate *A* is fastened to a coil *C*, and plate *B* to a pointer. These instruments respond to an alternating current because, although the iron plates change in polarity when the current reverses, each has the same polarity as the other and consequently they still repel each other.

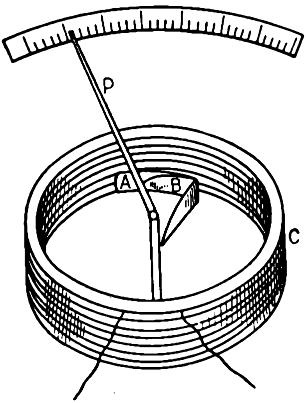


Fig. 195.—Alternating-current voltmeter.

In the inclined-coil type the field of the coil exerts a twisting action on a plate fastened to the shaft of the pointer. The coil is protected against stray fields by an iron shield.

A *voltmeter* of this kind has a coil with many turns of fine wire and a series resistance; an *ammeter* has a low-resistance coil with a small number of turns of heavy wire. In the less expensive models air damping is obtained by means of an aluminum plate fastened to the moving element. In models provided with magnetic damping the aluminum plate is controlled by a small permanent magnet. These types are accurate within 2 per cent at full scale.

Rectifier-type Meters.—In radio measurements it is essential to use instruments with low power consumption. In this respect the direct-current meter is to be preferred as compared with the alternating-current meter. It is possible, however, to have a meter that may be used for alternating-current measurements, while possessing the desired characteristic of low power consumption. These features are obtained by combining a sensitive direct-current meter with a rectifier. The rectifier[1] changes an alternating current to a pulsating direct current. This rectifying action takes place because the rectifier has a very high resistance to current flow through it in one direction, but a relatively low resistance to current flow in the opposite direction. Several types of crystal rectifiers such as carborundum and galena have been used for this application, but the copper-oxide rectifier is generally more satisfactory. The ratio of high to low resistance of this rectifier is about 50 to 1. The copper-oxide dry-contact rectifier consists of alternate disks of copper and copper oxide clamped together under pressure. A combination of four rectifiers with a meter as shown in Fig. 196 gives full-wave rectification. It can be seen from the figure that current flows through the meter in the same direction during each half cycle. The meter *M* is of the direct-current type.

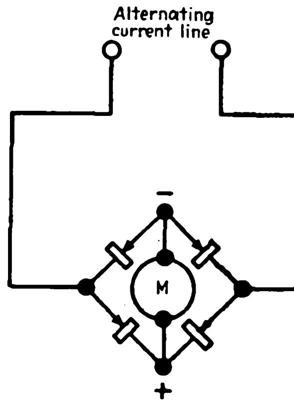


FIG. 196.—Combination of four copper-oxide rectifiers with ammeter.

The scale of a commercial type of *rectifier meter* is graduated or marked to indicate the effective value of the alternating current supplied by the line. But if the meter has a direct-current scale, the indication is 0.90 of the alternating current.[2] That is, the reading obtained with a direct-current meter must

[1] MOYER and WOSTREL, "Radio Handbook," p. 248, McGraw-Hill Book Company, Inc., New York.

[2] The reason for this is that the direct-current meter indicates the *average* value of the pulsating current. It can be shown that the *average* value of an alternating current of sine-wave form is equal to 0.637 times the *maximum* value, or 0.90 times the effective value.

be multiplied by 1 ÷ 0.90, or 1.11, to get the effective value of the alternating current.

The accuracy of commercial types of rectifier meters is stated to be within 5 per cent at full scale. Corrections for errors in indication caused by the effect of frequency (page 39) can be made if necessary.

Hot-wire Ammeter.—Another type of current-measuring device, the hot-wire ammeter, depends for its action on the expansion of a heated wire, instead of the effect of a magnetic field on a coil. It may therefore be used on *either direct or alternating current.* As shown in Fig. 197, the resistance wire fastened between points *A* and *B* will stretch when it is heated by the passage of an electric current. The change in length of the wire is taken up by the spring *S* and causes a movement of the pointer. The position of the pointer may be adjusted by a regulating screw.

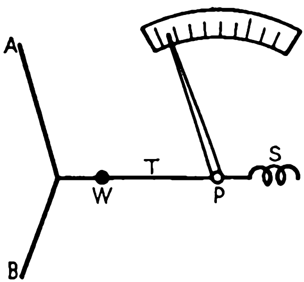


FIG. 197.—Hot-wire ammeter.

For heavy currents a number of hot wires in parallel must be used to avoid heating the wire so much that its resistance changes. The disadvantages of the hot-wire measuring device are that it is slow in response, that the pointer must be adjusted to zero position frequently, and that the accuracy is low.

This instrument can be calibrated for use with either direct current or low-frequency alternating current. Although such calibration is considered to be correct for radio-frequency currents it is best to compare the instrument with a standard meter for accuracy. This type formerly was used for the measurement of radio-frequency currents ranging from a few milliamperes up to about 5 amperes. A typical instrument giving full-scale deflection on 100 milliamperes may have a resistance of about 5 ohms.

The thermocouple meter (described next) is generally used instead of the hot-wire type for measurements at radio frequencies.

Thermocouple Ammeter.—A meter much used for the measurement of high-frequency currents depends on a thermoelectric effect and utilizes the voltage which is developed when the junction of two dissimilar metals is heated. The thermocouple consists of two wires of dissimilar metals such as copper and constantan, steel and constantan, or manganin and constantan. Two ends of these wires are welded together and connected, as shown in Fig. 198, to a conductor carrying the high-frequency current to be measured. The other two ends are connected to a sensitive indicator such as a galvanometer. The heat of the conductor affects the junction of the thermocouple and generates in the wires a voltage which actuates the galvanometer. This voltage, which always acts in one direction, depends only on the amount of heat and not on the direction of the current in the conductor. The deflection of the galvanometer is proportional to the square of the current flowing in the conductor. Hence the divisions of the scale are not uniform, having a greater *space* value at the upper end of the scale than at the lower. For currents of more than a few amperes these instruments are made with several thermocouples in series. The disadvantage of the thermocouple ammeter is that the thermocouple corrodes readily. Ammeters of this type are made with ranges from milliamperes to thousands of amperes. The range of voltmeters is up to a few hundred volts with a limiting frequency of about 1,000,000 cycles per second.

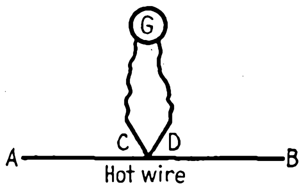


FIG. 98.—Thermocouple ammeter.

The power consumption of thermocouple ammeters having ranges up to about 25 amperes averages 0.2 watt per ampere.

Galvanometer.—The operation of a galvanometer depends on electromagnetic principles. This instrument may be used to detect the presence of small electric currents less than a millionth of an ampere, and to measure their *amounts* and directions. Its sensitiveness and frailty make it applicable mainly for laboratory work. Its action is based on the movement of a magnet placed in the magnetic field of a wire carrying a current. The magnet may be stationary and the coil movable, or the magnet may be movable and the coil stationary. The moving element carries a pointer which passes over a graduated dial. In the most sensitive types there are no pivots or springs and the coil is suspended by a long thin wire. Instead of an indicating pointer, a small mirror is attached to the coil to show its movements by the change in the direction of light reflected from it.

Telephone Receivers.—The direct-current resistance of a pair of telephone receivers is seldom more than 4,000 ohms and in some types may be as low as 50 ohms. The direct-current resistance is about one tenth of the alternating-current resistance and also of the impedance (page 68) at 1,000 cycles per second. The impedance at 1,000 cycles of various types ranges from 20,000 to 30,000 ohms. The sensitiveness of telephone receivers can be increased considerably if the receivers are designed for resonance at a certain frequency. Thus a telephone set that is resonant to 800 cycles might produce an audible response to a current of one thousandth of a microampere. The sensitivity of telephone receivers can be made higher than that of an alternating-current galvanometer, but is less than that of a direct-current galvanometer.

Ohmmeters.—Direct readings of resistance are obtained from an instrument known as an ohmmeter which consists in its simplest form[1] of an ammeter and a battery B connected as shown in Fig. 199. The scale of the meter is marked in ohms, the full-scale deflection of the pointer indicating the zero value of resistance. Before the device is used for a resistance measurement, it must be adjusted to zero, to compensate for any drop in battery voltage. In this adjustment the terminals of the instrument are short-circuited and the resistance R is varied until the pointer of the meter is at zero. Then the unknown resistance is connected between the

[1] An analysis of various ohmmeter circuits, their errors, and ways of obtaining greater accuracy is given in an article on "Ohmmeter Design," by Alfred R. Gray, *Radio News*, January, 1935.

terminals and its resistance in ohms is observed from the meter indication. In this circuit, the voltage being constant, the value of the current depends on the resistance, the current and resistance being inversely proportional. Since the movements of the meter pointer vary with the current, the meter scale can be marked to indicate ohms.

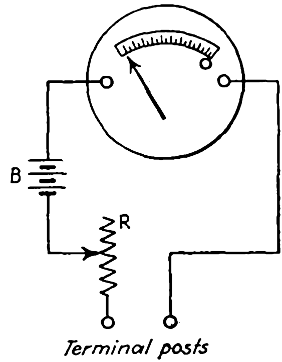


FIG. 199.—Simple ohmmeter.

The range of the instrument is taken as that resistance which causes a meter deflection of not more than 95 per cent of the scale. In ohmmeters of the multi-range type a number of resistance units are provided for use in series with the meter as a means of extending the range.

Commercial types of ohmmeters are available in ranges from several thousand ohms to half a megohm.

Volt-ohmmeter.—The volt-ohmmeter is an instrument which can be used as a multi-range voltmeter and milliammeter for direct-current measurements, as well as an ohmmeter. This arrangement is made possible by the use of a number of resistance units which may be connected in series with the meter. A panel picture of the Weston model 663 is shown in Fig. 200 and the circuit diagram in Fig. 201. There are six available resistance ranges from $R \div 5$ to $R \times 10{,}000$. The proper range is selected by means of the control switch near the bottom of the panel. The current needed to operate the device as an ohmmeter is obtained from dry-cell batteries mounted under the panel. The knob marked "Ohmmeter Adjuster" is used to bring the meter pointer to its zero position when the terminal leads are inserted in the jacks marked

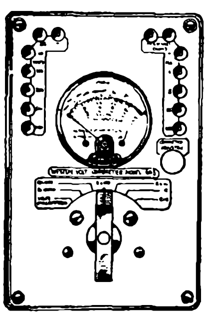


FIG. 200.—Weston volt-ohmmeter.

"Resistance Ohms" and short-circuited. The instrument has a range of 50 microamperes and a resistance of 2,500 ohms. The current drawn from the batteries and passing through the resistance being measured varies from 60 microamperes in the $R \times 10{,}000$ position to 300 milliamperes in the $R \div 5$ position. For a given range the current is a maximum when the meter pointer indicates zero ohms.

When the control switch is in the "Volts-milliamperes" position the internal wiring connections are so arranged that

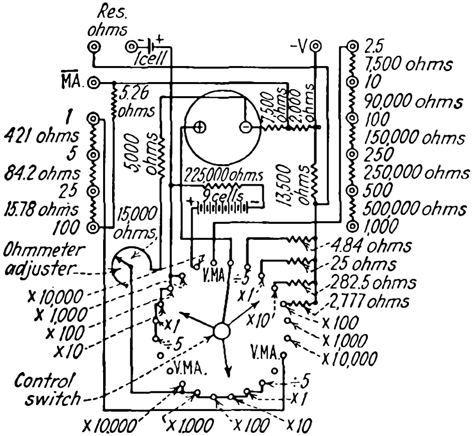


FIG. 201.—Wiring diagram of Weston ohmmeter.

the meter can be used to indicate either volts or milliamperes. Four ranges for voltage readings are provided through the jack terminals on the upper left-hand side of the panel. The instrument when used as a voltmeter has a resistance of 1,000 ohms per volt, and the scale is marked for ranges of 0–2.5–10–100–250–500–1,000 volts. The instrument may be used as a milliammeter by means of the jack terminals at the upper right-hand side of the panel. The ranges available are 0–1–5–25–100 milliamperes.

Output Meters.—An output meter may be used for comparing the degree of amplification produced by vacuum tubes. It may be utilized also generally as a sensitive indicator of voltage, as, for example, in the measurement of the signal output voltage produced by a radio receiver, or the amplification in a radio-frequency stage.

A sensitive output meter is essentially a direct-current meter connected with a rectifier. A panel view of a commercial type designed for output or volume measurements where a constant impedance is desired is shown in Fig. 202. The internal wiring connections are shown in Fig. 203. The rectifier used is of the copper-oxide type. A self-contained condenser for blocking any direct-current component is connected to a separate pin jack for use when desired. Five voltage ranges of 1.5, 6, 15, 60, and 150 volts are available at the pin jacks and may be selected by the dial switch. As shown in the circuit diagram, the resistance R_2 is in parallel with the meter while the resistance R_1 is in series with it. The arrangement is such that for any position of the switch, that is, for any of the available voltage ranges, the impedance of the entire instrument is constant at about 4,000 ohms. This approximates the impedance of a loud-speaker, or the impedance of the primary winding of an output transformer (page 24).

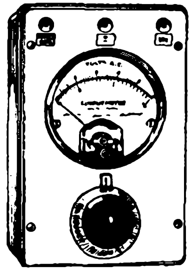


FIG. 202.—Weston output meter.

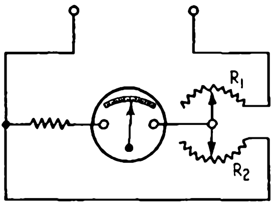


FIG. 203.—Wiring of Weston output meter.

Wheatstone Bridges.—A circuit called the Wheatstone bridge is used to measure an unknown resistance in terms of known resistances. A diagram of this circuit is shown in Fig. 204. The voltage drop between points a and c is the same over the path abc as over the path adc. Hence, some point b on the upper path must have the same voltage as a point d on the lower path. When such points have been located, a galvanometer or sensitive current indicator G connected

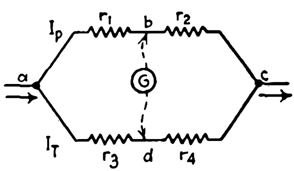


FIG. 204.—Typical Wheatstone-bridge circuit.

between points b and d will show no deflection. With a current I_p (amperes) in the upper circuit, I_t in the lower, and r_1 and r_3 being the respective resistances in ohms, the voltage drop $I_p r_1$ is equal to the voltage drop $I_t r_3$ so that $I_p r_1 = I_t r_3$ and $r_1 \div r_3 = I_t \div I_p$. Similarly in this figure, $I_p r_2 = I_t r_4$ and $r_2 \div r_4 = I_t \div I_p$, consequently $r_1 \div r_3 = r_2 \div r_4$ or $r_4 = r_2 r_3 \div r_1$. An unknown resistance r_4 may be calculated from this relation.

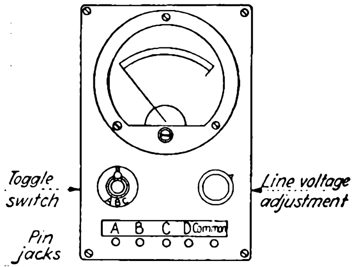


Fig. 205.—Hickok capacity meter.

Capacity Meters.—The instrument shown in Fig. 205 is intended for use as a capacity meter for measurements from 0.0001 to 20 microfarads. It is operated on alternating current having a frequency of 60 cycles per second, and is provided with a means of compensating for line-voltage fluctuations between 100 and 130 volts. The conventional circuit diagram of Fig. 206 shows the connections of the power transformer, pin-jack terminals, toggle switch, rectifier, meter, and voltage-adjustment unit. The meter is of the moving-coil type, with a range of 0.0003 ampere and a resistance of 150 ohms. The dial of the meter is marked with four scales A, B, C, and D, corresponding to the four ranges available through the pin-jack terminals. The rectifier is of the copper oxide type.

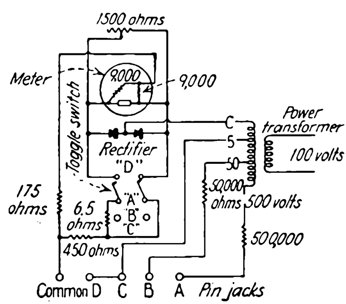


Fig. 206.—Circuit of Hickok capacity meter.

Connection to a source of power is made by means of a cord and plug on the meter. Then the test leads are inserted in the proper pin-jack terminals, one being connected to the "common" terminal, and the other to terminal A, B, C, or D, depending on the range. The toggle switch is set in the ABC

position when terminal *A* or *B* or *C* is used, and in the *D* position for terminal *D*. The meter should be adjusted if its pointer is not at zero. Then the test leads are touched together, and the control knob for line-voltage adjustment is moved until the pointer of the meter indicates a full-scale deflection. Next the test leads are connected across the condenser which is to be measured. The capacity in microfarads is obtained directly from the meter indication.

An electrolytic condenser[1] must be "formed" before it is measured in this device. The forming may be accomplished by applying to the condenser a direct current at a voltage of not less than 45 volts for a period of about 1 minute. Then the forming voltage is removed and a measurement is made immediately of the condenser capacity.

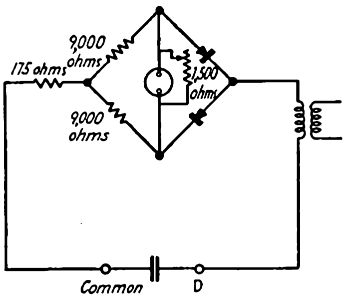


FIG. 207.—Simplified circuit of typical capacity meter.

Inductance measurements with readings in henrys can be made with this meter by means of tabulated values which show the inductances corresponding to capacities over the range of the instrument.

The action of this device may be described with the help of the simplified circuit diagram of Fig. 207. This diagram shows the circuit connections when a condenser is inserted between the "common" and the *D* terminals. The rectifier units are arranged to allow an alternating current to flow through the condenser, and a pulsating or rectified current through the meter. The variable resistance of 1,500 ohms acts as a shunt, being in parallel with the meter. When either of the terminals *A* or *B* is used, a higher voltage is applied. When the toggle switch is in the *ABC* position, a "Y" network of resistances is connected in parallel with the "Y" network

[1] MOYER and WOSTREL, "Radio Handbook," p. 104, McGraw-Hill Book Company, Inc., New York.

shown in the diagram. The current flowing in the circuit is proportional to the capacity (page 47).

Audio-frequency Oscillators.—A multitude of bridge measurements require a dependable source of alternating current of low power but of constant frequency. The source of current supply should also be simple in its operation, as well as rugged and reliable. One type of *audio-frequency oscillator* shown in Fig. 208 is suitable for such use. It has an output

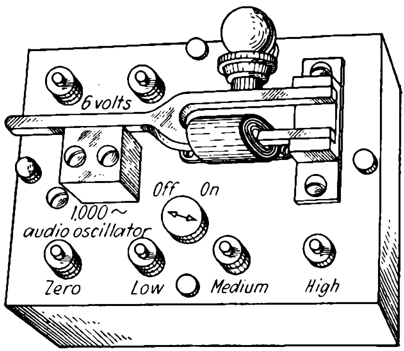


FIG. 208.—Audio-frequency oscillator. (*General Radio.*)

of about 0.06 watt at 1,000 cycles per second. External binding posts are so arranged that three output voltages may be obtained. The outputs obtainable with these three different connections are given in Table VII.

TABLE VII.—OUTPUTS OF TYPICAL AUDIO-FREQUENCY OSCILLATOR

Position	Voltage, volts	Current, milliamperes
Low	0.5	100
Medium	1.5	40
High	5.0	12

This type of oscillator can be used for general purposes where a small amount of power of good wave form is required for a single bridge.

For some capacity measurements it is desirable to use a high voltage. This increased voltage may be obtained by connecting an inductance and capacity in series across the high-voltage output terminals of the oscillator. By adjusting this circuit to resonance, voltages as high as 50 or 100 volts may be obtained by connecting output leads across the condenser. This instrument will operate satisfactorily on from 4 to 8 volts. The input current is approximately 0.13 ampere.

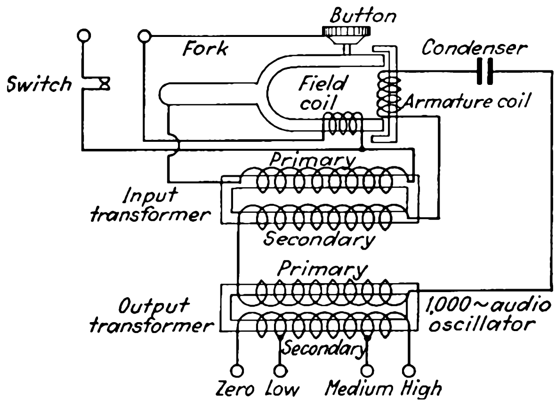


FIG. 209.—Circuit of audio-frequency oscillator.

When in operation, the oscillator may be heard for a distance of approximately 25 feet, or may be made silent by enclosing it in a sound-proof box. The circuit of this oscillator is shown in Fig. 209. The closing of the switch places the field magnetizing coil directly across the battery. The primary coil of the input transformer which is in series with the microphone button is also across the battery. The resonance circuit consists of the secondary of the input transformer, the primary of the output transformer, the armature coil, and the condenser. The secondary coil of the output transformer has three taps to permit the obtaining of three different output voltages. The use of the two transformers prevents the output wave from containing any direct-current components. Each transformer core has a small air gap to prevent distortion of the wave form. Since, however, the magnetic circuits are all nearly closed iron paths there is very little effect from outside fields. This feature is particularly important where the oscillator is being used in close proximity to a Wheatstone bridge. The tuning fork in this apparatus makes it possible to keep the frequency constant at 1,000 cycles per second. The resonance circuit is carefully adjusted to this value. Since the oscillator is self-starting, it may be operated by a switch placed at the bridge or located some distance away from the bridge.

By the use of the field magnetizing coil on one tine or prong of the vibrating fork, instead of relying on its permanent magnetism, the polarity and intensity of the magnetization of the tuning fork with respect to the armature are permanently maintained.

Success or failure in the operation of an audio-frequency oscillator or "hummer" lies very largely in the *microphone button*. If the button heats so that the oscillator cannot be run indefinitely, and also if the adjustment of the button is not permanent, or if slight mechanical shocks change its operating characteristics, the oscillator has little commercial value. A distortion of as small an amount as $\frac{1}{500}$ inch from the normal position of the button will destroy the perfect operation of the button. In order that the button may be insensitive to mechanical shocks and yet operate properly at 1,000 cycles per second, use is made of its high inertia effect at the latter frequency. One side of the button is attached to the tuning fork by means of a short, flat spring. The other side, which has a projecting mounting post, is held in position by a self-centering spring. This combination of springs enables the button to withstand severe shocks, yet it has sufficient inertia so that satisfactory operation is obtained. The adjustment of the button is permanent. This type of mounting, together with the fact that the electrical constants of the circuits have been adjusted to their best values, insures the continuous operation of the oscillator without heating.

The harmonic content of the output varies with the impedance of the load. For a normal resistance load the harmonic content is from 3 to 8 per cent. The variation in frequency caused by the effect of the load and by temperature changes has a maximum value of about 0.1 per cent. A variation of this magnitude is negligible for practically all bridge measurements. The load of the microphone button on the fork produces a frequency which is less than the rated value by 0.5 per cent.

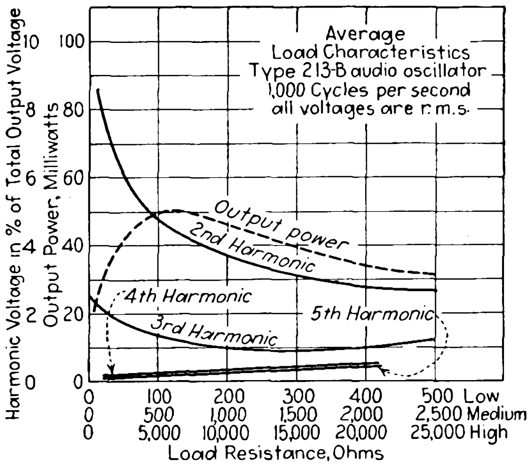


FIG. 210.—Load characteristics of audio-frequency oscillator.

This type of oscillator may be obtained for any 100-cycle multiple in the range from 0.4 to 1.5 kilocycles, with a self-contained filter arrangement to correct the wave form. The output characteristics showing both power and wave form for the 1,000-cycle type are shown in Fig. 210.

Resistance Measurements.—Occasionally a resistance measurement must be made when devices such as a Wheatstone bridge (page 241) or an ohmmeter are not available. In that case a simpler method[1] using the circuit shown in Fig. 211

[1] Other testing methods for resistance, inductance, and capacity measurements are given by Moyer and Wostrel in "Radio Handbook," in the section on Laboratory Equipment and Methods.

can be utilized. In this circuit are a battery or other suitable source of direct current and an ammeter I. The unknown resistance to be measured is inserted in the circuit between the points A and B. After a reading has been made of the current a known *variable* resistance is inserted in place of the unknown resistance, and its value is adjusted until the ammeter shows the same reading as before. The variable resistance must be marked in such a way that the value under any adjustment can be noted.

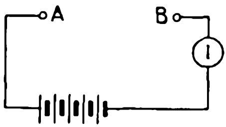


FIG. 211.—Simple circuit for resistance measurements.

Resistance Measurement with Voltmeter and Ammeter.—In this method the resistance R in ohms is calculated from the relation $R = E \div I$, where E is the drop in volts across the resistance R, and I is the current in the circuit in amperes. A voltmeter V and an ammeter I are connected into the circuit as shown in Fig. 212 for high resistances, and in Fig. 213 for low resistances.

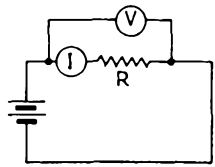


FIG. 212.—Arrangement of voltmeter in circuit of Fig. 211 when the resistance to be measured is high.

It should be noted that the resistance of the circuit is changed slightly when the measuring instruments are connected to the circuit. For most practical measurements this effect may be disregarded, if the resistance of the voltmeter is high compared with the resistance which is to be measured.

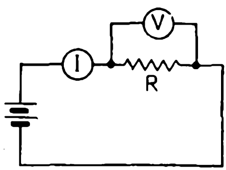


FIG. 213.—Arrangement of voltmeter in circuit of Fig. 211 when the resistance to be measured is low.

Measurement of Inductance.—One method of measuring the value of an inductance is based on the use of the Wheatstone bridge. In this method the unknown inductance is measured by comparing it with a known inductance. The arrangement of the bridge is shown in Fig. 214. In this circuit L is the unknown inductance, L_1 the known inductance,

T a telephone headset, and R and R_1 are variable resistances. A source of alternating current is connected to the circuit at points A and B. Next the resistances R and R_1 are adjusted until there is no current indication in the telephone receivers. Then the value of the unknown inductance L may be calculated from the relation $L = L_1R \div R_1$.

This Wheatstone-bridge circuit can be used also to measure directly the *mutual inductance* of coils. In some cases, however, it may be advisable to measure first the inductance of each coil and the total inductance. Then the mutual inductance M may be calculated from the relation that total inductance $L_t = L_1 + L_2 + 2M$.[1] This relation, however, is true only when the coils are in series and connected in such a way that their inductances do not oppose each other.

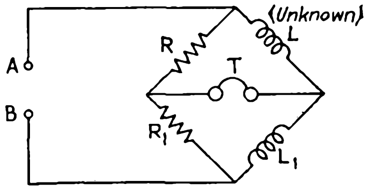


FIG. 214.—Circuit diagram for inductance measurement with a Wheatstone bridge.

Testing Coils with Ohmmeter.—Coils and windings such as are used in transformers and "chokes" (page 64) are generally made in commercial sizes with definite values of resistance stated by the manufacturer. An open circuit, a short circuit or a partial short circuit in a coil can be detected by an ohmmeter test. In this test the resistance of the coil as indicated by the ohmmeter is compared with the specified resistance rating of the coil. This comparison will show the nature of the defect.

A coil which is wound on an *iron core* may become grounded to the core. A short circuit of this kind can be detected by a test between each terminal wire and the core.

Measurement of Capacity.—The capacity of a condenser may be measured by means of a Wheatstone bridge. In this method[2] the unknown capacity is compared with a known capacity. The unknown capacity C in farads is calculated

[1] See p. 73.

[2] MOYER and WOSTREL, "Radio Handbook," p. 604.

from the relation $C = C_1R_1 \div R$, where C_1 is the known capacity, and R_1 and R are the resistances in ohms of the bridge arms (see Fig. 214).

The capacity of a condenser may also be readily calculated from the relation $I = 2\pi fCE$ (page 67). This relation gives the current I in amperes that flows in a condenser having a capacity of C farads when an alternating voltage of E volts at a frequency of f cycles per second is applied. If C is in microfarads and I in milliamperes this relation becomes $C = 1{,}000I \div 2\pi fE (\pi = 3.1416)$. The value of I is obtained from the indication of a milliammeter in series with the condenser when an alternating voltage is applied. The ordinary house supply circuit at 110 volts and 60 cycles per second can be used.

CHAPTER VI

TESTING VACUUM TUBES

Tube Testing for Service Work.—We have learned that the behavior of a tube is indicated in terms of certain electrical characteristics, such as amplification factor, plate resistance, mutual conductance or transconductance, emission, and power output. Consequently, a tube can be tested by measuring its characteristics and comparing them with standard values. But even a careful analysis made with accurate laboratory equipment does not give an absolute measure of the performance of the tube under *actual operating conditions* in a radio receiver. Because there may be this variation between analysis results and actual performance, it has become customary to check the condition of a tube by means of simple tests.

Experience has shown that the necessary degree of accuracy in testing is obtained if the value of a single characteristic, instead of several, is used to determine the condition of a tube. The characteristics generally selected for *service testing purposes* are (1) emission, (2) mutual conductance, and (3) power output. Each one of these has certain limitations which should be understood. With this information, the service man or experimenter can select the commercial testing device which best meets his requirements, or he can design equipment for special applications.

A complete service test would consist, in addition to the tests mentioned above, of an examination for (1) tube elements in contact, (2) excessive gas pressure, and (3) electrical leakage.

Emission Test.—A test of the electron emission of a tube as an indication of its condition is not in general favor because of the danger that the test results may be misinterpreted. One of the limitations of this test is that it is made under static conditions and thus cannot be an indication of the performance of the tube under actual operating conditions. There is also the danger that emission may be impaired permanently if the test voltage is applied for too long a period. In a vacuum tube the maximum current, or saturation current, is obtained at a certain value of plate voltage beyond which there is no practical increase of plate current. This current is called emission current or "emission" because it serves as an indication of the total emission of electrons. Generally, however, its value cannot be measured because if the current is increased to its maximum the tube may be damaged and the emitting conditions may be changed. Consequently a test of emission is made at a lower voltage which will not injure the tube. Comparisons of tests are valueless if the operating conditions are not alike.

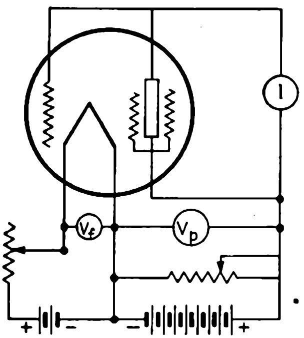


FIG. 215.—Typical circuit for emission testing.

A low value of *total* emission is a sign that the tube is approaching the end of its useful life. A low value of *test* emission, however, for a coated filament (page 12) may not mean that the tube is worn out, because this type of filament is capable of such copious emission that satisfactory operation is possible for an additional period of time.

A normal value of emission may be obtained under certain conditions, even though the tube would be unsatisfactory in operation. Thus a coated filament or cathode may have active spots from which the emission is so great that a normal test is obtained, yet the emitting area may be so restricted or confined that the grid does not have its usual control over the electrons.

A wiring diagram of a circuit for the emission test is shown in Fig. 215. All the electrodes or elements of the tube, except the cathode and diode (page 95) elements, are connected to the

TABLE VIII.—EMISSION DATA

Tube type	Filament voltage, volts	Emission voltage, volts	Emission current, milliamperes
1A6	1.50	50	3
2A5	2.5	50	50
2A6	2.5	50	40
2A7	2.5	50	40
2B7	2.5	50	40
6A4	6.3	50	40
6A7	6.3	50	40
6B7	6.3	50	40
6F7(pentode)	6.3	50	30
01A	5.0	50	25
10	6.0	100	60
WD-11	1.1	50	5.7
WX-12	1.1	50	5.7
112A	3.3	50	10
19	1.25	50	9
120	3.3	50	14
22	3.3	50	14
24A	2.5	50	40
26	1.5	50	40
27	2.5	50	40
30	1.50	50	3
31	1.50	50	5
32	1.50	50	3
33	1.25	50	9
34	1.25	50	3
35	2.5	50	40
36	6.3	50	40
37	6.3	50	40
38	6.3	50	40
39–44	6.3	50	40
40	5.0	50	25
41	6.3	50	45
42	6.3	50	75
43	25.0	50	75
45	2.5	50	85
46	2.5	50	50
47	2.5	50	85
48	30.0	50	100
50*	7.5	250	75
53	2.5	50	75 per cathode
55	2.5	50	25
56	2.5	50	40
57	2.5	50	40
58	2.5	50	40
59	2.5	50	50
71A	3.3	50	10
75	6.3	50	25
76	6.3	50	30
77	6.3	50	30
78	6.3	50	30
79	6.3	50	40 per cathode
85	6.3	50	25
89	6.3	50	50
99	3.3	50	5.7
5Z3	5.0	75	85 per plate
12Z3	12.6	20	40
25Z5	25.0	20	40 per plate
IV	6.3	20	30
80	5.0	75	55 per plate
81	7.5	150	125
84	6.3	25	30 per plate

* The emission for type 50 is measured with the control grid connected to one side of the filament.

plate. The meters specified for this circuit are of the direct-current type. Before a reading of the meter is taken, the tube should be operated for a period of time sufficient to heat it to a constant temperature. The cathode is operated at the rated voltage and the plate voltage is selected from Table VIII. It is seen from the table that a positive plate voltage of 50 volts is used for the majority of tubes. In the case of diodes a direct-current voltage of 10 volts is connected between each diode with a limiting current of 0.4 milliampere for each diode. Certain types of tubes, as indicated in the table, are tested at less than the rated filament voltage in order to avoid injury due to excessive emission. If a tube gives a reading of emission that is much less than the value in the table, it should be regarded as doubtful until tests for other characteristics indicate its general usefulness.

Mutual-conductance Test.—The characteristic used as the basis of measurement in many types of commercial tube testing devices is the mutual conductance or transconductance. It is commonly assumed that if the test on such a device shows a satisfactory value of mutual conductance, the amplification factor and plate resistance also are satisfactory. This assumption is made on the grounds that mutual conductance is affected by any change in the other characteristics, in gas pressure, and in electrode position.

Mutual conductance in mhos is defined as the ratio of the change in plate current in amperes to the change in grid voltage in volts. The commercial tube-testing device is designed to utilize this relation to give an indication of mutual conductance.

One type of testing device using the so-called *grid-shift* method is arranged so that a change is made in the value of grid voltage applied to the tube being tested, and a reading is taken of the corresponding change in plate current. If this reading compares favorably with values provided for use as a standard, the tube is normal. In this type of device direct-current voltages are applied to the electrodes of the tube to be tested. The grid voltage is shifted usually by 1 volt and the change in current is read on a direct-current ammeter in the plate circuit.

Another general type of mutual-conductance testing device is designed to give "dynamic" values of the characteristic. This device is arranged so that an alternating-current voltage is applied to the grid; and this voltage produces a plate current which has an alternating-current component. The usual type of alternating-current ammeter (page 234) is used to indicate the value of the alternating component of the plate current in milliamperes. Then if the voltage applied to the grid has a value of 1 volt (root-mean-square) (page 45), the mutual conductance in micromhos is equal to the plate current multiplied by 1,000. The majority of the commercial tube-testing devices intended for operation from an alternating-current house-lighting circuit are of this general type.

Power-output Test.—The justification for a power-output test is that it gives the best possible indication of the perform-

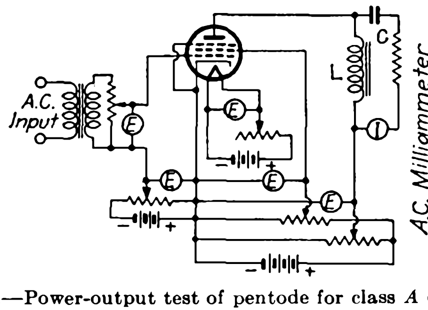


FIG. 216.—Power-output test of pentode for class *A* operation.

ance of a vacuum tube in actual operation. The power-output test on a tube intended for voltage amplification serves as a measure of the amplification and the output voltages which the tube can produce. On a tube intended for power-output services, the test gives a direct indication of performance. The testing method for a tube intended for class *A* operation (page 130) is different from that for a tube intended for class *B* operation, although the general procedure is the same.

The circuit diagram of a power-output test on a pentode tube intended for class *A* operation is shown in Fig. 216. It should be noted that an alternating-current voltage is applied to the grid. The alternating-current milliammeter in the plate circuit serves to give an indication of the alternating-current output voltage produced across the impedance *L* which acts as a plate load. The direct-current component of the plate current is "blocked" from the ammeter circuit by the condenser *C*. In this test the resistance of the plate load must be known. Then the power output is determined from the value of the current and the load resistance.

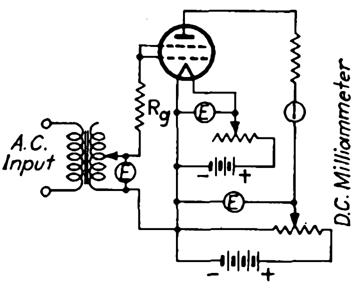


FIG. 217.—Power-output test of tetrode for class *B* operation.

The circuit diagram of the power-output test on a tetrode intended for class *B* operation is shown in Fig. 217. In this test also an alternating-current voltage is applied to the grid; but in this case, a direct-current milliammeter is used in the plate circuit to indicate the value of the direct current. Then the power output in watts is equal to the square of the current reading in amperes times the load resistance in ohms times the factor 0.405.[1]

Calculation of Static Characteristics.—Static characteristics are those relations which may exist between tube voltages and currents when there is no load in the plate circuit and when a direct-current grid-bias voltage is applied. It should be remembered that the relations which actually exist between voltages and currents, when the tube is operating in any of its applications, are determined not only by the characteristics of the tube itself but also by the properties of the radio apparatus used with the tube. Such relations, called the *dynamic* characteristics, are treated in a later section.

[1] See second footnote, p. 235.

The tube characteristics to be determined are the mutual conductance, the amplification factor, the plate resistance, and the grid resistance. The calculations are made from values taken from a curve showing the relation between plate current and grid voltage, and another curve showing the relation between plate current and plate voltage.

Plate-current Grid-voltage Curve.—A plate-current grid-voltage curve shows how the plate current is affected by changes in the value of the grid-bias voltage. The data for this curve of a vacuum tube are obtained by operating the tube at its rated filament voltage and plate voltage, with a direct-current bias voltage applied to the grid. Then the grid-bias voltage is increased in negative value until the point of *cut-off* (page 130) is reached, at which the plate current is reduced to zero. Next the grid-bias voltage is decreased in small steps to the zero value and then increased gradually to a

TABLE IX.—TEST DATA FOR PLATE-CURRENT GRID-VOLTAGE CURVE

Filament voltage........................ 5.00 volts
Filament current........................ 0.25 ampere
Plate voltage........................... 45.00 volts

Grid Volts, Negative	Plate Current, Milliamperes
6	0.0
5	0.1
4	0.2
3	0.4
2	0.7
1	1.1
0	1.6
Positive	
1	2.1
2	2.8
3	3.5
4	4.2
5	5.0
6	5.8
7	6.6
8	7.4
9	8.3
10	9.2

maximum positive value. At each step the grid-bias voltage and the corresponding plate current are observed and recorded. A test of this kind on a type 01A tube gives the data as shown on page 257.

Using these values a curve may be plotted on cross-section paper. It will have the shape of curve 45V in Fig. 218. Information such as the volts and amperes in the filament circuit and the plate voltage, as well as the other data of the test, should be recorded on the curve sheet.

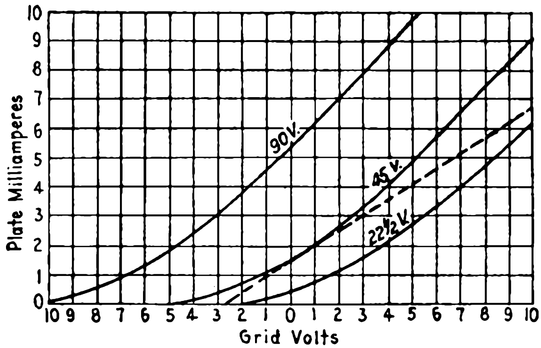


FIG. 218.—Mutual conductance determined by the tangent to characteristic curves of tubes.

Mutual Conductance.—It was shown, in the explanation of how a vacuum tube operates, that the ratio (mutual conductance) of changes in plate current to changes in grid voltage is a better measure than any other single factor for determining the relative merit of a tube. A curve, which represents the relation between these two factors with horizontal values (abscissas) for grid voltage and vertical values (ordinates) for plate current, is a graphical device to show the good or poor qualities of a vacuum tube. In the portion of such a curve where it is steep, there is a relatively large change in plate current for a change in grid voltage, and where the curve tends toward a horizontal direction, the plate current has a relatively smaller change. The slope of this curve is, therefore, proportional to the mutual conductance and is a measure of the good qualities of the vacuum tube which has been tested.

Since the slope of a curve showing the relation of plate current to grid voltage changes somewhat at different points, the values of mutual conductance should be taken at the point in the curve at which the vacuum tube is to be used. The grid voltage used in making such a curve is measured with respect to the negative end of the cathode. If the tube is to be used with the grid return connected to the negative end of the cathode, the slope should be taken at the zero of grid volts. If the tube is to be used with a negative grid-bias voltage of 1 volt with respect to the negative end of the cathode, the slope should be taken at a grid voltage of minus one (−1).

The slope of a curve showing the variation of plate current with grid voltage at the actual point where the tube is to be used is most easily determined by placing a straightedge tangent to the curve at the point corresponding to the grid voltage (with respect to the negative end of the cathode) and drawing a line intersecting the scales of plate milliamperes and grid volts. It may be assumed, for example, that the grid return is connected to the negative end of the cathode and that all values of current will be taken with the grid voltage at zero. In the case shown in Fig. 218, the vertical distance from the base line to the intersection of the tangent line with the right-hand edge of the curve sheet should be noted, this being 6.8 milliamperes; and then this value is to be divided by the distance along the base line from the right (adding positive and negative values), which is 13 volts. The value obtained by this division is 0.52 which is the slope of this line at the point where the tube is actually working and is the value of the mutual conductance of the vacuum tube. Its value, however, is not stated in the standard terms ordinarily used. This will be explained in the next paragraph.

Because the values of current are in milliamperes instead of amperes, it is necessary to divide this value of mutual conductance as obtained above by 1,000; and further, because resistances are expressed in micromhos instead of mhos, a multiplying factor of 1,000,000 must be used. The final result is that the above number must be multiplied by

(1,000,000 ÷ 1,000), or 1,000, to obtain the value of the mutual conductance of the vacuum tube in micromhos. Multiplying 0.52 by 1,000 gives 520 as the mutual conductance in micromhos.

Simplified Method of Finding Mutual Conductance.—The taking of the mutual-conductance values as given above is somewhat tedious, although it must be done where the actual curves are desired. A shorter method from which no curves can be made may be worked out which will check a tube with sufficient accuracy. In the application of this briefer method, the grid voltage is set at 2.5 volts (negative) and the plate current in milliamperes is read and recorded. Then the grid voltage is shifted to 2.5 volts (positive) and the plate current is again noted. The plate current will be higher for this second reading than for the first reading, the increase being due to the change in grid voltage. The first value of plate current when subtracted from the second value, gives the increase in plate current in milliamperes for a 5-volt total change in grid voltage, and when the change in plate current in milliamperes is multiplied by 200,[1] the value of mutual conductance in micromhos will be obtained. This method is not quite so exact as the method used when the curve is taken, but is sufficiently accurate for most commercial testing.

As an example of this method a type 01A vacuum tube was tested at a plate voltage of 45 volts. At 2.5 volts (negative) the plate current was 0.6 milliampere. At 2.5 volts (positive) the plate current was 3.2 milliamperes. This is an increase of 2.6 milliamperes and two hundred times this value gives 520, which checks with the mutual conductance obtained from the curve.

Amplification Factor.—The next important constant of a vacuum tube is the amplification factor. This is defined as the ratio of the change in plate voltage (which is necessary to change the plate current a given amount) to the change of grid voltage (which will produce the same variation in the

[1] This multiplication factor of 200 as used here is the value of the ratio 1,000 ÷ 5, or multiplier ÷ grid-voltage range.

plate current). The amplification factor u does not change much in value over the range of operating voltages. It undergoes a small and usually negligible decrease in value at low plate voltages. The amplification factor is useful for determining the quality of a vacuum tube as an amplifier. Values of amplification factors of standard tubes are given on page 617. This factor can be obtained from a curve showing the variation of plate current with grid voltage by taking a reading, preferably on the straight-line slope of the curve, at some slightly different value of plate voltage from that used for making the curve. This point should be plotted on the cross-section paper in its proper position with reference to grid voltage and plate current for this new value of plate voltage. For example, on the enlarged portion of the curve (Fig. 219), the point P is the new value which was taken at a plate voltage of 35 volts. The original curve was taken at 45 volts. Hence, the change in plate voltage is 10 volts, the grid remaining at zero voltage with respect to the negative end of the cathode. As shown in the figure, the value of plate current drops from 1.60 to 0.95 milliampere, a difference or change of 0.65 milliampere.

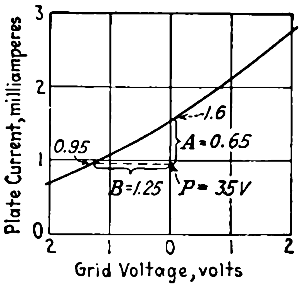


FIG. 219.—Amplification factor determined by slope of characteristic curve of tube.

From the above definition the amplification factor is equal to the change in plate voltage divided by the change in grid voltage. The grid voltage which would be necessary to produce this same change in plate current is the horizontal value from the point P to the curve which is marked by the distance B, in this case, 1.25 volts. The amplification factor of this tube under these conditions is then $10 \div 1.25$, or 8.0.

It should be noted that the above value is an average for operating conditions between 35 and 45 volts. To get this result more accurately, it is necessary that the change in plate voltage should be very much smaller than the values taken above, but this greater accuracy is scarcely worth while as the values obtained by the method that has been described will be found to check very closely with the values obtained by standardization laboratories with very elaborate equipment.

Plate Resistance.—The term *plate resistance*, as explained before (page 109), does not apply to the resistance offered to the flow of a direct current in the plate circuit, but is the resistance offered to the flow of an alternating current in such a circuit. The resistance offered to the flow of a direct current

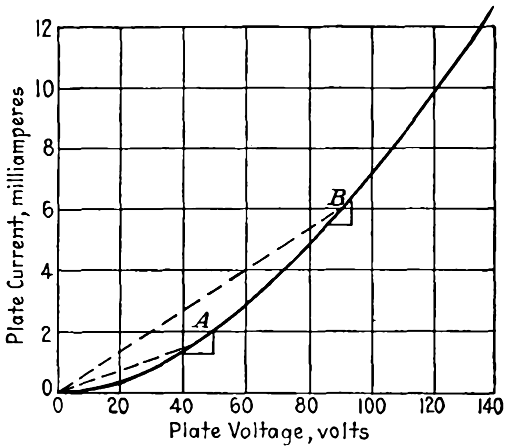


FIG. 220.—Method of determining direct-current resistance of tube from plate current—plate voltage curve.

may be considered as the internal or direct-current resistance of the tube.

The plate resistance may be obtained from the values already found as it is simply the ratio of the change in plate voltage to the change in plate current. The change in plate voltage for the conditions on page 261 was 45 − 35, or 10. The change in plate current was 1.60 minus 0.95 milliamperes, or 0.65 milliampere, or 0.00065 ampere, this value being shown as the distance *A* on the curve in Fig. 219. The ratio of 10 to 0.00065 is 15,400, which is the plate resistance.

A method of determining the *direct-current* resistance is from the ratio of plate voltage to the corresponding plate current. In Fig. 220 the variation of plate current with changes of plate voltage for a type 01A tube is shown. If a plate voltage of 45 volts is applied, the plate current at the point *A* is 1.70 milliamperes or 0.0017 ampere. The internal or direct-current resistance of the tube is equal to the reciprocal of the slope of the line connecting this point with the origin *O*. This direct-current resistance *R* may be computed from the current and voltage readings, as follows,

$$R = \frac{45}{0.0017} = 27{,}280 \text{ ohms.}$$

At the point *B*, with an applied voltage of 90 volts and a current of 6.0 milliamperes, the resistance is lower, being 15,000 ohms.

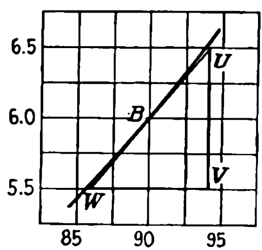


FIG. 221.—Method of determining plate resistance from the slope of characteristic curve for plate voltage of 90 volts.

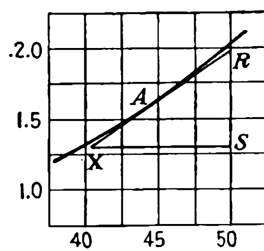


FIG. 222.—Method of determining plate resistance from the slope of characteristic curve for plate voltage of 45 volts.

The *plate resistance* r_p may be determined from the curve showing the relation between plate voltage and plate current by computing the slope of a tangent to the curve drawn through the point in question. For example, the tangent *UW* at the point *B* may be drawn as shown on the enlarged section of the curve in Fig. 221 and the triangle *UVW* constructed. Then *WV* represents the change in plate voltage and *VU* the corresponding change in plate current. From these values the plate resistance r_p may be computed. The plate-voltage change is 94 − 86, or 8 volts. The plate-current change is 6.50 − 5.50 = 1.0 milliampere, or 0.001 ampere;

and the plate resistance $r_p = 8 \div 0.001$, or 8,000 ohms. Similarly, the plate resistance at 45 volts (point *A*, Fig. 222) is 15,740 ohms.

These values are roughly one half of the direct-current resistance of the tube, which is 15,000 ohms at 90 volts. Similarly, the readings at 45 volts are 27,280 and 15,740, respectively. An estimate of the alternating-current plate resistance can be obtained by reading the plate current and plate voltage, computing the direct-current resistance from these readings, and taking one half of this value.

The plate resistance may also be determined from two sets of instrument readings. In this case, the grid voltage is left fixed, and the plate-current reading is taken with the plate voltage set a few volts below the value of plate voltage at which the plate resistance is desired. The voltage is then increased an equal amount above the nominal value of plate voltage and both sets of readings recorded. From these readings the plate resistance may be computed. Referring to Fig. 221, the readings are taken at points opposite *W* and *U*. When E_p is 94 volts, $I_p = 6.55$ milliamperes or 0.00655 ampere. When E_p is 86 volts, $I_p = 5.55$ milliamperes, or 0.00555 ampere, and

$$r_p = \frac{94 - 86}{0.00655 - 0.00555} = \frac{8}{0.0010} = 8{,}000 \text{ ohms.}$$

In addition to the curve shown in Fig. 220 and the values which were taken from it, curves may also be made from the following data: the variation of filament current I_f with filament voltage E_f; the variation of plate current I_p with filament voltage E_f; the variation of plate current I_p with filament current I_f; the variation of plate current I_p with plate voltage E_p. These values are self-explanatory and when plotted will show the operation of any tube and will make it possible to visualize the operation better than by any other method.

Grid Resistance.—Another characteristic which is useful in a study of a vacuum tube is the grid resistance or grid conductance, sometimes called the "input resistance" or "input conductance." This measures the alternating current flowing in the grid circuit for a given value of applied alternating voltage. The method of obtaining this is shown on the enlarged portion of the curve showing the variation of grid current with grid voltage in Fig. 223. If an alternating voltage with an amplitude of 0.25 volt is impressed on the steady grid voltage of +0.4 volt at the point *O* on the curve, the total voltage will vary between *R* and *S* and the current between *U* and *T*. The tangent to the curve at *O* coincides closely with the curve in that region. Now the conductance *g* is the ratio of maximum current to maximum voltage and hence $g = UR \div OR$ = slope of tangent. Hence, the conductance for small variations about a point on the curve is equal to the slope of the tangent to the curve at that point and the resistance is equal to the reciprocal of the slope.

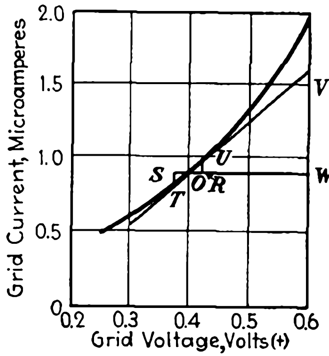


FIG. 223.—Method of obtaining input conductance from slope of curve showing relation between grid current and grid voltage.

The value of mutual conductance is obtained more accurately from the ratio $WV \div WO$.

Numerically,

$$g = \frac{0.72 \times 10^{-6}}{0.2} = 3.6 \times 10^{-6} \text{ mhos.}$$

$$R = \frac{1}{g} = 2.8 \times 10^{5} \text{ ohms.}$$

The conductance decreases and the resistance increases as the angle the tangent makes with the horizontal is reduced. That is, if the positive value of the steady grid voltage is decreased, the input resistance increases, or the value of an alternating current in the grid circuit is decreased, for a given alternating voltage applied to the grid. In order to keep the input power small, it is desirable to make the grid resistance high by setting the steady grid voltage at zero or even making it negative.

Plate Conductance.—Still another important characteristic called the plate conductance is obtained from the curve showing the relation of plate current to plate voltage. This curve shows how the plate current varies with plate voltage when the grid voltage is constant. The plate conductance at any point is equal to the slope of this curve at that point. The plate resistance is equal to the reciprocal of the plate conductance. These quantities measure the alternating current in the plate circuit for a given applied plate voltage when there is no appreciable external resistance or reactance in the circuit.

Leakage Current.—Any current that flows between the electrodes of a vacuum tube through the insulation resistance is termed a leakage current. The tube is prepared for a test of leakage current by bringing the cathode or heater up to its normal operating temperature. Then the cathode current is turned off, and the leakage current test is made immediately while the other tube electrodes are near their normal operating temperatures. For this test the tube should not be inserted in a socket. The test for leakage current between any two electrodes is made by applying a voltage between them, with the other electrodes free. The voltage applied should be high enough to give suitable readings. The value of the insulation resistance may be calculated from the voltage and current readings.

How to Build a Tube Tester.—The testing device described in this section is of the type which operates on alternating current with a frequency of 60 cycles per second and a nominal voltage of 120 volts. Alternating voltages are applied to the electrodes of the tube under test. The measuring or indicating instrument, as shown in the panel view of Fig. 224, is a milliammeter of the moving-coil type, with a range of 0 to 5 milliamperes and an internal resistance of approximately 10 ohms. The scale of the meter has a section marked "good" and one marked "bad." The deflection of the meter, caused by the action of the current flowing in the plate circuit of the tube being tested, is taken as a measure of the condition of the tube. The primary winding of the power transformer is connected in series with a rheostat by means of which the supply voltage can be adjusted to the correct value as shown on a line-voltage meter. This voltmeter has a resistance of about 1,500 ohms. A neon light bulb is utilized in a circuit arrangement to indicate leakage between tube electrodes. The unused sections of the various switches within the unit may be utilized to meet the requirements of new types of tubes.

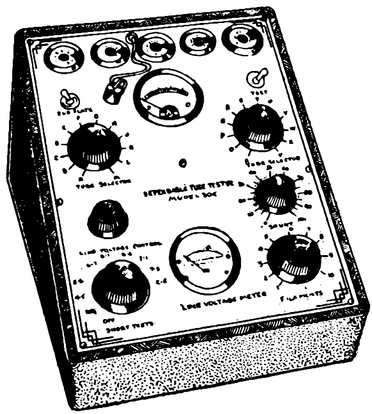


FIG. 224.—Panel view of Model 304 tube tester.

The wiring diagram of this tube tester is given in Fig. 225. The letter symbols that appear on this diagram are used to identify the various pieces of apparatus and correspond to the letter symbols in the accompanying Parts List. Only those items in the Parts List which are not self-explanatory will be described. *T*1 is a power transformer having three taps on the primary winding and ten taps on the secondary winding. The 500-ohm rheostat *VR*1 is for line-voltage adjustment. The 25-ohm rheostat *VR*2 is the milliammeter shunt. The selector switch *SW*1, used in the short-circuit test, is of the 12-point 3-deck type. The panel view shows two controls marked "tube selector" which consist of the selector switches *SW*2 and *SW*3. The switch *SW*2, with a range of positions from *A* to *M* marked on the dial, is of the 12-point 2-deck type. The switch *SW*2, with a range of positions from *N* to *Y*, is of the 12-point 3-deck type. The switch *SW*4 for filament-voltage control is of the 10-point single-deck type. Switches

*SW*5 and *SW*6 are of the single-pole double-throw toggle type. The complete parts list is given in Table X.

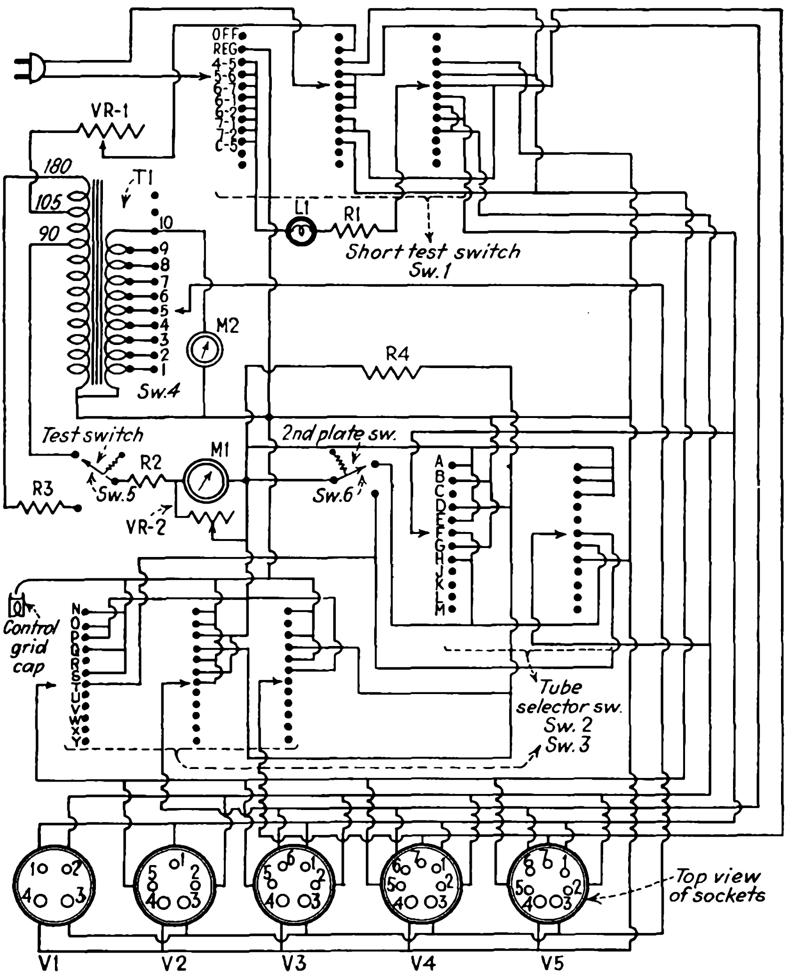


FIG. 225.—Wiring diagram of Model 304 tube tester.

Assembling and Wiring.—The first piece of apparatus to be mounted on the panel is the bracket for the neon lamp. The

TABLE X.—PARTS LIST OF TUBE TESTER*

Letter symbol	Quantity	Description
*L*1	1	Neon lamp and casing
*M*1	1	Milliammeter
*M*2	1	Line voltage meter
*R*1	1	Carbon resistor, 100,000 to 200,000 ohms
*R*2	1	Wire-wound resistor, 2,200 ohms
*R*3	1	Wire-wound resistor, 600 ohms
*R*4	1	Carbon resistor, 40,000 ohms
*SW*1	1	Selector switch, 12-point, 3-deck
*SW*2	1	Selector switch, 12-point, 2-deck
*SW*3	1	Selector switch, 12-point, 3-deck
*SW*4	1	Selector switch, 10-point, single-deck
*SW*5	1	Toggle switch, single-pole, double-throw
*SW*6	1	Toggle switch, single-pole, double-throw
*T*1	1	Power transformer
*V*1	1	Molded socket
*V*2	1	Molded socket
*V*3	1	Molded socket
*V*4	1	Molded socket
*V*5	1	Molded socket
*VR*1	1	Rheostat, 500 ohms
*VR*2	1	Rheostat, 25 ohms
	2	Insulating centering washers for rheostats
	1	Panel, etched and drilled
	1	Insulated control grid cap and lead
	4	Large knobs with indicators
	2	Small knobs with indicators
	1	Cord and plug
	1	Set of screws, nuts, wire, etc.

* This apparatus in kit form may be obtained from Radio City Products Company, New York.

lamp terminals must be kept from touching the panel to avoid a "ground."

Care should be taken that the insulation centering washers are not forgotten when the rheostats *VR*1 and *VR*2 are being mounted.

The wiring from one deck to another of each selector switch, as indicated on the wiring diagram, should be completed before the switch is mounted on the panel. This will not offer any difficulty if the plan of representing a switch on the wiring diagram is understood. The selector switch *SW*1, for example, which has three decks with 12 contact points on each deck, is represented by three vertical rows of black circles, there being

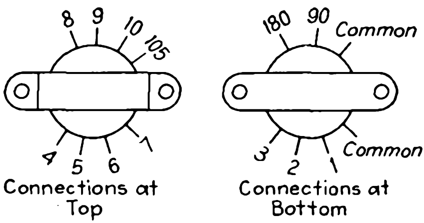


FIG. 226.—Power-transformer connections for Model 304 tube tester.

12 circles in each row. The arrow head pointing to a row represents the wire connection to the movable arm for that row. At the completion of this stage of assembling the selector switches *SW*1, *SW*2, *SW*3, and *SW*4 are wired and mounted on the panel.

After the five tube sockets are attached to the panel, the wiring from one socket to another is put in place. Then the connections are made between the sockets and the selector switches, as well as the connections from one to another of the selector switches. Wires which must pass around meters or other pieces of apparatus should be cut to allow for the extra length needed. Other wires may be cut close to size to produce a neat job.

The next part to be mounted is the power transformer. This transformer, as shown in Fig. 226, has two sets of connections, one set being near the upper end and one near the bottom. The connections numbered 1 to 10, inclusive, are to be wired to the corresponding points of selector switch *SW*4. The wiring for the other connections of the transformer is indicated clearly on the wiring diagram of Fig. 225.

Finally the toggle switches and the meters may be mounted and the remaining wiring completed.

Operating Procedure.—The plug is connected to an electric-light socket on an alternating current, 60-cycle, 110-volt-supply circuit. The left selector switch is turned to the *M* position, and the right selector switch to the *Y* position. The filament switch is turned to the number given in the Tube Table (page 272) for the tube being tested, and then the tube is inserted in the proper socket.

The test for short circuits and for leakage between tube electrodes is made by turning the "short-tests" switch to various positions, with the two tube-selector switches in positions *M* and *Y*, respectively. A bright glow in the neon light indicates a short circuit. A dim glow indicates a high-resistance leak. A very faint glow may occur on a resistance of over 5 megohms, but does not necessarily indicate that trouble is present. The operator should trace the wiring from the points of the "short-tests" switch *SW*1 to the tube sockets to understand the meaning of the numbers on the dial of the switch.

The first step in the test for tube condition is to turn the "short tests" switch to the *REG* position. Then the tube selector switches are set to the positions indicated in the Tube Table for the type of tube being tested. The adjustment for line voltage is made by moving the line-voltage control knob until the pointer of the line-voltage meter is at the arrow on the meter dial. The shunt-control knob is set to the position corresponding to the value given in the Tube Table. Then the test switch is pressed and the meter indicates the condition of the tube by the deflection of the meter needle on the "Bad-Good" scale.

Rectifier tubes are designated in the Tube Table by the letter *R* for half-wave types, and by *RR* for full-wave types.

TABLE XI.—DATA FOR TUBE TESTING

Tube	Filament or cathode switch	Tube-selector switches	Shunt setting	Tube	Filament or cathode switch	Tube-selector switches	Shunt setting	Tube	Filament or cathode switch	Tube-selector switches	Shunt setting	Tube	Filament or cathode switch	Tube-selector switches	Shunt setting
OOA	6	B	20	48	10	AN	95	85	7	CN	50	*2B7	4	AN	90
O1A	6	B	50	49	3	BO	80	(D)	..	DQ	0	(D)	..	MQ	0
(R)1	7	B	80	50	8	B	70	85AS	7	CN	75	6B7	7	AN	60
10	8	B	80	51	4	AN	0	(D)	7	DQ	0	(D)	..	MQ	0
12A	6	B	80	52	7	AN	95	87	7	AN	40	*6C6	7	AN	40
14	9	AN	0	53	4	AN	93	88	7	AN	50	*6C7	7	BN	90
15	3	AN	50	53	4	MP	..	89	7	AN	80	(D)	..	MQ	0
17	9	AN	85	55	4	CN	40	95	4	AN	93	6D6	7	AN	70
18	9	AN	80	55(D)	4	DQ	0	(RR)98	7	FN	85	*6D7	7	AN	90
19	3	AN	85	55AS	7	AN	70	99	5	B	50	*6E7	7	AN	90
19	3	MS	90	(D)	..	DQ	0	401	5	B	60	2F7	4	MS	85
20	5	B	70	56	4	AN	93	482	6	B	90	2F7	4	AN	60
22	5	A	50	57	4	AN	0	483	6	B	85	6F7	7	MS	85
24A	4	AN	40	57AS	7	AN	0	484	5	B	50	6F7	4	AN	60
26	2	B	70	58	4	AN	55	485	5	AN	80	(RR)6Y5	7	HT	85
27	4	AN	90	58AS	7	AN	20	486	5	B	50	(RR)5Z3	6	F	85
29	4	AN	90	59	4	AN	85	586	8	B	93	(R)12Z3	9	B	20
30	3	B	50	64	7	AN	50	841	8	B	0	(RR)6Z4	7	FN	85
31	3	B	80	65	7	AN	60	864	1	B	40	(RR)6Z5	7	HT	85
32	3	A	40	67	7	AN	70	*866	4	..	60	(RR)12Z5	7	GT	85
33	3	AN	90	68	7	AN	95	868	..	A	..	(RR)25Z5	10	GT	85
34	3	A	40	69	7	AN	93	874	..	B	..	(R)AD	7	B	85
35	4	AN	50	71A	6	B	90	(RR)985	6	FN	85	AE	9	AN	93

TABLE XI.—DATA FOR TUBE TESTING.—(*Continued*)

Tube	Filament or cathode switch	Tube-selector switches	Shunt setting	Tube	Filament or cathode switch	Tube-selector switches	Shunt setting	Tube	Filament or cathode switch	Tube-selector switches	Shunt setting	Tube	Filament or cathode switch	Tube-selector switches	Shunt setting
36	7	AN	90	*75	7	CN	90	1A6	3	EO	60	(RR)AF	4	F	85
37	7	AN	95	(D)	..	DQ	0	1A6	3	CO	60	(RR)AG	6	F	85
38	7	AN	70	76	7	AN	95	2A3	4	B	90	GA	6	AO	95
39	7	AN	0	*77	7	AN	95	2A5	4	AN	80	KR-5	7	AO	93
40	6	A	90	78	7	AN	50	*2A6	4	CN	90	KR-20	4	CN	60
41	7	AN	85	†79	7	AR	95	(D)	..	DQ	0	(D)	..	DQ	0
42	7	AN	85	†79	7	MO	93	2A7	4	AN	70	KR-22	7	CN	60
43	10	AN	93	(RR)80	6	F	8	2A7	4	MS	90	(D)	..	DQ	0
44	7	AN	30	(R) 81	8	G	85	6A4	7	AO	93	KR-25	4	AN	95
45	4	B	90	(RR)82	4	F	80	6A7	7	AN	70.	LA	7	AO	93
46	4	BO	85	(RR)83	6	F	85	6A7	7	MS	90	PZ	4	AO	95
47	4	AN	95	(RR)84	7	FN	85	12A5	7	AR	70	PZH	4	AN	95

NOTE: S after number on any tube simply designates spray-shield tube. Tests same as ordinary tube.

* Do not use the control-grid cap that extends through panel. Use the special cap connector and plug it into terminal 2 of any socket.

† Use special cap connector and plug it into terminal 5 of any socket.

The test switch must not be used for a check on rectifier tubes. In the case of full-wave rectifiers a check on the current from the second plate is obtained by throwing over the second plate switch.

A tube having a diode unit is given two sets of values in the Tube Table, the values marked *D* being for the diode unit. A deflection beyond the line marked "Diodes O.K." on the meter dial indicates that the condition of the diode tube is satisfactory.

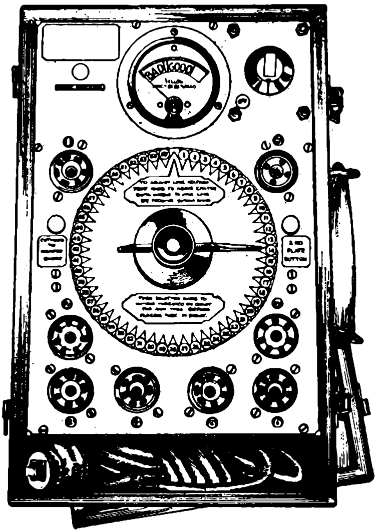


FIG. 227.—Panel of "Confidence" No. 6 tube tester.

The cap-to-socket connector mentioned in the Parts List (Table X) is an external connector used for certain tubes in order to apply a low positive voltage on the grid which has the external cap for its terminal.

Commercial Type of Tube Tester (Confidence No. 6).—A panel view of this testing device is shown in Fig. 227. The short-circuit indicator located at the upper left-hand side of the panel consists of a red pilot lamp which lights when the tube being tested has a short circuit from its plate or its screen grid to any other element, or a short circuit from its grid to its cathode. This pilot lamp, as indicated in the wiring diagram of Fig. 228, is connected between the $+H$ wire and one end of the middle secondary winding of the power transformer.

The *meter* has a scale which is marked "Bad" and "Good," to indicate the condition of a tube. One end of the meter circuit is connected to an end of the middle secondary winding of the power transformer. The other end of the meter circuit has three branches, one leading to the plate of the type 01A tube, one to a brass plate under the selector rotary switch, and one to a terminal of the push button that is marked "2nd plate button." This push button is located at the right-hand side of the panel, and below the tube socket marked No. 8. It is

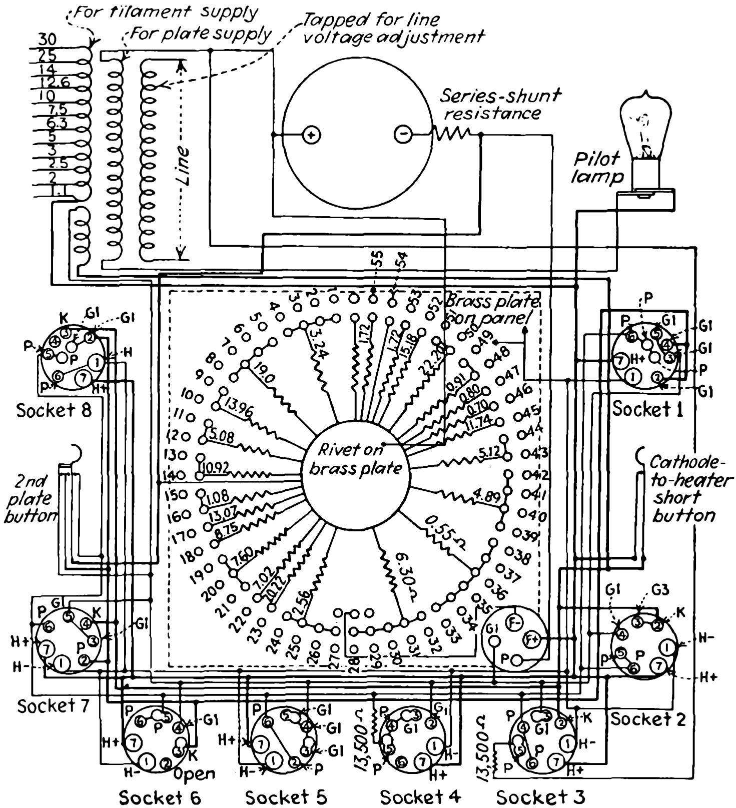


FIG. 228.—Wiring diagram of "Confidence" No. 6 tube tester.

used to provide a check on the current from the second plate of a tube having two plates.

The rotary switch at the upper right-hand corner of the panel is used in the adjustment for line-voltage variations. It is intended to select one of a number of taps on the primary winding of the power transformer, which is connected to the power-supply circuit.

The power transformer has two secondary windings, one of which has been mentioned in connection with the description of the meter. The other secondary winding is in two sections, one being used to supply the filament current for the tube to be tested, and the other being used to provide voltage to the *K* terminals and *G*1 terminals of the test sockets. It is also a part of the circuit connected to the "cathode-to-heater" push button. This push button is located on the left-hand side of the panel and below the tube socket marked No. 1. Power for operating the device is obtained through a cord-and-plug connection to any 110-volt, 60-cycle circuit.

Uniformity in these tube testers is obtained by means of a small resistance connected in series with the meter. This resistance may be adjusted to compensate for variations in the transformer, meter, cables, and so on.

The selector rotary switch has part of its mechanism above or on the panel and part below. Above the panel are the knob and pointer, and on the panel are the engraved numbers denoting certain switch positions. Below the panel are the pinwheel arrangement of switch points or contacts, and a central brass plate. This brass plate serves as a common terminal for the meter shunt resistances which are connected to the inner row of contact points. The outer row of contact points is connected to the taps marked 1.1 to 30 on the cathode secondary winding of the power transformer. The portion of the switch beneath the panel is so arranged that it turns two copper contact arms which make contact with both the inner and outer rows of contact points. These switch arms are placed in such a way that one is diametrically opposite the other; that is, when one is on point 14, for example, the other is on point 42. The wiring diagram shows how the connections are made to the various terminals of the eight tube sockets on the panel. The filament circuit connections are shown in Fig. 229.

Most commercial types of tube testers which are intended to give an indication of the transconductance (mutual conductance) of a vacuum tube perform the test by the application of arbitrary values of alternating voltages to the plate and grid, with one change in grid voltage. In this tester the

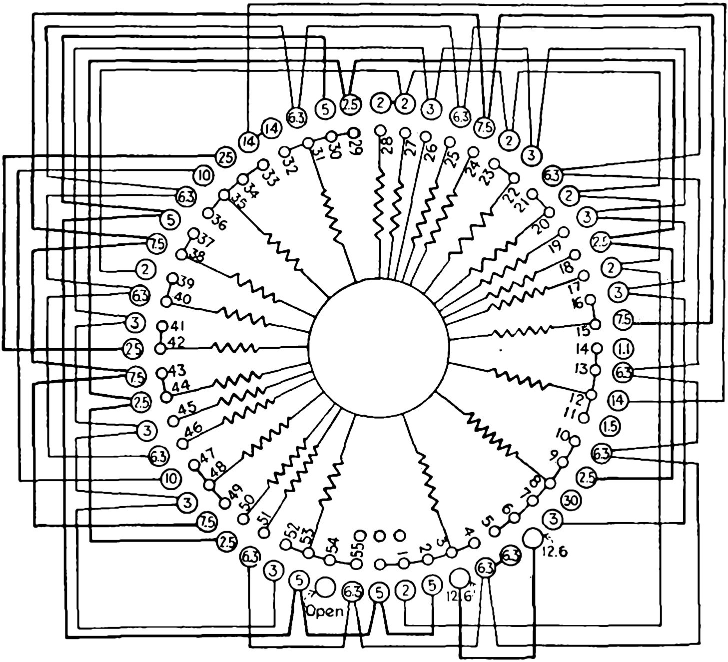


Fig. 229.—Filament circuit of "Confidence" No. 6 tube tester.

values of the operating voltages are such that the plate current is normally held high on the grid-voltage plate-current curve, and the test of the condition of a tube is made with a fixed value of grid-bias voltage on the grid. The circuit is designed so that the plate current cannot increase beyond a safe value.

Operating Directions.—The plug of the connection cord is inserted into any socket on a 110-volt, 60-cycle supply circuit.

In the adjustment for line voltage the selector switch is turned until it is in position between numbers 1 and 55. Then the rotary switch on the upper right-hand side of the panel is turned until the pointer of the meter reaches a mark at the center of the "Good" section of the meter scale. In this position of the selector switch its contact arm closes a circuit to light the filament of the type 01A tube which is enclosed in the device.

Next the selector switch is turned to the number for the tube being tested as given in the tube table provided with the instrument. Then the tube is inserted in the socket designated in the tube table. The condition of the tube is indicated by the meter reading. The portion of the Tube Table which follows is given to illustrate the general procedure:

Tube type	Selector	Socket	Test	Cathode
48	9	3	..	*C-H*

Tests of Multi-element Tubes.—Tubes of the multi-element type require special handling. The type 2A6, for example, which consists of a triode and two diodes, is tested as a triode for the triode portion, and as a diode for the other portion. All tubes having the multi-element construction are given separate tests for each portion of the tube. In the Tube Table such tests are indicated by the following abbreviations: "tri" for triode, "dio" for diode, and "pen" for pentode.

Tests of Rectifiers and Diodes.—A check on the current from the second plate of all full-wave rectifiers, except types 6Z4 and 84, is obtained by pressing the push button marked "2nd Plate." Tubes of the 6Z4 and 84 type are inserted in another socket for testing the current from the second plate.

Short Circuits.—In the test for a short circuit from the cathode to the heater of a tube, the button marked "Cathode to Heater Short" is pressed down. If there is no short circuit, the pointer of the meter turns to zero. If there is a complete short circuit from cathode to heater, the meter pointer retains its position temporarily and then gradually moves toward zero as the resistance of the short circuit increases.

The test for a short circuit from the grid to the filament is made by pressing the button marked "2nd Plate Button" and releasing it almost immediately. If there is no short circuit, the meter needle will swing to the extreme right. If there is a short circuit, the "Short Indicator" lamp will be lighted.

Any short circuit from plate or screen grid to any other tube element will make the "Short Indicator" lamp burn brightly. Some tubes which take a large current will cause the "Short Indicator" lamp to glow dimly but this glow does not indicate a short circuit.

Meter Readings.—If the test of a tube throws the meter needle to the extreme right of the scale marked "Good," the plate impedance of the tube is near the low limit, or the mutual conductance is near its high limit, or gas is present. A tube of this kind is no longer useful as a radio-frequency amplifier but might give satisfactory service as an oscillator or detector.

If the test of a tube throws the meter needle to the left end of the "Good" section of the scale the plate impedance of the tube is near the high limit, or the mutual conductance is near the low limit, or the emission is low. A tube having a high plate impedance might be used in a resistance-coupled amplifier, and a tube having low mutual conductance might serve temporarily in the first stage of audio-frequency amplification.

If the meter needle does not remain in a fixed position but creeps or swings from side to side, the elements of the tube are not functioning properly. In a case of this kind the cause may sometimes be located by tapping the tube lightly while it is being tested. A tube which gives erratic test readings probably will be noisy in a radio receiving set.

Commercial Type of Tube Tester (Supreme).—The instrument (Model 85) shown in Fig. 230 indicates the quality of a tube on the basis of "good" or "bad" transconductance (mutual conductance) emission, and leakage or short circuits between elements of the tube. Alternating voltages

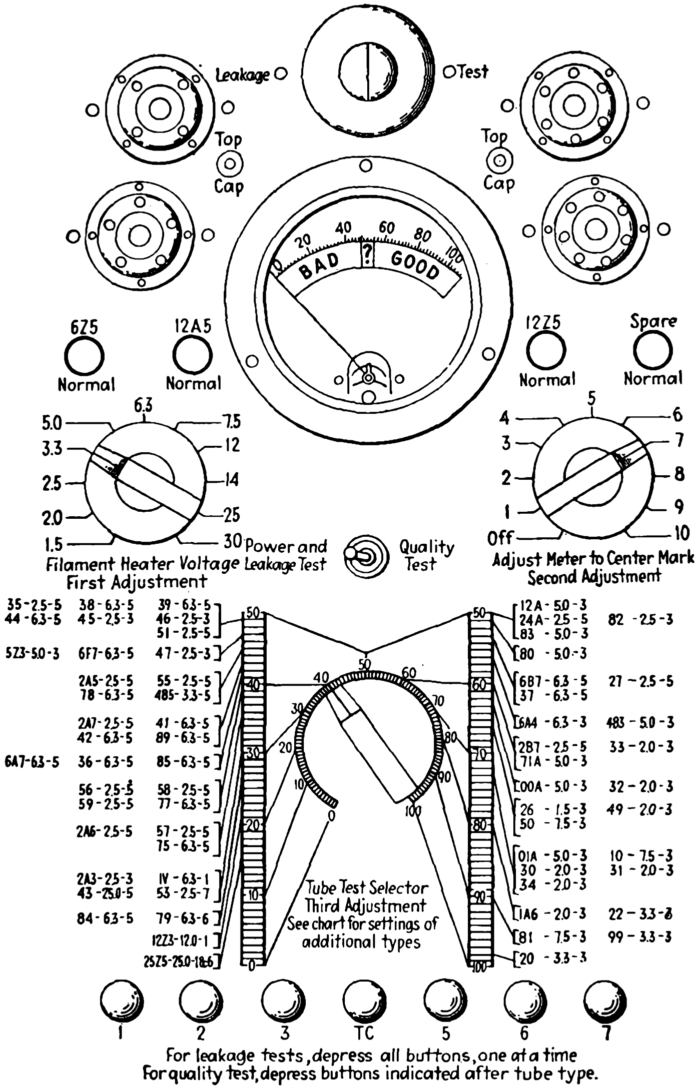


FIG. 230.—Panel of "Supreme" Model 85 tube tester.

are applied to all the elements of a tube subjected to tests. The wiring is such that all the elements of the tube inserted in a test socket are normally connected together. The

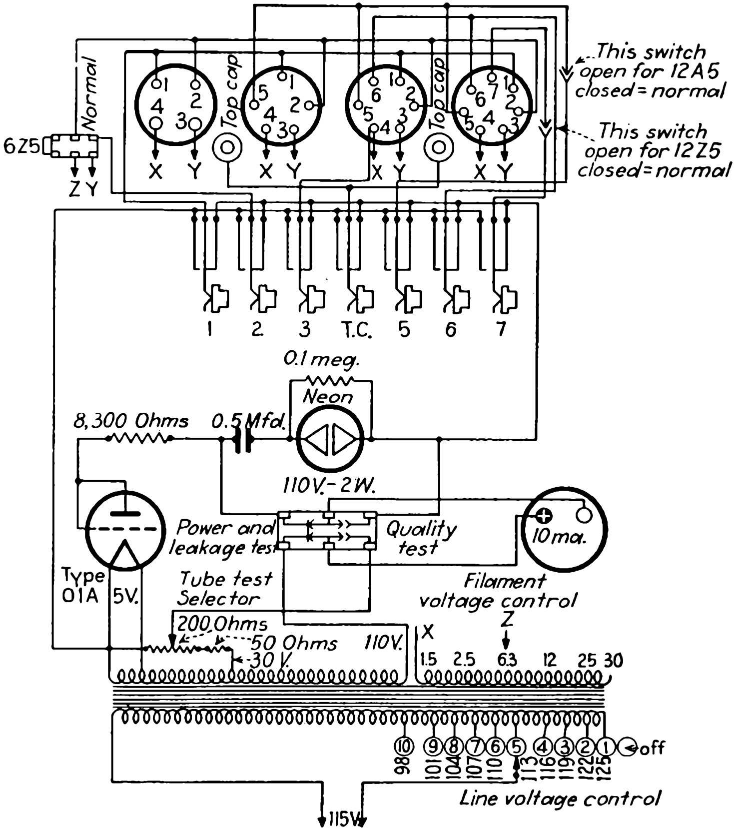


Fig. 231.—Wiring diagram of "Supreme" Model 85 tube tester.

operation of one of the numbered switches merely removes the corresponding tube element from electrical connection with the other tube elements. The rectified current for the tester is obtained from the type 01A tube which is provided with the testing device. This tube is shown in the wiring diagram in the lower left-hand side in Fig. 231. The neon tube, shown at the top of the panel, glows when there is a leakage current or a short circuit in the tube being tested. Four sockets are used in which the tubes are inserted when they are being tested; "four-pin" tubes being tested in the four-hole socket, "five-pin" tubes in the five-hole socket, etc. The wiring diagram shows the top views of the sockets. Below the sockets on the left-hand side of the panel are two switches, which are used in testing tubes of the 6Z5 and 12A5 types. Below the sockets on the right-hand side of the panel is a switch which is used for tests of the 12Z5 type of tube, together with one spare switch. The internal construction of the 6Z5 switch is the same as that of the toggle switch below the meter. The indicating meter in the center of the panel has a scale which is engraved to indicate "Good" or "Bad" readings. Below the meter on the left-hand side of the panel is a rotary switch which is used to select the proper filament voltage. This switch is shown in the wiring diagram of Fig. 231 as a variable contact in the filament secondary winding of the power transformer. The *X* terminal of the filament winding of the transformer is connected to each *X* terminal of the sockets. The *Y* terminals of the sockets are connected to the *Y* terminal of the switch marked 6Z5 and are shown in the upper left-hand corner of the wiring diagram. The *Z* terminal of the switch is connected to the *Z* terminal of the filament winding of the transformer. Below the meter on the right-hand side of the panel is a rotary switch that is used to make adjustments for variations in line voltage. This switch is shown in the wiring diagram as a variable contact in the primary winding of the power transformer. The toggle switch directly below the indicating meter is used to adjust the testing device for either the line voltage and leakage test, or for the quality test. On the lower half of the panel is a rotary switch marked "Tube-Test Selector." This switch, which acts on a variable resistance connected to a tap on the secondary winding of the power transformer, is used to select the voltage for the tube being tested. The seven cathode buttons at the bottom of the panel are used in both the leakage test and in the quality test, as explained in the section on operation.

The power necessary for operating this testing device is obtained from the ordinary 110-volt, 60-cycle alternating-current light socket by means of the cord and plug which are attached to the device.

Operating Procedure.—The first test to be made on the tube is the one for line voltage and leakage. To perform this test the toggle switch below the meter is set in the "Power and Leakage Test" position. Then the line-voltage adjustment is made by turning the rotary switch at the right-hand side of the panel until the pointer of the meter is at the center of the meter scale. Next it is necessary to consult a Tube Table provided with the instrument, in order to determine three values. In this table there are four columns of figures: the first gives the type of tube, the second gives the corresponding filament or heater voltage, the third gives the setting for the tube-test selector, and the fourth gives the number of the cathode button to be used in the test. The portion of the Tube Table which follows is given as an illustration.

Tube type	Filament voltage, volts	Tube-test selector	Cathode button
1A6	2.0	76.5	3

After these values are noted for a given type of tube, the rotary switch at the left-hand side of the panel is set to the proper filament or heater voltage. The tube is then placed in the proper socket, and the top cap terminal (if any) is connected to one of the top cap-pin jacks.

After these adjustments have been made, the test for leakage can be performed. To carry out the leakage test the cathode buttons are pushed down, one at a time, in order to obtain an indication of leakages or short circuits by the glowing of the two elements of the neon lamp. It must be kept in mind that a flicker of one element of the neon lamp indicates a discharge of a condenser rather than a defect in the tube. A leakage circuit which comes into action only intermittently may sometimes be detected if the tube is tapped slightly at the time the cathode button is pushed down. The numbering of the cathode push buttons corresponds to the numbering of the pinholes in the sockets, as shown in the wiring diagram. Thus, when button number one is pressed, the tube electrode connected to number one hole in any socket is removed from electrical connection with the other electrodes but is joined to the return circuit leading to the secondary winding of the transformer. The particular electrode of a tube in any socket can be identified with the help of the Socket Chart which is given on pages 305 and 306.

Quality Test.—After the preliminary adjustment of the device has been completed and the leakage test has been carried out, the tube may be tested for quality. For this test the toggle switch is thrown to the "Quality Test" position. Then the rotary switch of the tube-test selector is turned to the proper position, and the proper cathode button as indicated in the Tube Table is pushed down to obtain a meter reading. When the cathode button is pressed a return connection is made between the filament circuit and the other electrodes of the tube. After this test has been made, the rotary switch at the right-hand side of the panel should be turned to the "Off" position.

If the wrong button is pushed down, no harm results to the testing device and the pointer of the meter either does not move or moves slightly backward. In the quality test the pointer moves forward only when the correct button is pushed down. The setting of the tube-test selector switch is not critical. It may be moved to the end of its travel during the test on a tube without injuring either the meter or the testing device. An incorrect setting of the filament or heater voltage switch will not injure the testing device but may burn out the cathode of the tube.

Action of the Leakage-test Circuit.—The neon glow lamp used for this test is of the 110-volt, 2-watt type. The glow lamp is used instead of a meter or a pilot light for the leakage test because it does not have the mechanical inertia of a meter movement or the thermal lag of a pilot-light filament. This neon glow lamp is affected only by leakage voltages and not by rectified voltages because it is connected in series with a blocking condenser (page 256). During a leakage test one element of the lamp may flicker when one cathode button is pushed down, and the other element of the tube may flicker when another button is pushed down. Thus, in a test on a type 27 tube, one lamp element flickers when button number one is pressed down and the other element flickers when button number five is pressed down. This flickering is caused by the alternate charging and discharging of the blocking condenser.

A leakage or short circuit between any two elements of a tube will cause both elements of the neon lamp to glow when the two buttons corresponding to the tube elements are pressed down. For instance, a short circuit between the control grid and screen grid of a type 35 tube is detected when the *TC* button is pushed down and again when number one button is pushed down.

Slow-heating Filament.—The filaments of some tubes heat very slowly, in some cases, more slowly than indirectly heated cathode types. In extreme instances a heating period of 2 minutes may be necessary before a normal operating condition is reached.

Tubes with Three Heater Pins.—Some types of radio receiving sets intended for ordinary service are provided with vacuum tubes having filaments which may be operated on either 6-volt or 12-volt batteries. Such tubes may be designed with three heater pins. This indicates that such a tube has two 6-volt filaments which are connected in series internally with one external pin for each end of the combined filaments and one pin for the common ends. Thus, the tube may be operated from a 6-volt source with connections to one outside pin and to the common pin, or from a 12-volt source with connections to the two outside pins. Likewise, when such a tube is tested, the filament may be operated on either 6 or 12 volts. In this device, however, a filament voltage of 12 volts is applied so that the test will include the entire filament.

Switches are provided for use in tests on tubes of the 6Z5, 12A5, and 12Z5 types. These switches should be set in the position marked "Normal," except when one of these tubes having three heater pins is being tested, in which case the switch is used as indicated in the Tube Table. These switches serve to open the heater center-pin connections so that both portions of the filament are in series during the test.

Kellogg Tubes.—A Kellogg tube of the 401 or 403 type has a heater terminal located at the top of the tube. The top heater terminal must be connected to the filament contact of one of the sockets which is not being used. The tube itself is placed in the four-hole socket.

Diode and Multi-plate Tubes.—In this device the plates of full-wave rectifiers and of the diode-detectors are tested in parallel. An individual test on each plate, however, may be obtained by a change in the operating procedure.

The following instructions apply in the case of the type 82 tube. If the No. 1 button is pushed down together with No. 3 button during the quality test, the meter indication is for the current from the second plate. Then, if the No. 2 button is pushed down together with No. 3 button, the meter indication is for the current from the first plate. The same procedure may be used for a comparison of the plate currents of diode detectors and of full-wave rectifier tubes which have single-filament elements or filament elements connected in parallel. If a full-wave rectifier tube has two filament elements in series, a comparison of the plate currents cannot be made unless a special testing circuit is devised. In the tube tester described here, the plate voltage is measured from the filament pin which carries the plate and filament currents from the tube. Consequently, if a tube having a series filament is tested, one portion of the filament will be positive with respect to the other portion by half the filament voltage, and, therefore, the effective voltage acting on the two plates is not the same. However, the two parts of a series filament carry the same current, and the assumption may be made that one part will deteriorate at the same rate as the other. In general, the full-wave rectifier tubes of the 2.5-volt type have parallel filaments, and rectifiers of the 5-volt type have series filaments.

Rectifier tubes of the mercury vapor type show wide variations when tested in this device. The pointer of the meter may swing beyond the end of the scale during the tests of some of these tubes for which the tube-test selector adjustment may appear critical.

Future Tubes.—It is possible with this testing device to establish the settings for any new tubes that may appear. In the procedure for obtaining these settings the toggle switch is moved to the position marked "Power and Leakage Test," and the rotary switch for line-voltage adjustment is moved until the pointer of the meter is at the center of the scale. The rotary switch for the setting of the filament-voltage control is turned to the number which corresponds to the filament- or heater-voltage rating of the tube. Then the tube is inserted in the socket which will accommodate it, and the top cap terminal (if any) is connected to one of the top cap-pin jacks, the toggle switch being moved to the position marked "Quality Test." Next the button switches are pushed down in turn, beginning with No. 1 until the pointer of the meter moves to the right; the button which caused a movement of the pointer must be held down while the other buttons are tried in turn to determine whether they will increase the meter indication. The buttons which produce a forward movement of the meter pointer should be recorded in the fourth column of the Tube Table. Next, with the proper buttons held down, the rotary switch of the tube-test selector is adjusted until the pointer of the meter indicates a value of 77 which appears at the center of the section of the scale marked "Good." Then, with the meter pointer held at 77, several new tubes should be checked, to obtain values for the setting of the tube-test selector. The average of the tube-test-selector values may be recorded in the third column of the Tube Table. The values for the first and second columns of

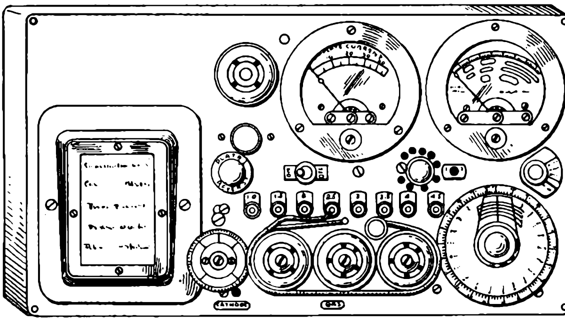


FIG. 232.—Panel of Hickok Model AC-47 tube tester.

the Tube Table can be obtained from the published tube specifications.

Commercial Type of Tube Tester (Hickok).—The device (model AC-47) shown in Fig. 232 is designed to test all types of tubes, with provision for additional sockets to accommodate new types. The electric power for the test is obtained through a type 80 rectifier tube and a B-eliminator from a 110-volt, 60-cycle supply circuit. No batteries of any kind are needed. This arrangement provides direct current for the plate and grid circuits and also allows the application of an alternating-current voltage to the grid.

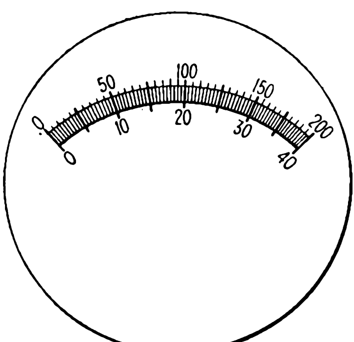


FIG. 233.—Dial of plate milliammeter in Hickok Model AC-47 tube tester.

The *voltage control* adjustment affords a means of compensating for line voltage changes. The test readings are indicated on a direct-current milliammeter and a mutual conductance meter with an average accuracy of 1 per cent. The meter dials are shown enlarged in Figs. 233 and 234. The wiring diagram of the device is given in Fig. 235. The device is protected from possible damage from short circuits by a fuse lamp in series with the primary winding of the power transformer. This lamp burns dimly under normal operating conditions.

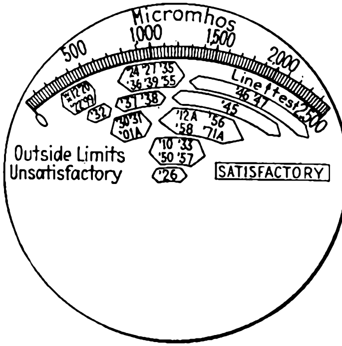


FIG. 234.—Mutual conductance meter in Hickok Model AC-47 tube tester.

The purpose of the instrument is to test a tube for the value of plate current, gas content, and mutual conductance. The plate-current indication is the result of the application of a direct voltage to the plate of the tube, a grid-bias voltage to the grid, and an alternating current through the filament.

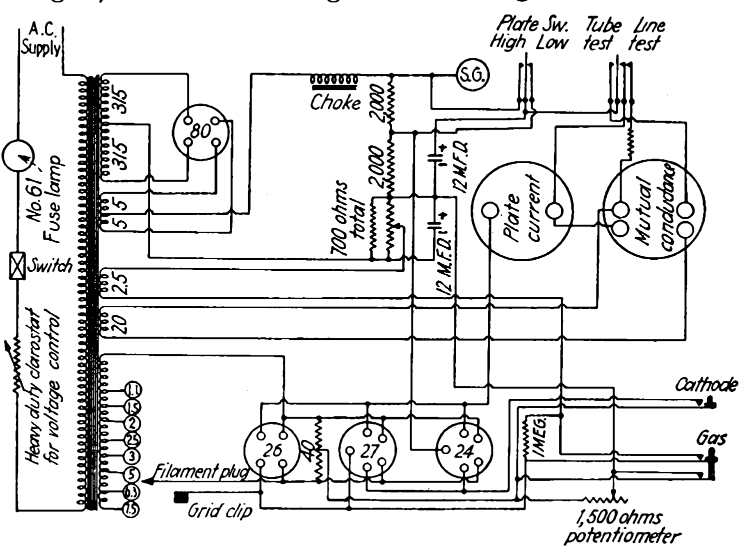


FIG. 235.—Wiring diagram of Hickok Model AC-47 tube tester.

The mutual-conductance reading as given by this instrument measures the change in plate current due to a change in grid voltage. This is accomplished by applying an alternating-current voltage to the grid and measuring the resultant alternating-current component of the plate current.

Testing Rectifier Tube for Use in the Tester.—The type 80 rectifier tube used in this device should be tested occasionally for emission. For this test, the tube is inserted in the socket marked 80 and the "High-Low" switch is set in the "Low" position if the milliammeter scale has a range of 0 to 35, and in the "High" position if the scale range is 0 to 50. The *test plug*[1] marked 280 is inserted in the socket for a type 27 tube, the "Tube Test-Line Test" switch is turned to the "Line Test" position, and the voltage control is adjusted until the mutual-conductance meter shows a reading of 2,000. Then, with the switch in the "Low" position, the milliammeter should show a reading of 19 to 21 milliamperes, or 39 to 42 milliamperes with the switch in the "High" position. A reading of the current from the other plate is obtained by inserting the multiplex socket *A* in the tester, observing the indication of the mutual-conductance meter, operating the No. 2 plate button, and again observing the indication of the mutual-conductance meter. If no change is observed, the emissions from the two plates are equal.

Adjustment for Line-voltage Variation.—The type 80 rectifier tube should be in the type 80 socket, and the tube to be tested should be inserted in the proper location. The "Line Test-Tube Test" switch is set in the "Line Test" position and the rheostat control (located between the two meters) is adjusted until the mutual-conductance meter shows a reading of 2,000, this point on the meter dial being also marked "Line Test." The "Line Test-Tube Test" switch may be turned to the "Line Test" position at any time during the test of a tube in order to check the line voltage.

Procedure for Tube Testing.—The tube to be tested is inserted in the socket for that type according to the specifications accompanying the device. The filament voltage which the

[1] This test plug consists of a resistance unit provided with base terminal pins and is used to place a load in the plate circuit.

tube requires is applied by placing the filament-voltage change plug in the proper position as determined by the value given in the specifications. The correct value of grid-bias voltage is obtained by turning the *potentiometer* (located at the lower right-hand corner of the panel) until its pointer is over the type number of the tube as marked on the dial. The plate current is read on the milliammeter and the mutual conductance on the other meter.

If a change in the mutual-conductance reading is noticed when the observer's hand is placed on or near the tube, the plug in the alternating-current-supply line should be reversed.

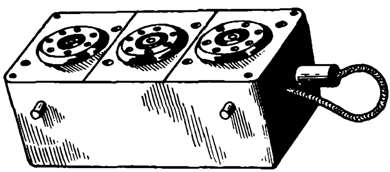


FIG. 236.—Multiplex socket for Hickok Model AC-47 tube tester.

A test on a ballast tube, type 6AA or type 10AB, can be obtained by setting the filament voltage at 1.1 and inserting the tube in the type 01A socket. The tube condition is satisfactory if the filament burns with a dull red color.

Multiplex Sockets.—The testing set is provided with sockets for type 24, 26, and 27 tubes. Other types of tubes may be tested by the use of the multiplex fitting which is illustrated in Fig. 236. This fitting contains three additional sockets (*A*, *B*, and *C*) and is designed for insertion in the sockets of the testing set. The sockets in the fitting are marked to indicate the tube types which they can take.

The general instructions which follow apply to the use of any one of sockets *A*, *B*, or *C*. After the multiplex fitting has been inserted in the sockets of the test set, the tube to be tested is inserted in the proper socket of the fitting. The plug on the right-hand end of the fitting is connected according to the type of tube. The regular instructions as to filament voltage, plate voltage, and potentiometer setting are to be followed. A reading on the plate milliammeter, as obtained in a test on a rectifier tube, gives the current from one plate only. A reading of the current from the other plate is obtained by pressing the "No. 2 Plate" button which is located on the side of the fitting. All rectifier tubes should give a reading of 39 to 42 milliamperes per plate, with the plate switch in the 180-volt position. In this case the "Test Plug" push button on the fitting is used instead of the test plug of the test set.

Short Circuit in Tube.—Short-circuited electrodes in a tube being tested will result in an increase of current flow. The effect of this current increase in the primary winding of the power transformer is to cause the fuse lamp to burn more brightly or even to burn out. The fuse lamp serves in this way to indicate a short circuit in the tube.

A short circuit between the filament and cathode may be detected by the use of the "Cathode" push button at the left-hand side of the type 26 socket. This button is pressed while a tube is being tested and the two meters are observed. These meters indicate zero if there is no short circuit between the filament and cathode. If the pointers of the meters do not indicate zero, there is a leakage of current between the filament and the cathode.

Noisy Tubes.—If the indications of the milliammeter and the mutual-conductance meter show a change when the tube being tested is tapped gently with the finger tips, the tube generally will be noisy in a radio receiving set.

Gas Test.—The test for gas is made by inserting a high resistance in the grid circuit, and then restoring the plate current to its original value by the insertion of sufficient resistance in the cathode circuit. There are several steps in the complete operation. First, the tube is tested for plate current and mutual conductance. Then the dial at the left of the type 226 socket is set to zero and the "gas" button is pressed down. If the plate-current reading shows an increase, the tube contains gas. Next the plate current is brought back to its original value by adjustment of the gas content dial. At this point the "gas" button should be pressed several times rapidly and a final adjustment should be made for the plate-current reading if any change is noted.

The "gas" dial is marked with average permissible values for gas content. A more exact indication of the amount of gas may be obtained from a reading of the grid current. After the plate current has been balanced as above, the value of the grid current in microamperes is found by multiplying the reading in ohms on the "gas" dial by the plate current in amperes. For example, with a plate current of 25 milliamperes and a "gas" dial setting of 200 ohms, the grid current in microamperes is 0.025×200 or 5.

Test Results.—The values for plate current and for mutual conductance as given in the specifications are the average values provided by the tube manufacturers. In some cases, however, the manufacturer's values have been changed to indicate the results that may be expected in a tube tested at the plate voltage supplied by the testing device. A tube which yields results that are 25 per cent more or less than the values given in the specifications will operate satisfactorily in most cases in a radio receiving set. Output tubes usually can be used even if the mutual conductance values are 35 per cent more or less than the tabulated figures. If best results are expected, however, tubes of the same type for a given radio receiver should be as nearly alike as possible, particularly those used in radio-frequency amplifiers, and in push-pull stages. A soft tube (page 22) when tested shows a plate current which is above average, and a mutual-conductance value which is below average.

Commercial Type of Tube Tester (Weston).—The panel, or top, view of Model 661 is shown in Fig. 237. This device is designed for operation from an alternating-current line, 100 to 130 volts, 50 to 60 cycles. The maximum power consumption is 30 watts. Tubes of the 4-prong, 5-prong, 6-prong, large 7-prong, and small 7-prong types can be tested in this device. Seventeen sockets are located on the upper half of the panel. The meter is of the permanent-magnet, moving-coil type, having a range of 6 milliamperes and a resistance of 20 ohms. The meter scale has 60 divisions with a center mark to be used in the line-voltage adjustment, two ranges being provided so as to allow for readings on all types of tubes. The rotary switch on the lower left-hand side of the panel is used for the line-voltage adjustment. The right-hand switch

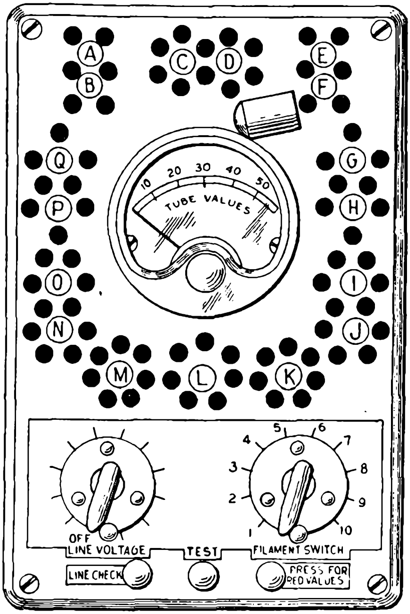


FIG. 237.—Panel of Weston Model 661 tube tester.

provides the control for filament voltage. There are three push buttons near the bottom of the panel, the left-hand one being used in the line-voltage adjustment, the middle one in the tube test, and the right-hand one to provide an extra range for the meter.

This device applies alternating voltage for the filament, plate, screen, and grid electrodes. The condition of a tube under test is indicated by the change in plate current when a change is made in the grid voltage. The grid voltage change is applied through the circuit connected to the button marked "Test," as shown in the wiring diagram of Fig. 238.

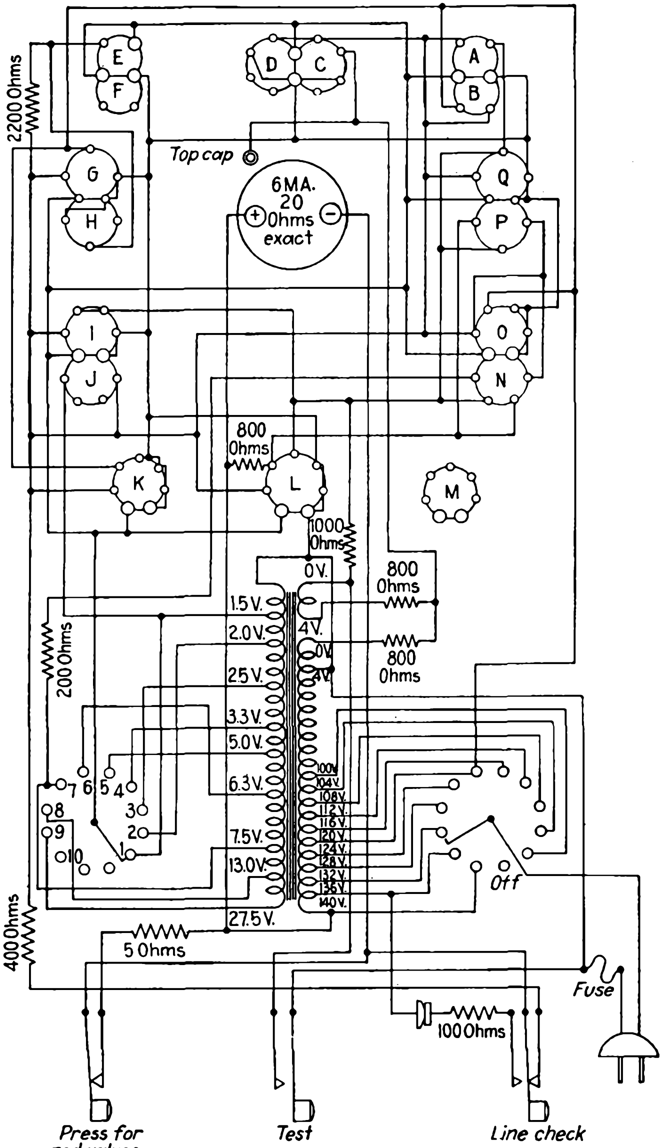


Fig. 238.—Wiring diagram of Weston Model 661 tube tester.

Operating Procedure.—The first step in a test is the adjustment for line voltage. After the connecting plug is attached to a 110-volt supply circuit the pointer adjustment *on the meter* is turned until the pointer is at zero. Then both of the rotary switch controls are turned to the left to the "Off" position. Next the "Line Check" button is pushed down. This completes a circuit, as shown in Fig. 239, consisting of several turns of the primary winding of the transformer, the meter with its shunt, and the contact rectifier for changing the alternating current to direct current. Finally the "Line Voltage" switch is turned until the voltage tap selected is such that the meter pointer moves to the center mark of the scale. Unless this adjustment is made, the test values given in the specifications with the instrument are valueless.

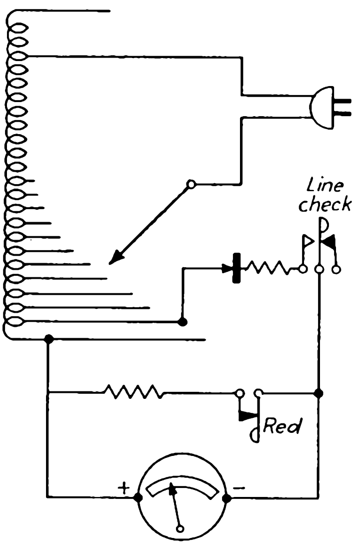


FIG. 239.—Circuit in line-voltage adjustment for Weston Model 661 tube tester.

The Tube Table in the specifications is arranged in such a way that each type of tube is assigned a certain filament setting, a certain socket, and a minimum value for the test reading of the meter. The portion of the Tube Table which follows is given to show how the values are used.

Tube type	47	48	49	50	52	53	55	56	57	58	59
Fil. switch	3	9	2	7	6	3	3	3	3	3	3
Socket	P	N	P	A	P	L	J	Q	O	O	L
Minimum	9.0	4.8	7.2	9.5	9.0	19.0	21.0 *R*	8.2	20.0 *R*	23.0 *R*	8.5

The tube test is carried out by setting the filament switch to the number given in the Tube Table and this switch selects a certain tap on the secondary winding of the transformer. Then the tube to be tested is inserted in the proper socket and the "Top Cap" wire is attached, if the tube has a top terminal. This top-cap wire supplies the necessary grid voltage. After the tube has been normally heated, the meter pointer is brought back to zero. Next the button marked "Test" is pushed down and the meter reading is observed and compared with that given in the Tube Table. If the value

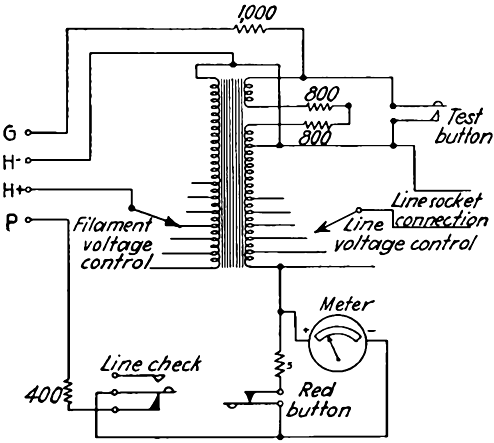


Fig. 240.—Simplified circuit diagram showing connections to socket *A* in Weston Model 661 tube tester.

given in the Tube Table is marked *R*,[1] the button marked "Press for Red Values" must be held down, and the meter set to zero before the test button is pressed. When the red button is pressed, a resistance is connected in parallel with the meter. The simplified diagram in Fig. 240 shows the connections to socket *A* and the circuits used in the test of a tube intended for that socket.

Rectifier Tubes.—In a test on a rectifier tube the filament switch and socket number are selected from the Tube Table. The tube is inserted in the socket and the meter reading is observed. The meter should not be set to zero and the test button should not be touched.

[1] In the table provided with this tester these values are printed in red.

A check is obtained on the current from the second plate of a full-wave rectifier tube by removing the tube, turning it 90 degrees clockwise, inserting it again in the socket, and observing the meter reading.

Commercial Type of Tube Tester (Dayrad).—The panel view of this tester (series 14) in Fig. 241 illustrates the various

Fig. 241.—Panel of Dayrad Model 14 tube tester.

controls. Four sockets for different types of tubes are provided, one of these being left unconnected to take care of *new types of tubes.* The alternating-current meter located in the upper center of the panel has a range of 5 milliamperes and a resistance of 20 ohms. The left-hand half of the meter scale is marked "Poor" and the right-hand half is marked "Good." The operating voltages are such that the meter indication for a normal tube will be in the "Good" section of the meter scale.

Operating Procedure.—Power is obtained from any alternating-current supply circuit having a voltage of 105 to 125 volts and a frequency of 60 cycles per second. The connection is made through the cord and plug on the instrument. Adjustment for line-voltage variation is obtained by means of the

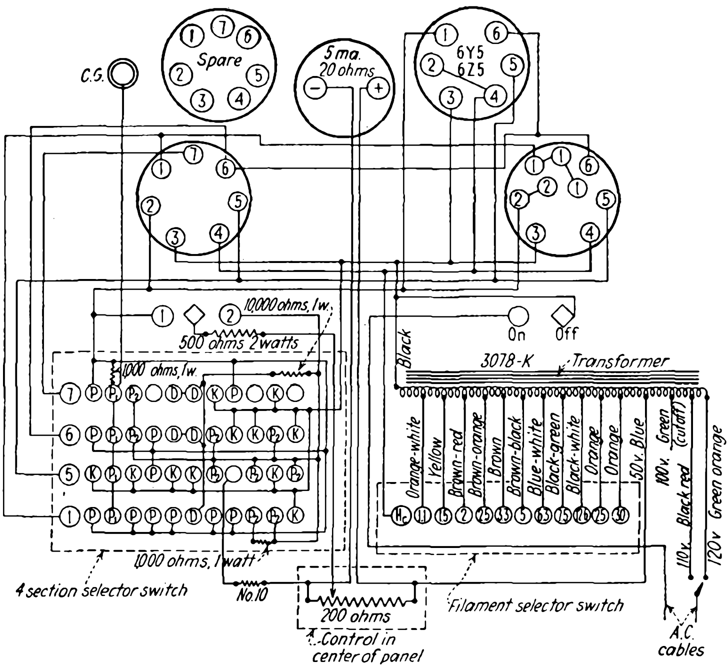


FIG. 242*a*.—Wiring diagram of Dayrad Model 14 tube tester.

toggle switch shown in the right-hand side of the autotransformer in Fig. 242*a*.

A chart which is provided with the instrument lists for each type of tube the value of filament voltage, selector adjustment, and plate adjustment. When these settings are made, and the tube which is to be tested is inserted in the proper socket, the meter gives an indication of the condition of the tube. During this test the switch on the lower righthand side of the panel should be in the "1st Test" position.

Operation of the filament switch serves to select an alternating-current supply for the filament circuit. The switch-point contacts are connected to taps on the coil winding of the auto-transformer.

The selector switch is made with four sections arranged as shown in the wiring diagram of Fig. 242*a*. The purpose of this switch is to provide the necessary alternating-current voltages for the grid and plate circuits. An explanation of the wiring of the selector switch will show how this is accomplished. The selector switch is of the four-section type with 11 contact points on each deck. As shown in Fig. 242*a* there are four rows of circles, each row representing one section or deck of the switch. The large circle at the left-hand end of a row represents the rotating arm of the selector for that row. When the selector knob is rotated the arms make contact with the points on the four rows. Thus when the selector knob is in the position marked "1" on the panel dial, arm 1 is connected to *P* (plate), arm 5 to *K* (cathode), arm 6 to *P* (plate), and arm 7 to *P* (plate). The 11 points of the switch are interconnected in such a manner that the voltages required for the plate, cathode, diode unit, first plate, and second plate, can be obtained for any tube now available.

The plate-adjustment control consists of a 200-ohm variable resistance connected in parallel with the meter.

Duplex, Diode, and Rectifier Tubes.—A duplex tube such as type 2A7, or type 6F7, is listed twice on the Tube Chart; that is, there are two groups of values for the control adjustments to show that two tests are necessary. The first test is made in the usual manner. Then the second group of control settings is used and the toggle switch on the lower right-hand side of the panel is placed in the "2nd Test" position. This connects the meter into the second-plate circuit. When the test is completed, the toggle switch should be returned to the "1st Test" position.

The general procedure for tubes of the diode type and the rectifier type is the same as outlined above, with specific directions given on the tube chart of the instrument.

Heater-to-Cathode Leakage Test.—In this test the tube is first checked in the usual manner. Then the selector switch is turned to a given position which releases the cathode connection. If there is any leakage between heater and cathode the meter will show an indication.

Short-circuit Tests.—This instrument is not arranged to indicate directly a short circuit between the electrodes of a tube. The meter reading however can serve as a general indication of short circuits because connections between certain electrodes have definite effects on the deflection of the meter. Detailed information about these relations is provided.

Commercial Type of Tube Tester (Triplett).—The instrument (model 1210-A) shown in Fig. 242*b* is designed to test *both metal and glass types* of tubes. The panel has four sockets, a direct-reading meter with a "Bad-Good" scale, three selector switches, one load control knob, one push button which is used to indicate the quality of the tube being tested, and one push button which is used to give separate readings for double-plate tubes.

The circuit arrangement is such that the meter indication depends on an emission test of the tube. The rectifier tube included in the device is of the 01A type. Cathode-leakage tests and short-circuit tests also can be made with this instrument. Operation is from a 60-cycle, 100 to 300-volt alternating-current line.

Dynamic Characteristics from Bridge Measurements.—For some laboratory requirements the "dynamic" characteristics of a tube are of more fundamental importance than the static values. To obtain such data it is necessary to apply an alternating-current potential to the tube and to make use of certain balanced-bridge measurements.

A commercial type of bridge is available which serves as a direct-reading device giving the following three fundamental dynamic characteristics of a tube: (1) amplification factor, (2) plate resistance, and (3) mutual conductance. A vacuum-tube bridge of this type is provided with suitable controls for the measuring circuits, tube sockets for various types of tubes, a transformer with the necessary controls for supplying alternating current to the filament circuit of the tube to be tested, terminals for battery connections, and a voltmeter for reading filament voltages. The auxiliary equipment consists of a source of supply voltage for the plate and grids of the tube, a

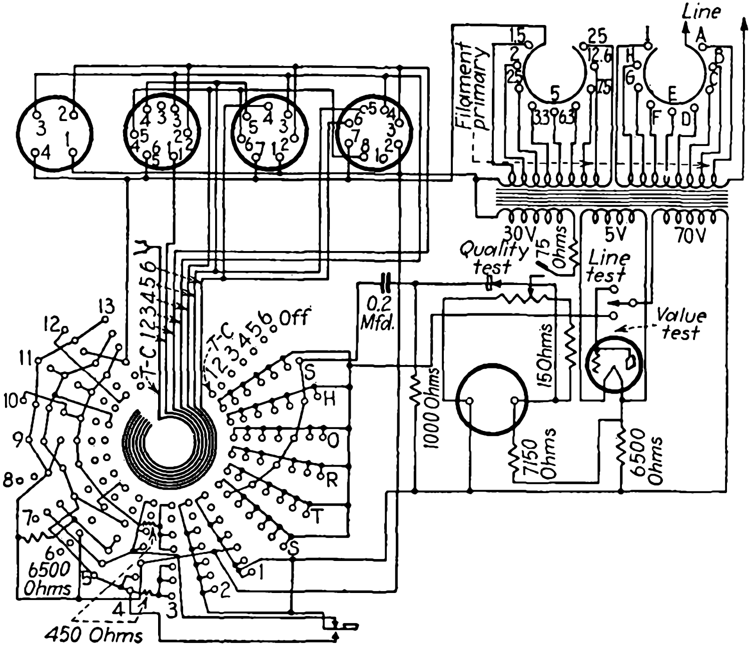


FIG. 242b.—Wiring of Triplett tube tester.

source of power supply at a frequency of 1,000 cycles per second, a pair of head-set telephone receivers, and a sensitive amplifier.

The procedure for the determination of each of the characteristics is the same. A control switch is turned to point toward the characteristic desired as indicated on a dial. Then circuit adjustments are made to provide the appropriate conditions for the tube to be tested. Next a balance is obtained by the adjustment of resistance switches and a capacity-balancing condenser. At the point of balance the characteristic can be read directly from the position of the resistance switches.

REACTIVATION OF VACUUM TUBES

Reactivation of Thoriated-tungsten Filaments.—Modern types of vacuum tubes for radio receivers are constructed with coated filaments, or with filaments of the heater type (also termed heater cathodes, unipotential cathodes, equipotential cathodes, or merely *heaters*). A filament of the coated type, or of the heater type, reaches the end of its useful life when it becomes inoperative because of loss of emission. Such a filament or cathode cannot be reactivated, and would be burned out by the application of the high voltage used in the reactivating process. Information as to the type of filament or cathode used in a tube is given on the data sheet placed in the tube package, or may be obtained from the manufacturer.

Thoriated-tungsten filaments are found in the following types of tubes: 00A, 01A, 10, 20, 40, and 99. The action of the thorium-oxide layer on the thoriated-tungsten filament of a vacuum tube is such that, when the filament is heated, some of the thorium oxide is reduced to metallic thorium and works out to the surface of the filament. When the vacuum tube is in use, this surface layer of thorium gradually evaporates and is replaced at the same rate by fresh thorium from the interior of the filament. This process continues uniformly throughout the life of the tube provided the normal temperature of the filament is not exceeded. If the temperature is raised a few hundred degrees above the normal temperature, corresponding to a voltage overload of about 10 per cent of the rated value, the balance between surface evaporation of thorium and its supply is disturbed and the active thorium layer is completely evaporated, leaving a plain tungsten surface from which the *filament emission* rapidly decreases. If the operator further increases the filament voltage, the overload on the tube is increased so much that no filament emission is obtained. The filament then is "paralyzed" but can be restored by *reactivation*.

Need for Reactivation. Emission Test.—An indication of the condition of a vacuum tube for filament emission is readily obtained by an *emission test.* In the test for filament emission described on page 253 the current for producing filament emission is set at a certain low value of filament voltage which is needed to produce the required amount of emission.

Voltages higher than those given in the table on page 253 must not be used because of the danger of damaging or possibly even burning out the tube. If the value of emission current indicated on the milliammeter in this test is above the minimum value specified in the table, the tube filament is in good condition and reactivation is not necessary.

The value of plate current, when the tube is operated at rated voltages, is not an accurate measure of filament condition. The reason for this is that small variations in the constants of the tube (especially the amplification factor) cause much greater variations in the plate current, even though the performance of the tube is not appreciably affected. If, however, the plate-current reading is low, and increases rapidly as the filament voltage is increased slightly above the rated value, it is likely that the filament is becoming inactive. If the plate-current reading of a used tube is less than 80 per cent of the reading when the tube was new (provided the operating voltages in each test are the same), improvement will result from reactivation.

Methods of Reactivating.—The kind and degree of overload which has been put upon a tube determine the method to be used in reactivating the filament.

First Method.—Tube filaments which have been overloaded only slightly may be reactivated by a simple process. According to this treatment the filament is burned at its normal voltage for from 10 to 20 minutes. During this treatment no voltage is applied to the grid or plate of the tube. Then an emission test is made. If the emission shows no improvement, it is evidence that the tube has been overloaded heavily over a long period of time. In such a case, the second method of reactivation, as described below, should be tried.

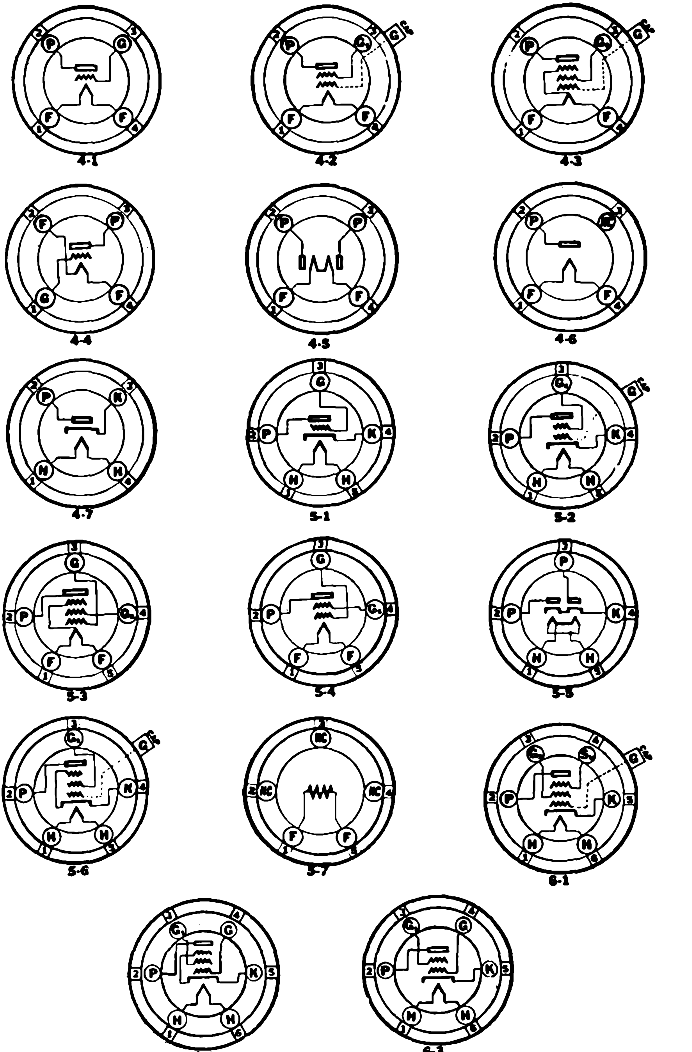


Fig. 243*a*.

Figs. 243*a* and *b*.—Diagrams of typical tube bases (viewed from bottom of base).

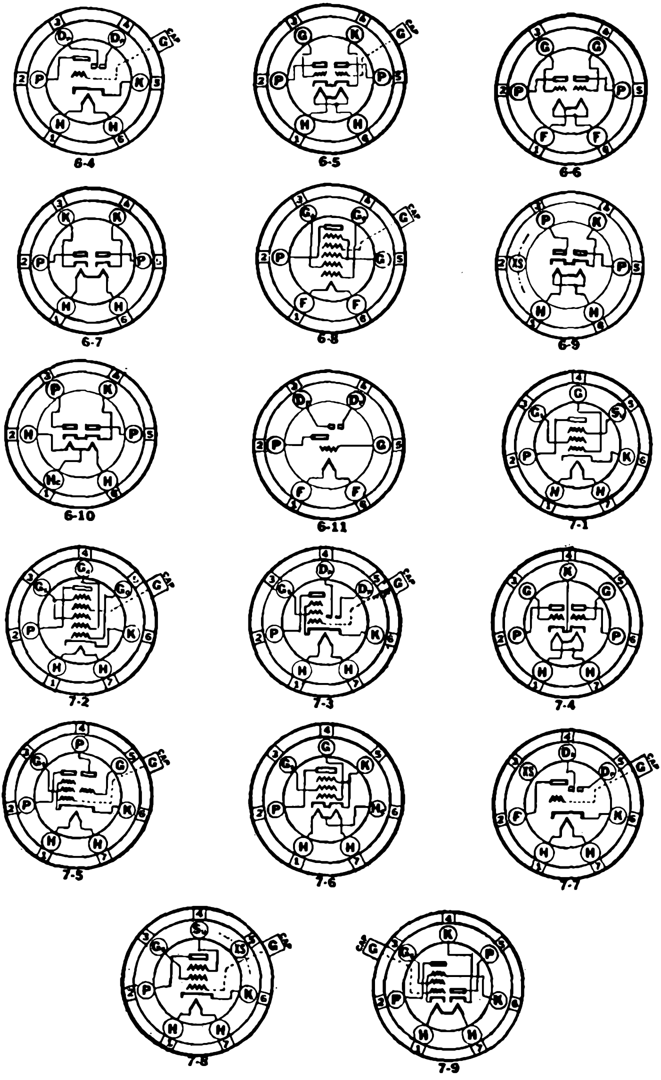


FIG. 243*b*.

Second Method.—According to the second method the filament is first "flashed" at three times its normal voltage for from 30 seconds to one minute.

This treatment accelerates the rate at which the thorium works out of the interior of the filament to the surface. Since there is no voltage on the grid or plate, the evaporation of thorium from the filament surface is slow.

The filament is then seasoned for a period of 10 minutes at 1.5 times its normal voltage. During these operations no grid or plate voltages are applied. If the emission current shows no improvement at the end of this period, the tube cannot be reactivated.

The high temperature developed in flashing is necessary to "strip" or clean the filament surface. After this step, which, in effect, completely paralyzes the filament, the seasoning voltage is applied in order to form another layer of fresh thorium on the filament surface. It must be expected that a small percentage of tube filaments will burn out when the flashing voltage is applied.

Tube-base Connections.—The connections between the base-terminal pins and the electrodes of radio vacuum tubes are shown in the charts in Figs. 243*a* and 243*b*. It should be noted that each diagram in these figures represents a view of the *bottom* of the base. The pin numbers on the base diagrams follow the system recently standardized by the Radio Manufacturers Association. According to this system, if the base of the tube is held toward the observer in such a way that the heater pins are at the bottom (the heater pins are larger in diameter than the others) then the left-hand heater pin is number one. The other pins are numbered consecutively in a clockwise direction.

The symbols used to designate the electrodes are given in Table XII as shown on page 308.

Each base diagram is identified by the number shown beneath the diagram in the figures. A diagram of this kind by itself would not serve to indicate the type of tube which is provided with such a base so that it is necessary to show also the relation between the base diagram and the type of tube. This is given in two of the tables which follow, the one (Table XIII) showing the base diagram number for each type of tube, and the other (Table XIV) showing the tube type or types which have similar bases.

TABLE XII.—ELECTRODE SYMBOLS

Dp	Diode plate	*Hc*	Heater center
F	Filament	*K*	Cathode
G	Control grid	*Nc*	No connection
Ga	Anode grid	*P*	Plate
Go	Oscillator grid	*Su*	Suppressor grid
Gs	Screen grid		Top cap
H	Heater	*XS*	External shield

TABLE XIII.—BASE ARRANGEMENTS BY TUBE TYPES

Type	Base	Type	Base	Type	Base	Type	Base	Type	Base
00A	4–1	6C7	7–7	25Y5	6–7	46A1	5–7	75S	6–4
01A	4–1	6D6	6–1	25Z5	6–7	46B1	5–7	76	5–1
1A6	6–8	6D7	7–8	26	4–1	47	5–3	77	6–1
1C6	6–8	6E7	7–8	27	5–1	48	6–3	78	6–1
1V	4–7	6F7	7–5	27S	5–1	49	5–4	79	6–5
2A3	4–1	6F7S	7–5	30	4–1	50	4–1	80	4–5
2A5	6–2	6Y5	6–9	31	4–1	53	7–4	81	4–6
2A6	6–4	6Z5/12Z5	6–10	32	4–2	55	6–4	82	4–5
2A7	7–2	10	4–1	33	5–3	55S	6–4	83	4–5
2A7S	7–2	12A	4–1	34	4–3	56	5–1	84	5–5
2B7	7–3	12A5	7–6	35/51	5–2	56AS	5–1	85	6–4
2B7S	7–3	12A7	7–9	35S/51S	5–2	56S	5–1	85AS	6–4
2S/4S	5–5	12Z3	4–7	36	5–2	57	6–1	89	6–1
2Z2/G84	4–6	15	5–6	37	5–1	57S	6–1	V-99	4–4
5Z3	4–5	18	6–2	38	5–6	57AS	6–1	X-99	4–1
6A4/LA	5–3	19	6–6	39/44	5–6	58	6–1	182B	4–1
6A7	7–2	20	4–1	41	6–2	58S	6–1	183	4–1
6A7S	7–2	22	4–2	42	6–2	58AS	6–1	485	5–1
6B7	7–3	24A	5–2	43	6–2	59	7–1	864	4–1
6B7S	7–3	24S	5–2	45	4–1	71A	4–1		
6C6	6–1	25/25S	6–11	46	5–4	75	6–4		

When the type number of a tube is followed by the letter S, the tube is a standard type but is equipped with an external shield, as specified for *Majestic* radio receivers. This shield, not shown on the base diagrams, is connected through the base to the cathode pin.

TABLE XIV.—TUBE TYPES BY BASE ARRANGEMENTS

Base	Type	Base	Type	Base	Type
4–1	00A, 01A,	5–2	24A, 24S,		75S, 85,
	10, 12A,		35/51,		85AS
	20, 26, 30,		35S/51S, 36	6–5	79
	31, 45, 50,	5–3	33, 47,	6–6	19
	71A, X-99,		6A4/LA	6–7	25Y5, 25Z5
	182B, 183,	5–4	46, 49	6–8	1A6, 1C6
	864, 2A3	5–5	2S/4S, 84	6–9	6Y5
4–2	22, 32	5–6	15, 38,	6–10	6Z5/12Z5
4–3	34		39/44	6–11	25/25S
4–4	V-99	5–7	46A1, 46B1	7–1	59
4–5	80, 82, 83,	6–1	6C6, 6D6,	7–2	2A7, 2A7S,
	5Z3		57, 57S,		6A7, 6A7S
4–6	2Z2/G84,		57AS, 58,	7–3	2B7, 2B7S,
	81		58S, 58AS,		6B7, 6B7S
4–7	1V, 12Z3		77, 78, 89	7–4	53
5–1	27, 27S, 37,	6–2	2A5, 18, 41,	7–5	6F7, 6F7S
	56, 56S,		42, 43	7–6	12A5
	56AS, 76,	6–3	48	7–7	6C7
	485	6–4	2A6, 55,	7–8	6D7, 6E7
			55S, 75,	7–9	12A7

Metal Tube Bases and Pins.—The metal shell is connected to a base pin and during operation of the tube the shell is at ground potential to eliminate any danger from electrical shock. The octal base for metal tubes requires a special socket because of the pin arrangement and because a locating key or lug is of assistance in locating the tube properly in the socket. The base is so designed that eight pins uniformly spaced can be used. Where the tube design is such that fewer pins are needed, the unnecessary ones are omitted and the spacing of the remaining pins is unchanged. With this arrangement a universal pin numbering system has been devised. In this system a number is assigned to each of the eight pin positions. Pin number one, for the shell connection, is the first pin to the left of the locating key when the base is viewed from the bottom with the key toward the observer. The direction of

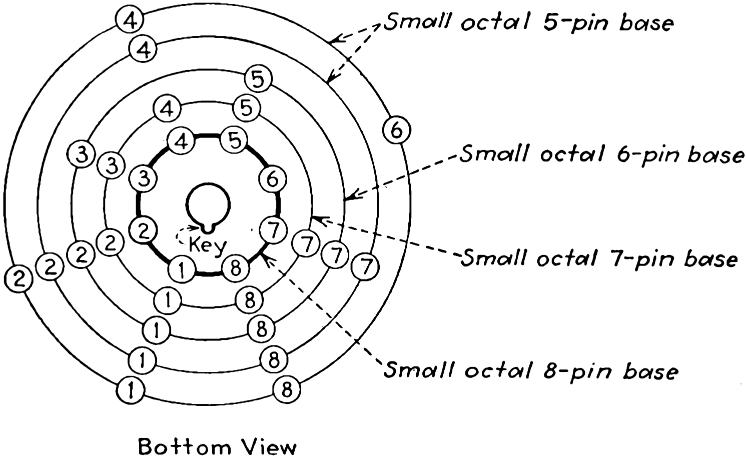


FIG. 243c.—General pin arrangement for metal tubes.

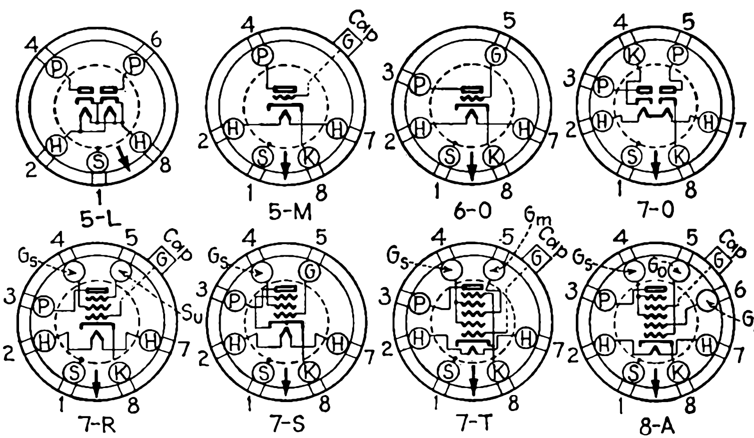


FIG. 243d.—Bottom views of bases for metal tubes.

numbering is clockwise. With this system, the pin numbers for a six-pin base are 1, 2, 3, 5, 7, and 8.

The pin connections for the various types of metal tubes are given in the following table. The drawing in Fig. 243c shows the general pin arrangement, and the drawings in Fig. 243*d* show the bottom views of the tube bases.

TABLE XV.—BASE ARRANGEMENTS BY TUBE TYPES (METAL TUBES)

Tube	Base	Pin positions and numbers								Top cap
		1	2	3	4	5	6	7	8	
		Pin connections								
5Z4	5-L	*S*	*H*	..	P_2	...	P_1	..	*H-K*	
6A8	8-A	*S*	*H*	*P*	G_S	G_O	G_A	*H*	*K*	*G*
6C5	6-Q	*S*	*H*	*P*	..	*G*	..	*H*	*K*	
6D5	6-Q	*S*	*H*	*P*	..	*G*	..	*H*	*K*	
6F5	5-M	*S*	*H*	..	*P*	...	..	*H*	*K*	*G*
6F6	7-S	*S*	*H*	*P*	G_S	*G*	..	*H*	*K*	
6H6	7-Q	*S*	*H*	P_2	K_2	P_1	..	*H*	K_1	
6J7	7-R	*S*	*H*	*P*	G_S	G_{SU}	..	*H*	*K*	*G*
6K7	7-R	*S*	*H*	*P*	G_S	G_{SU}	..	*H*	*K*	*G*
6L7	7-T	*S*	*H*	*P*	G_S	G_M	..	*H*	*K*	*G*

Explanation of pin symbols: G = control grid, G_A = anode grid, G_M = modulator grid, G_O = oscillator grid, G_S = screen, G_{SU} = suppressor grid, H = heater, K = cathode, P = plate, S = metal shell, ↓ = locating key.

CHAPTER VII

VACUUM-TUBE INSTALLATIONS

Filament and Heater Current.—The current for a filament or for a heater of a radio tube may be taken from a direct-current source such as a battery or a power line, or from an alternating-current source such as a house-lighting circuit, depending on the type of tube and the requirements.

In the case of direct-current operation the voltage applied to the filament is controlled by a resistance in series with the filament. For parallel connection of filaments the size of the required resistance R in ohms is found from the relation $R = (V - E_f) \div I$, where V is the supply voltage in volts, E_f is the rated filament voltage of the tube and I is the sum of the filament currents in amperes. The filament or heater voltage of a tube in operation should be measured at the socket. For example, if two dry cells are to supply the filament current for three type 32 tubes, two type 30 tubes and two type 31 tubes, all being connected in parallel, the size of the series resistance is found as follows: The supply voltage is 2×1.5, or 3 volts, the filament voltage is 2 volts, and the total filament current is 0.56 ampere, so that the resistance needed is $(3 - 2) \div 0.56$, or 1.8 ohms. The nearest commercial unit might be 2 or 3 ohms. For series connection of filaments the same formula is used; in this case the value used for the filament voltage must be the sum of the filament voltages of all the tubes, and the value used for the current is the filament-current rating of one tube. In a series filament connection only tubes having the same filament-current rating can be used. A tube having a lower rating must be provided with a shunt resistance across its heater terminals to take the excess of current.

For operation with alternating current the filaments or the heaters may also be connected either in parallel or in series. With a parallel connection the power is obtained from the supply circuit generally through a step-down transformer. A resistance may be used in series with the primary winding of the filament transformer if the voltage of the supply circuit must be reduced. If the voltage of the supply circuit must be increased, a so-called "booster" transformer may be connected between the supply source and the filament transformer. With a series connection a voltage-reducing resistance may be used in series with the heaters or the filaments. The procedure for calculating this series resistance is the same as that for the direct-current example already given. The so-called "Universal" type of radio receiving set which can be operated on either alternating or direct current uses the series filament method of connection. The power in watts dissipated in a resistance is equal to the voltage drop in volts across the resistance multiplied by the current in amperes.

Cathode Connection.—When the heater of a tube is operated with alternating current, the cathode should be connected to the mid-tap on the secondary winding of the heater transformer or the mid-tap of a resistance placed across the secondary winding. This connection is necessary to maintain a low potential difference between the heater and the cathode, as recommended by tube manufacturers. Where the demands of circuit design necessitate the use of a resistance between the heater and the cathode, the resistance should be by-passed with a suitable filter; otherwise an annoying hum may result. If the heater is operated from a storage battery the cathode should be connected directly or indirectly (through grid-biasing resistances) to the negative of the battery terminal; if the heaters are connected in series, the cathode circuits should be connected directly or indirectly to the negative terminal of the direct-current supply line.

B Voltage.—The "B"-voltage supply is needed to provide voltage for the plate circuits, screen circuits, and in some cases for grid-biasing circuits. This voltage supply may be obtained from batteries, from an alternating-current line through a rectifying and filtering device, from a direct-current line through a filtering device, or from a local electric generator. Several commercial devices have been produced to supply the plate power for automobile radio receiving sets[1] from the automobile storage battery or from an auxiliary engine-driven generator. The applied voltage, for filament-type tubes (except rectifiers) should be measured between the plate terminal and the negative terminal of the filament. For heater-type tubes the applied plate voltage should be measured between the plate terminal and the cathode terminal. For half-wave rectifier tubes the plate voltage should be measured across the entire high-voltage winding of the power transformer. For full-wave rectifier tubes the voltage applied between each plate and the filament or the heater is measured separately across each half of the high-voltage winding.

Grid Voltage.—The current for providing a grid-bias voltage may be obtained in several ways; namely, from a "C" battery, from a voltage tap on a direct-current power-supply unit, or from the drop in voltage across a resistance inserted in the cathode circuit (self-biasing[2] arrangement). If a "C" battery is used, the grid-return wire is connected to the negative battery terminal, and the positive terminal of the battery is then connected to the negative terminal of the filament socket or to the cathode terminal. Where alternating current is used on the filament, the grid return may be connected to the mid-tap of a resistance placed across the filament terminals, in order to reduce hum. If the grid-bias voltage is obtained from a voltage tap of a direct-current power-supply unit, the grid return must be connected to a tap which is more negative than the one used for the cathode. The grid-bias voltage recommended for a tube is stated with a definite reference point depending on the type of filament.

[1] Automobile radio receiving sets are described in Moyer and Wostrel, "Radio Construction and Repairing," 4th ed., p. 391, McGraw-Hill Book Company, Inc., New York.

[2] The term *self-bias* is used because the cathode current of the tube is utilized to provide the grid-bias voltage.

For a tube having a filament operated with direct current, the reference point is the negative terminal of the filament. For a tube having a filament operated with alternating current, the reference point is the mid-point of the filament. For a tube having a heater type filament the reference point is the cathode. The filaments of certain types of tubes may be operated with either direct or alternating current. In the case of these tubes the grid-bias voltage for filament operation on alternating current is greater than the grid-bias voltage for direct-current operation by an amount equal approximately to half the rated filament voltage, and the reference point is the mid-point of the filament.

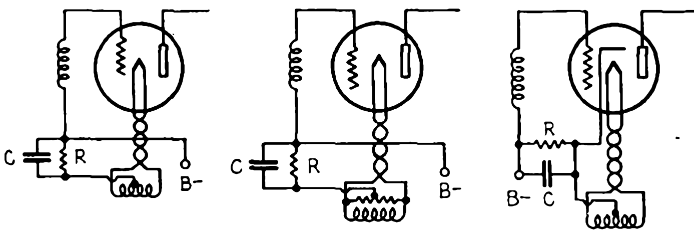


Fig. 244.—Self-biasing method of obtaining grid-bias voltage.

The *self-biasing* arrangement, shown in Fig. 244, depends on the voltage drop produced by the cathode current across a resistance which is connected from the negative terminal of the "B" supply to the cathode. The by-pass condenser *C* provides a path of low impedance. Sufficient condenser capacity must be provided so that there may be a minimum impedance between the cathode and the grid return connection. Attention must be given also to the value of the *time constant*. If this is too high the receiver may be *paralyzed* or blocked for a short time by a disturbance such as static. If the time constant is too low there may be difficulties caused by audio-frequency feed-back and by modulation distortion. A time constant of about $1/10$ second should give satisfactory results.

In a three-element tube the cathode current is equal to the plate current; and in a tetrode or pentode it is equal to the sum of the plate and screen-grid currents. The size of the required resistance R in ohms is found for one three-element tube from the relation $R = 1{,}000V \div I$, where V is the grid-bias voltage in volts and I is the rated plate current in milliamperes. For example, if the grid-bias voltage is to be 9 volts and the plate current is 3 milliamperes, the required resistance is $1{,}000 \times 9 \div 3$, or 3,000 ohms. If the current flowing through the resistance is from more than one tube the size of the resistance is determined by the *total* current.

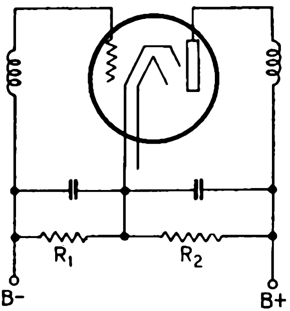


FIG. 245.—Circuit for providing a combination of variable and fixed grid-bias voltage.

The action of any cathode-resistance arrangement for providing grid-bias voltage can be understood when the value of the current flowing in the resistance is known, together with the direction of the current and the resistance of the unit. The path of the plate current, in the circuit shown in Fig. 245, is from the positive terminal of the power-supply unit to the plate of the tube, through the tube to the cathode, through the grid-biasing resistance R_1 to the negative terminal of the power-supply unit, and then through the supply unit back to the positive terminal. In this case the direction of current flow in the resistance R_1 is *away* from the cathode. Then the end of the resistance R_1 from which the current leaves is *negative* with respect to the cathode. In this circuit a combination of variable and fixed grid-bias voltages is obtained by the use of the bleeder resistance R_2. The variable portion of the grid-bias voltage is due to the flow of the cathode current, while the fixed portion is due to the current which comes from the bleeder resistance R_2.

The arrangement for obtaining a grid-bias voltage from a tap on the voltage divider of a power-supply unit is similar to the circuit shown in Fig. 245. In that case the resistances R_1 and R_2 are a part of the voltage divider. The grid-return wire is connected to a point that is more negative than the one used for the cathode connection.

In some circuits the cathode resistance, or a part of it, is common to two or more tubes. A simple arrangement of this kind is shown in Fig. 246. The resistance R_1 carries the cathode current of the tube shown as well as the cathode currents of other tubes connected to this circuit, while the resistance R_2 carries the cathode current of only one tube. The grid-bias voltage for this tube is the voltage drop across both resistances R_1 and R_2. The grid-bias voltage for the other tubes is the voltage drop across the resistance R_1, for the reason that the reference point for those tubes is the junction point of the resistances R_1 and R_2.

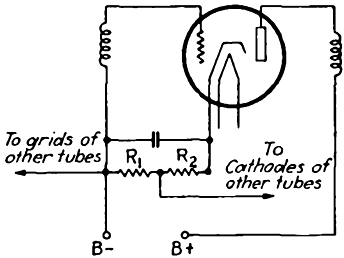


FIG. 246.—Cathode-resistance arrangement which is common to two or more tubes.

Grid-bias Voltage for Power Amplifiers.—The power output and amount of distortion from "over-biased" push-pull

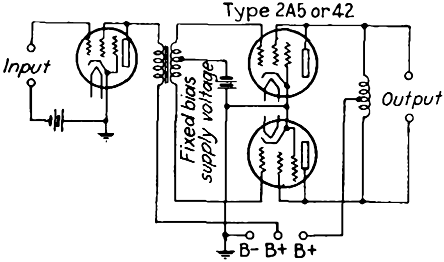


FIG. 247.—Fixed grid-bias arrangement using battery-supply current.

audio-frequency amplifiers are affected by the method used to provide the grid-bias voltage. Three general types will be considered: (1) fixed grid-bias voltage, (2) semi-fixed grid-bias voltage, and (3) self-biasing voltage. The grid-bias voltage supply in the fixed grid-bias type is provided by a battery or a separate rectifier, in the semi-fixed grid-bias type by a tap on the power-supply voltage divider, and in the self-biasing type by a cathode resistance.

The greatest power output and usually the least distortion are obtained with the *fixed grid-bias* arrangement using a

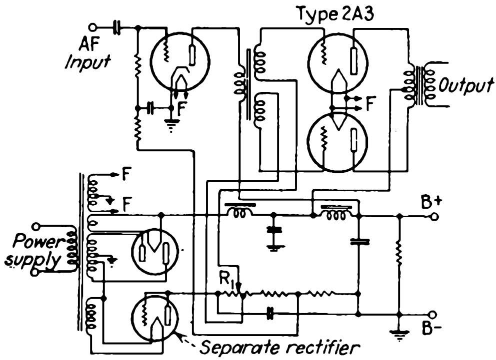


Fig. 248.—Circuit arrangement for obtaining grid-bias voltage from separate rectifier for circuit with type 2A3 tubes.

battery-supply current, because the voltage obtained from such a low-resistance source minimizes degenerative effects. The circuit connection[1] is shown in Fig. 247 for type 2A5 or

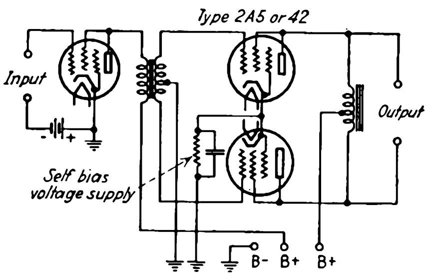


Fig. 249.—Self-biasing arrangement which produces a decrease in output and an increase in distortion.

type 42 tubes. If the grid-bias voltage is obtained from a separate rectifier, as shown in Fig. 248 for a circuit with type 2A3 tubes, the output is decreased slightly, and the distortion is increased.

[1] RCA Application Note 35.

A more marked decrease in output and increase in distortion are obtained with the *self-biasing* arrangement shown in Fig. 249. These changes are due to two reasons. First, the grid-bias voltage fluctuates because the direct-current flow in the plate circuit varies with the signal voltage. Second, the capacity of the condenser that is used to by-pass the alternating current around the grid-biasing resistance may not be adequate. Sufficient capacity should be used to reduce the impedance of the resistance to a value that becomes negligible.

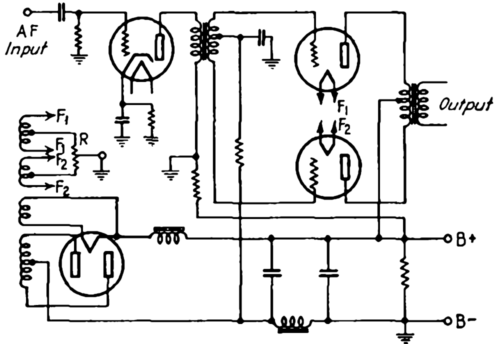


Fig. 250.—Circuit for semi-fixed grid-bias method.

The change in output and distortion that is obtained with the semi-fixed grid-bias arrangement is intermediate between the results with the fixed grid-bias method and with the self-biasing method. The circuit connection[1] for the *semi-fixed* grid-bias method is shown in Fig. 250. The reasons for the change in output and distortion with this arrangement are the same as those for the self-biasing method.

Grid-voltage Variation for Volume Control.—The volume of sound from a radio receiving set may be controlled by a variation of the voltage on the grids of the tubes in the stages of the radio-frequency amplifier.

All the systems commonly used for *automatic volume control* operate on the same principle that a portion of the carrier

[1] RCA Application Note 29.

voltage (page 125), rectified and filtered, is utilized to provide a grid-bias voltage for the tubes in the radio-frequency amplifier or in the intermediate-frequency amplifier, or both. This grid-bias voltage is obtained generally from the detector stage, but some designers use a separate tube which is supplied with a grid-bias voltage from the input circuit of the detector stage. There are several ways of applying this voltage variation, depending on whether the control is manual or automatic: (1) from a bleeder circuit by the use of a potentiometer, (2) from a variable resistance by a self-biasing arrangement, or (3) from a bleeder circuit in which the bleeder current is varied by a tube used for automatic volume control. The

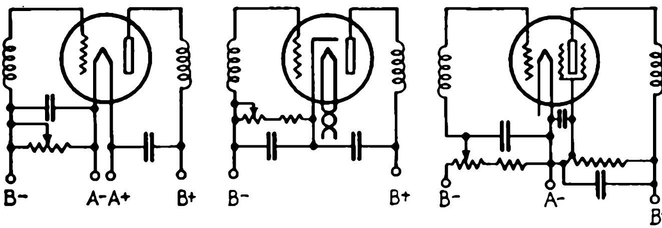


FIG. 251.—Grid-bias voltage variation for volume control.

first two methods are shown in Fig. 251. In these arrangements it is essential that the grid-bias voltage should not at any time be less than the minimum recommended value. This requirement is met by providing a fixed stop on the potentiometer, by a fixed resistance connected in series with the variable resistance, or by connecting a fixed cathode resistance to the variable resistance used for regulation.

Screen-grid Voltage.—The positive voltage required for the screen grid of the tetrode type of tube is generally taken from a tap connection on the B-supply unit (page 4), or through a potentiometer connected across that unit. In some cases a series "dropping" resistance and shunt filter condenser are used. The screen-grid voltage for a pentode tube, however, may be obtained by means of a resistance connected in series to a high-voltage supply, as shown in Fig. 252. The screen-grid circuit needs more thorough filtering than the plate circuit because it has a control effect similar to that of any other grid. The screen-grid voltage may be measured at the source of supply, or between the negative filament terminal or cathode terminal and the screen-grid terminal.

Control of volume in the older types of radio receiving sets was effected by the variation of the screen-grid voltage on the tubes in the radio-frequency amplifier stages. Such action is possible because a reduction in screen-grid voltage decreases the mutual conductance and thus results in less amplification.

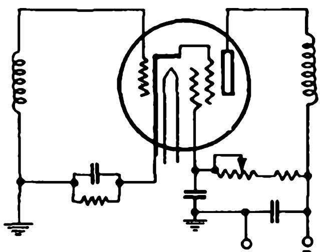


FIG. 252.—Arrangement for obtaining screen-grid voltage.

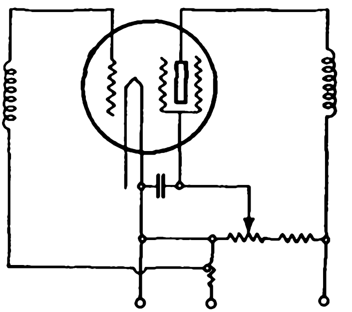


FIG. 253.—Volume-control arrangement using screen-grid voltage variation.

The variable voltage is obtained, as shown in Fig. 253, by the use of a potentiometer connected across the resistance which provides the screen-grid voltage.

Filters for Voltage-supply Wires.—It is customary to provide a filter in each voltage-supply wire that passes into a stage. This precaution is necessary to prevent coupling between the stages, owing to a voltage-supply circuit which is common to all stages. Two simple types of filters that can be applied to circuits carrying weak currents are shown in Fig. 254. In these filters, R is a resistance unit and C is a by-pass condenser. For circuits carrying strong currents the resistances in the filters should be replaced by radio-frequency choke coils. The filter provides a low-impedance path for the signal current to the cathode and thus by-passes the path through the voltage-supply circuit. The low-impedance path is through the condenser; and the resistance or the choke coil provides a high impedance to the power-supply circuit. A rule for the minimum practical size of the condensers, as stated by the RCA Radiotron Company is as follows: The impedance of the condenser at the lowest frequency

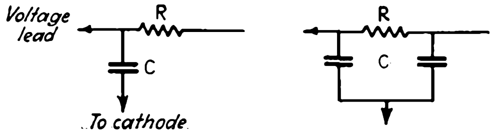


FIG. 254.—Electric filters for voltage-supply wires.

amplified should not be more than one-fifth of the impedance of the filter-choke coil or of the resistance at that frequency. In special cases better results are obtained if the ratio is not more than one-tenth. If stage shielding is used it should enclose the filter unit also. The use of filters for smoothing the output of rectifier tubes is described in Chap. IX.

Coupling Circuit for Power-output Tube.—The direct-current component of the current in the plate circuit of a power-

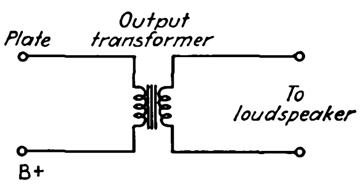


FIG. 255.—Coupling circuit of transformer type for power-output tube.

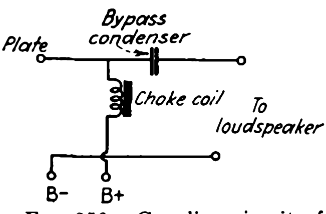


FIG. 256.—Coupling circuit of choke-coil type for power-output tube.

output tube would injure the winding of an electromagnetic loud-speaker.[1] For this reason some form of coupling must be provided which will allow the fluctuating component of the current to flow into the loud-speaker but which will exclude the direct-current component. Coupling is generally needed

[1] Moyer and Wostrel, "Practical Radio," 4th ed., p. 128, McGraw-Hill Book Company, Inc., New York.

also to transfer power efficiently from the output stage to the loud-speaker. Two types of coupling devices are shown in Figs. 255 and 256. The transformer type (first) consists of a primary and a secondary winding on an iron core; each winding can be designed to have the impedance needed in its circuit. In the second type of coupling device the choke coil, connected in series with the plate and the B-supply unit, allows the direct-current component to flow but opposes the fluctuating current; the by-pass condenser passing the fluctuating current. The impedance of the iron-core choke coil should be at least 10 henrys, and the capacity of the by-pass condenser should be 2 to 6 microfarads.

CHAPTER VIII

USE OF THE VACUUM TUBE AS DETECTOR

The average frequency of the waves of sound produced by the voice in speaking is about 800 cycles per second, but the range of frequency varies with the pitch of the tone. A change of inflection in speaking, a change of tone in singing or in the sound of musical instruments, causes changes in the frequency of the air waves which are produced.

Modulation.—The high-frequency energy that is generated by a radio broadcasting transmitter is utilized as a carrier for

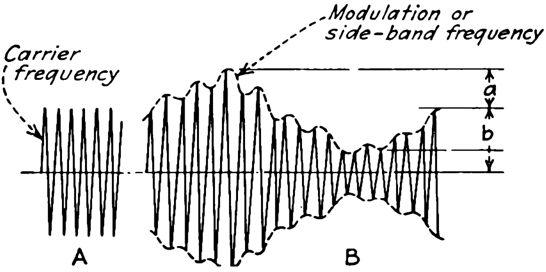


FIG. 257.—Carrier and modulation frequencies.

the transmission of a signal current of low or *audio frequency.* The process whereby the characteristics of the audio-frequency signal are impressed on the carrier frequency is called *modulation.* These two frequencies may be represented as in Fig. 257 in which A indicates an unmodulated wave of high frequency, and B the same wave after it has been modulated at an audio-frequency rate. The percentage of modulation depends on the ratio of the amplitude of the modulation frequency to that of the carrier frequency. Thus, from Fig. 257, the modulation in per cent may be expressed as $100a \div b$. At 100 per cent modulation the two amplitudes are equal. Broadcasting transmitters are seldom modulated over 90 per cent. The effect of the degree of modulation on the action of a detector is considered in a later section.

The modulated radio-frequency currents produce radio waves which retain the characteristics of the sound waves used for modulation. The radio wave is changed by the radio receiver into sound waves having the same characteristics as the sound waves which entered the microphone at the transmitter.

The high-frequency alternating currents used in radio transmission and reception will not flow to any considerable extent through the inductive windings of loud-speakers or of telephones. Even if the current did flow, the diaphragms of such apparatus could not vibrate at such high rates; and further, even if the diaphragms could vibrate at this rate, a note of such high frequency would be inaudible. The detector is a device by means of which the audio-frequency component is extracted from the modulated carrier, and is delivered in the form of a pulsating direct current. This current then can be used to operate a loud-speaker or if necessary is applied to an audio-frequency amplifier so that its *amplitude* may be increased.

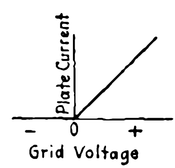


FIG. 258.—Relation between plate current and grid voltage in true detector.

True Detector.—A theoretically true detector would have a characteristic as shown in Fig. 258. When the input voltage is positive in value, the plate current varies directly with the voltage, and when the input voltage is negative, the plate current is zero. If, now, an alternating voltage is impressed on such a detector so that the average value of the voltage is at the zero point, a plate current will flow only when the impressed voltage has a positive value. The value of the resulting audio-frequency current is directly proportional to the strength of the radio-signal current. This theoretical action, however, is considerably different from that of an actual vacuum-tube detector in its normal operation.

Types of Detectors.—The types of detectors most commonly used are the diode detector, the triode detector arranged for plate-circuit detection, and the triode detector arranged for grid-circuit detection. Other types of detectors used to some extent are the alkali-vapor tube, the multi-element tube, the non-oscillating tube with regeneration, and the oscillating tube.

Detection with Diode.—The diode has two properties which make it suitable for use as a detector, where a *minimum of*

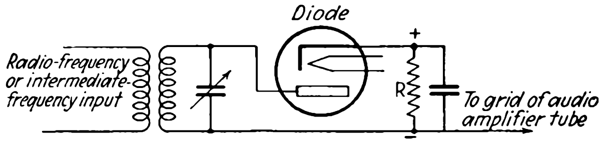


FIG. 259.—Half-wave rectification with diode.

distortion is required. These are its rectifying action and its low resistance in the direction of current flow. Because of this low resistance of the tube an approximately linear dynamic characteristic (page 333) can be obtained with a convenient size of load resistance. The diode, however, has no amplifying action. The circuit shown in Fig. 259 illustrates the use of a diode for half-wave rectification. The audio-frequency signal voltage across the load resistance R is impressed on the grid of the amplifying tube. To obtain a still lower tube resistance, two diodes may be connected with their plates in parallel.

Full-wave rectification is obtained by the use of two diodes, or a tube of the duplex-diode-triode type (page 141) as shown in Fig. 260. In this circuit the input is balanced so that no carrier frequency is delivered to the grid of the amplifier tube and consequently there is no need for a carrier-frequency filter. The double-diode portion of the tube acts as a full-wave rectifier. Its output is delivered to the triode portion of the tube which acts as an audio-frequency amplifier. The grid-bias voltage for the triode is obtained from the voltage drop across the resistance R; but this method should not be used unless the resistance in the plate circuit of the triode is large. This plate-circuit resistance must be large enough to keep the plate current from becoming excessive when the grid-bias

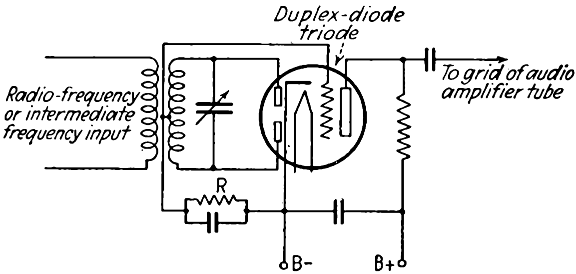


FIG. 260.—Full-wave rectification with duplex-diode triode.

voltage drops to zero at a time when there is no radio-frequency input. The grid-bias voltage on the triode may reach the cut-off value if the signal voltage is very strong. Full-wave

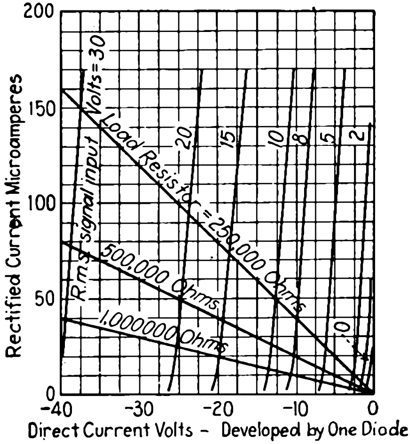


FIG. 261.—Average characteristics of single diode unit for half-wave rectification.

rectification, as compared with half-wave rectification, provides about half as much signal output but does not require carrier-frequency filtering.

Radio-tube Applications.—In addition to services as detectors and oscillators, vacuum tubes for radio receiving sets are utilized as amplifiers, rectifiers, frequency converters, and mixers in superheterodyne circuits.[1] These various services will be considered in detail in the following chapters.

Characteristic of Diode Detector.—The curves in Fig. 261 represent the average characteristics of a single-diode unit in half-wave rectification for duplex-diode triodes such as types 55, 85, 2A6, and 75, and also for duplex-diode pentodes such as 2B7 and 6B7. The curves show the relation that exists among the following four factors: (1) signal input voltage (root-mean-square value), in volts, (2) load resistance, in ohms, (3) rectified current, in microamperes, and (4) direct-current voltage, in volts, that is developed by the diode unit.

Typical Diode-detector Circuits.—Radio receiving sets in which diode detection is used generally have tubes of the duplex-diode-triode or the duplex-diode-pentode types. In some cases, however, a triode may be connected to give diode detection. In receiving sets designed for battery operation a screen-grid tube may be used for detection. A few examples of these types in commercial applications are given in the following paragraphs.

Type 75 *as Diode Detector.*—The use of a duplex-diode-triode tube, type 75 or 2A6, as a detector amplifier is illustrated in Fig. 262. In this circuit the diode units are connected to give half-wave rectification, and to provide rectified voltage for *automatic volume control.* When a signal voltage is applied to the tuned circuit *LC* and the diode plates are positive, a stream of electrons flows from the cathode to the diode plates, and through the tuned circuit and the 0.5 megohm resistance *R* back to the cathode. The flow of *current* is in the opposite direction. This current, being rectified, produces a rectified voltage across the resistance *R*. The rectified voltage is proportional in amplitude to the applied signal voltage. The 0.0001-microfarad condenser across *R* stores a small amount of energy from each cycle of the rectified

[1] See Chap. X.

radio-frequency current in the resistance R and consequently the available voltage has a form corresponding to the audio-frequency modulating signal voltage.

A portion of this audio-frequency voltage is taken from the tap on the resistance R and is applied through the condenser C_2 to the grid of the triode unit of the tube. The plate current of the triode returns to the cathode through the resistance R_1. With this connection the grounded end of the resistance R_1 is negative with respect to the cathode, and the other end is

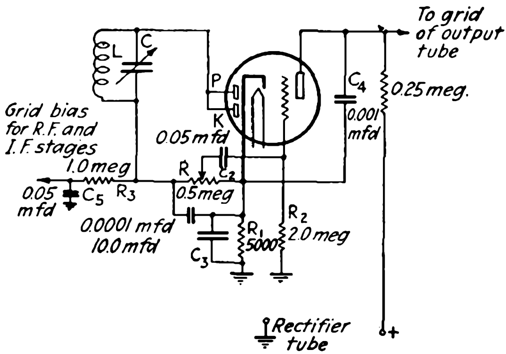


FIG. 262.—Circuit arrangement of duplex-diode-triode type 2A6 or 75 when used as detector-amplifier tube.

positive. The flow of plate current across the resistance R_1 produces a voltage drop which is utilized as a grid-bias voltage for the triode, and is applied to the grid through the resistance R_2. The condenser C_3 is used to improve the quality with regard to very low frequencies, and the condenser C_4 serves as a by-pass for any radio-frequency current that may be present in the triode-plate circuit.

The voltage for *automatic volume control* is obtained in the following manner: The current flow in the resistance R is in such a direction that the negative end of the resistance R is toward the tuned circuit LC. The current is smoothed out by the resistance R_3 and the condenser C_5. Then the voltage across the condenser C_5 is applied to the grid-return circuits of the radio-frequency and intermediate-frequency stages.

If the signal strength increases, the grid-bias voltage applied to these stages becomes more negative. The effect of a more negative grid-bias voltage is to reduce the mutual conductance of the tubes to which it is applied, with a consequent decrease in amplification. This results in a reduced signal voltage on the detector. The combination of the resistance R_3 and the condenser C_5 serves also as a timing circuit for the operation of the automatic volume control.

Type 85 *Tube as Diode Detector.*—The type 85 tube is rated as a duplex-diode triode. As used in the circuit of Fig. 263

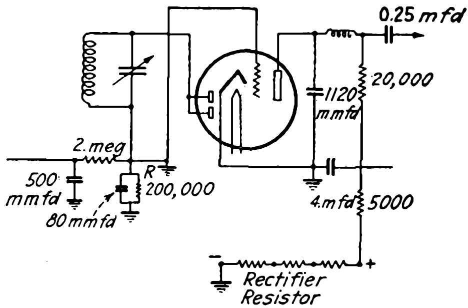


FIG. 263.—Duplex-diode triode (type 85) with diode electrodes used as detector and the grid and plate used for audio-frequency amplification.

the diode electrodes provide the detector action while the grid and plate give audio-frequency amplification. The output of an intermediate-frequency stage is applied through a transformer to the detector tube. A portion of the rectified voltage also gives a voltage drop across the resistance R which is used in one of the two automatic-volume-control systems. This voltage drop is applied to the second intermediate-frequency stage in all of the five tuning bands, and to the first detector and first intermediate-frequency stage in two bands. The detector output is coupled to the grid circuit of the driver stage (page 132), through a compensated volume-control system, a tone-control system, and a transformer.

Type 6*B*7 *as Diode Detector.*—The use of the diode units of the type 6B7 duplex-diode pentode for detection is illustrated in Fig. 264. The output of the first intermediate-frequency transformer is applied to the control grid of the type 6B7 tube. In this tube the intermediate-frequency signal is amplified and then is applied to the second intermediate-frequency transformer T_1. Both the primary and the secondary circuits of the transformer T_1 are tuned in order to provide maximum sensitivity. The signal then is applied to the audio-frequency diode unit of the type 6B7 tube. The signal voltage is applied also through the condenser C to the automatic-control diode unit of type 6B7. The output of the

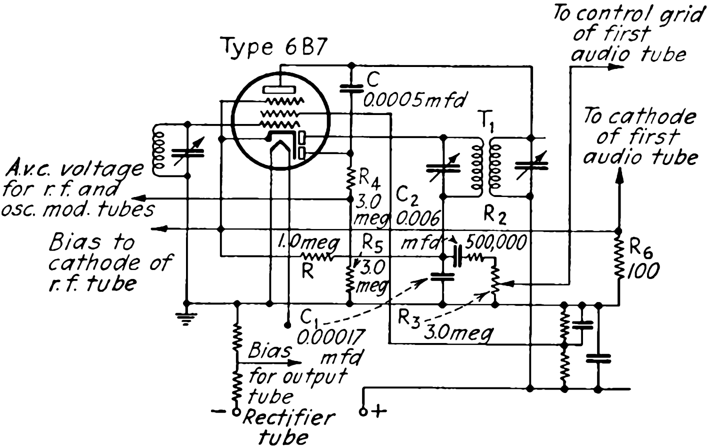


Fig. 264.—Diode units of type 6B7 (duplex-diode pentode) used for detection in Crosley model 61 receiver.

audio-frequency diode produces a voltage drop across the resistance R and the condenser C_1. In this circuit there occur also a direct-current voltage and some intermediate-frequency current. The audio-frequency signal voltage is separated from the direct-current voltage by the condenser C_2, and the intermediate frequency is filtered by the resistance R_2. The audio-frequency voltage is applied across the volume-control resistance R_3 and thence to the grid of the audio-frequency amplifying tube.

Automatic-volume-control voltage is developed, in the diode circuit, across the resistances R_4 and R_5. The voltage drop across the resistance R_5 is used as an automatic-volume-control voltage for the radio-frequency amplifying stage, and for the control grid of the oscillator-modulator tube. A *delay* voltage is obtained from the voltage drop across the resistance R_6. The audio-frequency diode resistance R returns the current directly to the resistance R_6. The grid-bias voltage for the pentode section of type 6B7 tube is obtained from the voltage drop across the resistance R_6.

Type 76 *Tube as Diode Detector.*—The output of the intermediate-frequency amplifier is applied to the grid of the type 76 tube which serves as a second detector. Type 76 is nominally a super-triode amplifier-detector but acts as a diode in this

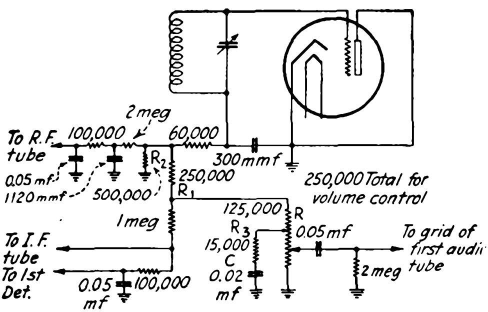


FIG. 265.—Super-triode amplifier and detector (type 76) used for detection and to supply automatic-volume-control voltage.

circuit because the plate is connected to the cathode. The tube is operated as a diode detector and is used to supply voltage for automatic volume control. The direct-current component of the rectified signal voltage produces a voltage drop across each of the resistances R and R_1 shown in Fig. 265, which is proportional to the wave that was rectified. The voltage drop across the resistance R (250,000 ohms) is used as the grid-bias voltage for the first detector and the intermediate-frequency stage. The voltage drop across both the resistances R and R_1 is used as the grid-bias voltage on the radio-frequency stage. These grid-bias voltages are used to provide the automatic volume control of the receiver. The resistance R_2 is connected in parallel across the resistances R

and R_1 in order to reduce the total resistance in the circuit to a proper value. The circuit consisting of the resistance R_3 and the condenser C in series, connected from a tap on the volume control resistance to the ground, provides low-frequency, low-volume compensation.

Analysis of Diode Detection.[1]—The wide-spread use of the diode detector in radio receiving sets is due to its numerous advantages. First, the diode detector does not become overloaded until the input increases beyond practical limits. Second, it can be used to provide a separate supply of voltage that is sufficient for the requirements of automatic volume control. Third, the quality of the audio-frequency output is good enough to match the overall performance of the radio receiving set.

The current of a diode detector may be considered as being proportional to the square of the voltage for small values, and as approaching a linear relation for large inputs.

In the socalled "linear" type of diode detector the ratio between the voltage developed and the input voltage is constant, and in the "square-law" type this ratio is *approximately* constant unless the load resistance becomes too high. Also, the effective resistance of the diode circuit is practically unaffected by changes in input voltage. Because of these relations it follows that the voltage produced across the resistance of the diode is proportional to the amplitude of the carrier wave (page 324).

In actual operation, however, the conditions are changed by the effect of the load on the tube, and by the degree of modulation of the input voltage. Then a new relation exists between the value of rectified current and the input voltage. In the case of the linear detector on signal voltages having low modulation the effect is a decrease in the voltage and a slight departure from the linear proportion. But on signal voltages having high modulation there is serious distortion because the current drops to zero before the carrier wave reaches its zero

[1] Kilgour and Glessner, "Diode Detection Analysis," *Proc. Inst. Radio Eng.*, July, 1933.

value. Even in the case of a signal voltage which has a degree of modulation lower than that at which cut-off occurs, the audio-frequency voltage is decreased to the extent that its peak value is not equal to the direct-current voltage times the modulation factor. The load consists of the coupling circuit shown in Fig. 266. The coupling circuit is used to transfer the voltage variations produced across the resistance of the diode detector to the following tube. This coupling acts toward audio-frequency currents as a shunt across the diode resistance without affecting its value to direct current. The effect of the load, however, for common values of the audio-frequency shunt may be neglected; that is, the average value of the direct current produced by the detector is assumed to be independent of the audio-frequency shunt. Then the effective resistance of the input circuit of the detector depends entirely on the direct-current value of the load.

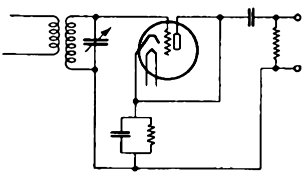


Fig. 266.—Simple diode-detector circuit.

In the case of the square-law detector in actual operation, the characteristic of rectified current is similar to that for the linear detector except that the current decrease at low values is more gradual, and the effect of the audio-frequency shunt is similar. But there is a difference in the effect of modulation when the series resistance is large compared to the detector resistance. Under that condition the distortion caused by current cut-off appears at a lower degree of modulation in the square-law detector than in the linear detector.

It is necessary also to consider the effect of the condenser. This effect is complicated because the condenser has impedance at both the carrier frequency and the modulation frequency. In general it can be stated of the linear detector that the efficiency of detection increases as the capacity of the condenser is increased; but at the same time the input impedance decreases. If a condenser of fair size is used to cut down the high-frequency voltage passing to the audio-frequency amplifier, it may have an appreciable conductance at audio frequencies and thus introduce modulation distortion.

In one circuit arrangement for delayed automatic volume control, the plate of a second diode unit is shunted by a resistance and is connected through a condenser to the detector in which the signal voltage is produced. A source of voltage is connected to this second diode circuit and is used to delay the building up of the direct current across the resistance. Distortion caused by the effect of this second plate, acting as a shunt to the driving circuit at high frequency and to the detector load at audio frequency, may be reduced if the resistance in the shunt circuit is relatively high.

For a complete picture of the action of a diode detector the driver tube with its transformer and the detector tube with its load should be considered as a unit or system. If the direct current developed across the diode resistance is compared with the high-frequency current applied to the driver tube, the gain under certain conditions is nearly independent of the size of the load condenser. If the condenser is small, the efficiency of detection is low, the input impedance is high, and there is a high gain in the tuned circuit. Conversely if the condenser is large, the efficiency of detection is high, the input impedance is low, and there is a low gain in the tuned circuit. For minimum distortion the voltage applied to the detector should have a linear relation to the voltage applied to the driver tube. In the ideal case, the grid-bias voltage and the load for the driver tube should have such values that the driver output is linear over the range from zero input to a limit which is double the maximum value of the average carrier wave to be received.

Detector Distortion.[1]—In the operation of a radio receiving set a *carrier voltage is applied through an impedance to a tuned circuit.* During the tuning operation the amplitude of the voltage across the circuit changes, and there is a shift in the phase of the resulting voltage across the tuned circuit. At resonance the two side bands (page 440) shift the same amount

[1] JARVIS, "Linear Detector Distortion," *Electronics*, December, 1934.

and hence remain symmetrical in phase. If the circuit is detuned, however, the side bands are unsymmetrical in phase, referring to the carrier, and distortion results. This distortion decreases as the degree of modulation is decreased. Comparing this distortion for linear and square-law detectors it is found that the linear detection shows less distortion at low phase shifts but has the disadvantage of producing a third harmonic (page 131) of considerable magnitude.

Another result of detuning is that the amplitudes of the side bands may be unequal. This condition also causes distortion which generally acts in such a way as to add to the distortion due to a shift in phase. Where these forms of distortion are found, there is present also the distortion produced by cross modulation which likewise has the effect of adding to the kinds of distortion mentioned previously.

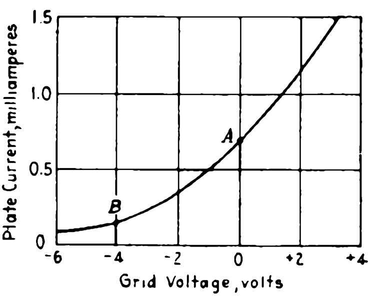


FIG. 267.—Characteristic curve of typical triode vacuum tube.

The remedies proposed for these conditions are: (1) an automatic tuning arrangement to provide correct tuning, and (2) a means for decreasing the percentage of modulation.

The Triode Detector.—A vacuum tube, in operation in a radio receiving set, is actuated by an alternating current due to the radio signal. The purpose of the vacuum tube when operated as a detector is to detect and amplify such alternating currents.

An understanding of this action of a tube may be gained from a consideration of a vacuum tube of which the curve in Fig. 267 shows the relation between plate current and grid voltage. At the zero value of a *steady* voltage on the grid which corresponds to point A on the curve, the plate current is about 0.7 milliampere. Now, if an *alternating* voltage having a maximum value of 2 volts is applied to the grid of the tube, its voltage will vary above and below the steady value and the plate current will similarly rise and fall. The plate-current variations are the same as the grid-voltage variations because the operation of the tube is on the part of the characteristic curve which is nearly straight. At a grid voltage of +2 volts, the plate current is about 1.1 milliamperes, and at −2 volts it is 0.3 milliampere. These relations are shown in Fig. 268.

The *varying* plate current in Fig. 268 may be considered as consisting of two *components*,[1] one of which is *alternating* and the other of which is *direct* current. The average value of the *varying* current is the same as the value of the *direct* component. The alternating component, in this case, has an amplitude of 0.4 milliampere and an *effective* value (see page 41) of about 0.3 milliampere.

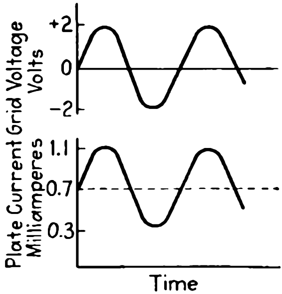


FIG. 268.—Relation of plate current to grid voltage at *A* in Fig. 267.

A direct-current ammeter indicates the average value of the current which passes through it, and hence would show no change in the value of the plate current, when the alternating grid voltage is applied.

Thus if the grid-bias voltage is such that the "point of operation" is on a straight portion of the curve showing the variation of plate current with grid voltage, then the plate current variations are similar to the grid-voltage variations. This illustrates the use of a vacuum tube as an amplifier.

If the same alternating voltage is applied to the grid when operation is at point *B* on the curve (Fig. 267) corresponding to a negative grid voltage of 4 volts, then the grid voltage will fluctuate from −2 to −6 volts. In this case, the plate current corresponding to a grid voltage of −4 volts is about 0.1 milliampere; for −2 volts on the grid it is about 0.3 milli-

[1] A *component* of an alternating electric current is one of the parts out of which the whole may be obtained by the principle of addition of instantaneous values. (See p. 43 and R. L. Dawes, "Industrial Electricity," Vol. II, p. 23.)

ampere; and for −6 volts it is only a little less than the value for −4 volts. These relations are shown in Fig. 269. It is obvious that the curve for the plate current is quite distorted in shape when compared with the curve for the grid voltage. This distortion is due to the fact that the "point of operation" is at the bend of the curve for plate current against grid voltage in Fig. 267. It is evident from this curve (Fig. 269) that the *average* value of the varying current is greater than the *steady* current flowing when no alternating voltage is impressed on the grid. Under these conditions an ammeter would show an increase in the plate current when the alternating grid voltage is applied. This change in the average value of the current is of importance in the operation of a vacuum tube as a detector.

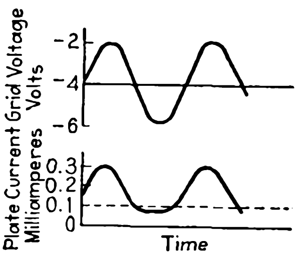


FIG. 269.—Relation of plate current to grid voltage at *B* in Fig. 267.

Detection by Plate Rectification.—A circuit illustrating the use of a triode as a detector with plate rectification is shown in Fig. 270. The reference point for all voltages is taken at the negative terminal of the filament. The grid-return wire is connected to the negative terminal of the "A" battery. The filament rheostat is in the negative leg of the filament. Hence the negative terminal of the "A" battery, and also the grid, is made negative with respect to the reference point at the negative terminal of the filament by an amount equal to the voltage drop across the rheostat. This negative voltage applied to the grid is called the *grid bias* or *biasing voltage* and fixes the "point of operation" on the curve showing how the plate current varies with the grid voltage. It is obvious that as the voltage of the "A" battery

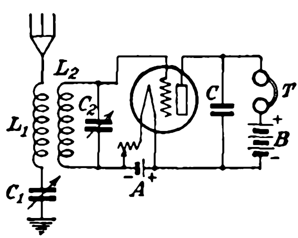


FIG. 270.—Simple circuit including non-oscillating vacuum tube as detector without grid leak and condenser.

is reduced the amount of grid-bias voltage also decreases. The connection in Fig. 271 provides a constant grid-bias voltage equal to that of the "C" battery. In this case, the rheostat is put in the positive leg of the filament. With a cathode-type tube the grid-bias voltage may be obtained by the self-biasing method (page 152) in which the flow of cathode current in a cathode resistance produces the required voltage. The radio-signal voltage is impressed across the vacuum tube between the grid and the filament. It has already been shown that, when an alternating voltage is applied to the grid under these operating conditions, the wave form of the current in the plate circuit is distorted from that of the grid voltage and that the plate current increases more above the normal value when the grid is positive (relative to the point of operation) than when it is negative.

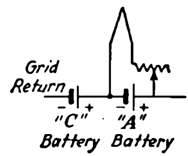


FIG. 271.—Part of circuit in Fig. 270 changed by adding "C" battery and putting rheostat in positive leg of filament.

The detection of voice-modulated continuous oscillations is illustrated in Fig. 272. Here, there is an increase of the plate current corresponding to the average value of the half cycles of radio-frequency current when the signal current is positive. This increase is the output of the detector that is utilized in the loud-speaker. The radio-frequency component[1] of the plate current flows through the by-pass condenser *C* in Fig. 270, and the pulsating audio-frequency component of the plate current flows through a telephone receiver or a loud-speaker.

In the action which has been described, detection results from the distortion due to operation on the bend of the curve in Fig. 267 showing the variation of the plate current with grid voltage. This method is called *detection by plate rectification*, or *detection with grid bias*, or *detection without grid leak and grid condenser*.

An *advantage of the plate-rectification method* of detection is that no current flows in the grid circuit because the average value of the grid voltage is maintained negative with respect

[1] See footnote p. 337.

to the filament in order to operate on the curved portion of the curve. Hence, no power is taken from the tuning circuits and no damping effect is exerted on them.

For radio-signal voltages of ordinary intensity, the mean value of the change of plate current is nearly proportional to

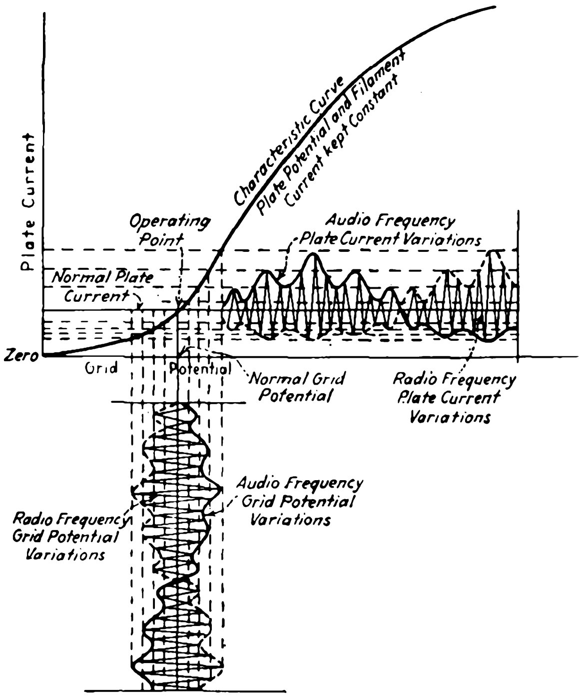


FIG. 272.—Detection of continuous oscillations as modified by the voice.

the square of the amplitude of the oscillations of the grid voltage, although the relation does not hold for strong radio-signal voltages.

In this method, operation at the upper bend of the curve is very similar to that at the lower bend. But it should be noted that, for operation at the upper bend, equal variations of the incoming oscillations produce unequal variations of the plate current, so that the plate current is decreased more than it is increased. In operation at the lower bend, the plate current is increased more than it is decreased.

The average value of the change in plate current increases most rapidly when the curve in Fig. 267 bends sharply at the "point of operation" or when the slope of this curve changes rapidly. Operation at the lower bend of this curve is preferable, because at the upper bend the grid is positive and the conductance of the input circuit is high enough to result in considerable damping of the receiving circuit.

In plate rectification, the result of the action of the tube may be considered equivalent to that of a stage of radio-frequency amplification and a detector. This is because the radio-frequency voltage that is applied to the input is amplified between the grid and the plate and is rectified in the plate circuit.

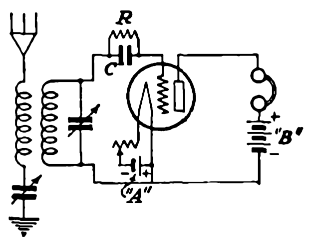


FIG. 273.—Non-oscillating tube used as detector with grid leak and condenser.

Detection by Grid Rectification. In this type of detector the tube operates on the bend of the curve showing how the grid current varies with the grid voltage, and on the straight portion of the curve showing variations of plate current with grid voltage. In the operation of this method a fixed condenser C is connected in series with the detector tube as shown in Fig. 273. It should be noted that the grid-return wire is connected to the positive terminal of the "A" battery.

When an incoming radio-signal voltage as represented in Fig. 274 is received by this circuit, similar voltage variations are communicated to the grid through the condenser C. Each time the grid becomes positive, the grid current which flows as the voltage e_0 increases more than it decreases when the grid voltage becomes less than e_0. Thus there is rectification of the current in the grid circuit. When the grid voltage becomes positive with respect to the filament, electrons are attracted to the grid, and when the grid voltage becomes negative during the next half cycle, the electrons cannot get away from the grid because they are "blocked" by the condenser *C*. As this action continues, more electrons are "trapped" on the grid. Hence, the grid continues to gain negative charges and the mean value of grid voltage becomes more and more negative with increasing strength of the incoming oscillations as shown at (3) in Fig. 274. This nega-

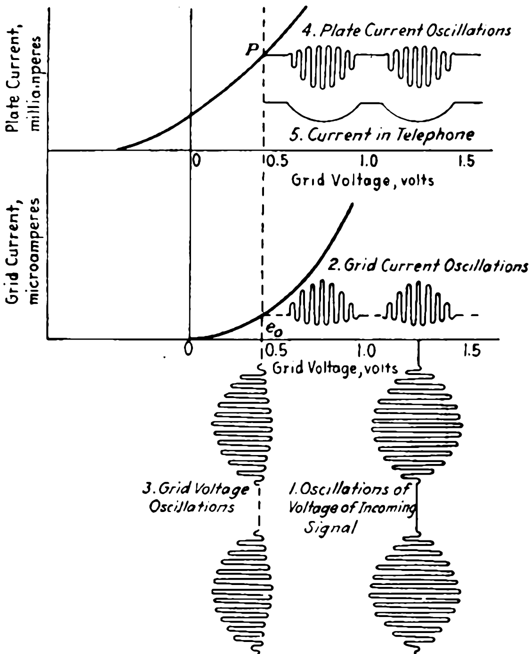


Fig. 274.—Use of detector tube with grid condenser on modulated continuous oscillations.

tive grid charge opposes the flow of electrons to the plate and magnifies the decrease in plate current as shown at (4) in the same figure. This charge can leak off through the condenser *C* or through the walls of the vacuum tube. If the insulation of the circuit and the condenser were perfect, the plate current would be so reduced that the tube would "block." But in order to make certain that this leakage occurs at the proper rate, a resistance R of a few megohms called a *grid leak* is shunted across the condenser C. Thus the grid leak has the effect of shifting the point of operation. In a *soft tube* (page 6) a grid leak is not needed because the charge can leak from the grid to the filament by means of the conducting path through the gas with which the tube is filled.

Values of the capacity C range from 150 to 500 micromicrofarads and the grid-leak resistance varies from 1 to 10 megohms. The value of R is such that the rate of leakage is proportional to the *period* of the *audio-frequency* variations of the radio-frequency oscillations and not to the *period* of the *radio-frequency oscillations*. The form of the current which flows through a telephone receiver is represented at (5) in Fig. 274.

In this method of detection (grid rectification), the operation is carried out on that portion of the curve showing variations of grid current with grid voltage which has the greatest curvature. At the same time, the plate voltage is so adjusted that the operation of the tube takes place on the steepest portion of the curve showing plate-current variations with those of grid voltage. In order to meet these conditions, the grid must be positive with respect to the negative end of the filament. The average voltage difference between them may be found, approximately, at the point of greatest curvature of the curve of grid current.

When a radio-signal voltage is received, the voltage of the grid depends on the value of the grid-leak resistance, the shape of the curve of the relation of grid current to grid voltage, and the relative voltage of the point to which the grid return is connected. If the capacity of the grid condenser is too small, it will not allow the radio-frequency voltage to be impressed on the grid without acting through the resistance and, thus, decreasing the voltage. The reactance of the condenser should be less than the grid-filament impedance. If the condenser capacity is too large the condenser requires more charge and thus may retard changes of grid voltage. This would impair the detecting action of the tube which depends on the fluctuation in average grid voltage.

In grid rectification, the result of the action of the tube may be considered equivalent to that of a detector and a stage of audio-frequency amplification. This is because the radio-frequency voltage applied to the input is rectified in the grid circuit and the audio-frequency variations are amplified in the plate circuit.

Comparison of Detection by Grid Rectification and Plate Rectification.—The grid-rectification method of detection is more sensitive than plate rectification and to this extent this method is better than plate rectification when the input voltages are small. The second-harmonic (page 131) distortion on weak signal voltages is approximately the same for both types. Overloading, however, will occur more readily with the grid-rectification method and the capacity of this method is limited because relatively low plate voltages must be used. When the input voltage is large, plate rectification may be used to take full advantage of the greater output voltage available for a given signal amplitude and of the freedom from distortion which results from overloading. In this circuit arrangement, the impedance of the tube is rather high so that the primary coil of the first audio-frequency transformer should have a high inductance.

A study[1] of detection for weak radio-signal voltages brings out a number of interesting conclusions. A rectifying detector depends for its action upon a non-linear relation between the instantaneous output current and the instantaneous applied voltage. If the impressed modulated voltage of a radio signal is small, the output contains the following *components:* (1) a constant current; (2) a current of modulation frequency; (3) a current of double modulation frequency; and (4) currents of frequencies equal to the sum and difference of the several modulation frequencies. All of these component currents

[1] Chaffee and Browning, "A Theoretical and Experimental Investigation of Detection for Small Signals," *Proc. Inst. Radio Eng.*, February, 1927.

are proportional to the square of the impressed voltage of the radio signal. The component of modulation frequency is proportional to the degree of modulation, and all the others depend on the square of the modulation or on the product of the two modulation factors, and, hence, are small in comparison with the current of modulation frequency if the degree of modulation is small.

A *hard tube used without a grid-circuit impedance*, that is, without a "blocking" condenser and grid leak or the equivalent, and with no radio-frequency impedance in the plate circuit, depends for its detecting action entirely upon the bends of the plate-current curve. The resulting "detection" is usually very small. A gas (soft) tube when used in this way gives much greater detection than a similar tube highly exhausted because ionization increases both the upper and lower bends of the plate-current curve. Ionization also causes kinks in the plate-current curve resulting in a high sensitivity at such points because of the very large values of the ratio of small changes in grid-plate conductance to small changes in grid voltage. A radio-frequency impedance in the plate circuit of a hard tube used without a grid impedance decreases the detection coefficient due to the lower bend of the plate-current curve. A *tickler coil* (page 346) when used will usually compensate for this decrease in the detection coefficient by increasing the strength of the impressed radio-signal voltage. All audio-output devices in the plate circuit should be shunted by a condenser having a small reactance for radio-frequency currents.

The sensitivity of a hard tube used *with* a grid impedance depends on the product of grid-plate conductance and the ratio of small changes in grid conductance to small changes in grid voltage and, also, upon a factor F which is equal to the equivalent parallel impedance of the grid impedance and the grid-to-filament resistance. For this case, when a hard tube is used, the sensitivity is usually much greater than the maximum sensitivity obtainable without a grid impedance. The grid-plate conductance should be made large by using the proper plate voltage. The value of the product mentioned before is a maximum for grid-biasing voltages of a few tenths of a volt, when positive, but F falls so rapidly for positive grid voltages, owing to the increase of grid conductance, that the point of maximum sensitivity is found at a grid voltage more negative than that which gives a maximum value of the product. The detection-coefficient[1] curves have very narrow peaks so that it is necessary to adjust the grid-biasing voltage to the proper value, usually 0.1 or 0.2 volt (positive). Because of the steady rectified component of current in the grid circuit, a strong radio-signal voltage unfortunately alters the grid-biasing voltage.

The ordinary grid-leak and blocking condenser is not the best form of grid impedance because of its variation with the frequency, and especially its large value at zero frequency. The ideal impedance is one having negligible resistance to steady currents, a high impedance for frequencies from 100 to 10,000 per second, and low impedance for radio-frequency currents. A tickler coil used with a detector provided with a grid impedance definitely increases the detection coefficient.

Performance of Various Types of Detector Tubes.—This description of detector-tube performance is based on an experimental study[2] of the newer types of tubes. The results obtained are shown in the chart of Fig. 275. This chart is drawn to give the relation between audio-frequency voltage (r.m.s. values) and radio-frequency voltage (peak values) at 1,000 kilocycles per second with a modulation of 30 per cent. Each curve is marked to indicate the type of tube which it represents. The coupling used was of the resistance type

[1] The *current-detection coefficient*, used as a measure of the detection current, is obtained from the second derivative of the curve showing the relation between plate current and plate voltage. The *voltage-detection coefficient*, meaning the equivalent steady voltage produced by plate rectification, is equal to the current-detection coefficient multiplied by the total resistance of the circuit, for a small change in current.

[2] Nelson, J. R., "Detector Tube Performance Curves," *Radio Engineering*, April, 1933.

(page 107), and the values of resistance were selected to provide the best performance consistent with high sensitivity and low distortion.

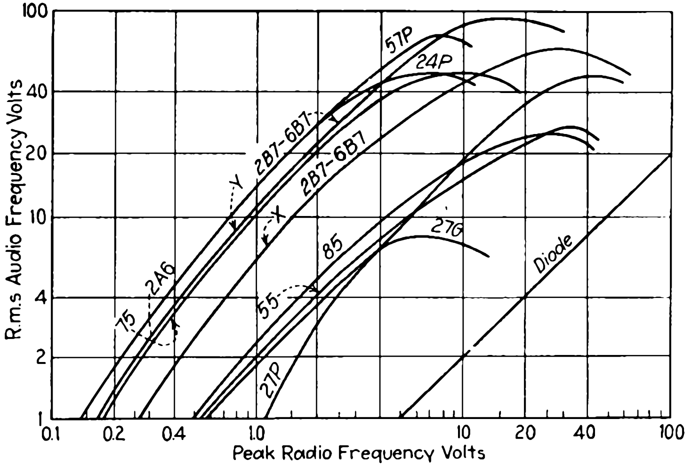


Fig. 275.—Average performance of typical detector tubes.

The wiring connections for the four types of circuits in which the tubes were operated are shown in Figs. 276 to 279. The values of the resistances are shown in these circuits and the values of the voltages applied to the tubes, are listed in Table XVI. The letter G following a tube-type number in the table and in the chart of Fig. 275 indicates that the tube was operated to give grid-circuit detection. The letter P indicates plate-circuit detection.

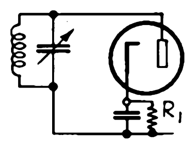


Fig. 276.—Typical two-element tube circuit for detection.

The circuit shown in Fig. 276 was used for the diode detector. Although the output has a linear characteristic for input voltages of 5 volts or more, it would show more curvature on lower inputs.

The circuit shown in Fig. 277 was used for such tubes as are represented by types 24, 27, and 57. For plate-circuit detection, the curves for type 24 and type 57 tubes coincide except

TABLE XVI.—RESISTANCE AND VOLTAGE VALUES

Type of tube	Circuit connections	Resistances, megohms				Voltages, volts	
		R_1	R_2	R_{SG}	R_L	E_{SG}	E_b
Diode	*a*	0.5					
27-G	*b*	0.5	.....	...	0.02	...	250
27-P	*b*	...	0.035	...	0.25	...	250
24-P	*b*	...	0.025	0.5	0.5	100	250
57-P	*b*	...	0.025	0	0.5	90	250
85	*c*	0.5	.....	...	0.3	...	250
55	*c*	0.5	.....	...	0.2	...	250
2A6	*d*	0.5	.....	...	0.25	...	250
75	*d*	0.5	.....	...	0.25	...	250
2B7-X	*d*	0.5	.....	...	0.027	100	250
6B7-X	*d*	0.5	.....	...	0.027	100	250
2B7-Y	*d*	0.5	.....	...	0.5	45	250
6B7-Y	*d*	0.5	.....	...	0.5	45	250

for a small section in the upper range where the type 57 tube has a much higher output. Somewhat the same condition is shown for the type 27 tube comparing plate-circuit detection with grid-circuit detection.

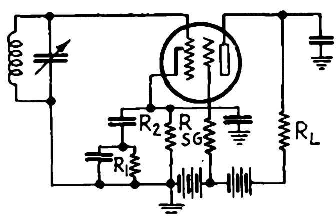


FIG. 277.—Typical detection circuit for four-element tubes.

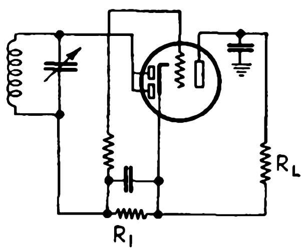


FIG. 278.—Typical detection circuit for duplex-diode-triode tubes.

The circuit shown in Fig. 278 was used for duplex-diode-triode tubes represented by types 55 and 85. A disadvantage of this arrangement, from the standpoint of operation at overloads, is that the grid-bias voltage is proportional to the carrier voltage. Hence the value of grid-bias voltage provided is excessive, as the modulation voltage must be equal to or less than the carrier voltage. Although the output available is sufficient, it may happen in a system using automatic volume control that the value of radio-frequency voltage is high enough to "over-bias" the triode unit of the tube and thus to cause plate-current cut-off. With an arrangement intended to provide a *fixed* grid-bias voltage in a circuit similar to that shown in Fig. 279, a greater increase in output voltage can occur before the tube is overloaded because the grid-bias voltage for the triode unit does not depend on the carrier voltage.

The circuit shown in Fig. 279 was used for duplex-diode high-mu triode tubes such as type 75 and type 2A6. In this type of tube the operating grid-bias voltage on the control grid must have a value which is nearly equal to that at which the flow of grid current begins, in order that there may be a grid current during at least a part of the cycle. The grid-cathode resistance must be kept high to avoid short-circuiting the grid-leak resistance of the diode circuit. This purpose is accomplished by the use of the 1-megohm resistance shown in the grid circuit.

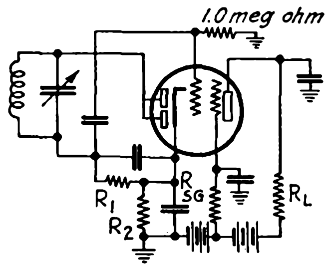


FIG. 279.—Typical detection circuit for duplex-diode high-mu triode tubes.

A duplex-diode-pentode tube, such as type 2B7 or 6B7, may be used with the diode units serving as detectors, and the pentode unit as an audio-frequency amplifier. The chart (Fig. 275) shows performance curves for this application of the tube. The curve marked *X* represents operation at a screen-grid voltage of 100 volts. This condition applies to the case in which the same value of screen-grid voltage is applied to the other tubes. More satisfactory operation, however, may be obtained at a screen-grid voltage of 45 volts, as shown by the curve marked *Y*.

The curves indicate that the sensitivity obtained with a tube of the duplex-diode high-mu triode type (2A6) is nearly as good as that for the duplex-diode pentode tube (2B7). Further, the triode type is less expensive than the pentode type. Both of these types have an advantage over tube type 24 or 57, in that they can be used to supply voltage for automatic volume control. The duplex-diode triode tubes such as types 55 and 85 show much better sensitivity and capacity for overload than the tubes of type 27, and in addition they can be utilized for other purposes such as automatic volume control.

In general it may be stated that the use of the new tubes allows for improved circuit performance with regard to sensitivity and overload conditions and, also for increased flexibility with regard to other tube functions such as automatic volume control.

Detection with Gaseous Detector.—A gaseous detector tube is one in which a small amount of gas is utilized to change the characteristics. The type 00A tube uses caesium vapor for this effect. In a tube of this type the particles of gas are ionized when they strike the electrons that are moving to the plate. Because of this action the characteristic curves show sharp bends at which exceptionally good detection may be obtained. Thus it is seen from Fig. 280 that best detection is obtained at a grid voltage of about minus 2.0 volts, which represents the point of greatest curvature. Either grid rectification or plate rectification may be used. Another result of the ionization is that there is a flow of plate current when both the plate and grid voltages are zero, and this flow is not stopped unless the grid-bias voltage is negative enough to produce cut-off. The value of plate voltage is not critical at 45 volts, but at lower voltages the sensitivity is decreased and at higher voltages the noise level is higher and consequently detector action suffers. The audio-frequency voltage in the output circuit is quite critical with respect to the adjustment of the grid-bias voltage, as shown in Fig. 281. Except at very low values of signal voltage the relation between the change in plate current and the signal voltage is practically linear. Noise is its main disadvantage.

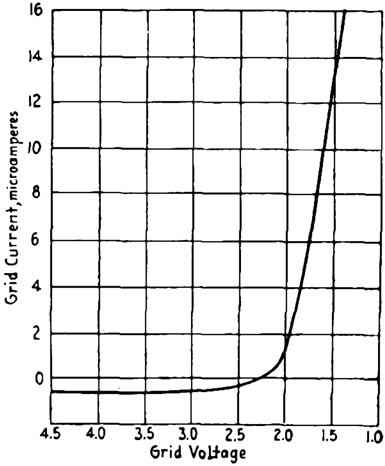


Fig. 280.—Characteristic curve showing best point of operation of UX-200A tube.

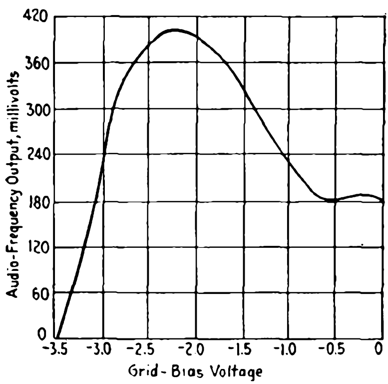


Fig. 281.—Variation of audio-frequency output with changes of grid-bias voltage for UX-200A tube.

Detection with Four-element Tubes.—A screen-grid tube used as a detector gives a high audio-frequency amplification per stage. The utilization of such high audio-frequency amplification is troublesome because of the increased difficulty from frequency distortion due to the coupling between the tubes which are in a common power-supply circuit, and also because microphonic disturbances in the detector cause more disturbance.

The amplification of a screen-grid tube can be utilized by using the tube as a detector and eliminating the first stage of audio-frequency amplification. Under these conditions the detector tube must be able to take a radio-frequency input voltage of several volts and must be able to supply 20 to 30 volts to the grid of the power tube.

The four-element tube of the screen-grid type is used more commonly for the detection of large than small signal voltages. In such service the screen-grid voltage should be less than the values recommended for amplification. The tube may be connected either for grid rectification or for plate rectification.

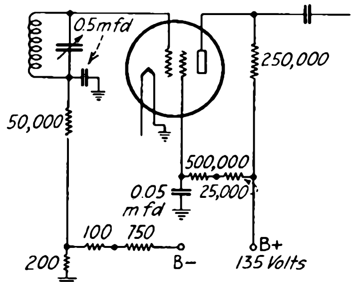


FIG. 282.—Application of screen-grid tube type 32 as detector in Spartan model 81A receiver.

As in a triode, the plate current in a tetrode is a function of two variables, (1) plate voltage and (2) control-grid voltage. Hence for either grid or plate rectification the performance of a screen-grid detector is comparable with that of a triode. A self-biased screen-grid detector has high sensitivity and low distortion on small signal voltages, but the distortion increases with higher signal input.

The use of a screen-grid type 32 tube as a detector is shown in Fig. 282. The grid-bias voltage is obtained by the self-biasing method.

Calculation of Output Voltage.—The curves of Fig. 283 show the variation of the plate current with the plate voltage of a screen-grid tube for various plate input voltages at 1,000 kilocycles per second. Different load lines are drawn from the point corresponding to 270 volts. The voltage applied to the screen grid was $E_{c2} = +67.5$, and the grid-bias voltage was $E_{c1} = -12.3$ volts. This tube was used as a detector in the circuit of Fig. 284. Here, $R = 5 \times 10^5$ ohms, $r = 2 \times 10^6$ ohms, and $C = 0.2 \times 10^{-6}$ farads. The alternating-current impedance of the combination is approximately 4×10^5 ohms.

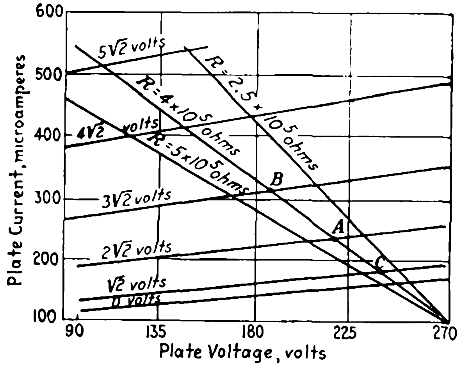


FIG. 283.—Relation of plate current to plate voltage in UX-222 tube for various input voltages and loads.

The output voltage for a given input voltage and load may be obtained from the curves that have just been mentioned. Thus, with a load of 400,000 ohms, an input voltage of 2 volts (root-mean-square value), modulated 50 per cent, the point A is taken as a reference. The alternating-current voltage across the resistance R will vary in value between B and C. This corresponds to an output-voltage variation of approximately 52 volts, so that the peak value is one half of the total, or 26 volts. For 40 per cent modulation, the peak value would be 80 per cent of this or 20.8 volts. For any given input voltage it is only necessary to draw two other curves; that is, for example, with an input of $2\sqrt{2}$ volts, curves may be drawn for values of input of $\sqrt{2}$ and $3\sqrt{2}$ volts. Then, the variation of voltage at 50 per cent modulation is found, and,

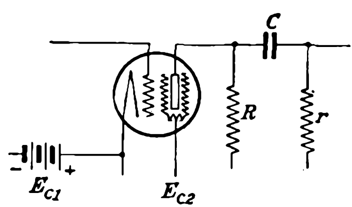


FIG. 284.—Typical circuit using UX-222 tube as detector.

since the output voltage is proportional to the modulation, its value for other degrees of modulation may be found.

Detection with Multi-electrode Tubes.—It has been shown (page 127) that a five-electrode tube, as commonly used, is similar to a screen-grid tube with an extra grid placed between the screen-grid and the plate, the extra grid being connected to the cathode. Then, at all except low plate voltages, the value of the plate current depends not on the plate voltage but on the screen-grid and control-grid voltages. Thus what holds for the screen-grid detector can be applied also to this

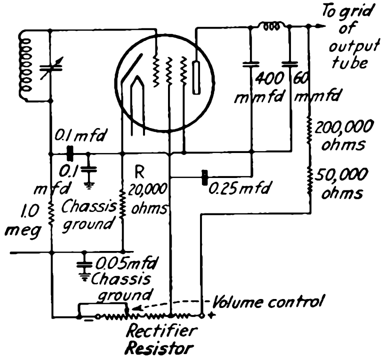


FIG. 285.—Circuit for using type 77 tube with self-biasing resistance as detector.

type of multi-electrode detector. Either grid-circuit or plate-circuit detection can be used.

Type 77 as Detector.—This type, known as a triple-grid detector, is useful as a grid-biased detector in the *universal receiving* set intended for operation on either alternating or direct current. The particular advantage of type 77 tube is its ability to deliver a large audio-frequency output voltage of good quality with a relatively small radio-frequency input-signal voltage. The cathode-resistance method of providing grid-bias voltage is better than the bleeder circuit or than the partial self-biasing method, because it permits a higher output at low modulation. The use of type 77 tube as a detector is shown in Fig. 285, where *R* is the self-biasing resistance for the detector tube.

Non-oscillating Tube as Detector with Regeneration.—It has been shown that the radio-frequency portion of the plate current of a detector tube does not enter into any action on the telephone receiver or other apparatus in the plate circuit. This radio-frequency current may be used to increase the radio-frequency voltage in the input circuit. To accomplish this a feed-back coil is coupled to the secondary coil in the grid circuit. For a given radio-signal strength, the radio-frequency voltages and currents are increased by the effect of regeneration and, consequently, the volume of sound is also increased. This action is cumulative up to a certain point, but beyond this value the tube begins to oscillate. A more complete description of regeneration is given in Chap. XI, but this elementary description serves to introduce the conception of an oscillating tube.

Oscillating Tube in Reception.—The frequency of an incoming radio-frequency current may be changed by a method which depends on the interaction of two currents of slightly different frequencies. Thus, if the input circuit is forced to carry a locally generated current having a frequency either greater or less than that of the incoming current, there is an interaction between the two frequencies which produces a current of a third frequency equal to the numerical difference between the other two. This general method is called *heterodyne action* and the current of the third (and lower) frequency is called the *beat current.* When the same tube generates the local oscillations and acts also as a detector, the action is known as *autodyne* or sometimes as *self-heterodyne.* When an additional tube is used to generate the local oscillations, the action is called *separate heterodyne.* The *super-heterodyne* or *multiple-heterodyne* or *double-detection* method of reception is based on the use of separate heterodyning and detecting stages. These various methods will be considered briefly in Chap. XI.

CHAPTER IX

VACUUM TUBES AS RECTIFIERS IN POWER-SUPPLY DEVICES

Types of Rectifiers.—A rectifier is a device by means of which an alternating current is changed into a current of which a part is direct. This definition is general enough to cover all types of rectifying devices, including not only electronic rectifying tubes but also dry-contact rectifiers, crystal rectifiers, electrolytic rectifiers, and mechanical rectifiers.[1] Still other types not used at the present time are the rectifying spark gap, the coherer, the magnetic detector, and the capillary detector.[2]

Of these various types only the electronic rectifiers are treated here. These may be grouped in two main classes, (1) high-vacuum tube types, and (2) the gas-filled- and vapor-filled-tube types. The action of typical tubes for rectifiers has been described in Chap. IV. Such rectifiers may be further defined and classified according to the form of their output voltage waves. Thus a *half-wave rectifier* is a device by means of which alternating current is changed into pulsating current, utilizing one half of each cycle only. A *full-wave rectifier* is a device having two elements so arranged that the current output flows in the same direction during each half cycle of the alternating-current supply. There are also *single-phase rectifier circuits*, and *multi-phase rectifier circuits*.

Capacities and General Applications of Electronic Rectifiers. Electronic rectifiers are available in a wide variety of voltage and current ratings. The current ratings range from micro-

[1] These types of rectifiers are described in Moyer and Wostrel, "Radio Handbook," Sec. V.

[2] These types are described by L. S. Palmer in "Wireless Principles and Practices," Chap. IX.

amperes to thousands of amperes, and the voltage ratings from millivolts to about 50,000 volts. The voltage rating is determined by the negative or *inverse voltage* which the insulation of the plate can withstand. The current rating of gas-filled and vapor-filled tubes, which have hot cathodes, depends on the emission limit of the cathode. When this limit is reached, the cathode surface may be impaired by the impact of positive ions.

Rectifier tubes of the high-vacuum type are designed for operation in *low-power* circuits, those with tungsten filaments being particularly adapted to *high-voltage* service. A tube of this type is made with the elements enclosed in a glass bulb. Rectifier tubes of the gas-filled and vapor-filled types are designed for operation in rectifier circuits in which a comparatively high current output is required. For such applications they are preferable to the high-vacuum types because of their low, constant voltage drop which gives better regulation and higher efficiency. For power applications the *mercury-arc rectifier*, controlled or uncontrolled, is used. This tube is of the gaseous type and has the same general characteristics. *Grid-glow tubes* may be used as rectifiers in certain applications in which special characteristics are required.

Specific industrial applications of various types of rectifier tubes are described in Chap. XIII.

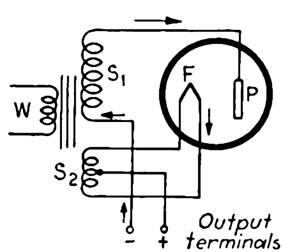


FIG. 286.—Simple rectifier circuit.

Simple Rectifier Circuit Using the High-vacuum Rectifier Tube.—Power-supply systems for radio apparatus are generally designed for operation on a single-phase, 110-volt, 60-cycle electrical line. A simple rectifier circuit for such a system, using a diode high-vacuum rectifier tube, in half-wave rectification is shown in Fig. 286. An alternating-current voltage from the supply line is applied to the primary winding W of the power transformer. The filament current is obtained from the transformer secondary winding S_2. When a load is connected across the output terminals, a rectified current flows through the circuit in the direction shown by the arrows. The rectified half-wave current is shown in Fig. 287.

A more detailed explanation is necessary to show the action of the tube in this circuit. The form of the voltage that is applied to the tube through the transformer secondary winding is shown in the drawing. In the first half cycle, when the voltage is positive, the upper end of the winding S_1 is positive and the lower end of S_1 is negative. Under these conditions a current flows through the tube from the plate P to the filament F, through the load connected to the output terminals, and back to the transformer winding S_1.

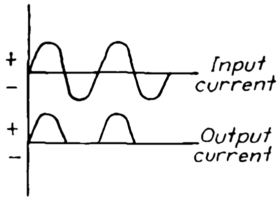


FIG. 287.—Forms of input and output current of simple half-wave rectifier.

When the second half of the first cycle begins, the applied voltage reverses. Then the plate of the tube becomes negative and no current flows. During the next cycle this operation is repeated. Consequently, the output current consists of a series of pulses or surges of a variable direct current. It is clear from the drawing that rectified current flows during half a cycle only. The connections for a half-wave rectifier which has a heater cathode are shown in Fig. 288.

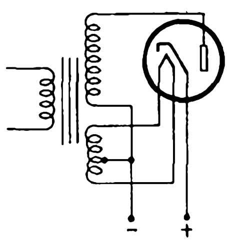


FIG. 288.—Circuit for half-wave rectifier with heater cathode.

Full-wave rectification, in which a rectified current flows during both halves of the cycle, is obtained by the use of two separate diode rectifiers, or by one duplex-diode rectifier. A duplex-diode rectifier actually consists of two diode rectifiers in one bulb, each rectifier having a plate and a filament. A rectifier circuit using one tube for full-wave rectification is shown in Fig. 289. The secondary winding S_1 is connected across the two plates of the tube and its center tap is connected to the negative output terminal. In the first half cycle, when the voltage applied to the tube is positive, the upper end of winding S_1 is positive, plate P_1 is positive, and plate P_2 is negative. Under these conditions there is a current flow through the tube from P_1 to F, through the load connected to the output terminals, and back through the center-tap connection to S_1. During this interval no current flows from the second plate P_2 to the filament. But when the second half of the first cycle begins, the applied voltage reverses, making plate P_2 positive, and P_1 negative. Under these conditions there is a current flow through the tube from P_2 to F, through the load in the same direction as before, and back to S_1. Thus the output current consists of a pulse or surge of variable direct current in the same direction in each half cycle. The wave forms of current input and output are shown in Fig. 290.

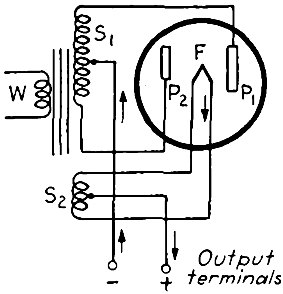


FIG. 289.—Rectifier circuit for full-wave rectification.

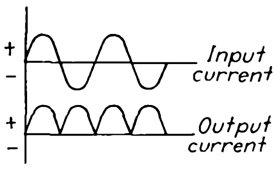


FIG. 290.—Forms of input and output current of simple full-wave rectifier.

Maximum Peak Inverse Voltage.—This is the value of peak voltage that a rectifier tube can withstand in a direction opposite to that of normal current flow. The action can be described by reference to Fig. 289, which represents the circuit connections for a full-wave rectifier tube. When the plate P_1 is positive and the plate P_2 is negative, there is a current flow from P_1 to S_2, but none from P_2 to S_2. The cathode of the tube is then positive with respect to the plate P_2. Consequently, at that instant the voltage between the filament and the plate P_2 is opposite or in inverse relation to the voltage that produces the flow of current. The peak value of this inverse voltage depends on the resistance and the character of the conducting space between the cathode and the plate P_2. The safe value or the maximum inverse peak voltage is that which does not cause a breakdown. For a full-wave rectifier tube on a single-phase supply line, the safe value of voltage is equal to the transformer peak voltage minus the drop in voltage across the active half of the tube. With a sine-wave form of voltage on the supply line, the safe value is about 1.4 times the root-mean-square voltage between plates P_1 and P_2. In polyphase circuits a graphical determination must be made to obtain the value of safe peak voltage.

Maximum Peak Plate Current.—This is the value of peak current that a rectifier tube can withstand in the direction of normal current flow. For the hot-cathode type of tube the safe value of current depends on the quantity of electrons emitted from the cathode, and on the electrode structure, but in a given circuit the actual peak value depends on the constants of the filter circuits. If the filter circuit is designed in such a way that a choke coil is adjacent to the rectifier tube, the peak current may be somewhat higher than the load current, but if a condenser is adjacent to the rectifier tube, the peak current may be several times the load current.

Electron Flow in Rectifier.—When the filament is heated, electrons are emitted at the filament surface and gather in the surrounding space. If a positive voltage is applied to the *plate* or *anode*, electrons are attracted to the plate. This passage of electrons produces a flow of current in the opposite direction, namely, from plate to filament, according to the accepted convention for current flow. If a negative voltage is applied to the plate, the free electrons in the space around the filament are forced back into the filament, and there is no current flow.

The plate when positive does not attract all the electrons emitted at the filament. Some of the electrons remain in the space around the filament and form a *space charge*. This space charge acts to repel electrons leaving the filament and tends to hinder their travel to the plate. The effect of the space charge depends on the temperature of the filament and on the plate voltage. If space charge could be eliminated a given flow of current could be maintained at a lower plate voltage. One method of decreasing the space-charge effect is used in rectifiers of the mercury-vapor type. The mercury in such a rectifier is vaporized when the tube is operated. The atoms of mercury vapor are bombarded by the electrons moving toward the plate with the result that some of the atoms become ionized. Ionized atoms lose electrons and thus are left positively charged, and these positively charged mercury ions act to neutralize the space charge. As the space charge is neutralized, increased numbers of electrons are available to produce current flow. The voltage drop of a mercury-vapor rectifier is relatively small, having a value of about 15 volts between the plate and the filament.

Rectifier Circuits and Filters.—The pulsating output delivered by the simple rectifier circuits described previously

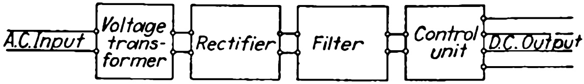


Fig. 291.—Apparatus for obtaining "pure" direct current.

may be acceptable for some applications, but for other uses the pulsations must be smoothed out to a degree depending on the purpose for which power is needed. This smoothing is accomplished by the use of filters and also to some extent by the use of special circuit arrangements.

The layout of power-supply apparatus is given in Fig. 291. This shows the relative positions of the rectifier unit, the filter system, and the control unit. In general, this type of apparatus can be used with either a high-vacuum rectifier or a gaseous rectifier.

A *filter* generally contains inductance in the form of *choke coils*, and capacity in the form of condensers. The coils and condensers have various values and are connected in various ways depending on the action desired and on the magnitude of the voltages and currents. A choke coil tends to smooth out fluctuations in current and must have more inductance for large than for small currents. A choke coil has a relatively low resistance and should be wound with wire that is heavy enough to carry the necessary current without overheating. A condenser tends to smooth out fluctuations in voltage. The smaller the voltage the larger the condenser must be to smooth out the fluctuations.

The control unit of power-supply apparatus for radio applications takes the form of a *voltage divider*. The voltage divider consists of a combination of resistances so arranged that required amounts of current at specified voltages may be obtained at various taps on the resistances. A method of calculating the resistance values is given later.

Voltage and Current Variations of Rectifier Output.—The voltage and current variations that are produced by various

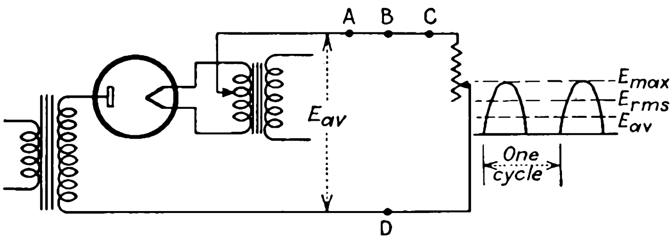


FIG. 292.—Typical rectified power-supply system.

arrangements of tubes for half-wave and full-wave rectification in single-phase and three-phase circuits are explained in this section.

Single-phase, Half-wave, One-tube Rectifier.—A simple arrangement for half-wave rectification with one tube in a single-phase circuit is shown in Fig. 292. This figure also indicates the form of the voltage wave which is developed across the resistance load. With this arrangement the various voltage relations are: $E_{av} = 0.318E_{max}$, $E_{av} = 0.45E_{rms}$, $E_{inv.} = 3.14E_{av}$; and the current relations are $I_{av} = 0.318I_{max}$, $tube_{av} = load_{av}$, $tube_{rms} = load_{rms}$, $tube_{rms} = 1.57\ tube_{av}$, and $load_{rms} = 1.57\ load_{av}$. This rectifier circuit can be used only in applications where a low average of load voltage is satisfactory and where large voltage variations do not cause disturbance.

Effect of Capacity and Inductance in Filter.—The supply of energy from a rectifier circuit can be made more uniform if a filter of condensers or choke coils, or both, is connected between the rectifier tube and the load. The filter absorbs part of the energy during the peaks of the input and delivers it during the periods when the supply is low. The electrostatic energy stored in a condenser is proportional to the applied voltage, and the electromagnetic energy stored in a choke coil is proportional to the rate of change of the current.

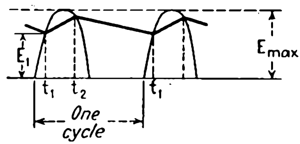


FIG. 293.—Effect on output voltage produced by connecting condenser across rectifier circuit.

If a condenser is connected across the rectifier circuit of Fig. 292 at the points *B* and *D*, its effect on output voltage is shown in Fig. 293. With this arrangement the average value of voltage can be increased until it is only a few per cent less than the maximum value. The condenser is being charged during the interval t_1 to t_2 of a cycle, and discharged during the interval t_2 to t_1. This procedure is repeated periodically. The average *direct-current* voltage is equal approximately to the average of the condenser voltages at charge and discharge, namely $(E_{max} - E_1) \div 2$. One disadvantage of this circuit arrangement is that the charging current taken by the condenser during the time interval from t_1 to t_2 is very high and must be kept below the peak current rating of the rectifier tube. Generally, the circuit is used only in applications where very small currents are needed.

Where a larger current is required, the amplitude of voltage ripple may be reduced by the addition of a filter choke coil in a rectifier circuit which has a high-vacuum tube. In the case of a load having a high resistance the choke coil is inserted in the circuit of Fig. 292 at the point *A*, producing an average voltage E_{av} which has a value of $0.45E_{rms}$ volts. In the case of a load having a low resistance the coil is inserted at the point

C. Under these conditions the voltage E_{av} has about the same value as when only a filter condenser is used, and the value of the charging current is high if the condenser is large. In the first arrangement the output voltage is lower because the condenser does not charge up to the peak of the alternating-current voltage on account of the limiting effect of the coil, the inverse voltage on the tube is higher, the peak value of current demand on the rectifier is reduced for a given output, the voltage regulation is improved, and for a given load voltage a higher transformer voltage is necessary.

The filtering action is improved, for given values of capacity and inductance, when they are distributed in sections rather

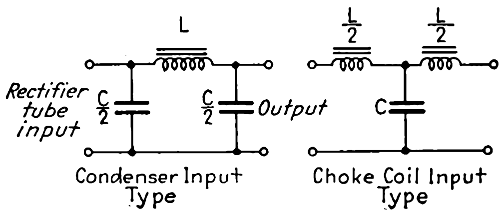


FIG. 294.—Two types of filter sections.

than placed in a single group. Two general types of filter sections are shown in Fig. 294. A filter condenser, particularly the input type, must be designed to withstand the instantaneous peak value of the alternating-voltage input; the peak value being approximately 1.4 times the root-mean-square[1] value as indicated by a voltmeter. The values of the inductances and condensers in the filter circuit, and the number of sections, vary with several factors, the most important one being the amount of ripple voltage which can be allowed. Other factors are the maximum current demand and the frequency of the line from which the alternating-current is taken.

Several departures as found in practice from the conventional filter system should be noted. A filter choke coil is generally inserted in the positive wire leading from the rectifier tube, but in some cases it is placed in the negative

[1] The root-mean-square (r.m.s.) or effective value is equal to 0.707 times the maximum value.

wire because in so doing it is possible to use the voltage drop across the filter choke coil for a grid-biasing voltage, and to eliminate the use of a by-pass condenser on the cathode of the output tube. One of the choke coils of a filter system may be

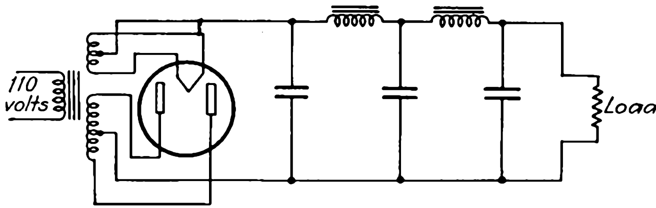


FIG. 295.—Circuit of full-wave rectifier with filter of condenser-input type.

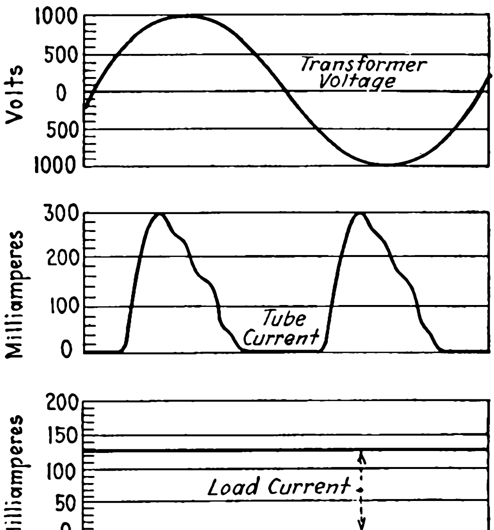


FIG. 296.—Oscillograph record of UX-280 tube with condenser-input type of filter.

replaced by the field winding of the loud-speaker, in fact, this winding may be the only choke coil in the filter system. A condenser may be shunted across the first choke coil to form a resonant circuit which will reduce hum frequencies.

Single-phase, Full-wave, One-tube Rectifier.—A circuit diagram of a full-wave rectifier with one type 80 tube, as commonly used for radio applications, is shown in Fig. 295. The *filter section* is of the condenser-input type with a recommended minimum value of 20 henrys for the choke-coil inductance and 2 to 4 microfarads for the condenser capacity. With this

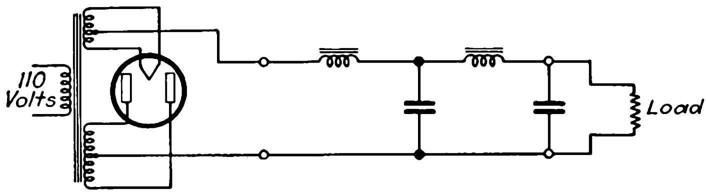


FIG. 297.—Circuit of full-wave rectifier with filter of choke-input type.

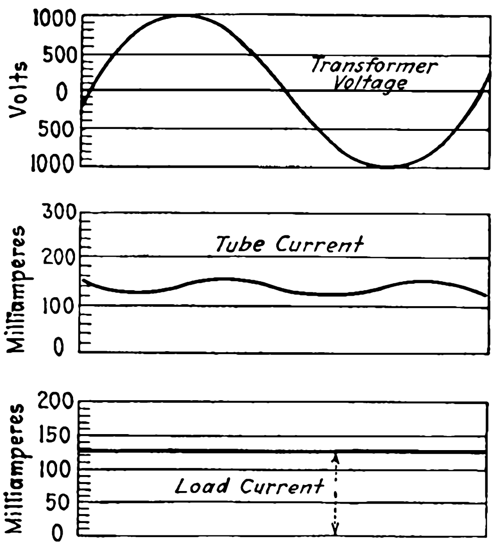


FIG. 298.—Oscillograph record of UX-280 tube with choke-input type of filter.

arrangement, the load on the tube is heavy, as shown on the oscillograph record in Fig. 296, which indicates instantaneous values of the current in the tube. This record shows that a current flows through the tube only when the transformer voltage exceeds the first filter-condenser voltage. The charging of the first condenser in the filter causes a very heavy current to flow through the tube for a short time, reaching a peak of 310 milliamperes. Since the average current ("load" current) is only 125 milliamperes, the peak current through the tube reaches a value of 2.5 times the average current. Thus, the cathode must be heavier and longer than would be the case if the rectified current could flow for a longer time, so that the high peak could be avoided.

A reduction in the value of the peak current is obtained by means of the filter circuit in Fig. 297, where the first filter condenser is omitted and the tube feeds directly into the inductance or choke coil. The oscillograph record (Fig. 298) shows the reduction in peak current, which is only 140 milliamperes or 1.1 times the load current. This reduction is possible because the tube no longer feeds directly into a condenser, and the choke coil keeps the current flowing through one anode, or both, during the entire cycle. Some voltage is lost in the choke coil, which, however, is a reactance load and does not consume power. The efficiency of the two systems is almost the same. The values in Table XVII show the advantages of the latter circuit in tube operation. Operation at this reduced peak current extends the life of the filament of the tube and allows a lower value of emission before the operating efficiency of the tube is affected. A tube having an emission of 200 milliamperes could be used satisfactorily in the circuit of Fig. 297 but not in that of Fig. 295.

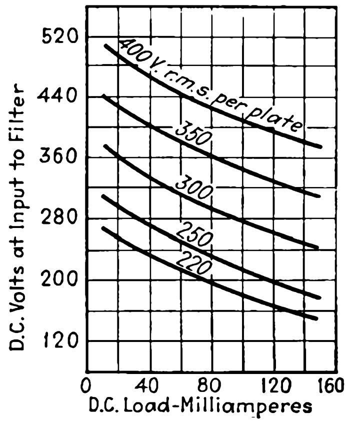


FIG. 299.—Regulation curves of voltage delivered to input of filter.

The condenser which is used across the input circuit in Fig. 295 should be added across the output of the filter of the circuit in Fig. 297 since the ripple voltage is slightly greater than that from the usual filter. The higher efficiency in the second case is the result of reduced tube losses because of operation at a lower temperature. As shown in Figs. 299 and 300, the regulation is better than when a condenser is used, except at very low values of power output.

TABLE XVII.—OPERATING CONDITIONS OF FILTER CIRCUIT

Circuit	Transformer, volts	Power input, watts	Load current, milliamperes	Load, volts	Power output, watts	Efficiency, per cent
Fig. 295	300	62	125	300	37.5	60.5
Fig. 297	360	59.5	125	300	37.5	63

A filter system, in which the input filter condenser is omitted, is not recommended for half-wave rectification, because the output current and voltage are reduced considerably so that the operation of the filter is impaired. The usual circuit design with a small input condenser of about 1.0 microfarad capacity reduces the peak current of the tube without noticeably reducing the output voltage.

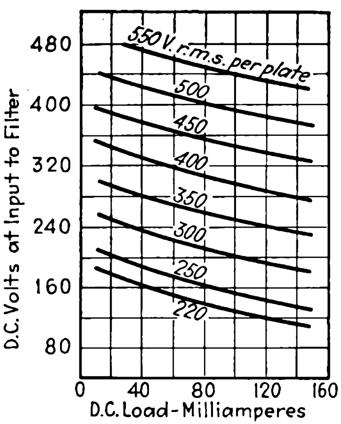


FIG. 300.—Regulation curves showing advantages of using circuit connections in Fig. 297.

Figure 299 illustrates the regulation curves of the voltage delivered to the filter input by the type 80 tube at various load currents with the type of filter shown in Fig. 295. If the filter resistance is known, the output voltage at the filter terminals can be determined. Figure 300 gives regulation curves which show the advantages, at load currents greater than 20 milliamperes, that are obtained by using the circuit connections in Fig. 297.

The full-line curves in Fig. 301 show the regulation of two type 81 tubes in a full-wave rectifier with a conventional filter. The dotted lines show the performance obtained in a similar circuit in which the first filter condenser is omitted. The superior regulation of the performance obtained with the use of the choke-input coil is evident. The circuit in which the first filter condenser is omitted is not satisfactory when the tube is

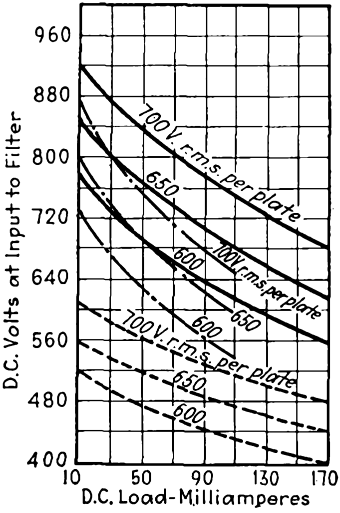


FIG. 301.—Regulation curves of two tubes in a full-wave rectifier with filter.

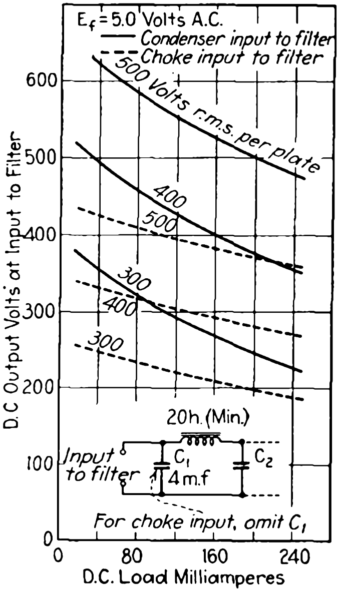


FIG. 302.—Characteristic curves of typical heavy-duty rectifier tube.

used as a half-wave rectifier. The dot-and-dash curves in Fig. 301 show the voltage delivered by the tube at the input (condenser type) to the filter for half-wave rectification.

The mercury-vapor type of rectifier was described on page 98. The capacities, ratings, and operating characteristics of tubes for such rectifiers and other types used in radio and low-power applications are given in the Tube Table on page 617.

The operation-characteristics curves of the type 5Z3 rectifier tube are shown in Fig. 302. This tube is a high-vacuum, full-wave rectifier designed for heavy duty. It is intended to supply rectified power to radio apparatus having very large direct-current requirements. Type 5Z3 tube is somewhat similar to type 83 which is a tube of the mercury-vapor type, the main difference being that the type 83 tube has a much lower internal voltage drop. These types are not interchangeable in a radio receiver unless the design is changed to conform to the tube characteristics.

Voltage-doubling Rectifier Circuit.—Two diodes may be utilized in a simple rectifier circuit as shown in Fig. 303 to

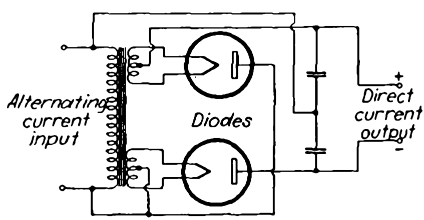


FIG. 303.—Simple rectifier circuit using two tubes connected so that rectification of each half cycle is obtained.

yield a voltage output which is equal to approximately twice the output from a half-wave rectifier. The two diode tubes are connected in such a way that rectification of each half cycle of the alternating-current supply is obtained. While a current is flowing through one diode during its conducting period, there is also a flow of discharge current from the condenser connected across the other diode. The effect of this combination produces a voltage which is equal to the direct-current output voltage of one tube plus the discharge voltage of the condenser. This total voltage is equal to approximately twice that obtained from a half-wave rectifier circuit. The output of a *voltage-doubler circuit* has a ripple frequency which is twice that of the supply voltage; consequently, in such a circuit, as also in a full-wave rectifier circuit, less filtering effect is necessary.

The type 25Z5 tube was designed particularly for full-wave, voltage-doubling rectifier service. It is essentially a high-vacuum *duplex diode*, containing two separate diode units each being provided with a coated unipotential heater cathode. Sufficient ventilation should be provided to prevent overheating. The tube is intended for supplying power as a half-wave rectifier to "transformerless" radio receiving sets

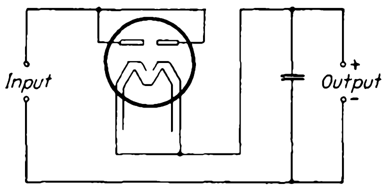


FIG. 304.—Half-wave rectifier using 25Z5 tube.

of the "universal" type (page 313), and in voltage-doubler circuits for supplying power to "transformerless" receiving sets operated by alternating current. These applications are possible because a separate base pin is provided for each of the two cathodes. The heater can be operated in series with the heaters of other tubes in the receiving set. The filter circuit should be of the condenser-input type, using an input capacity of 16 microfarads for half-wave rectification and a higher value for voltage-doubling service. For use as a half-wave rectifier the two plates of the tube are connected together and the two cathodes are connected together as shown in Fig. 304. Operating conditions are given in the Tube Table (page 617). For use as a voltage doubler the diode units of the tube are connected as shown in Fig. 305 and the operating conditions are the same as for half-wave service.

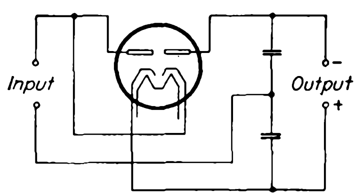


FIG. 305.—Voltage-doubling rectifier using 25Z5 tube.

Single-phase, Full-wave, Two-tube Rectifier.—Both halves of a cycle can be rectified by the method of using two tubes as shown in Fig. 306. With this arrangement the voltage relations are: $E_{av} = 0.318E_{max}$; $E_{max} = 0.448E_{rms}$; and $E_{inv} = 3.14E_{av}$. The current relations are: $I_{av} = 0.636I_{max}$; $tube_{av} = 0.5\ load_{av}$; $tube_{rms} = 0.705\ load_{rms}$; $tube_{rms} = 1.57\ tube_{av}$; and $load_{rms} = 1.111\ load_{av}$. The advantages of this arrangement as compared with that used in Fig. 292 are that E_{av} is

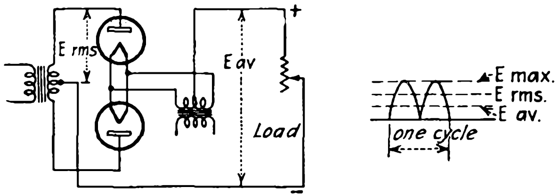


FIG. 306.—Method of rectifying both halves of a cycle with the use of two tubes.

doubled for a given input voltage, and that a smaller filter can be used because the frequency of the ripple voltage is twice that of the supply voltage. The use of the duplex-diode rectifier tube was described on page 371.

Single-phase, Full-wave, Four-tube Rectifier.—For a given voltage across each tube, the arrangement shown in Fig.

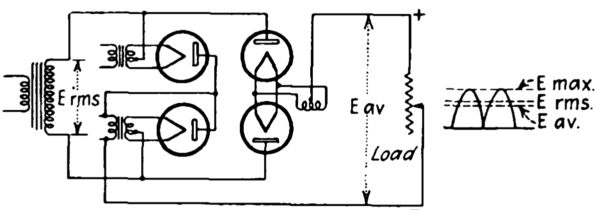


FIG. 307.—Method of rectifying both halves of a cycle with the use of four tubes to obtain twice the output voltage obtained from the circuit shown in Fig. 306.

307 can be used to provide double the direct-current output voltage obtained from the circuit of Fig. 306. With relation to the tube voltage, the alternating input voltage also is doubled. In the four-tube arrangement two tubes are in series during each half wave of the cycle. With this arrangement the voltage relations are: $E_{av} = 0.636E_{max} =$

$0.900E_{rms}$ and $E_{inv} = 1.57E_{av}$. The current relations are: $I_{av} = 0.636I_{max}$; $tube_{av} = 0.50\ load_{av}$; $tube_{rms} = 0.705\ load_{rms}$; $tube_{rms} = 1.57\ tube_{av}$; and $load_{rms} = 1.11\ load_{av}$.

Three-phase, Half-wave, Three-tube Rectifier.—When more than one phase is rectified, the effect is that more voltages are superposed, in different time relation to each other, but

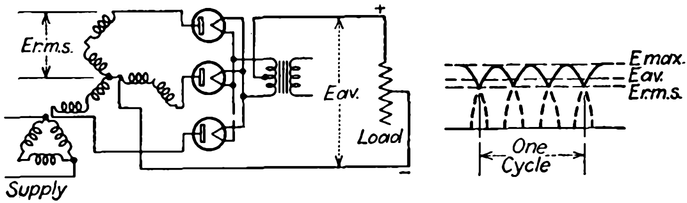


FIG. 308.—Three-phase rectifier circuit using three tubes for half-wave rectification.

having the same peak values. A three-phase rectifier circuit using three tubes for half-wave rectification is shown in Fig. 308 together with the wave forms of the rectified voltages. It is seen that with this arrangement there is an increase in E_{av} and a decrease in the amplitude of the ripple voltage. The ripple frequently increases with the number of phases.

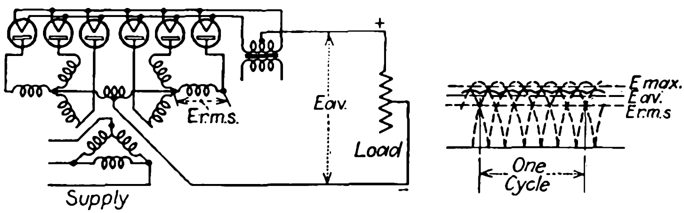


FIG. 309.—Three-phase rectifier circuit using six tubes for half-wave rectification with double Y connections.

With this arrangement the voltage relations are: $E_{av} = 0.827E_{max} = 1.170E_{rms}$ and $E_{inv} = 2.09E_{av}$. The current relations are: $Tube_{av} = 0.333\ load_{av}$; $tube_{rms} = 0.579\ load_{rms}$; $tube_{rms} = 1.76\ tube_{av}$; and $load_{rms} = 1.02\ load_{av}$.

Three-phase, Half-wave, Six-tube Rectifier.—The circuit in Fig. 309 shows the use of six tubes for half-wave rectification with a double *Y* connection on a three-phase system. The wave form of voltage indicates the increase in the ripple frequency. With this arrangement the voltage relations are: $E_{av} = 0.827E_{max} = 1.170E_{rms}$ and $E_{inv} = 2.090E_{av}$. The current relations are: $I_{av} = 1.910I_{max}$; $tube_{av} = 0.167\ load_{av}$;

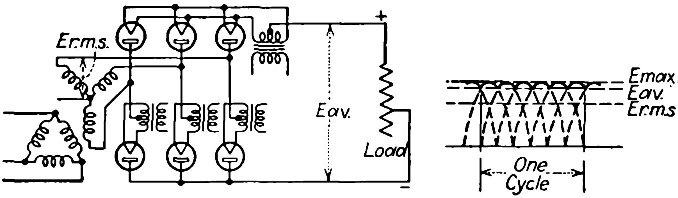


FIG. 310.—Three-phase rectifier circuit using six tubes with full-wave rectification.

$tube_{rms} = 0.280\ load_{rms}$; $tube_{rms} = 1.72\ tube_{av}$ and $load_{rms} = 1.02\ load_{av}$.

Three-phase, Full-wave, Six-tube Rectifier.—The circuit in Fig. 310 shows the use of six tubes for full-wave rectification on a three-phase system. With this arrangement the voltage

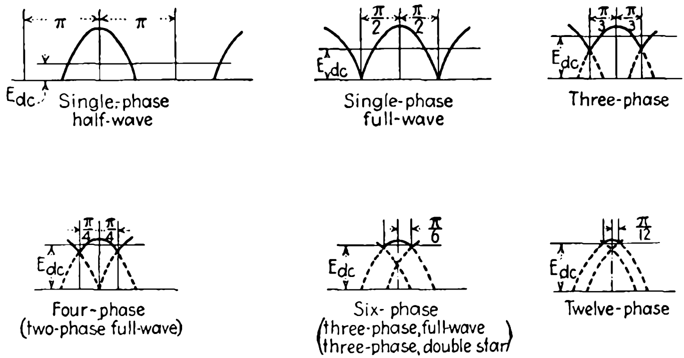


FIG. 311.—Relation of ripple frequency to direct-current voltage from a single-phase to a twelve-phase circuit.

relations are: $E_{av} = 1.65E_{max} = 2.34E_{rms}$ and $E_{inv} = 1.045E_{av}$. The current relations are: $I_{av} = 0.955I_{max}$; $tube_{av} = 0.333\ load_{av}$; $tube_{rms} = 0.561\ load_{rms}$; $tube_{rms} = 1.72\ tube_{av}$; and $load_{rms} = 1.02\ load_{av}$.

Effect of Number of Phases on Rectification.—The wave forms of rectified voltage in Fig. 311 show the increase in ripple frequency and the increase in direct-current voltage from a single-phase to a twelve-phase circuit. The rectifiers represented by the wave forms from the six-phase and the twelve-phase circuits can be derived from a three-phase circuit.

Table XVIII gives approximate values for the input voltage, output voltage, and output current for the circuits shown in Figs. 306 to 310 inclusive when a half-wave, hot-cathode, mercury-vapor rectifier tube such as type KI-605 is used.

TABLE XVIII.—INPUT AND OUTPUT FOR KI-605 RECTIFIER IN TYPICAL CIRCUITS

Circuit	Number of tubes	Input voltage, volts (r.m.s.)	Output voltage, d.c. volts	Output current, amperes
Fig. 306, 1-phase, full-wave	2	1,750 per tube	1,570	0.2
Fig. 307, 1-phase, full-wave	4	3,500 total	3,150	0.2
Fig. 308, 3-phase, half-wave	3	2,050 per leg	2,400	0.25
Fig. 309, 3-phase, double "Y"	6	2,050 per leg	2,400	0.6
Fig. 310, 3-phase, full-wave	6	2,050 per leg	4,800	0.3

This two-electrode tube, which is air-cooled and has an oxide-coated cathode, is rated as follows: Maximum crest inverse voltage = 5,000 volts; maximum crest anode current = 0.3 ampere; cathode voltage = 2.5 volts; cathode current = 2 amperes; tube drop = 15 volts.

Regulation of Voltage Supply.—Where the voltage of the power circuit used for the operation of radio apparatus shows considerable variation some method must be provided for voltage regulation. Two auxiliary tubes which have been used for this purpose are the voltage-limiting tube (type UX-874) and the ballast- or current-regulating tube (type UV-876). A description of these tubes is given on page 205.

Voltage Distribution.—The load on the rectifier circuits shown in the preceding diagrams is considered for simplicity as a single resistance. In a radio receiving set, however, positive voltages of various values are needed for plate and screen-grid supply, and negative voltages for grid-biasing. The maximum voltage available from the rectifier circuit is generally used for the plate requirements of the tubes. Lower values of voltage such as are needed for screen-grid supply are obtained from the high-voltage terminal through series resistance units. Negative voltages are obtained from resistance units placed either in the negative wire of the filter system or in the cathode circuit of the tube that requires a grid-bias voltage. In some power-supply systems the various resistance units are grouped together in an arrangement known as a voltage divider (page 362) and connected across the filter output. In this case the voltage divider is tapped at various points for voltages of the required values. In other systems the various resistance units are separated and so located that each may be considered in relation to the stage which it supplies.

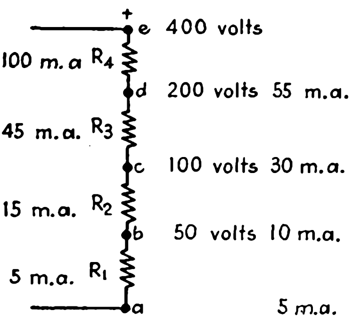


FIG. 312.—Conventional voltage divider.

Voltage-divider Calculations.—The arrangement of resistance units in Fig. 312 represents a conventional voltage divider. Arbitrary values of currents and voltages are assumed for ease in calculation. This divider is intended to provide 200 volts at 55 milliamperes, 100 volts at 30 milliamperes, and 50 volts at 10 milliamperes. The input to the divider is taken from a 400-volt rectifier-filter system.

The values for the resistances are calculated from the negative end of the divider. The resistance in ohms of any unit is equal to the voltage in volts across that unit divided by the current in amperes flowing through that unit. The current in the resistance R_1 is called the "bleeder" current which has in this circuit a value of 5 milliamperes. The voltage across the resistance R_1 is 50 volts, being the same as the value at the tap marked b. The resistance of R_1

must be 50 ÷ 0.005, or 10,000 ohms. The current in the resistance R_2 is the bleeder current of 5 milliamperes plus the 10 milliamperes taken from the tap *b*. The voltage across the resistance R_2 is the difference between the voltage at the tap *c* and that at the tap *b*, or is 100 − 50 = 50 volts. The resistance R_2 must be 50 ÷ 0.015, or 3,333 ohms.

The current in the resistance R_3 is equal to the current in the resistance R_2 plus the 30 milliamperes taken from the tap *c*, which is 45 milliamperes. The voltage across the resistance R_3 is the difference between the voltage at the tap *d* and that at the tap *c* or 200 − 100 = 100 volts. The resistance R_3 must be 100 ÷ 0.045 or 2,222 ohms. The current in the resistance R_4 is 100 milliamperes and the voltage across this resistance is 200 volts. The resistance R_4 must be 200 ÷ 0.100, or 2,000 ohms.

A resistance unit consumes power which is dissipated in the form of heat. The value of the power in watts is equal to the voltage in volts across the unit multiplied by the current in amperes in the unit. To allow for a margin of safety in overheating, the heat dissipation rating of a resistance unit should be double the power rating as calculated above.

Ignitron Rectifier Circuits.—The action of the ignitron, a controlled rectifier of the gaseous type, has been described in Chap. IV. The use of the ignitron for single-phase, half-wave rectification with early starting in the cycle and without phase control is illustrated in the circuit of Fig. 313. The anode *A* is connected to one side of the supply line and the cathode *C* to the other side in series with the load. A small auxiliary rectifier is connected from anode *A* to the igniter *B*.

At the beginning of the voltage cycle the voltage between the anode *A* and the cathode *C* starts to build up as shown by the curve *a* in Fig. 314 and the igniter current as shown by the curve *c*. The voltage across igniter *B* (Fig. 313) is equal to the anode voltage minus a constant "arc drop" of about 15 volts in the series rectifier. An arc forms at the junction of the mercury and the igniter rod when the igniter voltage and current reach the values *e* and *i*, respectively, in the curves. When the arc shifts to anode A, the anode voltage falls to the value of the arc voltage drop (10 to 15 volts), remaining constant for the remainder of the half cycle, and the igniter current falls to zero. The anode current follows a sine-wave form for the remainder of the half cycle. During the inverse cycle the ignitron is non-conducting,

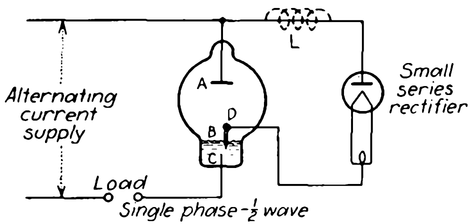


FIG. 313.—Ignitron tube used for single-phase, half-wave rectification without control of firing of anode.

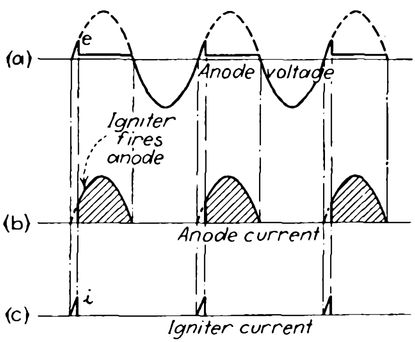


FIG. 314.—Relation of anode voltage to rectified anode current in ignitron rectification circuit in Fig. 313.

and the series rectifier prevents inverse current through the igniter. The ignitron can be used for single-phase, full-wave rectification with circuit connections as shown in Fig. 315.

Control of the starting point at which anode current begins to flow is obtained with the circuit arrangement shown in Fig. 316. Here the series rectifier is replaced by a grid-glow tube (page 199) and a suitable phase shifter which serves to change the phase of the grid-bias voltage applied to the grid of the grid-glow tube. No igniter current flows until the grid-glow tube breaks down at a time depending on its grid-bias voltage (Fig. 317). Thus the ignitron can be "fired" at practically any desired point on the positive half cycle. As a result the average rectified current output can be varied

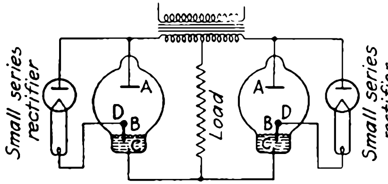


FIG. 315.—Ignitron tube used for full-wave, single-phase rectification.

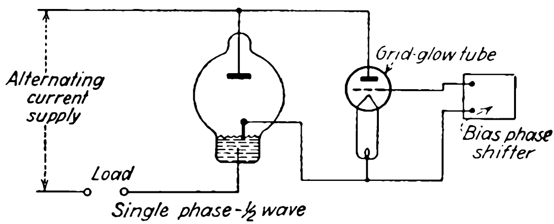


FIG. 316.—Ignitron tube used for half-wave, single-phase rectification with control by grid-glow tube and phase shifting.

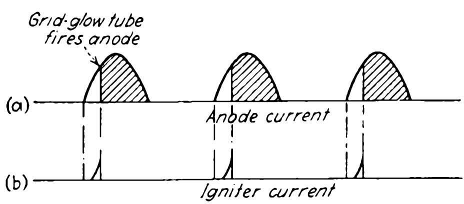


FIG. 317.—Rectified anode current and igniter current for ignitron-rectification circuit in Fig. 316.

from a value of practically zero when ignition occurs at the end of the half cycle, to a maximum when ignition occurs at the beginning of the cycle.

For some services the limitation of these circuits is that the igniter current must flow through the load and consequently delayed or inaccurate firing may result. An arrangement for a firing circuit independent of the load is shown in Fig. 318. In this circuit the condenser is charged on each inverse half cycle to a voltage much higher than the firing

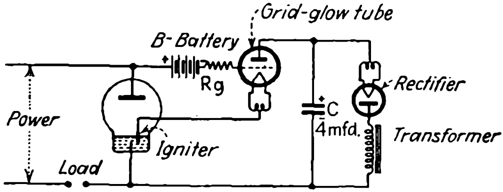


FIG. 318.—Ignitron-rectification circuit with the firing circuit independent of the load.

voltage of the igniter. This condenser voltage then acts across the grid-glow tube and the igniter. When this tube breaks down, the condenser discharges through the igniter producing a large current for an extremely short period. The time constant of the load must be such that the anode current can increase to a definite value during the condenser discharge. The time of discharge can be lengthened by the use of series resistance. To obtain a proper pick-up, the anode voltage must be maintained for a definite period following ignition. This voltage maintenance may be produced by the use of resistance or inductance in series with the igniter.

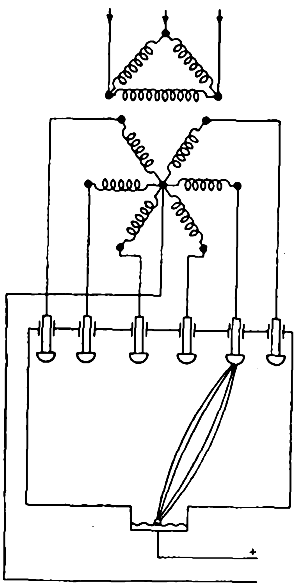


FIG. 319.—Simple method of connecting mercury-arc rectifier to transformer.

Mercury-arc-rectifier Circuit.—A description of this type of rectifier which belongs in the gaseous class, and its operating characteristic, is given in Chap. IV. The diagram of a simple method of connecting a mercury-arc rectifier to a transformer is shown in Fig. 319. The positive-load terminal is connected to the cathode, and the negative terminal to the neutral point of the transformer bank. The voltages at the anodes depend on the voltages of the transformer terminals to which the anodes are connected. The current goes in turn to that anode which is most positive. The connections of commercial units are more complicated, utilizing various wiring schemes to obtain certain desired characteristics.

The efficiency of the circuit depends on the voltage drop in the arc. This increases with the size of the unit, and also with the load, being about 18 to 24 volts for the 500-kilowatt rectifier shown previously. At a circuit voltage of 600 volts and an arc drop of 20 volts the efficiency of the rectifier alone is 96.77 per cent.

Rectifier Circuit for Cathode-ray Tube.—The circuit shown in Fig. 320 illustrates the use of rectifier tubes of the tungsten-

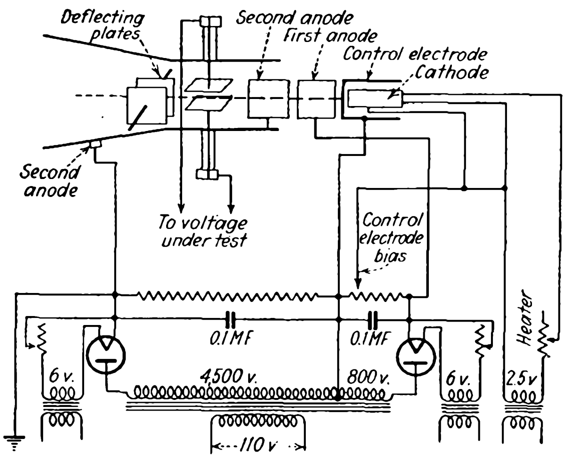


Fig. 320.—Rectifier supplying focusing and accelerating voltages to cathode-ray tube.

cathode type (page 98) for the operation of a cathode-ray tube, type RC-593. The output current of the rectifier is controlled by the adjustment of the cathode current. The voltages required by the cathode-ray tube are for focusing and accelerating the electron beam which is shown as a dotted line in the diagram.

The voltage which is to be tested is applied to the terminals of one set of deflecting plates. The other set may be used for a linear "sweep" circuit, or for connection to another voltage which is to be compared.

Rectifier Circuit for X-ray Tube.—The modern hot-cathode x-ray tube having a hot and a cold electrode passes current in

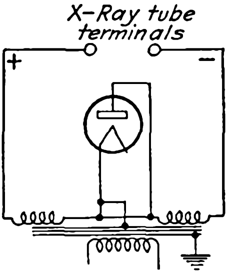


FIG. 321.—Half-wave rectification circuit with one rectifier tube and X-ray tube.

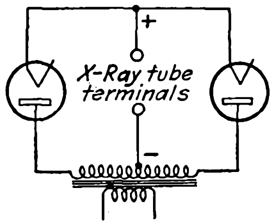


FIG. 322.—Full-wave rectification circuit.

one direction only so long as the cold electrode is not heated to the point where it emits electrons. Thus for moderate voltages and small currents, the tube can perform double duty as a rectifier and as an x-ray generator.

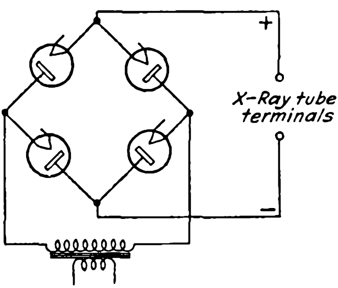


FIG. 323.—Full-wave rectification circuit with four rectifier tubes and X-ray tube.

Where a greater amount of energy must be applied or where the normal cold anode is brought to incandescence it is necessary to prevent any inverse polarity current from being applied to the electrodes of the x-ray tube. The present tendency is to use one or more rectifier tubes to rectify the current in preference to a mechanical rectifying switch driven by a synchronous motor.

In half-wave rectification a single rectifier is connected in series with the x-ray tube as shown in Fig. 321. The operation of this arrangement produces a low-power factor; but the system is satisfactory for the smaller types of apparatus. When more current is required, full-wave rectification is preferable for the reason that for the same line current about twice as much secondary current is obtained as with a half-wave-rectification circuit. In full-wave rectification either two or four rectifier tubes are needed. When two tubes are used as in the circuit of Fig. 322, only half of the voltage of the high-tension winding of the transformer is applied to the x-ray tube. When four tubes are used as in the circuit of Fig. 323, full voltage is applied to the x-ray tube.

CHAPTER X

USE OF VACUUM TUBES AS AMPLIFIERS

Simple Amplifier Circuit.—The fundamental circuit for a vacuum tube used as an amplifier is shown in Fig. 324. In this arrangement the voltage E_g which is to be amplified is applied across the input terminals; E_c represents the source of negative voltage that is used as a grid bias to maintain the grid negative with respect to the cathode; and E_b represents the source of plate-supply voltage. Under these conditions, when the grid-filament circuit is complete, a steady current will flow in the plate circuit, even though no signal voltage is applied to the grid. The static characteristic curve, showing the relation between plate current and grid-bias voltage is given in Fig. 325. Thus for a grid-bias voltage E_c the steady plate current is represented by the line C. Operation under these conditions takes place on the curve at the point A, known as the *operating point*. The position of the operating point on the curve is fixed by the value of the grid-bias voltage.

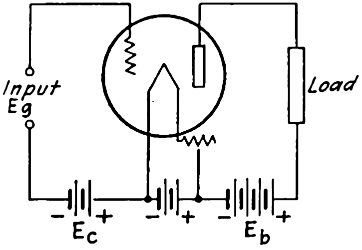


FIG. 324.—Simple circuit for vacuum tube used as amplifier.

In the actual operation of an amplifier tube in a radio receiver, an input-signal voltage as represented by E_g in Fig. 325 is applied to the grid. The corresponding variations of plate current may be represented by the curve marked "output signal." It should be noted that the operating point A is in the middle of the "straight" range of the characteristic curve. In this range the form of the output-signal voltage is exactly like that of the input-signal voltage. This similarity does not exist if operation is on the lower bend of the curve (near cut-off), or on the upper bend (near saturation). In operation on either bend the form of the output-signal voltage is unlike that of the input-signal voltage and distortion results.

The *mutual conductance* or *slope of the line* is equal to the ratio of a small change in plate current to the small change in control-grid voltage producing it (see page 115). This value can be used as a measure for determining the relative merits of amplifier tubes. The variations of voltage produced across a load in the plate circuit are much larger than the

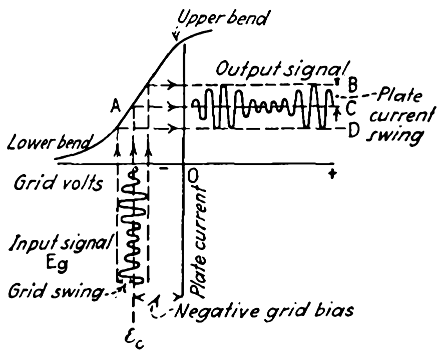


Fig. 325.—Static characteristic curve of simple amplifier.

voltage variations applied to the grid. This relation is an indication of the amplifying effect of the tube.

Input Circuit.—The method of applying the input signal to the grid of the tube needs consideration. If the value of the grid-bias voltage is such that the grid of the tube cannot become positive, the grid-input impedance of the tube is very high. Under this condition it is possible to use an input circuit which has high impedance. Where the signal is applied to the grid through the secondary winding of an input transformer, the secondary impedance may be as high as desired to match other design conditions. Where resistance coupling is used, the grid-resistance unit may have a value of from 0.5 to 2.0 megohms, depending on the type of tube and circuit.

Output Circuit.—The output circuit of a vacuum tube contains the apparatus for *using* the amplified variations of current and voltage. The voltage acting on the plate of a vacuum tube which has no load in the plate circuit is equal to the plate-supply voltage. But a tube in actual use as an amplifier may have one or more of the following in the plate circuit: a resistance, a primary winding of a transformer, an inductance, a loud-speaker.

Resistance Load.—When a varying plate current flows through a resistance load, the voltage acting on the plate is not constant because of the varying voltage drop across the load; that is,

$$E_p = E_b - I_p R_0$$

where E_p = plate voltage, volts.
E_b = supply voltage, volts.
R_0 = external resistance, ohms.
I_p = plate current, amperes.

It has been shown (page 110) that the effect of an alternating *grid* voltage E_g is to produce an alternating *plate* current $uE_g \div r_p$ in amperes, where u is the amplification factor (page 112) and r_p is the plate resistance, in ohms, and that the effect of an alternating *plate* voltage E_p is to produce an alternating plate current $E_p \div r_p$. The total plate current produced by grid and plate voltages in combination is, therefore,

$$I_p = \frac{uE_g}{r_p} + \frac{E_p}{r_p}.$$

This expression is true only if the plate-current variations are small enough to extend only over the straight-line portion of the plate-current–grid-voltage curve.

In the case of a resistance load R_0, the alternating current I_p flowing through the resistance R_0 produces an alternating-voltage drop of $E_p = I_p R_0$. The effect of this voltage drop is opposite to the action of the grid voltage; that is, if the grid is made more positive, the plate current and also the voltage drop across R_0 increase, and consequently the plate voltage decreases. Or, if the grid is made more negative the plate current and, also, the voltage drop across R_0 decrease, and the plate voltage increases. Hence, when I_pR_0 is substituted for E_p it is given a negative sign. When this substitution is made in the equation above, the plate current becomes

$$I_p = \frac{uE_g}{r_p} - \frac{I_pR_0}{r_p}, \text{ from which } I_p = \frac{uE_g}{r_p + R_0}$$

that is, the alternating current I_p in the plate curcuit for an impressed grid voltage E_g is the same as that which would be caused to flow in a circuit having a resistance of $r_p + R_0$ by an alternating voltage uE_g.

It is advantageous to consider the action of a vacuum tube as similar to that of an electric generator. The steady values of plate and grid voltages and plate current are considered only in so far as they affect quantities such as the plate resistance. The grid is omitted from the discussion except when the matter of grid current must be taken into consideration. The tube may then be regarded in effect as a device in which there is connected between the plate and filament an alternating-current generator having a resistance r_p and generating a voltage uE_g. The resistance r_p* is determined by the steady or non-varying grid and plate voltages. The alternating, or, more correctly, fluctuating plate current is produced by the voltage uE_g.

In a circuit containing only resistance, the impressed voltage is in phase with the current; that is, the variations of the impressed voltage occur in step with the variations of the current. The counter voltage is opposite in phase to the impressed voltage and to the resulting current. That is, in the tube circuit the plate current is in phase with the grid voltage, the phase difference between the plate voltage and plate current is 180 degrees, and the phase difference between the plate voltage and the grid voltage is 180 degrees.

* Actually, of course, r_p does vary with the alternating plate current.

Since the plate voltage E_p acting on the tube is equal to $E_b - I_pR_0$, where I_b is the "B" or plate-supply current, it is evident that when an external resistance is inserted in the plate circuit additional "B" or plate-supply voltage must be supplied to maintain the plate voltage at its proper value. If this is not done, the plate voltage E_p decreases, r_p increases, and the voltage amplification is reduced. When $R_0 = r_p$, the "B" or plate-supply voltage E_b must be about 50 per cent larger than the rated plate voltage of the tube. Under these conditions, a voltage amplification of $u \div 2$ is obtained.

Reactance Load.—The derivation of the expression for the value of plate current can readily be extended for the case of a reactance load. Thus consider that the plate circuit contains a loud-speaker having a resistance R_0 and an inductance L. The voltage divided by the impedance[1] gives the current as $I_p = uE_g \div Z$. Since the frequency term f appears in the impedance, it is clear that impedance varies with frequency as well as with resistance and inductance. The current lags behind the voltage by an angle α having a value such that

$$\tan \alpha = \frac{X}{r_p + R_0}.$$

These equations state that, for a given value of impressed grid voltage, the alternating plate current may be considered to have the same value and phase relations as a current flowing in a circuit having a resistance r_p, an impedance Z, and an applied voltage of uE_g.

When the plate circuit contains reactance as well as resistance, the phase difference between the plate and grid voltages

[1] The impedance Z of the plate circuit is $Z = \sqrt{(r_p + R_0)^2 + X^2}$, where $X = 2\pi fL$, and π is 3.1416.

If the plate circuit contains a load having a resistance R_0, an inductance L, and a capacity C, the current is $I_p = \frac{uE_g}{Z}$. In this case

$$Z = \sqrt{(r_p + R_0)^2 + X^2},$$

where $X = 2\pi fL - \frac{1}{2\pi fC}$. The phase angle α is given by $\tan \alpha = \frac{X}{r_p + R_0}$.

may not be 180 degrees. Thus, consider a load having an impedance Z made up of a resistance R_0 and a reactance X_0. If the plate current is represented by I_p, as in Fig. 326, then the voltage drop $I_p r_p$ in the tube is located as OY, the voltage drop $I_p R_0$ in the external resistance is YS, and the voltage drop $I_p X_0$ in the external reactance is ST, located at right angles to the axis. Then, the voltage drop $I_p Z$ in the external impedance is YT, the resultant of the resistance drop $I_p R_0$, and the reactance drop $I_p X_0$. The impressed voltage uE_g in the plate circuit is given by OT and is the resultant of the voltage drop $I_p r_p$ in the tube and the external impedance drop $I_p Z$. When the external impedance is equal to the plate resistance, that is, when OY equals YT in Fig. 326, the angle has a value of 45 degrees. Also E_p is equal to $-I_p Z$ and is represented in the diagram by OW which is parallel to $I_p Z$ or YT. The angle β which represents the phase difference between E_p and uE_g or E_g has a value of 157 degrees.

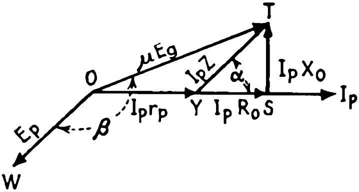


FIG. 326.—Typical vector diagram showing relation between plate current and voltage drops in external resistance and inductive reactance.

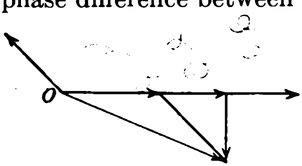


FIG. 327.—Typical vector diagram showing relation between plate current and voltage drops in external resistance and capacity reactance.

The phase difference between E_p and I_p is given by the angle whose value is such that its tangent is $X_0 \div R_0$, while that between uE_g and I_p is $\dfrac{X_0}{r_p + R_0}$.

Now, if the reactance X_0 were a capacity, the voltage drop $I_p X_0$ would be drawn in a direction vertical to I_p but downward, instead of upward as in Fig. 326 in which $I_p X_0$ is taken as an inductive reactance. The resulting relations would then be represented as in Fig. 327.

Classification of Amplifiers.—Amplifiers may be classified (1) according to the relation between the grid-bias voltage and the *fraction of a cycle during which current flows*, as class *A*, *B*, *C*, *AB*, and *BC* amplifiers; (2) according to the *frequency* level at which they are operated, as audio-frequency, intermediate-frequency, radio-frequency, and direct-current amplifiers; (3) according to the *type of coupling* used between the stages, as transformer-coupled, impedance-coupled, and resistance-coupled amplifiers; (4) according to the width of the frequency band for which they are designed, as tuned and untuned amplifiers.

Amplifier tubes for radio applications are grouped in two general classes: (1) *voltage-amplifier tubes*, and (2) *power-amplifier tubes*.

Class *A*, *B*, *C*, *AB*, and *BC* Amplifiers.—The voltage acting on the grid of an amplifier tube consists of two parts, one being the grid-bias voltage and the other the *exciting* or radio-signal voltage. The total voltage acting on the plate consists of two parts, one being the constant plate-supply voltage, and the other the load voltage (page 386). For any given plate voltage the plate current may be reduced to the *cut-off point*, that is, brought to zero, if the grid has sufficient negative grid-bias voltage. Then when an alternating signal voltage is applied to the grid (the grid-bias voltage being equal to the cut-off value), a plate current will flow during half of the cycle of the signal voltage, as shown in Fig. 328. In this diagram,[1] and in those which follow, the value of the grid-bias voltage at the point of plate-current cut-off is represented by the distance between the zero base line and the line marked *C*. No current can flow during the other half of the cycle of the signal voltage because the grid is more negative than the cut-off value. In general, the plate current flows for *less* than a half cycle when the grid-bias voltage is greater than the cut-off value; and for more than a half cycle when the grid-bias voltage is less than the cut-off value. The relation between the grid-bias voltage and the fraction of a cycle during which the signal current flows is used as a basis for classifying certain

[1] See McArthur, E. D., "Electronics and Electron Tubes," *Gen. Elec. Rev.*, November, 1933.

characteristics of amplifiers. This grouping pertains to class *A*, *B*, *C*, *AB*, and *BC* amplifiers.

A class *A* amplifier is designed with a load circuit (page 386), consisting of resistance or impedance, the performance of which is the same for all frequencies. The grid-bias voltage and the grid-exciting voltage have such values that the plate

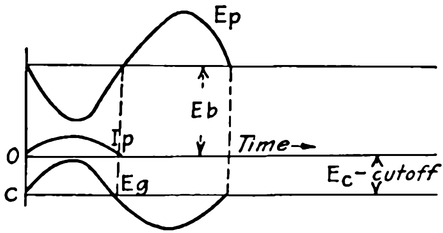


FIG. 328.—Relation between signal voltage applied to the grid and plate current flowing during half of the cycle of signal voltage.

current flows through the tube continuously. The grid-voltage variation is limited to that portion of the negative grid-voltage region of the mutual characteristic (see Fig. 46) which is nearly linear, and the value of the grid-bias voltage is much less than cut-off. A vacuum tube is usually operated

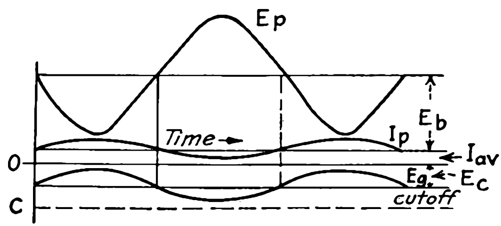


FIG. 329.—Average characteristics of ideal class *A* amplifier.

under such conditions because then the input impedance of the tube is high, and the amount of energy required for control is very small. In an *ideal class A amplifier* the form of the alternating component of the plate current is exactly like that of the input voltage, and the plate current flows during 360 electrical[1] degrees of the cycle, as shown in Fig. 329. The

[1] One cycle corresponds to 360 electrical time degrees.

class *A* amplifier with a *triode* power tube has low output, high power amplification, low efficiency, and low distortion. When *pentode* power tubes are used, the power output and efficiency are higher than when a triode is used, but the distortion also is increased.

A class *B* amplifier is designed with a resistance load or with a tuned circuit. The resistance load is generally used in audio-frequency amplifier circuits with two tubes. The tuned circuit is used in amplifiers dealing with a single frequency. The grid-bias voltage and the grid-exciting voltage have such

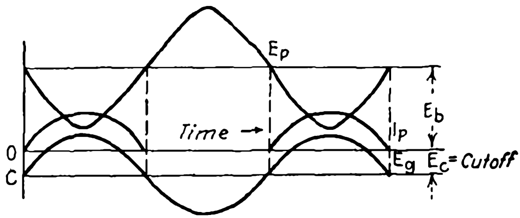


Fig. 330.—Average characteristics of ideal class *B* amplifier.

values that the plate current is reduced practically to zero when there is no grid-exciting voltage, and so that the plate current flows during half of each cycle. The operating grid-bias voltage is set at a value equal to or near the plate-current cut-off. Where only one tube is used, the amount of distortion is high because only half of the input-voltage wave is amplified, and the applied signal voltage is large enough to make the grid positive. Generally two tubes are used in a push-pull circuit, so that both halves of the wave are amplified. The power output is proportional to the square of the excitation voltage. In an ideal class *B* amplifier the form of the alternating component of the plate current is nearly an exact reproduction of the input voltage during that half of the cycle when the grid is positive with respect to the grid-bias voltage, and the plate current flows during 180 electrical degrees of the cycle as shown in Fig. 330. The class *B* amplifier, as compared with one of class *A*, is capable of higher output, lower power amplification, and somewhat higher efficiency.

A class *C* amplifier is designed with a tuned circuit and is used only in applications involving a single frequency. The grid-bias voltage and the grid-exciting voltage have such values that the plate current flows during considerably less than half a cycle. The grid is "biased" at a value beyond plate-current cut-off, as shown in Fig. 331, and the applied signal voltage is large enough to make the grid positive. The output varies as the square of the plate voltage. The class *C* amplifier is capable of high power output at high efficiency and hence is

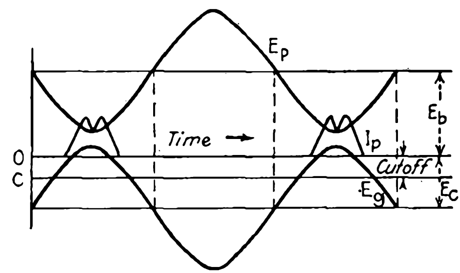


FIG. 331.—Average characteristics of ideal class *C* amplifier.

utilized in radio transmission where high efficiency in the plate circuit is essential and the degree of linear relation between the output and input is not important.

In class *AB* or class *A prime* amplification, the grid-bias voltage and the grid-exciting voltage have such values that the plate current flows during a period of the cycle which is greater than 180 electrical degrees but less than 360. The class *AB* amplifier has an output and efficiency which fall between the values for class *A* and class *B* amplifiers. In class *BC* amplification the grid-bias voltage and the grid-exciting voltage have such values that the plate current flows during a period of the cycle somewhat less than 180 electrical degrees. The class *BC* amplifier has an output and efficiency which fall between the values for class *B* and class *C* amplifiers.

Applications.—Any one of these classes of amplifiers, in either a one-tube or a push-pull circuit, may be used in radio-frequency amplification where the amplifier output feeds into a selective tuned circuit (as in a radio transmitter), or for services where some distortion is permissible. In audio-frequency amplification with a one-tube circuit, operated under the requirement that distortion must be kept below 5 per cent for triodes and below 7 to 10 per cent for tetrodes or pentodes (page 127), only the class *A* amplifier can be used. By means of a push-pull stage, however, the distortion can be reduced and the output increased. A class *B* amplifier for audio-frequency amplification is designed with a balanced stage using two tubes. This design produces a power output with practically no distortion because the even harmonics (page 131) are eliminated. A class *A* power amplifier may be used to supply power to a class *B* output stage. The tubes in the class *A* amplifier may be either triodes or pentodes, but the triode type produces less distortion than the pentode type.

Increased output from a class *C* amplifier may be obtained by the use of power tubes in either push-pull or parallel connection. For the same grid-signal voltage the output with a parallel connection is twice that obtained from one tube. Twice the grid-signal voltage is necessary to operate the push-pull connection, but the advantages over single-tube operation are: (1) increased power, (2) elimination or reduction of distortion caused by harmonics of even order, and (3) control of hum due to fluctuations of the voltage of the plate-supply unit. Also, the power output as compared with that from one tube can be more than doubled because the load resistance can be smaller without causing any increase in distortion. A gain in economy of operation is realized because both the grid-bias and signal-input voltages can be greater than the values permissible when only one tube is used.

Class *A* Voltage Amplification.—In the simple case in which the external load consists of a resistance R_0 the alternating-voltage drop across R_0 is, $I_pR_0 = \dfrac{uE_gR_0}{r_p + R_0}$ (page 387). The ratio of this alternating voltage which operates in the plate circuit to the alternating grid voltage is the voltage amplification, usually expressed as $A = \frac{uR_0}{r_p + R_0}$. When a tube is in use as a voltage amplifier, its maximum amplification is obtained by making the load resistance as high as is practical. This becomes evident from a consideration of the above equation for A. That is, with very high load resistances the term r_p becomes negligible and the voltage amplification approaches the amplification factor u of the tube.

When the external load consists of an inductance coil and if the resistance R_0 of the coil is small compared to r_p and wL,* then the voltage across the output circuit is $V = I_p wL = uE_g \frac{wL}{\sqrt{r_p^2 + (wL^2)}}$. The voltage amplification $\frac{V}{E_g} = \frac{uwL}{\sqrt{r_p^2 + (wL)^2}}$ may be made nearly equal to u if wL is large. The "B" supply voltage need not be greater than the rated plate voltage of the tube because the resistance of the coil is assumed to be negligible. The form of inductance, depending on circuit requirements, may consist of an air-core coil, an iron-core choke, or the primary winding of a transformer.

Maximum Power Output.—The voltage amplification may be considered as the load voltage drop per volt input since

$$\frac{uR_0}{r_p + R_0} = \frac{uE_g}{r_p + R_0} \times \frac{R_0}{E_g} = \frac{I_pR_0}{E_g}.$$

The current output per volt of input is $\frac{I_p}{E_g} = \frac{u}{r_p + R_0}$. The product of these two expressions gives the power output per volt squared of the input as $\frac{I_pR_0}{E_g} \times \frac{I_p}{E_g} = \frac{I_p^2R_0}{E_g^2} = \frac{u^2R_0}{(r_p + R_0)^2}$. It can be shown by differentiating this equation that the condition for *maximum* power output occurs when $R_0 = r_p$, that is, when the load resistance is equal to the plate resistance of the tube. The equation then reduces to $u^2 \div 4r_p$. It is important to remember that this result is obtained by considering the tube as a generator and neglecting the effect of distortion which modifies the relations considerably.

* The symbol w is used in place of the term $2\pi f$.

Distortion in Power Tubes.—Two causes of distortion in power tubes will be considered here. First, the distortion due to the curvature of the plate-voltage–plate-current curves at low values of plate current; second, the distortion resulting from the flow of grid current.

The effect of distortion due to the amount of curvature of the curves is shown by an inspection of the plate voltage–plate current curves in Fig. 332. While these curves do not indicate

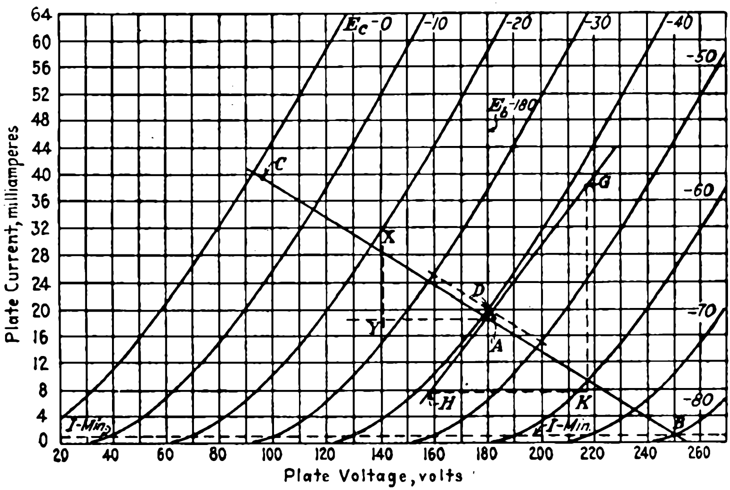


FIG. 332.—Curves showing distortion effects in power tubes.

actual conditions of operation because they are taken with no load in the plate circuit, the procedure outlined below may be used to determine the behavior of tubes with a plate load.

The plate current–plate voltage curves of a type 71A tube for various grid voltages are given in Fig. 332. When a plate voltage of 180 volts is applied, the tube operates along the vertical line at 180. The value of the plate current for a grid bias of −40 volts is found to be 20 milliamperes at the intersection of the vertical line and the "bias" line. Now, if a signal voltage having a peak amplitude of 10 volts is applied to the grid, the range of operation of the plate current is along the vertical 180-volt line from its intersection with the −30 volt "bias" line to that with the -50 volt "bias" line. The positive swing of the grid produces an increase in plate current of 18 milliamperes, but an equal negative swing produces a decrease of only 14 milliamperes. This effect is due to the increased curvature at low plate voltages of the plate current–plate voltage curve, and causes distortion by introducing into the output current a second harmonic component (page 402) which did not exist in the impressed signal voltage. The effect of the curvature increases rapidly as the amplitude of the signal voltage is increased. At low values of plate current the curvature is much greater, and, therefore, the instantaneous value of plate current must not come close to zero. Under the load conditions given in the following paragraphs, the minimum value of instantaneous plate current for satisfactory reproduction is taken to be 1.0 milliampere. This is indicated by the dotted line at the bottom of Fig. 332.

When the load resistance is very high, the range of plate current is no longer on the vertical voltage ordinates, and the line representing the conditions of operation is then swung, about the "operating point," away from the vertical, until it is nearly parallel to the 20-milliampere line. This new line of operation intersects all of the equidistant curves at the same angle so that it is clear that the distortion due to the curvature of the characteristic curve is eliminated. The power output, however, is decreased and approaches zero in the limiting case.

When the load resistance is lower than in the preceding case, an intermediate condition obtains. This may be shown graphically by drawing the "load line" for a given load resistance in the plate circuit. Thus in Fig. 332 the line CAB represents operation at a grid-bias voltage of -40.5 volts with a plate load of 3,900 ohms. This "load line" is located by the "operating point" and has a slope equal to the reciprocal of the load resistance. If this figure had been made with a scale of ordinates in amperes, the slope of the "load line" would be given by 1/3,900, and for a milliampere scale the slope becomes 1,000/3,900, or 10/39. If one point A on the "load line" is known, any other point X may be located by using this value of the slope, by the method of drawing through the point A a horizontal line AY equal to 39 on the scale of abscissas, and at Y drawing a vertical line YX equal to 10 on the scale of ordinates. Then through the points A and X the required "load line" CAB can be drawn.

In the first part of this discussion the distortion occurring with no plate load was shown for operation with -40 volts of grid-bias voltage. The effect of the plate load of 3,900 ohms in decreasing this distortion is evident from a consideration of the "load line" through the point D at -40 volts. With no plate load a 10-volt radio signal causes the plate current to range from 18 milliamperes in one direction to 14 milliamperes in the other. The same signal voltage along the 3,900-ohm "load line" causes a range of plate current of 5 milliamperes in each direction. This shows that under these operating conditions the effect of the second harmonic is really not appreciable.

The second cause of distortion mentioned previously is that due to a flow of current in the grid circuit. It has been shown that the distortion resulting from the negative swing of the grid voltage on the lower portion of the characteristic curve which has a pronounced curvature is eliminated by using a very high plate-load resistance. If, however, the impressed grid voltage is too high it may cause a swing which extends beyond the curve for $E_c = 0$ in Fig. 332. When this happens a grid current flows. As the grid becomes more positive the grid current increases quite rapidly and the grid-to-filament resistance of the tube is decreased. This decrease, however, occurs only when the grid swings positive and, consequently, a very uneven load results on the transformer; this unevenness of the load produces distortion. Operation should be such that the grid is always negative with respect to the filament except under the conditions given later for class AB and class B amplifiers (pages 405, 408).

Maximum Undistorted Power Output.—The conditions for maximum power output are limited by the extent to which the output is considered as undistorted. The two forms of distortion already discussed must be quite severe in order to affect the quality of reproduction so much that it is perceptible to the listener. A distortion of 5 per cent is quite imperceptible to the listener and, hence, may be allowed, especially because only a relatively small power increase is obtained if the distortion is greater. Undistorted power output, then, may be considered as the amount of power which is obtained when the input signal voltage does not become greater than the value producing a 5 per cent distortion due to the introduction into the power output of harmonics of the second and higher degrees.

It has been shown that the power output is a maximum when the resistance of the external load resistance $R_0 = r_p$ (plate resistance of the tube). In this explanation, however, the distortion which is introduced is neglected. To avoid excessive distortion the grid "swing" must be limited, that is, the minimum value of plate current must be greater than 1 milliampere.

Investigations[1] indicate that a maximum *undistorted* power output is obtained when the load resistance $R_0 = 2r_p$, with the plate and grid voltages adjusted to their best values. The maximum may occur at a different relation between the external load resistance R_0 and the plate resistance of the tube r_p if the applied voltages are not set to the best values. That is, the best load resistance is found to have a certain value at a given plate voltage; now, if the grid-bias voltage is reduced in order to allow a moderate decrease in plate voltage without a sacrifice in output, the best value of the load resistance is less than that found before.

Class *A* Power Amplifier.—A tube used in the output stage must supply relatively large amounts of power to the loudspeaker. For this application the tube is designed to provide a large power output rather than a high voltage amplification. For class *A* service (page 390) the triode power tubes as compared with pentode power tubes have low power sensitivity, low plate-power efficiency, and low distortion.

[1] *Proc. Phys. Soc.* (London), Vol. 36.
Proc. Inst. Radio Eng., Vol. 14.

The power output may be increased by the use of two tubes connected either for parallel or for push-pull operation. The *parallel circuit* is shown in Fig. 333 and the *push-pull circuit* in Fig. 334. The output of the parallel circuit is double the output of a one-tube circuit operated with a given signal voltage. The output of the push-pull circuit is at least double the output of a one-tube circuit but the signal voltage required is double that of a one-tube circuit. With the push-pull circuit, however, the distortion produced by harmonics of even order and the hum caused by fluctuations of the plate-supply voltage are eliminated or greatly reduced through cancellation. Because of the decrease in distortion, it is possible to reduce the load resistance and thereby to increase the output.

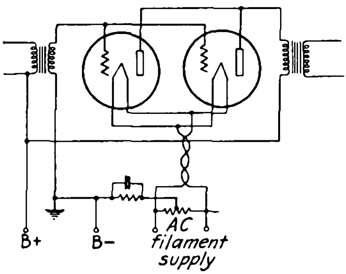


FIG. 333.—Two class *A* power amplifiers in parallel circuit.

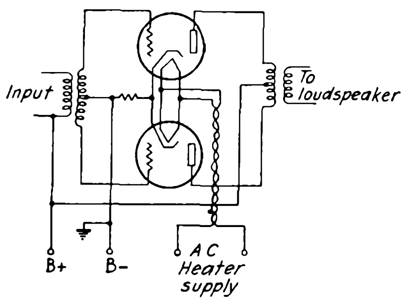


FIG. 334.—Two class *A* power amplifiers in push-pull circuit.

Another advantage of the decrease in distortion is that a stronger input signal can be allowed because the grid-bias voltage can be increased to a value greater than is permissible for a one-tube circuit.

A class *A* power amplifier may be used to supply power to a class *AB* or to a class *B* output stage. For such service either triodes or pentodes may be used, but triodes produce less distortion than pentodes.

Power Output and Distortion of Triodes.—Calculations for the *undistorted* power output of a triode used as a class *A* amplifier in a one-tube circuit can be made without serious error from the curve of plate current plotted against plate voltage, by assuming that the load consists of resistance only. The calculations may conveniently be made graphically for given conditions of operation. For a type 71A tube the maximum plate voltage to be supplied is 180 volts and the grid-bias voltage is -40.5 volts. Determinations of the best load, the power output, and the second harmonic distortion may be made from the curves in Fig. 332. In this case the value of 3,900 ohms for the load resistance was taken after consideration was given to the plate resistance of the tube. This tube resistance may be read directly from the curve in which plate resistance is plotted against grid voltage, at a plate supply voltage of 180 volts; or it may be obtained from the slope of the plate current–plate voltage curve at the point *A*. The tube resistance at the operating conditions represented at the point *A* is equal to the reciprocal of the slope of the curve at this point. To get the slope of the curve at this point, a line *GH* is drawn through *A* parallel to a tangent to the curve for $E_c = -40$. If a triangle such as *HGK* is constructed, the slope of the curve is given by $GK \div HK$ and the reciprocal of the slope, or the tube resistance is $HK \div GK$. Numerically, this plate resistance of the tube is equal to $\frac{216.5 - 158.5}{0.038 - 0.008}$ or 1,950 ohms. A load resistance of twice the tube resistance is equal to 3,900 ohms.

The power output of the tube is equal to the product of the *effective* values of the alternating plate voltage and the alternating plate current. These values are determined by the intersection of the "*load line*" *CAB* with the line of minimum plate current. Thus in Fig. 332 the "load line" intersects the line for minimum plate current at the point *B* which falls on the curve for E_c at -80 volts. This corresponds to a *maximum* negative grid swing of 80 − 40.5 = 39.5 volts. A positive swing from the point A would extend to the point C on the curve for $E_c = -1$ volt, since 40.5 − 39.5 = 1.0 volt. The fluctuating plate voltage as defined by these voltage limits has a value of 250 volts at the point B and 96 volts at the point C. The alternating component of this fluctuating voltage has an amplitude of (250 − 96)/2, or 77 volts, and an effective value (page 41) of 0.707 × 77, or 54.4 volts. The fluctuating plate current defined by these limits has a value of 0.001 ampere at B and 0.039 ampere at C. Its *alternating component* has an amplitude of (0.039 − 0.001)/2, or 0.019 ampere, and an effective value of 0.0134 ampere. Therefore, the power output, which is the product of the effective values of voltage and current, is equal to 54.4 × 0.0134, which is 0.73 watt or 7.30 milliwatts.

This method for the calculation of power output may be represented by the following equation:

$$\text{Power output} = \frac{(E_{max} - E_{min})(I_{max} - I_{min})}{8}$$

in which E_{max}, E_{min}, I_{max}, and I_{min}, are the maximum and minimum values of plate voltage and plate current for the given value of grid-voltage swing.

The *second* harmonic distortion D_2 depends on the difference between the average fluctuating current and the steady plate current. It may be stated as a percentage of the fluctuating plate current by the following expression, in which I_0 is the value of the plate current at the point of operation:

$$D_2 = \frac{\frac{1}{2}(I_{max} + I_{min}) - I_0}{I_{max} - I_{min}}$$

Numerically, the distortion D_2 in the example given is,

$$D_2 = \frac{\frac{1}{2}(0.039 + 0.001) - 0.0185}{(0.039 - 0.001)} \times 100 = 0.039, \text{ or } 3.9 \text{ per cent.}$$

There are several ways of reducing this distortion, such as decreasing the input signal voltage, increasing the load resistance, or slightly decreasing the grid-bias voltage and at the same time reducing the input voltage. Such changes, however, also reduce the power output.

The *maximum undistorted power output* of a number of tubes in common use is given in the Tube Table (page 617).

Load and Power Output for Push-pull Triodes.—The proper size of the plate-to-plate load for two triodes connected in a push-pull circuit and operated as a class A power amplifier may be calculated by use of the diagram in Fig. 335, which shows the plate current–plate voltage curves for the amplifier tube. A load line is drawn from E_0 which is the operating plate voltage, to the point I_m which is the intersection of a vertical line through E with the grid voltage curve $E_c = 0$. The point E is obtained from the relation $E = 0.6E_0$. The reciprocal of the slope of this load line, multiplied by 4, gives the value of the plate-to-plate load. Thus for two type 45 triodes operated at 250 volts (E_0), the plate-to-plate load $= 4(E_0 - 0.6E_0) \div I_m = 4 \times 100 \div 0.096 = 4160$ ohms.

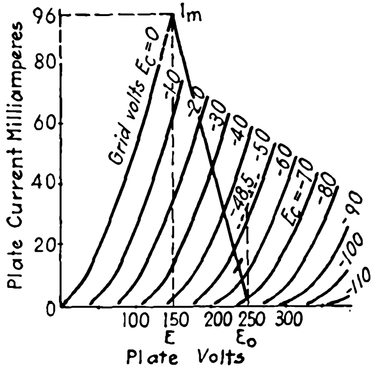


FIG. 335.—Diagram for calculating plate-to-plate load for two triodes in push-pull circuit operated as class A power amplifier.

The grid-bias voltage, at an operating plate voltage E_0, may have any value between E_g' and 0.5 E_g'', where E_g' is the grid-bias voltage specified for single-tube operation at a plate voltage E_0, and E_g'' is the grid-bias voltage which produces cut-off of plate current at a plate voltage of $1.4E_0$. Thus for a type 45 tube, $E_g' = 50$ volts, $E_g'' = 110$ volts at $1.4E_0$ (or 350 volts), and $0.5E_g'' = 55$ volts.

Power Output.—The power output obtained from two triodes, connected in a push-pull circuit and operated as a class A amplifier, may be obtained from the relation,

$$\text{Power output} = I_m E_0 \div 5$$

where power output is given in watts, I_m is expressed in amperes, and E_0 in volts For the conditions shown in Fig. 335 the power output $= 0.096 \times 250 \div 5 = 4.8$ watts.

Power Output and Distortion for Pentodes.—Calculations for the undistorted power output of a pentode used as a class *A* amplifier can be made graphically from curves in which plate current is plotted against plate voltage as shown in Fig. 336. The load–resistance line is drawn in such a way that the reciprocal of its slope is equal to the load resistance. I_0 represents the plate current, and $E_{c1} = V$, represents the

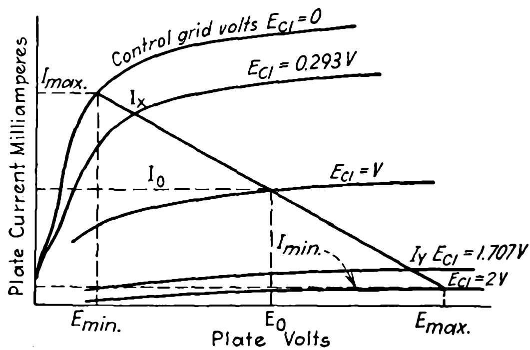


FIG. 336.—Average characteristics of pentode used as class *A* amplifier.

grid-bias voltage, both at the operating point. The formula below gives the power output in watts when I is in amperes, and E in volts. The term r_p represents the tube resistance.[1]

$$\text{Power output} = r_p[I_{\max} - I_{\min} + 1.41(I_x - I_y)]^2 \div 32.$$

Distortion.—The calculations for distortion, using the terms already defined, may be made with the following formulas: The *second* harmonic distortion D_2 is

$$D_2 = \frac{I_{\max} + I_{\min} - 2I_o}{I_{\max} - I_{\min} + 1.41(I_x - I_y)}$$

[1] The *tube resistance* r_p may be found from the relation

$$r_p = (E_{\max} - E_{\min}) \div (I_{\max} - I_{\min}).$$

I_x is the current at a control-grid voltage of $0.293V$, and I_y is the current at a control-grid voltage of $1.707V$.

The third harmonic distortion D_3 is

$$D_3 = \frac{I_{\max} - I_{\min} - 1.41(I_x - I_y)}{I_{\max} - I_{\min} + 1.41(I_x - I_y)}$$

The *percentage* of total distortion $100D_t$ due to the second and third harmonics is

$$100D_t = 100\sqrt{(D_2)^2 + (D_3)^2}.$$

Types of Power-output Tubes.—Power-output tubes for class *A* service may be

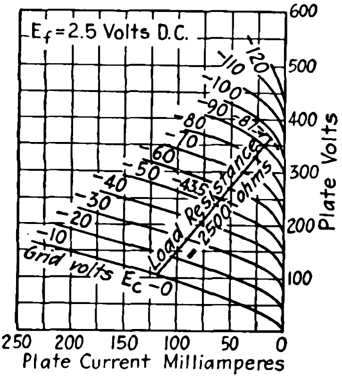


Fig. 337.—Power-output of twin triode used as class *A* amplifier.

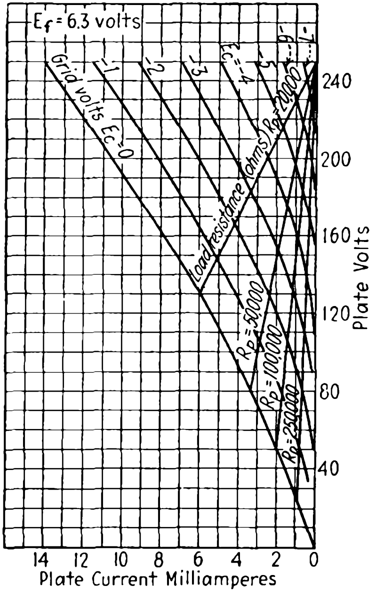


Fig. 338.—Power-output of dual triode used as class *A* amplifier.

grouped, according to their construction, as triodes, twin triodes, dual-grid triodes, tetrodes, and pentodes. The plate current–plate voltage characteristic curves with load lines for representative types in each group[1] are shown in Figs. 337 to 340, inclusive. Output calculations for these types may be made in a manner similar to that described on page 402.

Class *AB* Power Amplifier.—This arrangement was designed to overcome the relatively high distortion that is obtained with a class *B* amplifier at low levels of output. The class

[1] For type 46 (dual grid), see Chap. IV p. 133.
For type 47 (pentode), see Chap. IV p. 129.

AB amplifier consists of a stage of power-output triodes in push-pull connection operated at an *over-biased* condition as compared with a class *A* amplifier, or at *under-biased* conditions as compared with a class *B* amplifier. The class *AB amplifier has class A characteristics on small input voltages, and class B characteristics on full input.* At most input voltages the amplifier operates with class *A* characteristics and hence class

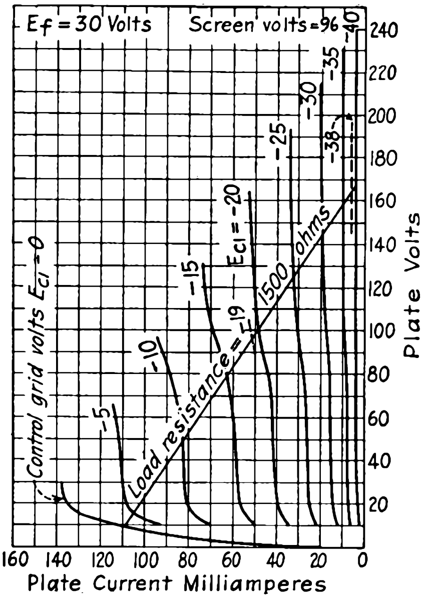


FIG. 339.—Power-output tetrode used as class *A* amplifier.

A power-output tubes are used. Certain precautions in design[1] are necessary if the amplifier is to give satisfactory results. The design of the amplifier is conveniently carried out by fixing a definite output or load requirement and then calculating the operating voltages and circuit constants from the output transformer toward the input transformer.

The output-load impedance is determined by the operating voltages and not from characteristic curves taken at class *A*

[1] "Class *AB* Amplifier Design," *Radio Eng.*, April, 1935.

voltages. The load impedance should be approximately double the class *A* value. The output transformer must have a suitable frequency response and power rating. The input transformer should have the characteristics of a class *B* input transformer, should deliver a high grid voltage, and should have a high primary impedance to allow a high-voltage gain in the driver.

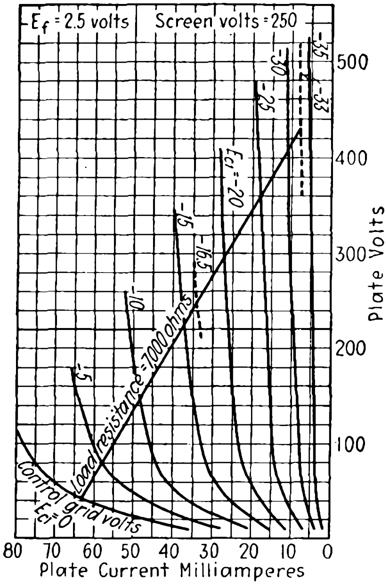


FIG. 340.—Power-output pentode used as class *A* amplifier.

The *power-supply unit* must be capable of delivering a greater average load than is necessary in class *B* service, but it need not have as fine regulation. The output stage must be driven to the point where a small amount of grid current flows on full signal input, without appreciable distortion. The driver tube should have high power-output capacity and should be operated over a limited portion of its characteristic curve to minimize the possibility of non-linear response.

The self-biasing method of supplying grid-bias voltage is not satisfactory. Some form of semi-fixed or stabilized grid-bias voltage should be used. In one method the grid-bias voltage is obtained by placing the voltage-dropping resistance for the driver and voltage amplifier tubes in the negative side of the power-supply unit and using the resistance to provide the grid-bias voltage for the output tubes.

Class *B* Power Amplifier.—The class *B* power amplifier is intended to supply a very high output of good quality with comparatively small tubes operated at a relatively low plate voltage. The distortion, however, may be higher in the usual range of signal voltages than that produced by a class *A* amplifier using tubes with the same maximum power-output rating. The overall power consumption is low because the plate current is low when no signal voltage is applied. The amplifier is designed with two tubes in push-pull connection. By means of this arrangement the distortion due to even harmonics is eliminated. For this service it is advantageous to use in the output stage a tube of the twin triode type which contains two class *B* amplifier triodes in one bulb.

When the grids of the output tubes are "driven" so as to become positive, the resulting distortion is allowable if sufficient input power is available for the grid circuit. This power is supplied by a driver stage operated as a class *A* amplifier and connected to the output stage through a special push-pull interstage transformer having a step-down ratio. The value of this ratio depends on the type of driver tube, the load on the power tube, the allowable distortion, and the efficiency of the transformer. The transformer must have good power efficiency because power is transferred, and it should be as nearly independent of frequency as possible.

The driver tube must be able to supply the amount of power required by the output stage, with allowance for the efficiency of the transformer. In class *B* service the driver stage must be capable of supplying the necessary input voltage to the output stage under the condition where an appreciable amount of power is taken by the grid circuit of the output stage. Its load resistance should be higher than that used in class *A* amplifier service if low distortion is a requisite.

If the amplification factor of a class *B* tube is sufficiently high, the tube may be operated with a zero value of grid-bias voltage. With this arrangement the grid-biasing resistance is not needed and there is a consequent gain in sensitivity. Also, the entire voltage of the power-supply unit can be used for the plate-supply voltage. The power-supply unit must maintain good voltage regulation regardless of the variation of average plate current with the intensity of signal voltage, and particularly for peak power demands. Either a vacuum

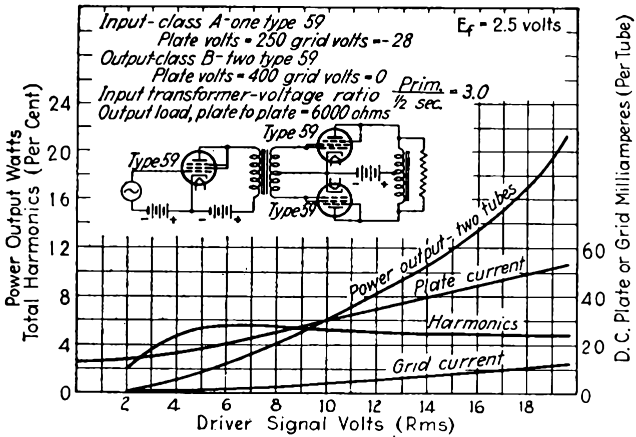


FIG. 341.—Operation characteristics of type 59 triple-grid power amplifier tube in class *B* service.

type or a mercury-vapor type of rectifier tube may be needed, depending on the circuit design. The filter choke coils and the windings of the power transformer should have low resistance.

The operation characteristics in class *B* service of the type 59 triple-grid power amplifier tube are shown in Fig. 341. The drawing also gives the circuit arrangement and operating voltages for which the characteristics were obtained. In this kind of application the first and second grids are connected together, and the third grid is connected to the plate. A diagram for a typical class *B* audio-frequency amplifier using a type 59 *driver* tube, and two type 59 output tubes, with an output of 20 watts, is shown in Fig. 342. The circuit constants are: C_1 = 0.1 microfarad, C_2 = 10 microfarads (50 volts), C_3 and C_4 each = 0.06 microfarad, C_5 = 16 microfarads (500 volts), C_6 = 8 microfarads (350 volts), R_1 = 250,000 ohms (1 watt),[1] R_2 = 1,100 ohms (2 watts), R_3 and R_4 each = 3,500 ohms (1 watt), R_5 = 2,600 ohms (10 watts), L_1 = 15 henrys at 100 milliamperes and a direct-current resistance of 80 ohms or less, L_2 is a 1,500 ohm loud-speaker with a field voltage of

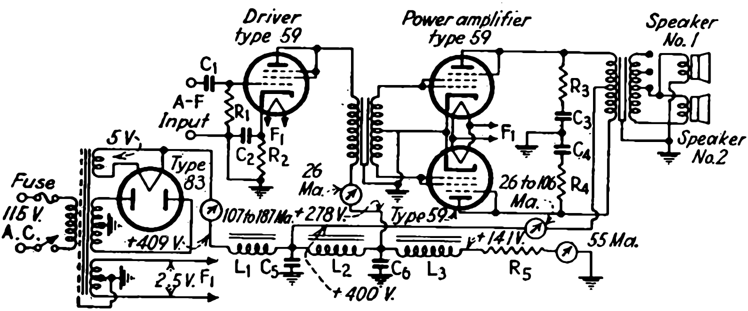


FIG. 342.—Audio-frequency amplifier using type 59 driver tube and two type 59 output tubes in class *B* service.

120 volts, and L_3 is a 2,500-ohm loud-speaker with a field of 140 volts.

AUDIO-FREQUENCY AMPLIFICATION

Resistance Coupling.—A circuit diagram of a resistance-coupled audio-frequency amplifier is shown in Fig. 343. An incoming signal voltage produces a current through the coupling resistance R_1 in the plate circuit of the first tube. Voltage variations across R_1, diminished by any voltage drop caused by the blocking condenser C, are impressed on the input circuit of the second tube. Grid-voltage variations applied to the second tube cause corresponding variations of plate voltage which are impressed on the input circuit of the output stage.

[1] This reference to power rating in watts needed for the resistances is explained on p. 313.

The *blocking condenser* is necessary to insulate the grid of the tube from the high positive voltage of the plate supply. Because the grid is thus insulated it would tend to accumulate negative charges. To prevent this accumulation, a high-resistance leakage path is provided through the *grid leak* R_g which ordinarily has a resistance of the same magnitude as the internal grid-filament resistance of the tube. The grid leak is utilized also to apply a grid-bias voltage to the grid of the second tube.

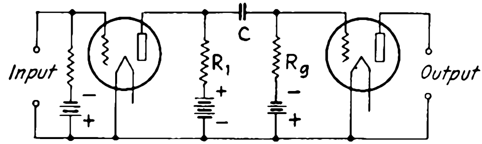


FIG. 343.—Resistance-coupled audio-frequency amplifier.

Size of Coupling Resistance.—A consideration of the relation for voltage amplification $\frac{E_{g2}}{E_{g1}} = \frac{uR_0}{r_p + R_0}$ shows that the voltage amplification increases as the resistance R_0 increases. When R_0 is so large that the tube resistance r_p (page 109) may be neglected, the value of voltage ampiification reaches its maximum value, $E_{g2} \div E_{g1} = u$ but practically does not exceed $0.75u$. In this connection R_0 is the equivalent resistance of R_1 and R_g in parallel (Fig. 343). Generally the coupling resistance may have a value which is twice the plate resistance of the tube.

The theoretical relation between voltage amplification and the load resistance for a tube with an amplification factor of 8, a plate resistance of 10,000 ohms, and a mutual conductance of 1,000 micromhos is shown in Fig. 344. The amplification increases rapidly for relatively small load resistances but more slowly as the load is increased. It is necessary to remember that when the plate circuit is loaded with a resistance, the supply voltage must be increased to compensate for the voltage drop in the resistance.

Size of Grid-leak Resistance.—A grid leak and a blocking condenser when connected in series act as a *shunt* to a coupling resistance (page 107), as shown in Fig. 345. If the grid-leak resistance is too high, the tubes may be temporarily inactive. When the grid-leak resistance is low, the total impedance of the input circuit of the stage is decreased, the voltage drop across the coupling resistance is reduced, and the amplification

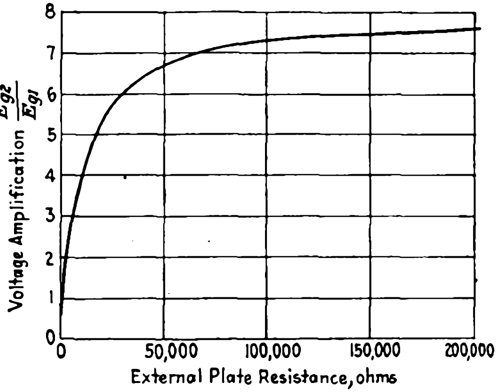


FIG. 344.—Theoretical relation of load resistance to voltage amplification in typical radio receiving tube.

is cut down. Hence the value of grid-leak resistance should be less than the value which will permit the tubes to "block." Values commonly used range from 0.25 to 1.0 megohm.

Size of Blocking Condenser.—Several factors are involved in the determination of the size of a blocking condenser, and the final choice is a compromise among them. The rapidity with which the condenser responds to voice amplitude variations requires that the *time constant* $R_g \times C$ be small, where C is the capacity of the blocking condenser and R_g the grid-leak resistance. In order to make $R_g \times C$ small, C must be as small as possible for the reason that if R_g is decreased it causes such a reduction in the impedance of the grid-filament circuit that the voltage drop across the coupling resistance is diminished and the amplification is

FIG. 345.—Grid leak and blocking condenser acting as shunt to coupling resistance.

reduced. Generally the capacity of the blocking condenser *C* is not larger than 0.1 microfarad.

The reactance of the grid condenser acts to reduce the voltage across the coupling resistance and thus diminishes the voltage available in the grid-to-filament circuit. The reactance of the grid condenser must be small compared with that of the circuit from the grid to the filament. The circuit is made up of the capacity and resistance of the grid to the filament and the grid-leak resistance. At *audio frequencies*, the impedance between the grid and the filament consists mostly of the grid-leak resistance in parallel with the grid-to-filament resistance of the tube and has a value of several hundred thousand ohms. This impedance is not affected appreciably by the reactance of the capacity of the grid-to-filament circuit which may be equal to about a million ohms. A condenser of 0.003 microfarad capacity has a reactance at 1,000 cycles per second of about 53,000 ohms.

Use of Tubes Having High Amplification.—With resistance coupling, the amplification is practically dependent on the tube alone and the resistances in the circuit decrease slightly the tube amplification. It is, therefore, desirable to use tubes having as high an amplification factor as is practical for this service. On the other hand, the response characteristic (curve of amplification against frequency) obtained with such tubes shows a drop at the higher frequencies.

Effect of Frequency on Amplification.—One of the advantages of resistance coupling is the good response obtained at very low audio frequencies. The frequency range over which uniform response is obtained may be brought to as low a frequency as may be desired in practice by using the proper size of blocking condenser. If the capacity of the blocking condenser is such that its reactance at low frequencies is of a magnitude which approaches that of the grid leak, the amplification is decreased at a rate which becomes more marked as the reactance increases; but the response of the ordinary loud-speaker below 50 cycles per second may not be satisfactory. The frequency characteristic begins to drop at about 5,000 cycles per second because the capacity of the input circuit of the tube acts as a low reactance shunt to the coupling resistance and thus decreases the amplification. But even at 10,000 cycles per second the decrease in amplification is only moderate.

The good response obtained at very low audio frequencies, however, increases the possibility of trouble from a common plate-voltage supply. The by-pass condensers ordinarily used are not very effective at very low audio frequencies and therefore the common voltage supply acts as a coupling between the stages. The coupling, due to the common voltage supply, gives rise to oscillations in the amplifier called "motor-boating." Such action may be avoided by using a low-resistance grid leak across the input circuit of each stage, or by using a smaller blocking condenser. These changes, however, reduce amplification at low frequencies.

Impedance Coupling.—The impedance-coupled audio-frequency amplifier uses a coil in place of the coupling resistance shown in Fig. 343. Its action is similar to that of the resistance-coupled amplifier. Here, also, as in the case of resistance coupling, the voltage amplification obtained from the circuit is due to the amplifying action of the tube. The advantage of impedance coupling over resistance coupling is that the supply voltage does not have to be increased to compensate for the small voltage drop in the coupling unit.

Size of Impedance.—The coupling must have a high reactance at the frequency for which the amplifier is intended, and a low resistance to direct current. An inductance unit for audio-frequency work is made with an iron core and must have low iron losses and small internal capacity. If the resistance of the coupling unit is assumed to be negligible, the expression for voltage amplification is given as

$$\frac{E_{g2}}{E_{g1}} = \frac{uX_0}{\sqrt{r_p^2 + X_0^2}}$$

where X_0 is the reactance of the unit at a stated frequency. The curve in Fig. 346 shows the theoretical relation between voltage amplification and the reactance of the coupling unit, using a tube having the characteristics described on page 411. There is not much gain in amplification at reactances greater than about 30,000 ohms. At a frequency of 50 cycles per second the inductance of a 30,000-ohm reactance is nearly 100 henrys.

Size of Blocking Condenser and Grid Leak.—The resistance of the grid leak should be several times the plate resistance of the tube. The effect of voltage drop in the coupling condenser on amplification at low frequencies is minimized if the capacity is such that at a given frequency the capacitive reactance is equal to R_g and the inductive reactance is equal to R_1. It may be stated here that the resistance type of grid leak in general may be replaced to advantage by the inductance type, in which case the coupling is termed *double impedance.* An inductance type of grid leak is made with a large value of inductance but a comparatively low resistance, and, therefore, an accumulated charge can leak off the grid in a shorter time than if a resistance type of grid leak is used. The inductance type and a coupling condenser may be designed for resonance at the low end of the frequency range with consequent improvement in the frequency characteristic.

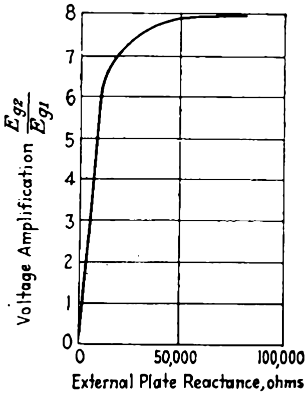


FIG. 346.—Relation of voltage amplification to external plate reactance in typical radio receiving tube.

Effect of Frequency on Amplification.—The frequency characteristic obtained with impedance coupling is a curve which indicates a higher amplification over the middle portion of the range of audio frequencies than with resistance coupling but a marked drop at each end of the range. At low frequencies the amplification is decreased on account of the low impedance of the choke coil compared with the high resistance of the tube. The high effective capacity of the input circuit of the tube together with the inductive reactance of the coil may result in resonance, or in extreme amplification, or even in oscillations at frequencies from 100 to 300 cycles per second. At high frequencies a marked decrease in amplification is caused by the high effective capacity of the input circuit of the tube.

Transformer Coupling.—The diagram of a transformer-coupled amplifier is given in Fig. 347. The alternating voltage of the radio signal which reaches the grid circuit of tube A produces in the plate circuit of that tube a pulsating current. This current flowing through the primary winding of the transformer T_2 induces a stepped-up voltage in the secondary winding which is applied to the grid circuit of tube

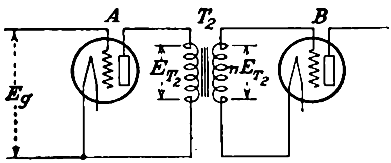


Fig. 347.—Circuit of transformer-coupled amplifier unit.

B. The variations of this stepped-up voltage are amplified reproductions of the grid-voltage variations which were impressed on tube A.

Voltage Amplification.—An elementary study of the transformer action between tube A and tube B in Fig. 347 can be made when certain conditions are assumed. The tube capacities between the grid and the filament, and between the plate and the filament, which are very small except at high audio frequencies, are neglected. The transformer is assumed to be perfect, that is, it has no leakage or magnetizing current. Also it is assumed that the load on the secondary winding of the transformer consists of a non-inductive resistance equal to the grid-filament resistance r_g of tube B. For a study of the action of such a circuit on alternating current, the transformer may be considered as an equivalent resistance[1] in the primary circuit and equal to the resistance r_g of the

[1] If secondary current $I_s = nE_{T2} \div r_g$ and primary current $I_p = nI_s$, then $I_p = n^2E_{T2} \div r_g$.

secondary circuit divided by n^2 where n is the transformer voltage ratio. The voltage acting on the plate circuit of tube A is taken as uE_g. It is then possible to represent the plate circuit of tube A as in Fig. 348. The relation of the voltage E_{T2} in the figure to uE_g is the same as that of the equivalent resistance $r_g \div n^2$ to the total resistance $r_p + \frac{r_g}{n^2}$. That is, $E_{T2} = E_g \frac{ur_g}{r_g + n^2 r_p}$. Since nE_{T2} is the voltage acting on the grid of tube B the voltage amplification is equal to $\frac{nE_{T2}}{E_g} = \frac{unr_g}{r_g + n^2 r_p}$. From this expression it is seen that the voltage amplification depends directly on u and that as r_g increases the voltage amplification increases, approaching un as a limit. Therefore, r_g should be made as large as possible by keeping a negative grid-bias voltage on the grid. In practical applications, r_g is equal to about a million ohms but under certain conditions of operation may have a value of only a few hundred thousand ohms. Further, the expression for voltage amplification has a maximum value when $n = \sqrt{r_g \div r_p}$ which indicates the best value for the transformer ratio. The voltage amplification, in terms of this value of n, is $un \div 2$. Both the voltage amplification and the transformer ratio, however, are decreased by imperfections in an actual transformer.

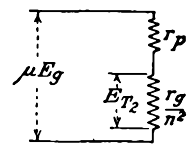


FIG. 348.—Equivalent of plate circuit of tube A in Fig. 347.

Transformer Construction.—The greater the impedance of the primary winding of a transformer relative to the plate impedance the larger will be the voltage impressed on the primary winding of a transformer, and consequently, also the amplification. A primary inductance of 100 henrys has an impedance of 628,000 ohms at 1,000 cycles per second and 62,800 ohms at 100 cycles per second. The reduction of impedance with frequency decreases the amplification at low frequencies. The inductance of the primary winding depends on the number of primary turns, the cross section of the core, the length of the iron core path, and the amount of direct current flowing in the primary winding. High core losses diminish the amplification at all frequencies. The voltage amplification increases rapidly with an increase of the primary no-load reactance at low values, but more slowly at higher values. Beyond a certain point, then, there is little to be gained by increasing the reactance. The factors of size and cost must be considered, also, for an increase in the core increases the size of the unit, and if more primary turns are used, more secondary turns are necessary for a given value of n.

Since the primary and secondary windings of a transformer cannot occupy the same space there is a certain amount of magnetic flux called "leakage flux" which does not link both coils. This produces the leakage inductance which decreases amplification at all frequencies.

The capacity effect between the turns and between the layers of the primary and secondary windings is small and affects amplification only at the higher frequencies. The capacity effect between the primary winding and the secondary winding also acts as a short circuit at the higher frequencies and tends to decrease amplification.

If the transformer ratio n is made high, and there are many turns on the primary winding, a large number of turns are needed on the secondary winding. This results in an increased internal capacity effect which, with the input capacity of the next tube, brings the natural frequency of the secondary circuit within the range of audio frequencies and causes a resonance peak. Amplification beyond this natural or cut-off frequency is very poor.

It has been shown that amplification of low frequencies requires a large number of turns of the primary winding and that a large number of turns of the secondary winding diminishes the amplification at high frequencies. Consequently a transformer is made with a rather low ratio of turns, a core having a large cross section, low internal capacity, and a low leakage inductance.

Amplification Curves.—At low frequencies there is a decrease in amplification caused by the low impedance of the primary winding of the transformer. At high frequencies the amplification curve may show resonance peaks caused by the internal capacity and the leakage inductance of the transformer. Such peaks may be reduced by the use of a high resistance secondary winding or by a resistance across the secondary circuit. Radio transformers are generally designed for cut-off (page 130) at 8,000 to 10,000 cycles per second.

A condition of resonance at 5,000 cycles per second or more does not produce a very noticeable effect on reception because the efficiency of the loud-speaker at such frequencies begins to drop off. A condition of resonance at moderately low frequencies may be detected by laboratory measurements but, if small, does not perceptibly affect the performance of the amplifier.

The performance of a multi-stage amplifier may differ considerably from the frequency characteristic of a single transformer. Interstage coupling may increase the effect of resonance conditions, and the coupling resulting from a common plate-voltage supply may cause a considerable change in amplification at low audio frequencies.

Balancing Plate Currents in Push-pull Amplifier.—In some cases it is advisable to provide some means for balancing the plate currents of tubes in a push-pull power amplifier in order to remove the hum voltages present in the plate supply.

Two methods may be used for producing this effect. In one method, as illustrated in Fig. 250 (page 319) an adjustment of the grid-bias voltage on the output tubes may be made by means of the potentiometer R which is connected between the center taps of the filament windings. In the second method the grid-bias voltage on one of the output tubes may be adjusted by means of a potentiometer R_1 in the circuit shown in Fig. 248 (page 318). In this arrangement the secondary winding of the input transformer must have two separate windings. The potentiometer is connected with its center tap to one of the windings, and its arm to the other.

Loud-speaker as a Load.—The loud-speaker commonly used may be classified as of the *dynamic type* which uses a moving coil to drive a cone, or of the *magnetic type* which uses a magnetic armature as the driver. The efficiency of this device is very low, being generally less than 5 per cent. Loud-speakers of the dynamic type have an input impedance of less than 10 ohms. For the proper operation of this type of loud-speaker the direct current in the plate circuit of the output tube must be kept out of the moving coil, and the impedance of the speaker circuit must be matched to that of the output tube in order to obtain a maximum transfer of energy. These requirements are met by the use of an output transformer having a step-down ratio of windings. The turns ratio must be such that the impedance of the primary winding is greater than the plate resistance of the output tube.

Amplification Comparison.—An amplifier when supplied with input power is intended to deliver a greater amount of output power. In an *attenuator*, however, this process is reversed, the output power being less than the input power. For the comparison of power values there is needed a unit which can be used conveniently for both large and small amounts. The unit in electrical and sound calculations for the comparison of power values in amplifiers and attenuators is the *bel*. One bel indicates the amplification obtained when the ratio of a power P_1 to a power P_2 is equal to 10. The *decibel* (abbreviated *db*), equal to one-tenth of a *bel*, is commonly used in the comparison of amplification values. The decibel has the advantage, with regard to sound intensity comparisons, that it expresses the smallest difference which can be detected by ear.

By definition, the ratio in decibels of two powers P_1 and P_2 is equal to $10 \log_{10} (P_1 \div P_2)$. Tables are available which give the decibel equivalent of various values of power ratios. The ratio is termed a "gain" when P_1 is greater than P_2, and a "loss" when P_1 is smaller than P_2. A power compared with one that is smaller is said to be "up" a certain number of decibels from the lower level. Similarly, a power compared with one that is greater is said to be "down" a certain number of decibels.

The unit decibel indicates the value of a *ratio* and not the *amount* of power involved, that is, if the amplification of a device is given as so many decibels, a definite *reference value* or *level* in watts is understood. The *amount* of power then is equal to the decibel value times the *level value.* The reference level used in radio work is 6 milliwatts (0.006 watt).

The decibel unit can be used also for comparison of two voltages, or two currents. This may be done because the power consumed in a resistance is proportional to the square of the voltage or to the square of the current. The value in decibels of a voltage ratio is equal to 20 $\log_{10} (E_1 \div E_2)$, and that of a current ratio is 20 $\log_{10} (I_1 \div I_2)$. These expressions, however, cannot be applied unless the resistances of the circuits for a given comparison are equal.

Table XIX gives the relation between decibels and power ratios for a range of 1 to 50 decibels (page 420). It is convenient to remember that the decibel equivalent of a power ratio of 10 is 10. The values in the table show that doubling the *gain* or halving the *loss* increases the decibel equivalent by 3 decibels.

TABLE XIX.—RELATION BETWEEN DECIBELS AND POWER RATIOS

Power ratios \ Decibels	1	2	3	4	5	6	7	8	9	10	20	30	50
Gain	1.25	1.6	2.0	2.5	3.2	4.0	5.0	6.3	8	10	100	1000	100,000
Loss	0.80	0.62	0.50	0.40	0.31	0.25	0.20	0.16	0.13	0.10	0.01	0.001	0.00001

VOLUME CONTROLS

Types of Controls.—One of the first methods used for volume control depended on the adjustment of the filament current supplied to a vacuum tube by means of a rheostat in the filament circuit. This arrangement was applied to both the battery type and the alternating-current type of tube. When manufacturers recommended that tubes should be operated at a non-variable filament voltage, the volume control was moved to other sections of the receiver. Some of these

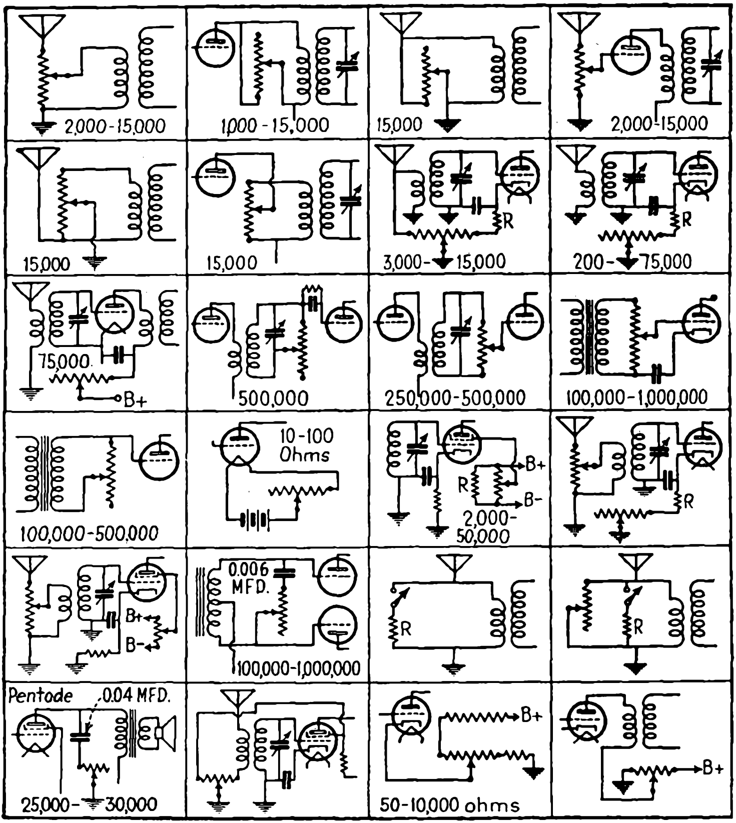


FIG. 349.—Typical volume-control arrangements.

arrangements, as illustrated in Fig. 349, include a potentiometer in parallel with the primary winding of a transformer in a radio-frequency stage, a potentiometer in parallel with the grid-filament circuit of a vacuum tube, and a series resistance in the plate-voltage lead of a vacuum tube, usually in a radio-frequency stage.

In the early kinds of radio receiving sets using screen-grid tubes the control of volume generally was obtained, at first, by the variation of the voltage applied to the screen grid and later by the use of double controls. These controls were designed in many forms, such as (1) screen-voltage adjustment with a variable resistance in the antenna circuit or with a provision for grid-bias-voltage variation; (2) parallel resistance in the audio-frequency stage with antenna circuit adjustment or with screen-grid-voltage adjustment, and so on.

In the more recent receivers using multi-element tubes the volume is controlled generally by variation of the grid-bias voltage on tubes in certain stages. The arrangement may consist of *manual control* on the antenna circuit and one tube, or manual control on the antenna circuit and several tubes, or *automatic control*, or combinations of manual and automatic control.

Manual Volume Controls.—In the circuit[1] shown in Fig. 350 the manual-volume-control device consists of a variable

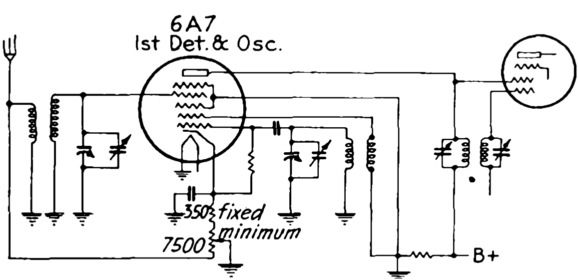


FIG. 350.—Circuit for manual volume control.

portion having a resistance of 7,500 ohms and a fixed minimum portion of 350 ohms. The arrangement is double-acting in that it simultaneously reduces the antenna output and increases the grid-bias voltage on the type 6A7 tube.

In the circuit[2] shown in Fig. 351 a modulated voltage drop is produced across the 500,000-ohm volume control. The

[1] Stewart Warner model R-123 chassis.

[2] Stewart Warner model R-125 chassis.

volume is varied by impressing any part of this voltage on the triode section of the type 75 tube.

Tube Action in Automatic Volume Control.—The volume of sound from a radio receiver can be controlled by the maintenance of a constant value of carrier input to the audio-frequency detector tube. This constant value is obtained by regulating the gain (page 150) of either the radio-frequency or the intermediate-frequency amplifier stages or both. Such regulation is accomplished by utilizing a rectified voltage which is dependent on the carrier-signal voltage in a radio-frequency or intermediate-frequency stage. The rectified-voltage regulation is applied to the electrodes of a tube in a number of ways; for instance, in the case of a pentode in a radio-frequency stage the regulating voltage may be applied to the suppressor electrode or to either the plate or screen electrodes or both. Ordinarily the regulating voltage is applied to the grid of a radio-frequency amplifier tube.

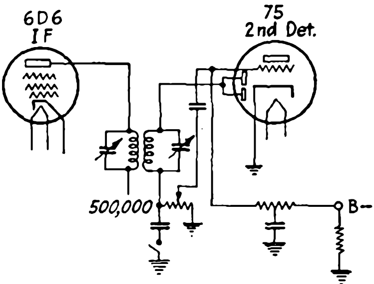


FIG. 351.—Circuit utilizing demodulated voltage drop for volume control.

A circuit arrangement for automatic volume control with a diode-detector tube is shown in Fig. 352. Consider this circuit first when the grid-biasing battery and its by-pass condenser are omitted so that the resistance R and its by-pass condenser C_1 are connected directly to the cathode of the tube. Then, as soon as any signal voltage is received, a current will flow through the diode (page 95) from plate to cathode, through the load resistance R to the tuning circuit, and conse-

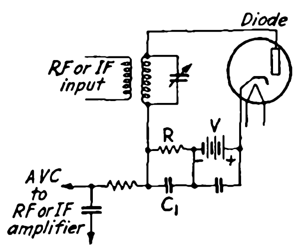


FIG. 352.—Circuit for automatic volume control with a diode detector.

quently the cathode end of the load resistance R is at a positive potential with respect to the cathode; and the other end is at a negative potential. A connection is made at the negative end of this resistance to provide a negative grid-bias voltage for the grids of the radio-frequency amplifier tubes. The resistance R has such a value that for a given signal voltage, the voltage drop across it "biases" the regulated tube to a degree which provides the desired volume of sound. Then if the signal input becomes smaller, the voltage drop across the resistance R becomes smaller, thus reducing the grid-bias voltage on the regulated tube and thereby increasing the sensitivity of the receiver, so that the desired sound volume is maintained. If, on the other hand, the signal-voltage input becomes greater, the voltage drop across the resistance R is increased; thus increasing the grid-bias voltage on the regulated tube, and thereby decreasing the receiver sensitivity. The value of the resistance R should be such that for a given signal voltage the grid-bias voltage produces a receiver sensitivity of the right degree for the desired volume. In this arrangement, the mutual conductance of the tube is decreased as the grid-bias voltage is made more negative, and consequently the voltage amplification is decreased.

In *delayed* automatic volume control (d.a.v.c.), the control action does not start until the signal strength attains a certain value. This delayed action is made possible by the application of a fixed negative direct-current voltage V to the plate of the diode, as indicated in Fig. 352. With this arrangement the diode current does not flow until the peak value of a positive swing of signal voltage exceeds the value of the negative voltage V. The amount of *delay action* depends on the result that is expected. In general, delay action is intended to prevent overloading of the receiver, but if the delay effect is too great, the advantage of automatic volume control may be lost.

Tube Action in Automatic Noise Suppression.—The sensitivity of a receiver which has automatic volume control is increased greatly when the receiver is being tuned from one station to another. In this region the effects of static and other interference are amplified excessively. The noise which comes from a receiver until a desired signal voltage from a transmitter is tuned in completely may be suppressed automatically through control of the audio-frequency amplifier tubes. This control is obtained by the use of an additional tube known as a *noise-suppression-control* (*n.s.c.*) *tube.* This tube in turn is controlled by means of a voltage which is supplied from the detector-tube circuit. The control of the audio-frequency tube is effected by varying the voltage on its control grid, screen grid, or suppressor grid, the use of the control grid for this purpose being preferred because extremely

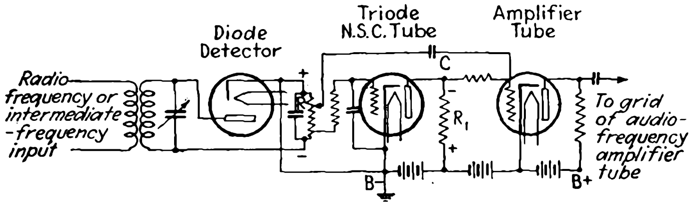


FIG. 353.—Simple circuit for automatic noise suppression.

small current and voltage changes are needed for the control operation. This system is known also as a *squelch* system or as a *quiet automatic volume control* system (q.a.v.c.).

A simple circuit for automatic noise suppression is shown in Fig. 353 with a diode-detector tube, a triode noise-suppression-control tube, and the controlled audio-amplifier tube. When there is no signal voltage across the input transformer, there is no plate current in the diode tube and consequently no grid-bias voltage across the resistance R. The noise-suppression-control tube, having no grid-bias voltage, allows the maximum value of plate current to flow through the resistance R_1. The voltage across R_1 is used as a grid bias for the amplifier tube and has such a value that no plate current can flow. As a result, the audio-frequency stages of the receiver are inoperative. When, on the other hand, there *is* a signal voltage across the input transformer, a plate current flows through the diode tube and through the resistance R, producing across that resistance both a direct-current voltage and an alternating-current voltage. The direct-current voltage on the resistance R is applied as a grid bias to the noise-suppression-control tube and has such a value that no plate current can flow in that tube. Thus there is no current in the resistance R_1, and the amplifier tube operates under its usual minimum fixed grid-bias voltage to amplify the audio-frequency signal voltage applied to its grid from the resistance R through the condenser C.

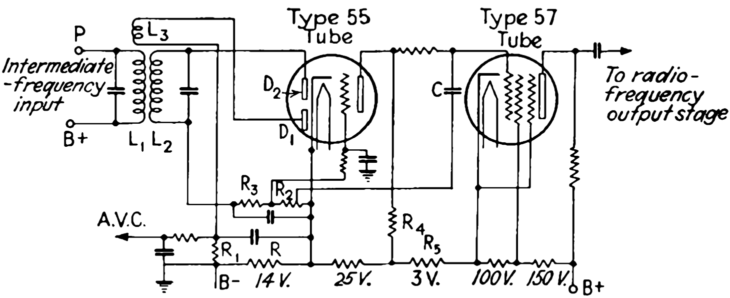


FIG. 354.—Circuit for noise suppression, delayed automatic volume control, and diode detection.

The circuit of Fig. 354 shows how a type 55 and a type 57 tube are utilized to obtain diode detection, *delayed automatic volume control* (d.a.v.c.), and noise-suppression control. The diode D_1 provides the d.a.v.c. action, diode D_2 provides the detector action, and the triode provides the noise-suppression-control (n.s.c.).

When there is a signal voltage across the input transformer, a current flows from the diode plate D_1 to the cathode, and through the resistances R and R_1 back to the plate. The negative grid-bias voltage needed for diode D_1 to obtain delayed-automatic-volume-control action is provided by the voltage drop of 14 volts across the bleeder resistance R. Thus when the peak value of the signal voltage exceeds 14 volts, a voltage for automatic volume control is obtained across the resistance R_1. At the same time that a current flows from the diode D_1 there is a flow of current from the diode plate D_2 to the cathode and through the resistances R_2 and R_3 back to the plate. The voltage drop across these resistances provides a negative direct-current grid-bias voltage for the triode of the type 55 tube, and an audio-frequency voltage which is applied to the type 57 audio-frequency amplifier through the condenser C. The value of the negative grid-bias voltage for the triode of the type 55 tube is such that no plate current flows when a signal is being received. Thus there is no voltage across the plate resistance R_4, and the plate current of the type 57 tube is limited only by the minimum value of grid-bias voltage supplied by the bleeder resistance R_5. The audio-frequency voltage obtained from the diode D_2 is amplified in the type 57 tube and delivered to the audio-frequency stages. When there is *no* signal voltage across the input transformer, there is no plate current through either of the diodes D_1 or D_2. Under these conditions there is no automatic-volume-control action because the diode D_1 has a negative grid-bias voltage of 14 volts. Consequently a maximum plate current flows through the triode producing a voltage drop across the resistance R_4 which is applied as a grid-bias voltage to stop the flow of plate current in the type 57 tube. There is no audio-frequency voltage to pass on to the audio-frequency amplifier tubes. The audio-frequency stages are consequently suppressed and no sound is heard.

The coupling coil L_3 is needed because it was found that when the receiving set was *slightly detuned for the signal voltage*, the circuit for noise-suppression control did not act to cut out audio-frequency amplification until the action of the automatic-volume-control circuit in maintaining a constant value of input to the detector tube was stopped. Consequently some noise and carrier hiss are heard, although the arrangement for noise suppression is effective when the receiver is *considerably* detuned. The remedy is to reduce to a minimum the delay in effecting noise-suppression control. This delay can be reduced provided that separate sources are used to supply the signal voltages for the automatic-volume-control tube and for the noise-suppression-control tube. Further, the circuit arrangement must be such that, when the receiver is being detuned, the signal voltage supplied to the noise-suppression-control tube must be decreased at a greater rate than the signal voltage for the automatic-volume-control tube. Both requirements are met by the use of the coupling coil L_3 which is coupled more closely to the coil L_1 than to the coil L_2, and hence the selectivity of the coil L_3 is less than that of the coil L_2. Consequently, when the receiver is being detuned, the signal voltage on the diode D_2 is reduced more than the signal voltage on the diode D_1. In this way the noise-suppression effect is made to start before the sensitivity of the receiver is increased to its maximum value by the action of automatic volume control.

Tubes of the duplex-diode type are used with the diodes connected together to provide both the voltage for automatic volume control and for audio-frequency detection. With this arrangement the number of units is reduced; but the filter circuits are connected to the second detector circuit. An illustrative example is shown on page 435.

Filter Circuits for Automatic-volume-control Systems.—In a typical automatic-volume-control circuit such as shown in Fig. 355 the application of a signal voltage to the plate of the diode produces several different currents, which develop correspondingly different voltages across the resistance r. The voltages which must be considered are (1) a direct-current voltage proportional to the signal carrier, (2) an alternating-current voltage proportional to the modulation of the carrier, and (3) an alternating-current voltage proportional to the carrier voltage. As explained previously the direction of the flow of the direct current is such that the point A is negative with respect to the cathode. The direct-current voltage developed across the resistance r is applied to the grids of the controlled tubes. The series resistance including R_1, R_2, and R_3 does not change the value of this grid-bias voltage because any tendency for direct current to flow through them is blocked by the condensers C_1, C_2, and C_3.

The other voltages developed across the resistance r must not be allowed to enter the tube circuits. The amplifier tubes might be made to oscillate if the radio-frequency voltage reached their grids. Distortion due to audio-frequency modulation would result if the audio-frequency voltage reached the grids. The resistances (except r) and the condensers are used to filter out these alternating-current voltages. The first section RC[1] of the filter is designed so that the alternating-current voltage across C is small in comparison with the voltage across the resistance r. Other filter sections such as R_1C_1 are provided for each tube. The voltage that

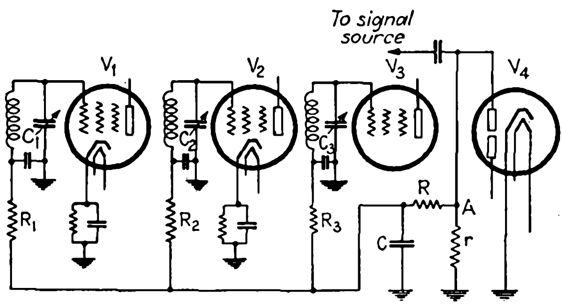


FIG. 355.—Automatic-volume-control circuit with filters.

does reach the grid of tube V_1 is that across the condenser C_1 which is small compared with the original value. Additional filtering action, if needed, could be provided by the use of a condenser across the resistance r, or by another filter section. If the condensers C_1, C_2, and C_3 are not large enough, there may be a small voltage developed across them owing to alternating currents in the tuned circuits. This condenser voltage would be fed back to the grids of the controlled tubes because they are connected to a common point, and might thus produce oscillations. In this respect the grid resistances tend to isolate the grid-return voltages. If tube V_1 is a radio-frequency amplifier, V_2 a first detector, and V_3 an intermediate-frequency amplifier, the resistances R_1 and R_3

[1] The section RC of the filter refers to the combination of the resistance R and the condenser C.

may not be needed. The reason for this is that any voltage that may exist across the condenser C_3 would be an intermediate-frequency voltage and would cause no disturbance if it reached the radio-frequency amplifier V_1. The first detector tube, however, carries both radio-frequency and intermediate-frequency currents and would be affected by voltage variations from either the tube V_1 or the tube V_3. Therefore it is seldom possible to omit the resistance R_2.

Size of Filter Units.—The size of the units in the filter circuit in an automatic-volume-control system depends on the value of the so-called *time constant* of the circuit. The time constant of a filter circuit is equal to the product of the capacity in farads and the resistance in ohms and thus is proportional to the time required to discharge the condenser. When a direct-current voltage across the resistance r is produced by the application of an input-signal voltage, the condensers C, C_1, C_2, and C_3 become charged to the voltage that exists across the resistance r. The effect of the other resistances in the filter circuit is to delay the charging of the condensers. Then when there is no signal voltage, the condensers begin to discharge. The path of the discharge current from the condenser C is first from it to ground, then, because the ground side of the condenser is positive, through the resistances r and R back to the condenser C. The currents from the other condensers flow to the ground and then through the resistances r, R, and their respective grid resistances back to the condensers. If all the condensers have equal capacity, the time of discharge will depend on the resistance in the path of discharge. Consequently the grid-bias voltages applied to the tubes do not change at the same rate as the voltage across the resistance r. If a fading station is being received, the fading may be so rapid that the compensation provided by the automatic-volume-control action is inadequate. The effect on tuning of a large time constant is that the operator adjusting a receiver in which the automatic-volume-control action lags will tune just off the station because the maximum response is observed at that point.

Under such conditions accurate tuning can be obtained, however, if the adjustment is made slowly and carefully.

The value of the *time constant* should be about 0.05 second but not over 0.06 second. This value is obtained by taking the product of the capacity in microfarads of the condenser which discharges through the largest resistor, and the resistance in megohms through which it discharges. Thus, in Fig. 355, if each of the resistances r and R has a resistance of 0.5 megohm, if each of the resistances R_1, R_2, and R_3 has a resistance of 0.25 megohm, and if each condenser has a capacity of 0.05 microfarad, the time constant for the circuit containing the controlling condenser is

$$0.05(r + R + R_1) \text{ or } 0.05 \times 1.25 = 0.06 \text{ second.}$$

Values commonly used are given in Table XX.

TABLE XX.—VALUES FOR CALCULATION OF TIME CONSTANT

Resistances, megohms			Capacities, microfarads	
R_1, R_2, R_3 each	R	r	C_1, C_2, C_3 each	C
0.25	0.5	1.0	0.03	0.03
0.1	0.5	0.5	0.05	0.05
0.1	0.5	1.0	0.04	0.04

These resistances cannot be made too small without affecting the performance of the circuit. With the arrangement of Fig. 355 both r and the RC circuit are in parallel with the secondary winding of the intermediate-frequency transformer in the plate circuit of the preceding amplifier tube. If the resistances are very small they will introduce a shunting effect and reduce the gain of the amplifier.

Double Automatic-volume-control System.—In an all-wave receiver the conditions of reception on the different bands may show considerable variation. For example, in the broadcast and long-wave bands the signal-voltage levels are relatively high. Also, a constant input to the second detector is needed because of the use of aural compensation (page 439) with the volume control. In this range the automatic-volume-control system, using a separate tube, provides a constant input and therefore does not function on an extremely weak signal voltage. In the short-wave bands the signal strength may be very low and may fluctuate widely. For this reason it is desirable to have some automatic-volume-

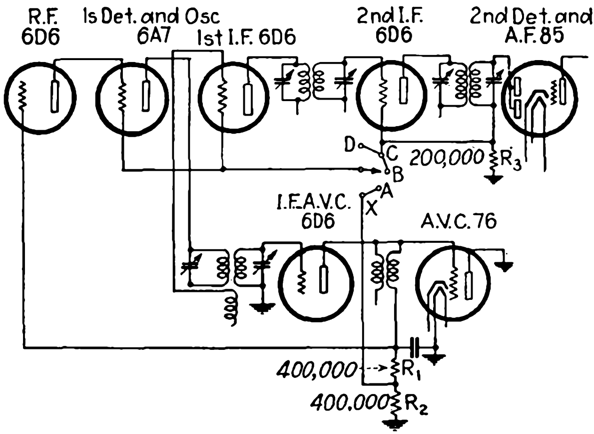


FIG. 356.—Circuit for double-automatic-volume control.

control action below the level at which the ordinary system operates. Such control is provided by means of a voltage drop obtained from the diode section of the second detector tube. This voltage drop operates on the second intermediate-frequency stage for *all* bands, and on the first-detector and first intermediate-frequency stages for the *short-wave* bands.

In one five-band all-wave circuit[1] the double automatic-volume-control system is arranged as shown in simplified form in Fig. 356. The output of the first detector tube is applied through two tuned circuits to the grid of the intermediate-frequency and automatic-volume-control stages. Energy

[1] RCA Victor Model 381.

from the secondary winding of the transformer in the second tuned circuit is applied through a coupling coil to the first intermediate-frequency stage which in effect is in parallel with the intermediate-frequency and automatic-volume-control stages. The output of the first intermediate-frequency stage is applied through a transformer to the second intermediate-frequency stage, and thence through a second transformer to the second detector tube.

The output of the intermediate-frequency and automatic-volume-control stages is applied to the tube for automatic volume control through an untuned intermediate-frequency transformer. The type 76 tube in the automatic-volume-control stage is operated as a rectifier, its plate being grounded and only the grid being used. A small grid-bias voltage of about 5 volts is maintained so that rectification does not occur until the signal voltage exceeds this value. When the signal voltage exceeds 5 volts, a portion of the rectified voltage produces a voltage drop across resistances R_1 and R_2. The voltage drop across both of these resistances is used as the automatic grid-bias voltage for the radio-frequency stage. The drop across the resistance R_2 is used as the automatic grid-bias voltage for the first detector tube and the first intermediate-frequency stages on the bands *X* and *A*.

A portion of the rectified voltage of the second detector tube produces a voltage drop across the resistance R_3. The voltage drop is used as a second automatic-volume-control voltage and is applied to the second intermediate-frequency tube for all bands, and to the first detector and the first intermediate-frequency tubes for the bands *B* and *C*. The change in the automatic-volume-control system is made by the addition of a group of contacts on the band-selector switch. The switching arrangement for changing the automatic-volume-control system in the various bands is shown in Fig. 356.

Audio-Frequency Methods for Automatic Volume Control.— Most of the automatic-volume-control circuits are intended to vary the amplification of a receiver in proportion to the strength of the signal voltage by changing the carrier-wave voltage. With this arrangement all stations having the same degree of modulation would produce equal audio-frequency outputs. But when the receiver is tuned from one station to another which has a different degree of modulation, the volume must be readjusted.

One solution for this difficulty is the use of an audio-frequency limiting device as illustrated in Fig. 357. This arrangement[1] provides automatic volume control on the audio-frequency section of the tube in order to avoid audio-frequency overload when the signal voltage is changed from one of low to one of high modulation. Since the pentode unit of the 6B7 tube is of the variable-mu type (page 123), the application of a control of this kind does not produce any appreciable distortion and the audio-frequency output is practically constant. With the extension of automatic volume control to the audio-frequency stage it becomes possible to obtain more satisfactory automatic-volume-control performance in small receivers.

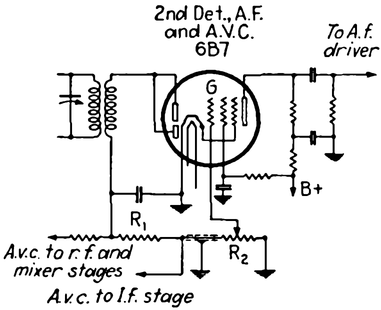


FIG. 357.—Automatic volume control on audio-frequency section of tube.

The direct-current voltage drop developed across the resistances R_1 and R_2 is used for automatically regulating the control grid-bias voltage of the radio-frequency and the mixer stages. The smaller voltage developed across the resistance R_2 is applied for automatic-volume-control action to the control grid of the intermediate-frequency stage. This arrangement is designed to reduce the distortion that might result if a tube is operated near its cut-off point. In each successive amplifier stage the variations of plate voltage become greater and may even approach the value of the plate-

[1] *Service*, April, 1935.

supply voltage, while the condition is aggravated as the negative grid-bias voltage is increased by automatic-volume-control action. The audio-frequency and direct-current components of the detected signal voltage are taken from the resistance R_2 and are applied to the control grid G of the type 6B7 tube. Since the cathode is connected to the ground, there is no grid-bias voltage on the control grid when no signal voltage is received. When a signal voltage is applied, however, the control grid receives a negative grid-bias voltage which increases as the signal voltage increases.

Retroactive Automatic-volume-control Circuit.—In the circuit shown in Fig. 358 automatic-volume-control action is

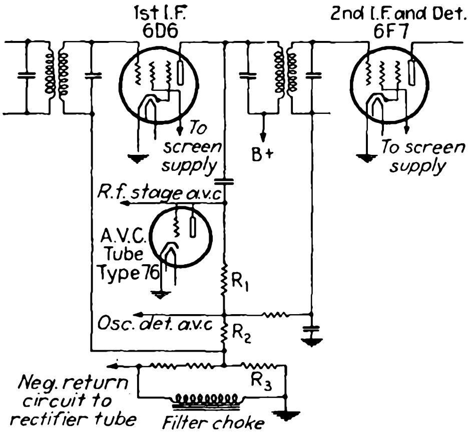


FIG. 358.—Retroactive circuit for automatic volume control.

obtained from a type 76 tube which is fed from the plate of the first intermediate-frequency tube through a condenser. The voltage developed across the resistances R_1 and R_2 is used for automatic volume control. This voltage is applied to the radio-frequency tube, to the oscillator-detector tube, and also to the second intermediate-frequency tube. With this arrangement the automatic-volume-control voltage applied to the second intermediate-frequency tube depends on the signal voltage that is developed *before* that tube. This arrangement is useful in reducing distortion that may be caused by overloading from a strong signal input, because while both intermediate-frequency tubes are controlled, the automatic-volume-control tube is fed from a point in the circuit at which the gain (page 151) is below its highest value. Another advantage is that a partial automatic-volume-control effect is obtained without the use of a separate tube for that purpose. The reason for this is that the automatic-volume-control tube is operated from a point of reduced selectivity; consequently, when the receiver is tuned from one station to another, the interchannel noise serves to reduce the gain. The sensitivity of the receiver to weak-signals currents, however, is not greatly reduced. Because of the grid-bias voltage developed across the resistance R_3 the noise level must be comparatively high before the automatic-volume-control tube begins to operate.

Circuit Arrangements in Automatic-volume-control Systems.—Certain precautions as to location of units in an automatic-volume-control system must be observed in order that proper performance may be obtained. Thus in a superheterodyne receiver, common grid returns in the radio-frequency and intermediate-frequency stages must be avoided in order to prevent coupling between the stages. This precaution is necessary because some carrier frequencies are harmonics of the intermediate frequency.

The load for the diode unit of the second detector tube in the circuit arrangement shown in Fig. 359 is the resistance R_3. This resistance should be connected so that the current is returned directly to the cathode, except where a special signal delay action (page 425) is desired. If the connection is made to the ground instead of to the cathode, the diode unit is "biased" by an amount equal to the drop in the cathode resistance R_4. Such a connection produces a marked decrease in the sensitivity of the receiver on low-voltage signals. In the early designs of automatic-volume-control systems an initial grid-bias voltage was not applied to the tubes which were controlled. The disadvantages of this arrangement are that a grid current may flow if the tube does not have a large enough grid-bias voltage, with the result that the voltage drop is produced in the isolating resistance. This condition leads to excessive plate current, coupling difficulties, and possible damage to the tube. In later designs a grid-bias voltage of the correct value is obtained either by properly proportioning

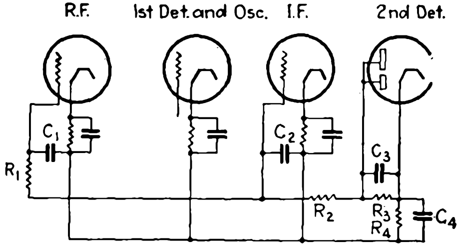


FIG. 359.—Circuit details for automatic volume control.

the cathode resistance, or from a tap on the voltage-supply unit.

The introduction of the pentagrid-converter type (page 147) of tube makes possible the application of a grid-bias voltage for volume control to the detector unit of the tube. One

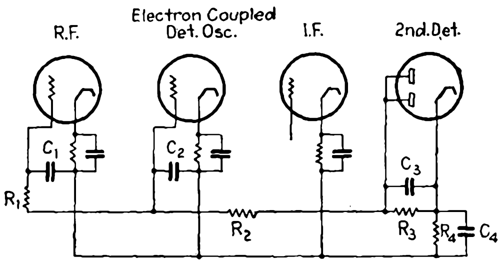


FIG. 360.—Circuit providing grid-bias voltage to detector unit of pentagrid converter for automatic volume control.

circuit for such an arrangement is shown in Fig. 360. If the automatic-volume-control action is needed for two tubes only, the tube in the intermediate-frequency stage is not so treated. But in that case the grid-bias voltage on that tube must have such a value that the grid will not become positive on the strongest signal voltage that may be received.

In the circuit shown in Fig. 361 the pentagrid converter is followed by two intermediate-frequency stages. With other types of combined detector-oscillator tubes a variable control grid-bias voltage could not be applied for the purpose of obtaining volume control, with the result that the performance of the oscillator was hindered by a strong local incoming signal. But with the pentagrid converter a variable grid-bias voltage can be applied to the detector unit of the tube. The circuit shown gives satisfactory performance if the

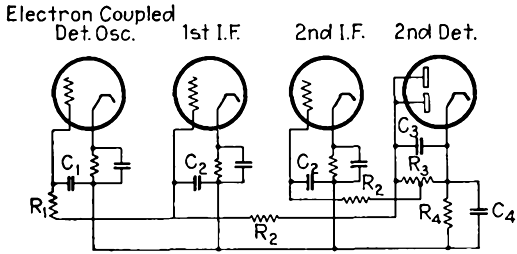


FIG. 361.—Circuit providing grid-bias voltage for automatic volume control on intermediate-frequency stages.

automatic-volume-control voltage is not applied to the second intermediate-frequency stage.

Tone Control.—Tone control changes the "frequency response" of a receiving set and thus affects the timbre of the reproduction while volume control changes the output of sound. One method of tone control is to divert the higher-frequency currents from the loud-speaker. This is accomplished by a set of small by-pass condensers arranged so that they may be cut in or out of the circuit as desired. Another method utilizes a large variable resistance in series with a fixed by-pass condenser which has a capacity of from 0.5 to 1.0 microfarad. This combination of resistance and capacity in series is connected across the secondary winding of the input transformer in the audio-frequency amplifier (see also Fig. 263).

RADIO-FREQUENCY AMPLIFICATION

Function of Radio-frequency Amplifier.—The three factors which enter into radio-frequency amplification are (1) sensitivity, (2) selectivity, and (3) fidelity of reproduction.[1] Sensitivity indicates the extent of the response to signal voltages of the frequency to which the receiver is tuned. It is measured by the signal voltage needed in the antenna circuit to produce a standard output from the receiver. *Selectivity* is the ability of the receiver to differentiate signal voltages of different frequencies. A signal voltage that has several side bands each with a width of 5,000 cycles per second requires a 10-kilocycle (10,000 cycles per second) transmission channel. For operation under these conditions a receiver must have 10-kilocycle sensitivity. *Fidelity* of reproduction is determined by the response of the receiver to the frequency range of the side bands. This is for the reason that when a carrier wave is modulated at audio frequency, these three frequencies are present: (*a*) carrier frequency, (*b*) carrier frequency plus the audio frequency, and (*c*) carrier frequency minus the audio frequency. The last two are called the *side bands*. If the fidelity is to be good, the side bands must be fully reproduced. A radio-frequency amplifier must select the desired frequency and must amplify the carrier frequency together with its side bands. The resonance curve must not be sharp at the top, or the side bands will be cut off. On the other hand, if the resonance curve is too broad, interference may be caused by the amplification of other frequencies.

Types of Radio-frequency Amplifiers.—The radio-frequency amplifier has the same general form as an audio-frequency amplifier, but the same designs cannot be used for interstage coupling, because of the effect of tube capacity at high frequencies. Such amplifiers are classified according to the type of coupling between stages, as (1) resistance-coupled, (2) impedance-coupled, and (3) transformer-coupled amplifiers. Usually a circuit is used which must be tuned to resonance (page 77) to provide the necessary amplification and selectivity. The "tuned radio-frequency amplifier"

[1] For standard measurements see Sec. VIII, "Radio Handbook," by Moyer and Wostrel, McGraw-Hill Book Company, Inc., New York.

is one form of such a circuit. In another type, the *superheterodyne*, the signal is amplified to some extent at radio frequency and is then converted to a lower frequency for further amplification.

The operation of radio-frequency amplifiers in *receiving sets* is carried out under class *A* (page 399) conditions. Radio-frequency amplifiers operated under class *B* and class *C* conditions are used in *power transmitters*.

Resistance Coupling.—At high frequencies, the impedance of the grid-to-filament circuit consists largely of the reactance of the grid-filament capacity. The disadvantage of this is that the capacity reactance of the grid-filament circuit is so small that it has the effect of a short circuit on the coupling resistance and, therefore, decreases the amplification. The blocking condenser must have a capacity such that its reactance is smaller than the grid-filament capacity reactance as stated above. This shows that the capacity of a blocking condenser for use at high frequencies may be made smaller than that of one for use at low frequencies. A resistance-coupled amplifier for high-frequency work is similar to one for audio frequency, except that the blocking condenser must be smaller. The distributed capacity of the coupling resistance should be as small as possible; otherwise, it would reduce the impedance of the coupling unit and thus diminish the amplification. A resistance-coupled radio-frequency amplifier is noisy because it amplifies audio frequencies as well as radio frequencies.

Impedance Coupling.—At 600 meters (500,000 cycles per second) the inductance of a 30,000-ohm reactance is 0.01 henry. It is difficult to build a suitable inductance without iron so that its internal capacity is small and its size is not too large. The effect introduced by the distributed capacity (page 89) is that excessive amplification exists at a frequency equal to the natural frequency of the coupling unit. The performance of an amplifier using inductance alone is not satisfactory for short wave lengths. Also, an amplifier of the inductance-coupled type, just like one of the resistance-coupled type, amplifies audio frequencies as well as radio frequencies and hence has poor selectivity.

If a condenser and inductance in parallel are used, they may be tuned to the required frequency. With such a construction the value of inductance may be low because the tuning is accomplished by the condenser, but the impedance of the unit may be high. Tuned amplification of this kind is useful for radio-frequency amplification because of the great selectivity which it provides.

Transformer Coupling.—For radio-frequency amplification it is customary to use air-core transformers (although satisfactory iron-core transformers have been developed) with a 1 to 1 ratio. On very long wave lengths a step-up ratio has been found advantageous.

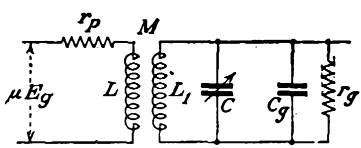


FIG. 362.—Equivalent circuit of tuned radio-frequency stage.

If two *low-loss circuits* are coupled "loosely" by means of a transformer with a primary winding of few turns and a secondary winding of many turns, the voltage amplification is increased because of the step-up ratio and the tube amplification. A circuit of this kind, however, gives maximum amplification at only one frequency and poor amplification at adjacent frequencies. In order to obtain a circuit which gives more uniform amplification than the untuned circuit over a band of frequencies, a variable tuning condenser is used across the secondary winding of the transformer. Such a circuit is called a *tuned radio-frequency amplifier*.

Voltage Amplification.—The equivalent circuit of a tuned radio-frequency stage is shown in Fig. 362. The expression for the voltage amplification according to the principles and notation of Chap. III is $\frac{(2\pi f)^2 ML_1 u}{R_e r_p + (2\pi f M)^2}$. From this expression it is seen that the voltage amplification varies with the amplification factor u of the tube, the secondary inductance L_1, the coupling M between the coils of the transformer, the plate resistance r_p of the tube, and the effective resistance of the secondary circuit R_e. The mutual inductance M between L and L_1 is equal to $k\sqrt{LL_1}$ in which k is the coefficient of coupling. The total series resistance of the secondary circuit R_e is equal to the L_1 coil resistance (3.4 ohms) plus the equivalent resistance of r_g. The equivalent resistance of r_g is $(2\pi fL_1)^2 \div r_g$. In order to illustrate the use of the expression for voltage amplification assume that $f = 500{,}000$ cycles per second, $k = 0.3$, $L = 35$ microhenrys, $L_1 = 250$ microhenrys, $u = 8$, $r_p = 10{,}000$ ohms, and $r_g = 1{,}000{,}000$ ohms. Then the equivalent resistance of $r_g = \dfrac{(6.28 \times 500{,}000 \times 250)^2}{10^{12} \times 10^6} =$ 0.62 ohm and $R_e = 3.4 + 0.62 = 4$ ohms, approximately. $M = 0.3\sqrt{35 \times 250} = 28$ microhenrys. The substitution of these values in the expression for voltage amplification gives

$$\frac{(6.28 \times 5 \times 10^5)^2 \times 28 \times 250 \times 8}{\left[4 \times 10^4 + \left(6.28 \times 5 \times 10^5 \times \frac{28}{10^6}\right)^2\right] \times 60^6 \times 10^6} = 11.6.$$

It is important to keep enough negative grid-bias voltage on the grid circuit of the tube so that the resistance r_g of the grid-filament circuit may be high.

Resonance Curve.—The shape of the resonance curve depends on the effective resistance of the secondary circuit, on the coupling between the coils, and on the grid-plate capacity of the tube, which couples the input and output circuits. Increased coil coupling increases the secondary circuit resistance and has the effect of broadening the resonance curve and diminishing the selectivity. Amplification improves as the coupling is increased until the best point is reached, beyond which it slowly decreases. The degree of coupling generally used is well below the best value, to obtain stability and selectivity. The tuning of the secondary circuit is broadened at high frequencies.

Because of the grid-plate capacity, the output circuit, under the usual load conditions, reacts on the input circuit. The feed-back action is greater at high than at low frequencies and tends to offset the broadened tuning. The effect is equivalent to the addition of a condenser and resistance across the secondary circuit. The constants of the output circuit determine whether this resistance has a positive or a negative effect. The action of a negative resistance is to offset the losses in the secondary circuit. When the losses in the secondary circuit are offset in this manner, the tuning is made sharper unless the negative resistance supplies all the losses; and in that case the circuit will oscillate.

Tubes for Radio-frequency Amplification.—A tube having a fairly high output resistance may be used efficiently for radio-frequency amplification. The limiting factor as regards the permissible tube resistance is the increase in resistance of the secondary or tuned circuit. Ample voltage amplification, that is, good sensitivity, is obtained with a high-resistance tube which is coupled closely to a tuned secondary winding of the transformer, but the selectivity is poor because of the increase in effective resistance of the circuit. A low-resistance tube can be used with less coupling than a high-resistance tube, with improvement in selectivity. But if a low output resistance results from decreasing the amplification factor, the sensitivity is reduced and the drain on the rectifier is increased.

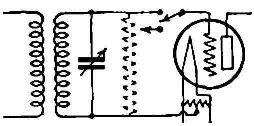


FIG. 363.—Methods of stabilizing circuits by use of grid-bias voltage to prevent oscillation.

Methods of Stabilizing to Avoid Oscillation.—There are several methods of stabilizing a circuit so that it will not oscillate. Two common methods are shown in Fig. 363. In one of these methods the grid return is varied by a potentiometer in such a way that a positive grid-bias voltage may be applied to the grid. A current then flows in the grid circuit and has the effect of decreasing the resistance between the grid and the filament and increasing the effective resistance of the tuned circuit. The main disadvantages of this method are the heavy plate current which flows when the grid is positive, and the increased damping of the tuned circuit. The other method utilizes an adjustable potentiometer, *shown by* *the dotted lines,* connected across the tuning condenser. Adjustment of the potentiometer varies the voltage applied to the grid and thus serves as a control of amplification and stability.

A better method than either of the two preceding methods is shown in Fig. 364 where the grid circuit has a resistance *R* of from 100 to 1,000 ohms. The decrease in amplification caused by the use of the resistance *R* is more pronounced at high than at low frequencies, which is an advantage because the feed-back increases with the frequency. A disadvantage, however, is introduced by the broader tuning due to the greater damping of the circuit.

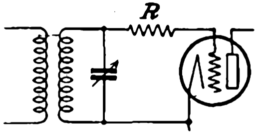


FIG. 364.—Method of stabili ing circuits by use of grid resistance to prevent oscillation.

The insertion of resistance in the "B" plus lead may be used to secure stable operation by lowering the effective plate voltage. The advantages of this method are the saving in plate supply current, and the sharper tuning which is possible because there is not much increase in the damping of the resonant circuit.

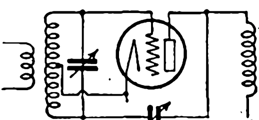


FIG. 365.—Rice method of stabilizing by neutralizing the capacity of a tube by another capacity.

The best method of obtaining stability is to neutralize the capacity of the tube by means of another capacity. Two ways of connecting this additional capacity are the *Rice method* and the *Hazeltine method.* The Rice method is shown in Fig. 365. The center of the input coil is grounded so that the coils must be carefully arranged. Otherwise, the balance obtainable may be upset by capacity coupling between the coils. The capacity effect may be minimized by increasing the spacing of the coils or by using a shield between the coils. Some decrease in sensitivity may be expected when this circuit is used because the input voltage applied to the tube is half of that obtained across a tuned circuit.

The coils L_1 and L_2 required in the Hazeltine method, shown in Fig. 366, have a double-wound primary winding of the transformer, which is used to obtain close coupling. An "alternate" connection may be made by omitting the inductance L_1 and connecting the variable condenser C as indicated by the dotted lines. In this case the inductance L_2 must be placed adjacent to the lower portion of the secondary winding of the transformer in order to obtain close coupling. Either of the last two methods is nearly independent of frequency over the usual range of frequencies used in broadcasting.

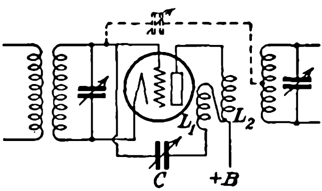


FIG. 366.—Hazeltine method of stabilizing by neutralizing the capacity of a tube.

Circuit Arrangements.—In a radio-frequency amplifier, regeneration may be caused not only by the grid-plate capacities of the tubes, but also by impedances which are common to several stages, and by stray coupling between coils and between condensers.

Stray coupling can be minimized or even eliminated by properly locating the pieces of apparatus or by the use of adequate shields. To reduce electrostatic and magnetic coupling it may be necessary to shield completely each stage.

Regeneration due to common impedances occurs frequently where the same supply source provides grid-bias or screen-grid or plate voltages for several stages. Regeneration from such causes can be reduced by adequate filtering so that the radio-frequency currents are by-passed around the voltage-supply sources (page 321).

The effect of the grid-plate capacity of three-element tubes may be counter-balanced by the use of various neutralizing systems. In modern receivers, however, multi-electrode tubes are used in which a shield is provided between the control grid and the plate.

Gaseous Discharge Tube as Visual Tuning Indicator for Amplifiers.—A *superheterodyne* radio receiver having a sharp resonance curve must be adjusted exactly to the carrier frequency of a desired station to obtain the most satisfactory reproduction. This adjustment is frequently difficult to make because the signal is received with considerable volume when the receiver is not accurately tuned. The *visual tuning indicator* was devised to minimize this difficulty in the operation of radio receivers provided with automatic volume control. One indicator[1] of this kind consists of a *gaseous discharge* or *neon tube* (page 206) having a short anode, a long cathode, and an auxiliary electrode. The use of this device with radio-frequency amplifier tubes, in which the grid-bias voltage is controlled, is shown in Fig. 367*a*. As the current in the plate

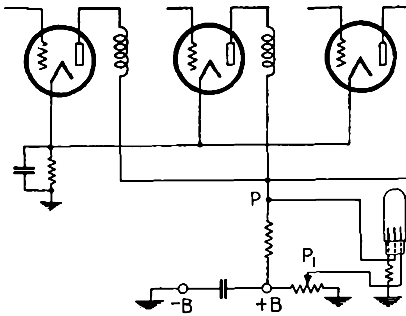


FIG. 367*a*.—Circuit of visual tuning indicator for amplifier.

circuit decreases, the voltage between the points P and P_1 of the indicator increases. This increase in voltage across the indicator tube causes the gas column in the tube to increase in length, moving up the long cathode. The height of the discharge is proportional to the increase in voltage between P and P_1 above the value when the column is stationary. In the commercial types of indicator tubes such as the *Flashograph, Tonebeam, Tunalite,* and others, the column height also is directly proportional to the current between the cathode and the anode (about 2 milliamperes at full height). The initial ionization of the indicator tube is produced by the use of a third electrode connected to a point that is more negative than P_1, by about 40 volts. Adjustment of the voltage obtained at the

[1] "Gaseous Discharge Tubes for Radio Receiver Use," *Electronics*, February, 1933.

point P_1 may be necessary to compensate for variations in line-voltage and amplifier-tube current.

Tuning Indicator Tube.—Type 6E5 is a tube of the high-vacuum kind designed to indicate *visually* the effect of a change

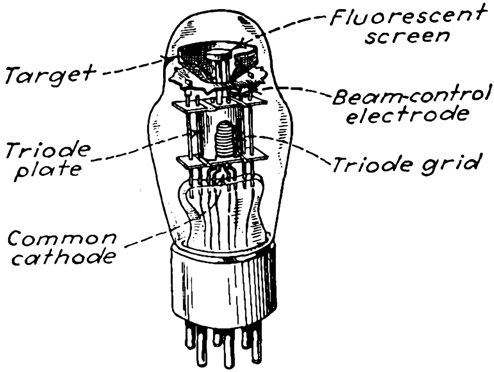


FIG. 367*b*.—Tube to indicate visually changes in control voltage.

in the control voltage for the tube. The width of a shaded area on a fluorescent screen will show how much departure there is from the condition of resonance. The shaded area that appears on the screen varies from a very narrow pattern to approximately a quarter of a circle. The extent of this pattern depends on the grid voltage of the tube. The tube, as shown in Fig. 367*b* consists of a triode section and a cathode-ray section, both having a common cathode. The electrode which controls the shape of the electron beam, and thereby the shaded area on the screen, consists of an extension of the triode plate between the cathode and the target.

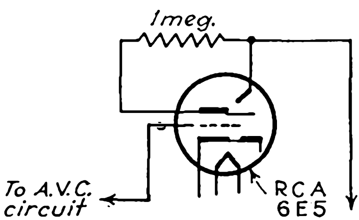


FIG. 367*c*.—Circuit for tuning indicator.

This tube may be connected for indicator service as shown in Fig. 367*c*. When the receiver approaches a condition of resonance during tuning, the automatic-volume-control voltage is increasing. This increasing voltage, when applied to the triode grid of the tube, acts to decrease the triode plate current and to increase the voltage on the beam- or ray-control electrode. The width of the shaded area on the screen decreases as the voltage on the beam-control electrode is increased.

OTHER TYPES OF RADIO AMPLIFIERS

Superheterodyne Receiver.—It has been shown that the operation of a multi-stage, radio-frequency amplifier is effective over only a limited frequency range. In the superheterodyne circuit shown in Fig. 368 the high-frequency

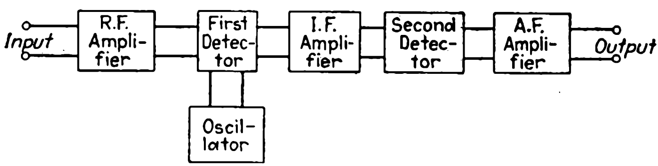


FIG. 368.—Typical superheterodyne receiving set

alternating current of the received signal current is transformed into an alternating current (generally of lower radio-frequency) called the *beat frequency*, which is better suited than the signal current to the amplifier. This transformation is accomplished by *combining* the received signal current with a locally generated alternating current of suitable frequency. The current having this beat frequency goes through a filter, which passes only the desired frequency, and is then amplified in a number of intermediate stages which are tuned to the beat frequency. The output of the last intermediate-frequency stage is "detected" and passes through the usual stages of an audio-frequency amplifier. Beat frequencies of from 30 to 1,100 kilocycles per second have been used, depending on the range of frequencies to be received. At 50 kilocycles per second the reactance of the grid-filament capacity of a vacuum tube is high enough so that it causes very little interference with the action of the amplifier.

The first oscillator radiates energy from the antenna unless it is preceded by a properly balanced circuit. In one type of superheterodyne circuit the interference from such radiation is reduced by operating the oscillator at half the required frequency so that its second harmonic (page 131) is used as the locally generated frequency. In this way the amount of radiation is reduced and the frequency of the radiated energy is outside of the range of broadcasting frequencies.

Although the general layout in Fig. 368 includes all the parts needed for the functions performed by a superheterodyne receiver, commercial types show some variations in design. Thus the input radio current may be taken from a loop antenna instead of an antenna; and the number of stages in the radio-frequency amplifier will vary. The oscillator and the first detector stages may be separate tubes, or the equivalent service may be performed by a single tube. There is no standard number of stages in the intermediate-frequency amplifier. The choice of the intermediate frequency varies over a wide range. The intermediate frequency may be obtained either by adding the signal-current frequency and the oscillator frequency, or by subtracting them, but generally the oscillator frequency is higher than the signal-current frequency. The audio-frequency amplifier may have one or more stages.

It should be noted that a superheterodyne designed as indicated has several disadvantages, unless it is provided with filter circuits of the proper kind, and with an input-current amplifier which can be adjusted for sharp tuning. First, there are two settings of the control device for the local oscillating frequency, either of which in combination with a given carrier frequency will give the required beat frequency. Also, for a given oscillating frequency, there are two carrier frequencies which will combine with it to give the same beat frequency.

Reflex Amplification.—The reflex system of amplification was developed to reduce the number of tubes required in a multi-stage receiver. In this system when used with three-element tubes, the radio-signal current is first passed through a number of stages of a radio-frequency amplifier, detected in a separate stage and then returned through some of the radio-frequency stages to obtain audio-frequency amplification.

The *inverse reflex system* was devised to equalize the load on the grids of the various tubes. In a receiver having three radio-frequency tubes, the audio-frequency plate current is returned to the last or third radio-frequency tube and thence to the second tube; that is, the third radio-frequency tube

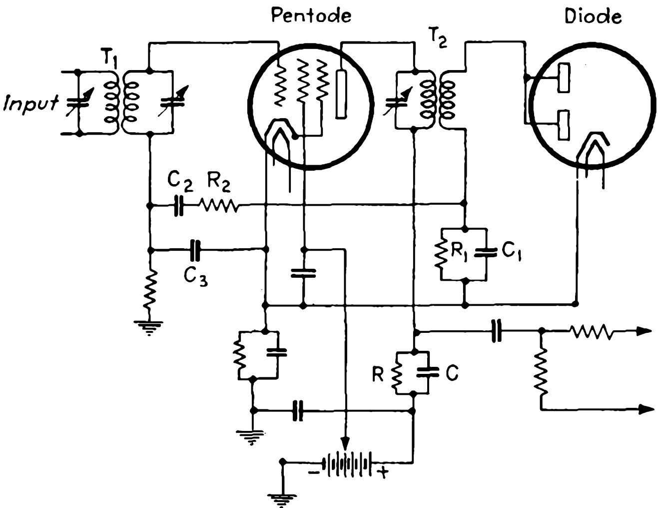


FIG. 369.—Reflex circuit including pentode and diode for amplifier.

serves also as the first audio-frequency tube and the second radio-frequency tube serves also as the second audio-frequency tube. Since two stages of audio-frequency amplification are ordinarily used, only two tubes may be eliminated by this method regardless of the number of radio-frequency stages in the receiver.

The reflex circuit[1] shown in Fig. 369 illustrates the use of a diode and of a pentode which are "reflexed" to amplify both intermediate and audio-frequency voltages. These two tubes now are available in one envelope such as in the type 6B7 tube.

[1] STINCHFIELD and SCHADE, "Reflex Circuit Considerations," *Electronics*, June, 1933.

In the operation of this circuit the input voltage consisting of an intermediate-frequency signal voltage is applied through the input transformer T_1 to the control grid of the pentode unit. The audio-frequency load resistance R in the plate circuit of the *pentode* unit is by-passed by the condenser C to provide low impedance for intermediate-frequency currents. The diode unit is coupled to the intermediate-frequency amplifier by means of the output transformer T_2. The diode unit serves as a detector, producing an audio-frequency output. The audio-frequency voltage developed across R_1C_1 is fed back to the pentode control grid through C_2. The filter R_2C_3 prevents any intermediate-frequency component from passing back to the control grid. The secondary winding of the transformer T_1 must have a low impedance to audio-frequency currents. The audio-frequency voltage thus applied to the pentode produces an amplified audio-frequency voltage across the resistance R. The primary winding of the transformer T_2 must have a low impedance to audio-frequency currents. Then the voltage developed across load resistance R can be applied either to an output tube or to another audio-frequency stage.

In any circuit of the reflex type, the reflexed frequency should differ as much as possible from the other frequency. The circuit illustrated shows how an audio-frequency voltage is reflexed through an intermediate-frequency amplifier. It is possible but more difficult to reflex intermediate-frequency voltage through a radio-frequency amplifier.

Direct-coupled Amplifiers.—Multi-stage amplifiers having transformer or capacity coupling cannot be used to amplify alternating currents of very low frequency, for example, those of less than 10 cycles per second, or slow shifts of direct currents. With some modifications a resistance-coupled amplifier can be used in such applications. If the grid or coupling condenser is omitted in a resistance-coupled amplifier, the voltage drop across the coupling resistance is applied to the grid of the next tube. Thus this grid is at a high positive voltage with respect to its filament or cathode. In one arrangement, as shown in Fig. 370, the necessary voltage relation between grid and filament is obtained by using separate plate batteries for each stage, and by applying through a "bias" battery a grid-bias voltage of sufficient

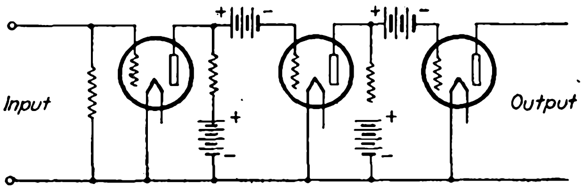


FIG. 370.—Typical direct-coupled amplifier.

value to counteract the voltage drop across the coupling resistance and to maintain the grid negative with respect to the filament.

When tubes with heater cathodes are used, a different arrangement is possible. In that case the heaters may be

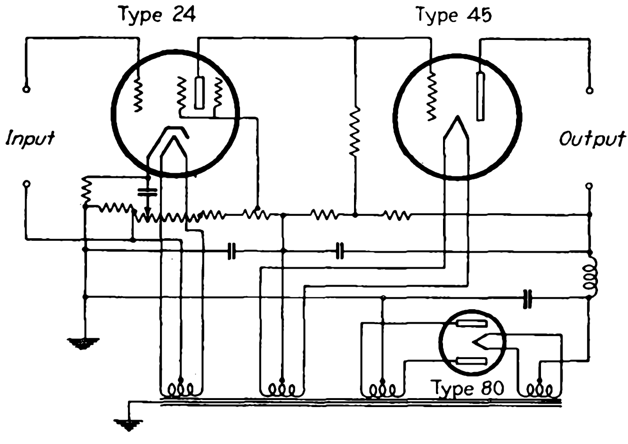


FIG. 371.—Loftin-White direct-coupled amplifier.

operated from the same battery or from a transformer, and each cathode may have a different grid-bias voltage with respect to the ground. Then the "bias" batteries mentioned before are not required, and the plate voltages may be obtained from one source of supply. With this connection the grid of a tube may be negative with respect to its cathode, but positive with respect to the cathode of the preceding tube.

The Loftin-White direct-coupled amplifier is designed to avoid the distortion introduced in audio-frequency amplifiers by inductances in transformer coupling and by the condensers in resistance coupling. In this arrangement,[1] shown in Fig. 371 the cathode grid-bias voltage and also the plate voltage of the second tube are higher than the plate voltage of the first tube. Any direct-coupled amplifier must have some stabilizing arrangement so that the operating points of the tubes will not move as a result of changes which may occur during operation.

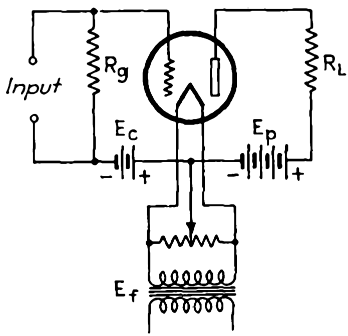


FIG. 372.—Simple amplifier circuit.

INDUSTRIAL TYPE AMPLIFIERS

Simple Amplifier Circuit.—Many industrial applications of vacuum tubes require only one stage of amplification such as is shown in Fig. 372. The tube may be of either the filament type or the cathode type, supplied with heating current from a battery or from a transformer. In the case of the cathode type the plate and grid return wires are connected to the center tap of the cathode transformer, or to a resistor as shown, in order to reduce the effects of the alternating current in the filament circuit on the plate current. The plate-voltage supply is taken from a direct-current source such as a battery. A grid-bias voltage is applied to maintain the grid negative with reference to the cathode. If the grid-input circuit is

[1] LOFTIN-WHITE, "Direct-coupled Amplifier," *Radio Engineering*, June, 1930; and LOFTIN-WHITE, "Cascaded Direct-coupled Tube Systems" *Proc. Inst. Radio Eng.*, April, 1930.

not conducting and therefore presents a very high resistance to direct current, a grid resistance R_g is needed.

The load resistance R_L consists usually of a contact-operating relay, or of a meter for indicating or recording. The amplifier may be operated as an off-and-on circuit by delicate contacts across the grid circuit. In other applications the amplifier may be used in a continuous-control circuit in which a recording meter shows the changes resulting from voltage variations applied to the grid.

Amplifiers Operated with Alternating Current.—In some applications of amplifiers the expense and complexity of a rectifier to provide grid and plate voltage may not be justified. Operation with alternating current where the grid and plate voltages are 180 degrees out of phase is possible provided that the impulses which actuate the tube are long in comparison with the frequency of the supply voltage, and provided that the action of the tube is not required to occur within a few cycles.

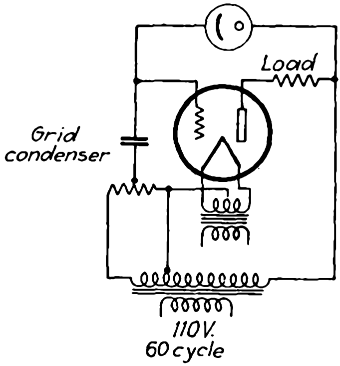


FIG. 373.—Amplifier circuit with tube action similar to that of grid-control rectifier.

The circuit of an amplifier in which the grid and plate voltages for the tube are obtained from a 60-cycle alternating-current supply line is shown in Fig. 373. The action of the tube is essentially that of a grid-controlled rectifier. When the grid voltage is positive, the grid current is limited to a low value by the high resistance of the grid resistance, and also by the negative plate. The plate current flows during each positive half of the alternating-voltage cycle on the plate. If the phase relation between the grid and plate voltages is shifted appreciably, as by the effect of plate-to-grid interelectrode capacity and also by a reactive plate load when the grid-circuit resistance is high, the amount of grid-bias voltage required to block the plate current is greater than the calculated value.

Under these conditions of operation, care must be taken that the tube rating is not exceeded. Since the root-mean-square value (page 42) of the plate current is about twice the average value, and the average value is about 0.3 of the peak value, the plate dissipation in the tube is greater than that for the same average direct current. Therefore, the *maximum permissible output*, as limited by peak current and plate dissipation, is less than half the value allowable on direct current. The amount of power output that is available when the tube is supplied with alternating current is sufficient for such applications as relay and meter operation. In cases where greater amounts of power output are required, a rectifier should be used to provide rectified voltages for the tube.

Resistance-coupled Amplifiers.—The circuit in Fig. 374 shows a voltage-amplifier tube coupled to an output tube by

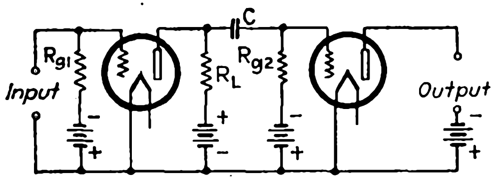


FIG. 374.—Resistance-coupled amplifier.

means of resistance coupling. The action of this amplifier is similar to that of a resistance-coupled amplifier (page 410) designed for other circuits.

The voltage applied to the grid of the output tube is that voltage produced across the resistance R_{g2}. In order that this voltage may be as large as possible, the capacity of the *coupling condenser C* must be large enough, so that at the lowest frequency to be amplified the condenser impedance is low compared to the resistance R_{g2}. On the other hand, as the capacity of the condenser C is increased, its direct-current leakage resistance decreases. Further, if the grid of the output tube becomes positive—as may occur with an excessive signal voltage the coupling condenser collects a negative charge and thereby tends to make the grid-bias voltage more negative. As the condenser discharges, the grid-bias voltage returns to its normal average value, at a rate which is slower for large than for small condensers. The values selected for R_L, C, and R_{g2} depend on the type of tube and on the lowest frequency which is to be amplified.

Impedance-coupled Amplifiers.—This type of amplifier is similar to the one shown in Fig. 374 except that it uses an impedance instead of the resistance R_L. Such an impedance generally has an inductance ranging in value up to several hundred microhenrys and has a low resistance to direct current. The operation of the circuit is the same as that of the resistance-coupled amplifier, but less plate voltage is required.

Transformer-coupled Amplifiers.—The circuit for a two-stage transformer-coupled amplifier is shown in Fig. 375.

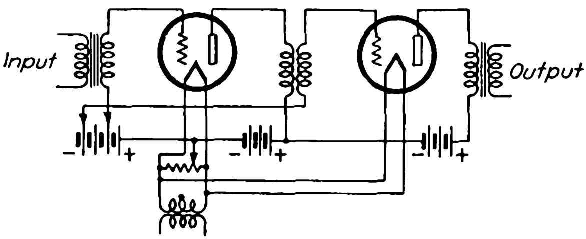


FIG. 375.—Transformer-coupled amplifier.

This arrangement as compared with other forms of coupling has the advantage that a voltage gain is obtained in the transformer. Tubes having a relatively low plate impedance are used and hence the inductance of the primary winding of the transformer need not be high. The transformer ratio can be increased to give more voltage gain. The maximum ratio is limited by the lowest value of frequency as well as by the frequency range. Higher ratios can be used than are allowable in audio-frequency amplifiers, because the frequency range generally is small. If the frequency is fixed, the plate circuit can be tuned by the use of a condenser connected across the primary or the secondary winding of the coupling transformer. High amplification can be obtained when the resonant impedance of the transformer is high.

Direct-coupled Amplifiers.—This type of coupling is used in amplifiers that are designed for the amplification of slow

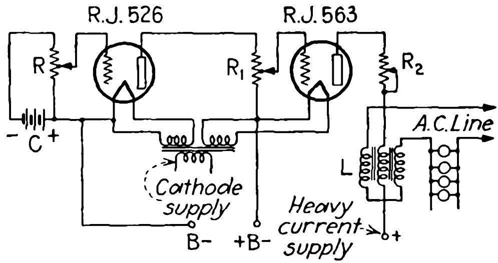


FIG. 376.—Direct-coupled amplifier for slow-voltage variations with potentiometer and resistance adjustments.

voltage variations. Two typical circuits are shown in Figs. 376 and 377. In Fig. 376, C is the grid-bias voltage supply, R is a control potentiometer, R_1 and R_2 are the adjustable resistances for minimum and maximum output, respectively, and L is a triple-unit reactance.

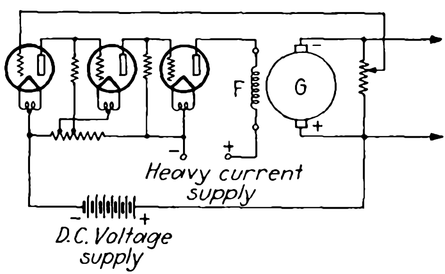


FIG. 377.—Direct-coupled amplifier for slow-voltage variations with generator-field adjustments.

In Fig. 377, G represents a generator which is controlled by the amplifier arrangement acting on the generator field F.

AMPLIFYING CIRCUITS FOR PHOTOTUBES

Amplifying Circuits for Phototubes.—The current which can be passed through a phototube is so small that it is measured in microamperes and can be used to operate only small and very sensitive relays or other similar instruments. In order to increase the power of a phototube, a method of amplification almost exactly the same as that applied in radio receiving sets has been devised to increase the power or, in other words, to amplify the effect obtainable with this type of tube. The phototube, when supplemented with an amplifier unit, makes available currents of electricity which are measured in milliamperes instead of microamperes; and the outfit is so arranged that changes in illumination of the tube cause corresponding changes of the plate current in the amplifier. Several vacuum-tube amplifiers may also be used in "cascade" (in series) in various ways to secure a large amplification or increase in value of the original current passed through the phototube.

Types of Amplifiers for Phototubes.—The most common method for coupling the phototube to the vacuum-tube amplifier is by means of a grid resistance as shown in the diagrams which follow. There are many varieties of circuits for the amplifier. Thus there are single-stage amplifiers, multi-stage amplifiers, amplifiers designed for operation on direct current, and amplifiers designed for operation on alternating current. There is still another classification depending on the direction of change of amplifier current with variation of illumination on the phototube.

The vacuum-tube amplifier can be connected to a phototube so that its output current (page 117) either increases or decreases when the amount of illumination on the phototube is varied. The kind of circuit in which the output current of the amplifier increases with an increase of illumination of the phototube is called a *forward circuit;* the one in which the output current of the amplifier decreases when the illumination of the phototube increases is called a *reverse circuit.*

A vacuum-tube amplifier when supplied with direct current is the most sensitive amplifying device that is available. It has the further advantage that the output current of the amplifier per unit of illumination of the phototube is proportional to the product of the sensitivity of the phototube and the grid resistance. It is, therefore, possible to obtain almost any degree of sensitivity by using a very sensitive phototube and a high value of grid resistance. This highest value of grid resistance must be determined by its effect on the stability of the circuit in which it is to be used.

Unless very great sensitivity is actually required, it is usually desirable to avoid the use of the direct-current type of vacuum-tube amplifier and use instead the simpler type of amplifier operating with alternating current. The direct-current amplifier, if used in connection with alternating-current apparatus, must have, of course, for its filament circuit, direct current from a rectifier or from a battery, although the current from a transformer of suitable secondary voltage can be used as a current supply for *heating* the filament. If, however, no appreciable hum or ripple is permissible in the output of the amplifier, the transformer method cannot be used even for supplying the current for heating the filament. Most applications of phototubes will permit small amounts of hum or ripple in the output circuit, as most applications are for the operation of relays.

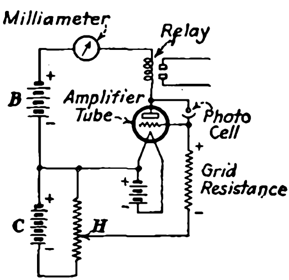


FIG. 378.—Typical direct-current forward circuit.

The forward circuit and the reverse circuit in such applications are very much alike. The forward circuit is the one more commonly used, except when the apparatus and the light source receive current at a somewhat varying voltage.

Single-stage Direct-current Amplifiers for Phototubes.—A typical *forward* circuit for a single-stage amplifier intended for operation on direct current is shown in Fig. 378. In this arrangement the plate voltage plus the grid-bias voltage acts as the effective voltage for the phototube. When the phototube is dark, the grid of the vacuum-tube amplifier will be at a negative potential with respect to the filament as determined by the potentiometer *H*, as shown at *A* in Fig. 379. This is on the assumption that zero grid current is flowing through the grid resistance. When light falls on the phototube, a current flows from the positive terminal of the "B" battery through the milliammeter and relay to the anode or positive terminal of the phototube. From this point the flow is through the tube, the grid resistance, and then to the point *H* of the potentiometer and the negative terminal of the battery. The current flow produces a voltage drop over the grid resistance in such a direction as to cause the grid to become more positive with respect to the filament as indicated in Fig. 378 by the signs beside the grid resistance. Because of this change in the grid-bias voltage, at such a point as *B* in Fig. 379, an increased current will flow through the vacuum-tube amplifier. The current change in output of the amplifier will be linear with respect to light under proper circuit conditions, since the response of the phototube varies directly with respect to the

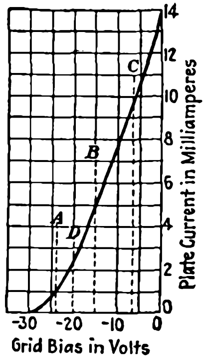


Fig. 379.—Characteristics of typical amplifier tube.

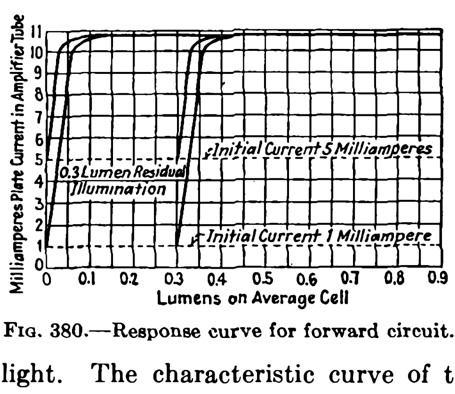


Fig. 380.—Response curve for forward circuit.

amount of light. The characteristic curve of the amplifier tube shown in Fig. 379 explains this relation, except at the extremes of the grid-bias voltage. The amplifier should, therefore, be operated on the straight part of its characteristic curve and a grid resistance should be used which has a resistance that does not change appreciably with a change of voltage.

In Fig. 380 is shown the *characteristic curve* of the circuit in Fig. 378 plotted with plate current of the amplifier tube as a function of units of light intensity (lumens) on the phototube for various initial current settings and illuminations. It will be noted that a point is reached as the illumination is increased at which the plate current seemingly saturates. As the point of zero grid current is passed in the positive direction, the current begins to flow from the circuit of the phototube to supply the positive grid current. A point is finally reached at which the increase in current passing through the phototube supplies the grid with current without an appreciable change in the plate current.

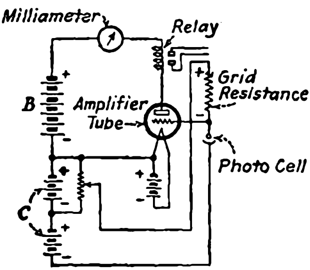


FIG. 381.—Typical direct-current reverse circuit.

A typical *reverse* circuit is shown in Fig. 381 for operation with batteries, although, as already explained for the forward circuit, a transformer can frequently be used for the filament supply. The operation of this circuit is only slightly different from the operation of the forward circuit. When the phototube is dark, the grid-bias voltage is obtained in the same manner as before, although less "bias" voltage is used to produce a current as indicated by the point C in Fig. 379. When the phototube is illuminated, a current flows from the midpoint of the potentiometer through the grid resistance,

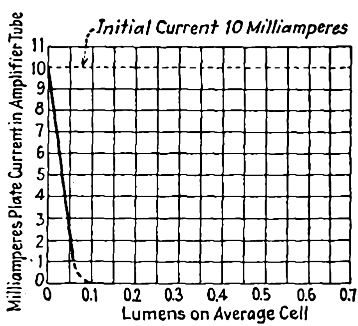


FIG. 382.—Response curve of reverse circuit.

the phototube, and back to the negative terminal of the battery. The grid resistance will then have a voltage drop over it tending to make the grid more negative. The grid thus receives a higher negative potential, as at the point *D* in Fig. 379. In Fig. 382 is shown the characteristic curve of the circuit in Fig. 381, plotted with the plate current of the amplifier tube as a function of the lumens (page 462) on the phototube. The plate current cannot be less than zero and, as is shown in Fig. 379, decreases to zero as the negative grid-bias voltage is increased.

Speed of Operation.—The speed of operation of the *phototube and an amplifier tube* in combination depends entirely on the size of the grid resistance in the circuit of the amplifier tube, since, individually, the amplifier tube and the phototube will respond to radio frequencies. The grid resistance and input capacity of the amplifier tube have a *time constant* depending on the input capacity of the particular tube and circuit, and the grid resistance. The actual time delay may be about 0.001 second for an average circuit.

Single-stage Alternating-current Amplifiers for Phototubes. The vacuum-tube amplifier when used with alternating current is suitable for any relaying, indicating, or recording application in which sufficient sensitivity is obtained with its use. A factor to be remembered, however, is that the output of this circuit is *pulsating* direct current. Consequently, extremely rapid variations in light (short compared with one-half cycle) will not be faithfully amplified. This circuit is used in *smoke-recording devices* with a view to obtain a very simple design.

Figure 383 shows a typical forward circuit of this type. Obviously, this circuit is similar to the circuit shown in Fig. 378. It is possible to operate the amplifier tube and the phototube directly on alternating current, because both the amplifier tube and the phototube are half-wave *rectifiers*. The amplifier tube is operated so that when the alternating-current wave is such that the plate is positive, the grid is negative with respect to the filament. When the voltage is on the other half of the cycle, no current is passed, owing to rectification, and it is immaterial what happens in the grid circuit, as long as desirable conditions of control and of grid-bias voltage are obtained on the positive half of the cycle. During the part

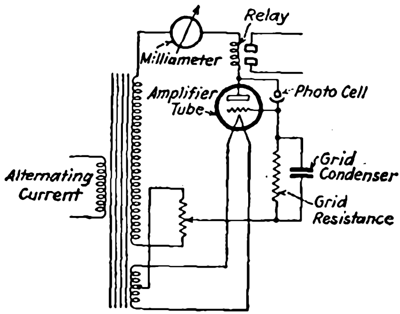


Fig. 383.—Alternating-current circuit of photoelectric tube and amplifier.

of the cycle in which the amplifier is capable of passing current, the phototube also passes current creating a voltage drop over the grid resistance in a manner similar to that in a direct-current circuit. The grid condenser serves the purpose of reducing the grid-bias voltage required to reduce the plate

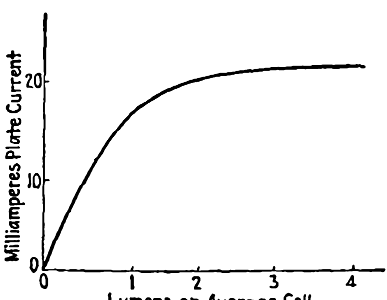


Fig. 384.—Response curve of circuit in Fig. 383.

current to a given value when the phototube is dark. Without the grid condenser, the effective negative grid voltage is thrown out of phase with the plate voltage at high grid resistances, thus rendering the grid control ineffective. The out-of-phase condition, obtained when the grid condenser is absent, is caused by the input capacity of the tube acting in combination with the high grid resistance. The grid condenser brings the effective negative grid voltage into phase with the plate voltage, thus assuring the most effective use of the grid-bias voltage. The importance of the grid condenser is due to the fact that the "dark" current of the amplifier is unaffected if the grid resistance changes in service and lower grid-bias voltages are required. In Fig. 384 is shown the characteristic curve of the circuit in Fig. 383. This characteristic curve is similar to the one shown in Fig. 380 for the direct-current forward circuit except that less sensitivity to changes in illumination is obtained.

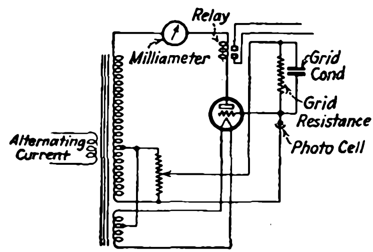


Fig. 385.—Reverse circuit for alternating-current operation

A typical reverse circuit of this type is shown in Fig. 385. In theory of operation, it is similar to the ones in Figs. 381 and 383. It is similar to Fig. 381 since it is a reverse circuit, and similar to Fig. 383, since the circuit is for alternating-current operation. In Fig. 386 is shown the characteristic curve of the circuit in Fig. 385, with the output current plotted as a function of the illumination on the phototube. It will be noted that this circuit is somewhat more sensitive than the one in Fig. 382.

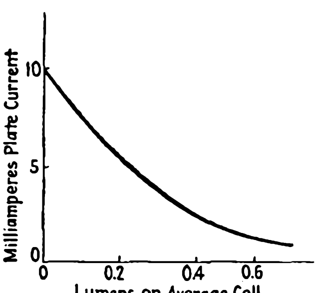


Fig. 386.—Response curve of circuit in Fig. 385.

Series Connection of Phototubes.—Figure 387 shows a circuit identical with that of Fig. 378, except that a group of phototubes have been connected in series in place of the single phototube. This circuit is valuable in applications requiring the *scanning of reflecting surfaces* for dark spots. When one phototube is darkened, the result is the same as when darkening all the phototubes. This makes it possible to detect smaller spots than would be possible with a single large phototube, unless a complicated mechanical scanning device is used.

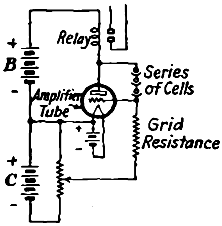


FIG. 387.—Photoelectric tubes in series.

Types of Multi-stage Amplifiers for Phototubes.—There are three general types of multi-stage amplifiers for phototubes. These three general types can, however, be modified in a number of ways for special services. All the amplifiers used in connection with phototubes belong to one of the types now in use, these being: (1) resistance-coupled amplifiers, (2) condenser-coupled amplifiers, and (3) transformer-coupled amplifiers.

Resistance-coupled Amplifiers for Phototubes.—A typical circuit in which the amplifier is connected by the method of resistance coupling is shown in Fig. 388. According to the arrangement of this circuit, when the phototube is not illuminated, the first stage has a negative grid-bias voltage, meaning that the grid is negative with respect to the filament by an amount determined by the setting of the potentiometer *P*. The amount of grid-bias voltage or the negative charge on the grid will determine the amount of current flowing through the plate circuit of the amplifying tube. This flow of plate current will result in a voltage drop over the plate resistance *R* in the direction indicated by the algebraic signs. The grid-bias voltage in the second stage will then be the difference between the voltage drop over the resistance *R* and the battery voltage between *A* and the negative terminal

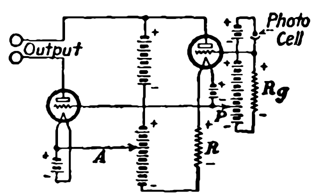


FIG. 388.—Resistance-coupled amplifier including photoelectric tube.

of the battery, with the voltage over the resistance R always smaller than the battery voltage. The second-stage plate current or output of the amplifier will then be determined by this grid-bias voltage.

If a small amount of light falls on the phototube, a current will flow from the positive terminal of the battery through the phototube, and then through the grid resistance to the negative terminal of the battery. As a result of the current flow in the direction indicated, a voltage drop will occur across the resistance R_g, with the polarity as shown by the plus and minus signs. This voltage drop will make the grid of the first tube of the amplifier more positive; and as a result more current will flow in the plate circuit and through the resistance R. The increased current flow through this resistance will increase the voltage drop over its length and make the grid of the second amplifying tube more positive, with a resulting higher output from the second stage of amplification.

This amplifier is most useful where it is absolutely essential to obtain the amplification of "pure" direct current. The number of stages which can be added to this circuit is limited, because, as successive stages are added, small variations in the first-stage tube characteristics are reproduced in increasing effect through the amplifier.

Condenser-coupled Amplifiers for Phototubes.—The condenser-coupled amplifier circuit shown in Fig. 389 is particularly valuable when amplification of very low frequencies is necessary. It is possible to adjust the circuit constants so that frequencies as low as two or three cycles per second can be correctly amplified. This circuit is similar to that in Fig. 388, except that a condenser is used to prevent the effect of the direct-current flow in any stage on the grid of the next succeeding stage. As a result, only impulses above a certain frequency are accurately transmitted to the grid of successive stages. This amplifier is much more stable than the one shown in Fig. 388 for the reason that small changes in the vacuum tubes and other minor variations are not transmitted through the amplifier unless they are of considerable frequency. The voltage amplification of a circuit of this type is from 4 to 100 per stage, depending largely on the amplifier used. The higher figure is for a screen-grid tube (page 119), in which case the circuit shown should be modified somewhat to suit the tube.

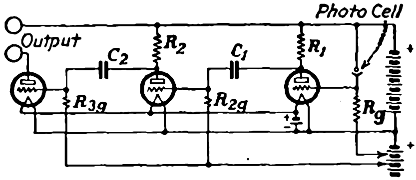


FIG. 389.—Condenser-coupled amplifier including photoelectric tube.

Transformer-coupled Amplifiers for Phototubes.—The transformer-coupled amplifier circuit shown in Fig. 390, does not differ greatly from that in Fig. 389, since a transformer is used to block the plate voltage of one stage from affecting the grid voltage of successive stages. Unlike the circuits in Figs. 388 and 389, however, the successive stages are insulated from each other instead of using a conducting

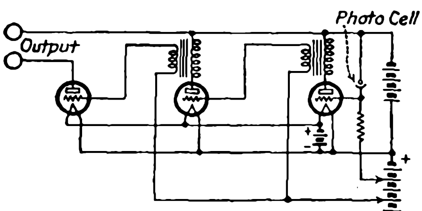


FIG. 390.—Transformer-coupled amplifier including photoelectric tube.

medium between the plate circuit of one tube and the grid circuit of the following tube. The voltage amplification of this type of amplifier is from 20 to 200 per stage, depending on the amplifier used. The higher figure is for a screen-grid tube.

Many special forms of this type of amplifier can be designed. For instance, an amplifier can be designed to respond only to certain predetermined bands of frequencies such as from

800 to 1,200 cycles per second. With a proper design, amplifiers can be built to give essentially constant amplification over the range from 20 to 10,000 cycles per second. This limit can be extended still further by careful designing.

Grid-glow-tube Amplifiers for Phototubes.—A gaseous tube such as the grid-glow tube may be used to amplify the output current of a phototube. In the grid-glow tube no anode-cathode current can flow if the grid is sufficiently negative with respect to the anode. Thus the tube can serve as a sensitive relay controlled by the phototube. The advantages of this combination are that it is simple, inexpensive,

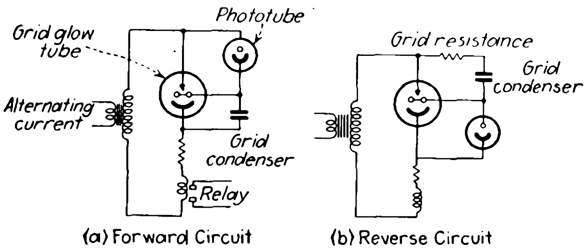


FIG. 391.—Forward and reverse circuits for operation of grid-glow-tube amplifier including photoelectric tube.

and well adapted for applications in which the light change is relatively large and sudden, as in counting, relaying, and various kinds of automatic control.

Either the forward or the reverse circuit can be used, but both must have a current-limiting device in the anode-cathode circuit to prevent arc formation. The *vacuum* type of phototube is used because the voltage developed by the gas-filled phototube is high enough to cause damage by producing a glow discharge in the phototube.

Forward and reverse circuits for operation on alternating current are illustrated in Fig. 391. Within certain limits the output current is proportional to illumination, as in the vacuum tube and phototube circuits. The combination of phototube and condenser acts as an impedance potentiometer. The voltage on the grid depends on the illumination on the phototube because the effective resistance of the phototube varies with illumination. The sensitivity is proportional to the sensitivity of the phototube, and inversely proportional to the capacity of the grid condenser and to the current-limiting resistance. The sensitivity can be controlled by changing the circuit constants. The output current reaches a saturation value as the illumination increases. The maximum current should be less than the current capacity of the tube. The point of saturation is determined by the anode-cathode voltage and the current-limiting resistance. In the operation of this device the alternating voltage, the current-limiting resistance, and the grid-condenser capacity are fixed, while the illumination is varied.

The reverse circuit operated with alternating current has a discontinuous characteristic; that is, as the light varies, a point is reached at which there is either a definite current or no current, for a very small light change. The output current is not proportional to the light on the phototube. The sensitivity of this circuit is proportional to the sensitivity of the phototube and inversely proportional to the capacity of the grid condenser. In the reverse circuit the potentiometer controlled by the phototube is reversed as compared with the forward circuit in order to obtain an opposite form of control.

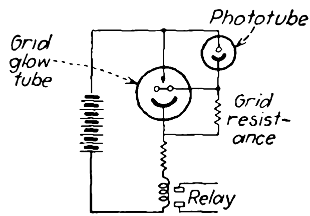


FIG. 392.—Forward circuit for operation of grid-glow-tube amplifier with direct current.

With alternating-current operation, the speed of these combinations is limited only by the time required for the voltage to reach the proper half of the cycle. A relay used in the circuit will close in a few cycles after it has been energized.

The forward circuit for operation with direct current is shown in Fig. 392. On direct current the action of the grid-glow tube is not reversible. The anode-cathode voltage must be reduced to a value less than the cut-off voltage to stop the current flow, even if the illumination is restored to the value existing before breakdown. This "lock-in" effect may be utilized in the detection of transients of very short duration in the light. A relay then is allowed enough time to operate at a reasonable speed. The reversed circuit differs only in that the phototube and the grid resistance are interchanged.

NOISE IN VACUUM TUBES AND CIRCUITS

Development in radio communication, television, and industrial applications which depends on the amplification of very small voltages is limited by the noises originating in the tubes used for amplification and in their associated circuits. The noises which can be controlled easily are those caused by microphonic action; by vibration of the radio receiver, by imperfect connections of wires and tube-pin contacts, and by poor power supply due to deteriorated batteries or to a power unit with inadequate filtering action. There are, however, other noises which though small may actually determine the natural minimum noise level. Of these the more important ones are those produced by thermal agitation, by shot effect (page 170), and by positive ions. Noises of lesser degree are produced by the effect of secondary electron emission, by photoelectric effect, by the insulator of heater cathodes, by electric leakage through or over the insulation between electrodes, and by the effect of static electricity which may collect on the glass surface of the bulb. The effects of atmospheric static and man-made static are not considered here.

The amplitude of noise voltage may be constant, but usually its frequency is variable and dependent on the frequency characteristics of the receiving apparatus. The value of total *noise voltage* across a 0.25-megohm resistance may be as high as 100 microvolts.

Thermal Agitation.—The electric charges, as well as the atoms, in a wire or other conductor of electricity, are in a state of thermal agitation. This movement of charges in a part of a circuit affects the voltage across that part, and is present even though the wire does not carry a current. The noise produced by such a voltage change varies directly with resistance, temperature, and the width of the frequency band; but does not depend on the kind of material or the shape of the wire. The calculated[1] thermal noise voltage is 9.03 microvolts (r.m.s.) for a resistance of 0.5 megohm at a temperature of 80°F. measured with an amplifier having a band width of 10,000 cycles per second. Noise of this magnitude in the grid-resistance unit of an amplifier can prevent the satisfactory reception of a *signal voltage* of less than 100 microvolts. This effect in the tuned input circuit connected to the grid of a vacuum tube is amplified and produces a hissing noise. If the input impedance is high the noise may be greater than that caused by thermal agitation in the output circuit. The noise produced in the output circuit is of importance only when the input impedance is low; in this special case the plate noise can be reduced if the tube is designed for saturation at a low temperature of the filament.

In the ordinary circuit with a well-designed tube practically all the noise due to thermal agitation comes from the high-impedance circuit on the grid side of the tube.

Shot Effect.—Noise caused by *shot effect* is due to irregularities in the flow of electrons from the filament to the plate. Investigation of this effect shows[2] that when the filament current is increased from zero to a value corresponding to temperature saturation, the noise increases sharply to a point where the space charge becomes effective and then

[1] From Application Note No. 25, August 1934, R.C.A. Radiotron Company, Inc. If it is assumed for simplicity that resistance is constant with frequency and that the frequency characteristic is constant over a band of width W_f, then the root-mean-square (r.m.s.) value of the noise voltage is $E^2 = 5.49 \times 10^{-23} TRW_f$, where T = absolute temperature of the condenser (273 + °C.), R = the resistance portion of the impedance, and W_f = the frequency band width factor (cycles per second).

A bibliography of 42 references is given in an article on "Limits to Amplification," by J. B. Johnson and F. B. Llewellyn, *Elec. Eng.*, November, 1934.

[2] Llewellyn, "A Study of Noise in Vacuum Tubes and Attached Circuits," *Proc. Inst. Radio Eng.*, February, 1930.

falls to a value which is practically unaffected by the current in the filament. At the same time that the space charge comes into play and causes a reduction of noise, the resistance of the tube begins to decrease and also causes a reduction of noise. At the point of temperature saturation a further increase in filament temperature does not increase the number of electrons reaching the plate. At that point, then, the shot effect is reduced to zero. As a result of these relations it is stated that the filament of a vacuum tube should be capable of operation at the point of temperature saturation. Under the conditions stated in the preceding paragraph, and a plate current of 4 milliamperes, the theoretical value[1] for shot effect with space charge is 890 microvolts.

Flicker Effect.—This term is applied to the abnormally high values of shot effect which occur at low frequencies. This behavior is said to result from changes in the degree of activation of the emitting surface of the cathode. In oxide-coated cathodes the flicker effect becomes noticeable at a frequency of the order of several thousand cycles per second, increasing as the frequency decreases. In tungsten filaments the flicker effect occurs at a few hundred cycles per second, increasing as the frequency decreases. Flicker effect, like shot effect, is smoothed out by the space charge. By suitable design the fluctuation noise, as caused by shot and flicker effects in the space current, can be made negligible.

Ionization and Secondary Emission Effects.—Positive ions coming from electron bombardment of the gas particles, from the filament, or from thermal ionization of gas particles at the heated surface of the filament, are not drawn to the plate but pass into the space-charge region. The effect of such disturbances may be considerable because a small change in

[1] The theoretical value for shot effect *without space charge* is

$$E^2 = 3.18 \times 10^{-19} I Z^2 W_f,$$

where E^2 is the mean-square shot voltage, I the electron current, Z the resonance impedance of the tuned circuit, and W_f the frequency band-width factor. *With a space charge,* as obtained at normal filament voltage, the shot voltage is reduced to half the values given by this equation.

the space-charge region produces a much greater change in the space current. The relative importance of these sources of positive ions depends on the degree of vacuum in the tube, on the electrode voltages and spacing, and on the temperature of the filament. The noise caused by these effects under exceptional conditions such as when plate resistance is quite high and gas pressure is above normal may amount to a fraction of the thermal noise but under ordinary conditions is assumed to be negligible.

Photoelectric Emission.—A source of noise which may require consideration is that of electrons emitted from the plate or the grid because of the effect of light. No definite values for this action have been demonstrated but its presence may be viewed in terms of the experiment described on page 218 which gives a measure of the photoelectric response of certain radio receiving tubes.

Leakage and Collected Charges.—A leakage of current may take place through or over the glass seal and through the insulator of a cathode heater. A flow of current in the glass seal may be observed by measurement between the tube electrodes. A leakage current through the cathode-heater insulator may be detected by observing the noise effect of a voltage applied between the heater and the cathode.

Charges which collect on the glass surfaces until a sufficient voltage is built up to cause discharge may be considered as a source of noise, although no measurable effects have been observed.

Experimental Results.—A study of an actual tube circuit gave the results shown[1] in Figure 393. In this figure the sketch *a* represents the total noise energy from an ideal tube, with no positive ions and no secondary emission, plotted against the power required for heating the filament. Sketch *b* represents the noise energy from the shot effect only, and sketch *c* represents the noise energy from thermal agitation only.

[1] LLEWELLYN, *Proc. Inst. Radio Eng.*, February, 1930.

A description of the relation between noise and filament current has already been given. The curve for the shot effect shows a rise proportional to the space current with a dropping-off at the point *A* where the space charge becomes effective, and a reduction to zero at the point *B* when the full space-charge condition is attained. Two other factors must be considered in connection with the noise caused by shot effect: (1) plate resistance of the tube, and (2) filament temperature. A reduction in plate resistance reduces the plate-to-filament impedance and thus tends to reduce the noise, while an increasing filament temperature also increases the effective temperature of the plate resistance and thus tends to increase the noise. The thermal agitation curve is taken with a cold filament at the start and, at that point, shows the noise due to the resistance portion of the external circuit impedance. The noise increases as the filament gets hotter. At first the increase in temperature of the plate resistance is stronger than the decreasing plate resistance, but later the decreasing plate resistance becomes more effective in reducing the noise. It was found also that noise caused by ions was increased as the grid-bias voltage was made more and more negative. The tests for gas, that is, the effect of ionization by direct collision, showed a negligible amount of noise from this cause in high-vacuum tubes.

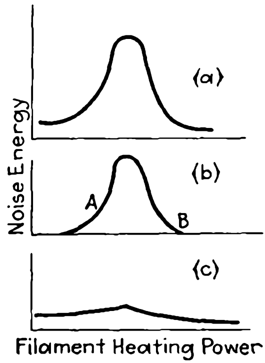


FIG. 393.—Experimental results showing relation of noise energy to filament heating power.

Screen-grid tubes in general showed a rather high noise level due to poor temperature saturation of the filament, and to high plate impedance. The high amplification, however, gives a ratio of signal to noise which is about equal to that of other tubes with the same filament-temperature saturation.

Relation between Noise and Signal Voltages.—The diagram in Fig. 394 may be used to represent a radio receiver for the purposes of this description. Only the noise voltage which originates in the grid circuit or in the plate circuit of the first tube requires consideration. In the case in which the gain (page 151) in these circuits is very low, the second tube also may be responsible for noise production. This noise, existing as a series of pulses, excites a circuit at that range of frequencies to which the circuit responds. From this circuit the noise is passed on to succeeding stages. In the converter

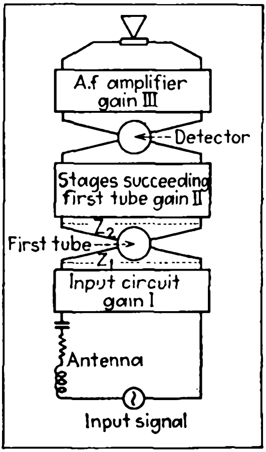


FIG. 394.—Diagrammatic representation of typical radio receiver.

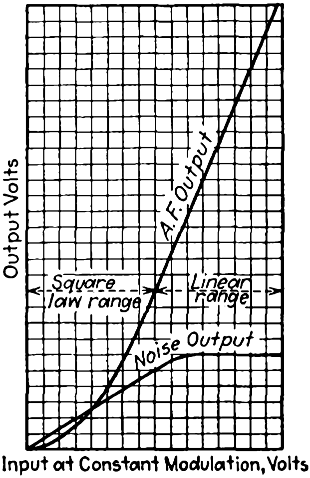


FIG. 395.—Relation of audio-frequency output voltage to applied signal input voltage at constant modulation.

the noise-signal voltage is changed, just as any other signal voltage is changed, to the intermediate-frequency level. Consequently the noise exists in the input to the detector, and in the audio-frequency output; but the noise in the output may not be audible until sufficient carrier voltage is supplied to the detector. In an experiment[1] to determine the relative noise in a group of receivers for radio broadcasting, adjusted to a common sensitivity, there was a noise variation of from one to nearly 6, in arbitrary units.

[1] BALLANTINE, "Fluctuation Noise in Receivers," *Proc. Inst. Radio Eng.*, August, 1930.

The relation between the audio-frequency output voltage and the applied signal voltage is shown in Fig. 395. The output voltage is proportional at first to the square of the input voltage, and at larger inputs it is directly proportional. This relation holds for diode detectors as well as for other types, but the range of the "square-law" region varies with different types. Thus, in the case of a diode detector which is operated with a large input voltage, the square-law region may be very small.

Signal-to-Noise Ratio of Receiver.—The method[1] for estimating the signal-to-noise ratio of a radio receiver, as developed in the Bell Telephone Laboratories, is based on the assumption that there is a definite low limit of noise and that the best possible signal-to-noise ratio bears a certain relation to this limit.

In a receiving system a thermal-noise voltage produced in the input circuit of the first tube is impressed on the grid. If the noise produced in the other parts and circuits of the receiver disappears when the input circuit is detuned or short-circuited, then the signal-to-noise ratio of that receiver cannot be improved with the given input circuit. Further, if the amplification of the receiver is increased the noise will increase directly with increases of the signal voltage. Noise produced at points other than in the input circuit of the first tube; for example, the noise produced by thermal agitation (page 471) in the plate circuit of that tube, increases the noise level but not the signal voltage. Under this condition the signal-to-noise ratio is decreased. If the amplification obtained in the first stage is sufficient to raise the noise level to a value considerably above that of noise produced in other parts of the stage, then the signal-to-noise ratio of the receiver, for a given strength of signal field, is fixed by the signal-to-noise ratio of the input circuit.

The signal-to-noise ratio of two receivers can be compared by comparing the relative increase in noise caused by tuning

[1] LLEWELLYN, *Proc. Inst. Radio Eng.*, March, 1931.

the input circuits of the receivers through the point of resonance. The ratio for each receiver may be stated as a fraction having for a numerator the noise output of the receiver when the input circuit is tuned to resonance, and for a denominator the noise output when the input circuit is detuned. For all practical purposes such a comparison is allowable because the effect on the signal-to-noise ratio caused by variations in the form of the input circuit is small, and is less than the effect caused by variations in other parts of the receiver. If the receiver amplification is not high enough to allow the measurement or observation of noise when a carrier-signal voltage is not available a local oscillator having the *carrier frequency* may be used to produce the necessary voltage. This oscillator-signal voltage combines with the noise-signal voltage in the detector and produces a resultant current strong enough for measurement.

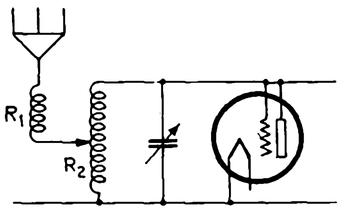


FIG. 396.—Circuit for study of signal-to-noise ratio of receiver.

An elementary analysis of the signal-to-noise ratio for a simple circuit in which the antenna is coupled directly into a tuned circuit can be made. The circuit arrangement is shown in Fig. 396 in which R_1 is the radiation resistance of the antenna, and R_2 is the *anti-resonant* resistance of that portion of the tuned circuit across which the antenna is tapped. The effective root-mean-square (r.m.s.) value of the noise voltage produced in the input circuit by thermal agitation is proportional to the resistance component of the impedance between the grid and the filament; that is, the mean noise voltage N is proportional to the square root of the resistance of R_1 and R_2 in parallel. The mean voltage V is equal to $ER_2 \div (R_1 + R_2)$ where E is the effective signal voltage in the antenna, E being proportional to the effective height of the antenna and thus also to the square root of R_1. From these relations it is seen that the ratio $V^2 \div N^2$ is proportional to $R_2 \div (R_1 + R_2)$.

The ratio of the mean voltage V to the mean noise voltage N improves as the resistance R_2 is increased by moving the antenna tap nearer to the top of the anti-resonant circuit. The fact that there is a limit to the allowable increase in the resistance R_2 is shown by taking the extreme position at the top of the circuit. The difficulty then is that the impedance of the input circuit, viewed from the grid of the tube, is low, and that an impossibly high amplification would be needed to bring the noise level above that in the plate circuit. In other words, the improvement in the ratio obtained in the input circuit would be offset by the noise added in the plate circuit. Under the usual conditions of operation the adjustment of the input circuit is such that the antenna impedance and the input impedance are matched, and the resistance R_1 is equal to the resistance R_2. The signal-to-noise ratio then is decreased about 3 decibels (page 421) below the maximum value given here.

If the resistance R_2 is reduced further by moving the antenna tap, the resistance as viewed from the grid is increased, the signal voltage is decreased and the noise is increased. Apparently the best condition for signal strength as obtained when the impedances are matched is also the most practical for operation with regard to signal-to-noise energy ratio. Under this condition the signal-to-noise energy ratio on the grid of the first tube is equal to one half of the best ratio that it is possible to obtain under any conditions.

Effect of Circuit Constants on Noise.—This relation can be studied by short-circuiting the input to the first tube of a receiver as represented in Fig. 394 so that only the noise produced in the plate circuit is amplified. Then the noise input voltage to the detector may be varied by adjusting that portion of the receiver which produces gain II. The effect of changing the impedance of the plate load Z_2 of the first tube is the same as the effect of changing gain II. In this case both the noise and the signal are affected equally.

The human ear being most sensitive to high frequencies, an *apparent* reduction in noise is obtained when the width of the frequency band in either the intermediate-frequency or the audio-frequency stages is lessened. This has the effect, however, of reducing also the higher frequencies of the signal. If the noise input voltage to the detector is low enough so that the action of the detector becomes linear before the noise voltage reaches the audible level (about 0.1 volt across a resistance of 4,000 ohms), an increase in signal voltage will not produce audible noise. In a consideration of the relative effects of thermal agitation voltage and of shot voltage on output noise the tube amplification must be included. When the amplification in the first tube is large, the noise voltage produced in the plate circuit is negligible compared with that produced in the grid circuit. When the gain in the input circuit (gain I) is large the signal is increased with respect to the noise at the first grid.

Influence of Tubes and Operating Voltages.—Theoretically the shot voltage varies in proportion to the square root of the plate current. The noise voltage produced in the plate circuit varies in proportion to the square root of the plate current, but is affected only slightly by changes in plate, screen-grid and grid-bias voltages, or by the presence or absence of oscillator-input voltage.

High gain (page 151) in the first tube gives low output noise for any receiver sensitivity. For example, in a superheterodyne receiver, a first detector tube gives less gain for the same plate current than an amplifier tube. Hence, for a given sensitivity, a receiving set which uses a first detector in the first tube position will have more noise than a similar set which uses an amplifier. When gain is controlled in the first tube, the gain decreases faster than the square root of the plate current. That is, noise and gain are both decreased, but the gain is decreased more than the noise is decreased. It would be advantageous then, as regards noise, to secure this decrease in gain in the succeeding stages. If the first tube can be operated at a fixed grid-bias voltage with small signal input, the lowest noise will be obtained by choosing a tube with high gain and low plate current, and by operating this tube at the highest permissible value of plate current. Operating with high plate current increases the gain more than it increases the noise. It is assumed that the plate resistance is not reduced enough to affect the results.

Similarly, if two or more tubes are operated in parallel and the plate resistance remains high enough to be negligible, the gain will be increased n times, where n equals the number of tubes in parallel. The plate current is increased n times, also, and the noise is increased by the square root of n. The noise, for the same overall sensitivity, is thus reduced by a factor of 1 over the square root of n.

Tube Design for Noise Reduction.—Not many tubes commercially available can be said to possess low-noise characteristics, but worthwhile progress has been made in this direction. The FP-54 type, a low-current amplifier tube developed by the General Electric Company, has a grid construction that is intended to eliminate or greatly reduce microphonic currents. This tube, however, having an amplification factor of 1, is not intended for voltage amplification. The PJ-11 type, a voltage-amplifier tube developed by the same company, has an amplification factor of 40 and is similar to the RCA 240. This tube also is designed to reduce the effects of microphonic action, leakage currents, and ionization.

CHAPTER XI

USE OF VACUUM TUBES AS OSCILLATION GENERATORS

Explanation of Action as an Oscillator.—The three-element vacuum tube, connected in a suitable circuit, may be used as an oscillator to establish and maintain an alternating current of constant frequency. The constants of the circuits may be designed to cover a frequency range of from one cycle per second to about 3,000 megacycles (millions of cycles) per second. The usual detector or amplifier tube may be used as an oscillator but for large outputs of power a tube specially designed for such use and called an *oscillator* is necessary.

The operation of simple radio-transmitting sets as well as that of heterodyne receiving sets depends on this action. In laboratory and industrial work the vacuum tube oscillator finds application as a source of pure alternating current of constant amplitude. The production of such an alternating current depends on the control which the grid voltage exerts on the plate current; that is, a small amount of energy applied to the grid controls a large output from the plate circuit. Several mechanical illustrations of this action may be given. Thus, a steam hammer is controlled by applying a very small force to the steam valve through an operating handle. The steam valve allows the boiler pressure to act. The action may be made automatic by an arrangement which moves the valve when the hammer reaches the end of its stroke. Here, a portion of the power in the controlled circuit is put back into the controlling circuit to maintain the action. In the case of the vacuum tube, the grid corresponds to the steam valve and the plate supply voltage corresponds to the steam pressure.

Another mechanical illustration is that of the action of a clock. As the pendulum swings it operates the escapement which permits the main spring to deliver a push to the pendulum during each swing in such a direction as to increase the extent or amplitude of the swing. When the friction of oscillation becomes equal to the impulse given by the spring, the amplitude of oscillation will stop increasing and remain constant. In the case of the vacuum tube, the grid corresponds to the clock escapement, the source of plate power supply corresponds to the main spring, and the current in the oscillating circuit, which is connected to the plate of the tube, corresponds to the pendulum. The current in the oscillating circuit reacts on the grid so as to change the value of the voltage across the grid circuit. This change in grid voltage produces a change in the plate supply current, which, in turn, acts upon the oscillating circuit so as to increase the oscillating current. This action continues until a balance is reached between the losses due to radiation and heat, and the power supplied by the tube. Beyond this point, the amplitude of the oscillating current remains constant in value.

Simple Oscillator.—If a certain portion of every oscillation produced in the plate circuit is put back into the grid circuit in the correct time relation, the pulsating-current wave generated in the plate circuit will be continuous.

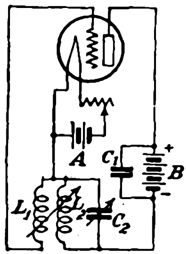


FIG. 397.—Simple oscillator for producing alternating current.

A simple arrangement for producing an alternating current by the use of a vacuum tube is shown in Fig. 397. The inductance coil L_2 and the condenser C_2 have values such that their natural period of vibration corresponds to the desired frequency. The inductance, or the capacity, or both, may be variable if it is desired to change the frequency (wave length) of the current. The inductance coil L_1 which is coupled (page 56) to the coil L_2 receives some energy from the oscillating circuit L_2C_2. The coupled coils L_1 and L_2

must be connected in such a manner that the oscillations in the grid circuit *assist* those in the plate circuit. The degree of coupling must be such that the small amount of energy transferred to the grid circuit will, when amplified, maintain the variations of current and cause the plate oscillations to be continuous. The first electrical disturbance in the oscillating circuit might be caused by a movement of electrons in the tube as a result of a change in the capacity of the circuit, or because of the flow of a small current when the "A" or the "B" current supply circuit is closed. These weak oscillations in the oscillating circuit will induce an alternating voltage in the coil L_1 which acts upon the *grid* and produces variations in the *plate* current flowing through the oscillating circuit. If the coupling between the coils is correctly adjusted, the original oscillations are reinforced. Although the amplitude of the current during the first cycle may be small, the additive effect of the feed-back action increases the amplitude of each successive wave. This increase continues until the energy generated is just sufficient to maintain a current of a certain strength. Beyond this point a pure unvarying wave of alternating current is produced in coil L_1 or any other coil in a circuit coupled to the plate circuit. Usually, the constant state is reached in a very small part of a second after operation of the tube is started. The frequency of the alternating current then flowing in the circuit is very nearly that of the natural period of the oscillating circuit. The operation of the tube is quite like that of a *regenerative amplifier* (page 149), because the tube actually amplifies the small amount of energy transferred from the plate circuit to the grid circuit.

A current in the plate circuit sets up in the L_2C_2 circuit, a voltage which is 90 degrees out of phase with the plate current, provided that the resistance of the L_2C_2 circuit is very small. The oscillating current in the L_2C_2 circuit is in phase with the voltage in this circuit because the L_2C_2 circuit may be considered as non-reactive at the frequency of oscillation. This oscillating current induces in the *grid* coil L_1 a voltage which is

90 degrees out of phase with the oscillating current. That is, the plate circuit reacts upon the grid circuit in such a way that the induced grid voltage is in phase with the plate current.

Detection of Oscillating Condition.—The most accurate and absolute test to determine when a tube is oscillating is to use a sensitive radio-type alternating-current ammeter in the oscillating circuit. The meter will show a reading when the oscillating current is established.

Typical Oscillator Circuits.—There is a great variety of circuits in which the plate circuit is coupled back to the grid circuit in such a manner as to supply a small amount of power

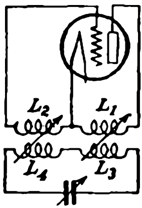


Fig. 398.—Meissner oscillating circuit.

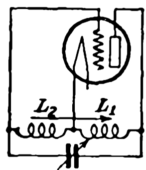


Fig. 399.—Hartley oscillating circuit.

to the grid and make the surplus available for use in an external circuit in the form of continuous oscillations.

This *feed-back action* can be obtained by the use of (1) direct coupling from the plate back to the grid circuit, (2) by inductive coupling, or (3) by electrostatic coupling. The main requirement for continuous oscillations is that the voltage induced in the grid circuit must produce variations in the amplitude of the plate current which are sufficient to maintain the voltage in the grid circuit.

A number of the usual arrangements are shown in Figs. 398 to 402. In Fig. 399 the coils L_1 and L_2 may be coupled together if desired, and in Fig. 400 such coupling is usually necessary in order that the voltage applied from the plate circuit may maintain the oscillations. In Fig. 401 the coupling is necessary in order to obtain the control of the grid voltage because the coil L_2 is not in the oscillating circuit. A reversal of the coil connections in these circuits (except the "Colpitts," Fig. 402) usually will change the phase relations.

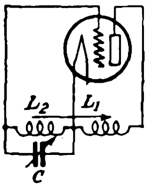


FIG. 400.—Tuned-grid oscillating circuit.

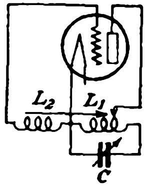


FIG. 401.—Tuned-plate oscillating circuit.

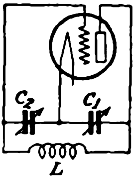


FIG. 402.—Colpitts oscillating circuit.

Conception of Negative Resistance.—In an ordinary oscillating circuit, the circuit resistance in ohms is proportional to the rate of energy consumption in the circuit. In an oscillating circuit used with a vacuum tube as described above, the tube through its operation feeds back energy to the circuit. The rate of such feed-back may be considered as a *negative* resistance which tends to neutralize the ohmic resistance of the oscillating circuit. If this negative resistance is less than the ohmic resistance of the oscillating circuit, the oscillations are damped. The extent of this damping, however, is less than if no negative resistance was introduced. If the negative resistance is equal to the ohmic resistance, the oscillations are maintained indefinitely once the process is started. If the negative resistance is greater than the ohmic resistance, the circuit will start oscillating of itself. The amplitude of oscillations will increase until the capacity of the circuit to supply energy is reached.

Requirements for Oscillations.—Some of the general conditions for oscillation have been stated. In order to examine the requirements more in detail, it is necessary to consider the character of the plate current and the influence of the constants of the circuit.

The varying plate current may be taken to consist of two parts, a direct current and an alternating current. It is this alternating current in the oscillating circuit which gives rise to the voltage acting on the grid and maintaining the oscillations.

In order to bring this about, the alternating plate current and the grid voltage must be in phase. That is, when the alternating plate current reaches its maximum positive value, for example, the total value of plate current is high and the oscillating current must act through the grid coupling in such a manner that the grid voltage is at a positive maximum. If the voltage applied to the grid produces, by means of feed-back, an equal or greater voltage on the grid, the tube will oscillate.

A determination of the effect of the circuit and tube constants upon the requirements for oscillation may be made in a simple manner. A circuit such as that of Fig. 400 may be used with the assumption that the oscillations are small in value, that the impedance of L_1 is small compared to the tube resistance r_p, and that the characteristic curve is a straight line. The alternating plate current then is

$$I_p = \frac{uE_g}{r_p}$$

where E_g is the alternating voltage applied to the grid and u is the amplification factor. The voltage induced in the grid circuit by means of the mutual inductance M depends upon this plate current I_p and is equal to $I_p wM$ or, by substitution, $uE_g wM \div r_p$, where w is equal to $6.28f$ ($2\pi \times$ frequency). This voltage causes a current to flow through the resistance R of the tuned-grid circuit equal to $uE_g wM \div Rr_p$. This feed-back current multiplied by wL_2 or by $1 \div wC$ gives the value of the voltage E_g' impressed on the grid through the feed-back action. That is, $E_g' = uE_g M \div Rr_p C$. The tube will oscillate if E_g' is equal to or greater than E_g. Since

$$\frac{E_g'}{E_g} = \frac{uM}{Rr_p C}$$

the condition for oscillation is given by the statement that $uM \div Rr_p C$ must be equal to or greater than 1. That is, the tendency for the generation of oscillations is increased by increasing u or M or decreasing R or r_p or C.

The circuit shown in Fig. 401 requires a somewhat different expression for the oscillation requirements. In this case, the oscillating circuit L_1C has a resistance R. In a freely oscillating circuit like L_1C, when not connected to a tube, the resistance R determines the action. It may be shown that the oscillating circuit L_1C of Fig. 401, however, behaves as if its resistance were $R + \frac{L_1 + uM}{Cr_p}$. That is, the oscillating circuit resistance is increased by an amount $\frac{L_1 + uM}{Cr_p}$. The quantities L_1, C, u and r_p are positive but M may be either positive or negative, depending upon the coupling connections between the coils. If M is positive, the equivalent resistance of the oscillating circuit is increased and the damping of oscillations is more rapid than would be the case in a freely oscillating circuit. If M is negative, the equivalent resistance is decreased and may be made equal to zero or even negative. In order that the quantity $\frac{L_1 + uM}{Cr_p}$ may be equal to $-R$, the term M must be equal to or greater than $-\frac{Cr_p}{u}\left(R + \frac{L_1}{Cr_p}\right)$. If the equivalent resistance is negative, the amplitude of the oscillations increases up to the energy limits of the tube. Beyond this point the amplitude is constant and the current has a frequency of $f = \frac{1}{2\pi}\sqrt{\frac{R + r_p}{r_pL_1C}}$. As the term $(R + r_p) \div r_p$ generally is small, the frequency is very nearly equal to the natural frequency of oscillation of a freely oscillating circuit L_1C, which is given by $f = \frac{1}{2\pi}\sqrt{\frac{1}{L_1C}}$.

Frequency of Oscillation.—When the grid circuit is connected to an outside source of power the tube will reproduce in the plate circuit the frequency which has been impressed on the grid circuit. But when the tube is self-excited by coupling the grid and plate circuits together, the frequency on the grid is the same as that which is produced in the plate circuit. The frequency of operation then is determined by the electrical constants of the circuit and corresponds to the natural frequency of a mechanically vibrating body. This critical frequency is known as the *resonant* or *natural frequency.*

The frequency of oscillation of the circuit shown in Fig. 399 is

$$f = \frac{300,000,000}{1,884\sqrt{(L_1 + L_2)C}}$$

where f is the frequency in cycles per second, L_1 and L_2 are the inductances of the coils in microhenrys and C the capacity of the condenser in microfarads. If there is any magnetic coupling between the coils and if M is the mutual inductance of the two coils the expression for frequency becomes

$$f = \frac{300,000,000}{1,884\sqrt{(L_1 + L_2 + 2M)C}}.$$

Frequency Control with Piezoelectric Crystal.—The vacuum tube transmitter used in broadcasting must generate a con-

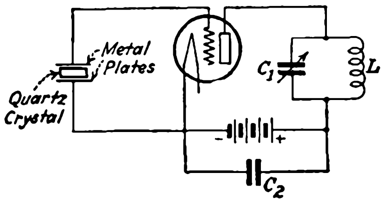


FIG. 403.—Device for frequency control with quartz crystal.

stant frequency. Accurate maintenance of frequency is possible by the use of a piezoelectric crystal control if the temperature of the crystal is kept constant.

Certain crystals such as quartz possess the property of developing an electric charge when they are put under pressure, and *vice versa;* that is, they change in shape under the action of an electrostatic field. Consequently, the frequency of oscillation of a vacuum tube may be controlled by the mechanical vibration of a quartz crystal.

This effect is obtained by an arrangement such as that of Fig. 403. The condenser consisting of a small disk of quartz between two metal plates is placed in the grid circuit of a vacuum tube. If an alternating potential difference is established between the two plates of the condenser, the crystal will vibrate mechanically at its natural period. When the plate circuit is tuned electrically to the same frequency as that of the crystal, the circuit will oscillate and variation of the capacity C_1 does not affect the frequency of oscillation. A small *master oscillator* of this kind is used to excite a large power tube and thus controls the frequency accurately.

Variation of Oscillation with Coupling.—As the coupling between the coils of the circuits in Figs. 398 to 402 is made looser, a greater alternating current in the coil L_1 is required for a given alternating grid voltage induced in coil L_2. Thus, as coupling is reduced, the oscillation increases until the plate current varies between the saturation value and approximately zero, as shown in Fig. 404. When the condition of stable oscillation has been reached, the oscillating current has a value of

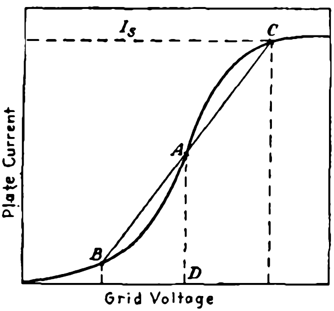


FIG. 404.—Variation of oscillation with grid voltage.

$\frac{I_s}{2w}\left(CR + \frac{L_1}{r_p}\right)$ where I_s is the saturation current. Since the plate current cannot increase beyond this upper value, an additional reduction of coupling will decrease the induced grid voltage until the action stops.

A different result is obtained as the coupling is increased. Under this condition, the oscillations decrease and stop when the coupling is too tight. The best value of coupling, then, for allowing oscillation to be greatest, is seen to lie between the upper and lower limits, at each of which the oscillations reduce to zero.

When the coupling between tuned circuits is close, oscillations of two different frequencies may take place. When the direct-coupled circuits are used, harmonics are found in the output circuit. Consequently, it is advantageous to sacrifice efficiency, when coupled circuits are used, so that the interference may be decreased.

In some cases, the presence of another oscillation frequency is caused by the distributed capacity of coils, the inductance of the wiring, and the tube interelectrode capacities. This difficulty is minimized in a capacity-coupled circuit as in Fig. 402, because the capacities of the tube electrodes and of the wiring are in parallel with the circuit condensers. Similarly, the circuit arrangement in Fig. 399, in which the internal grid-plate capacity of the tube is in parallel with the capacity C of the oscillating circuit, is suitable for use at high frequencies.

In most circuits, the coupling between the input and output circuits is adjusted by changing the mutual reactance. When a change in coupling, however, depends upon a change in capacity, as in the circuit of Fig. 402, the frequency of the oscillating circuit is affected. One way of avoiding this difficulty is to insert, in series with the inductance, another condenser which may be used to regulate the frequency.

Variation of Oscillation with Grid Voltage.—The operating point A in Fig. 404 is taken at the center of the characteristic curve. Then, if the mutual inductance M has the value given above, the oscillations will start and the grid voltage will vary about the original value D. When the amplitude of oscillations increases until the plate current varies over the line BC, a stable condition is obtained.

Now, if the grid-bias voltage is made more negative so that operation is at the lower bend of the characteristic curve, the mutual conductance $u \div r_p$ (slope of the curve at the operating point) decreases. This may affect the conditions for oscillation to such an extent that the generation of oscillations will not take place unless the coil coupling is increased.

If a still greater negative grid-bias voltage is used, so that operation takes place on a horizontal part of the curve, the mutual conductance is zero. If the oscillating circuit is started in some way, an alternating voltage is induced in the grid circuit. Variations of this grid voltage, however, do not cause any variations of the plate current. Consequently, the oscillations die away and the tube does not operate.

In practice, however, the grid is not negative enough at all times with respect to the filament to prevent the flow of grid current. For example, when a grid condenser and grid-leak resistance are used to keep the grid negative, the grid becomes positive during a part of the cycle. If the plate becomes *less* positive as the grid becomes *more* positive, the flow of grid current increases and if, at any instant, the highest positive grid voltage approaches the value of the lowest plate voltage, the plate current is decreased considerably. Consequently, saturation seems to occur at a value of plate current which is lower than the normal value.

It should be noted that the output power increases with the square of the alternating voltage applied to the grid for small values of voltage. For large values of grid voltage, however, the output power may vary with a fractional power of the grid voltage.

Variation of Oscillation with Plate Voltage.—With a given plate voltage, only a certain portion of the filament emission can be utilized, but, with a given emission, an increase in plate voltage increases the output up to the limit of the tube.

The expression which has been given for the condition necessary to generate oscillations may be stated in another form. That is, M must be equal to or greater than $\frac{r_p}{u}\left(CR + \frac{L_1}{r_p}\right)$, or, $\frac{u}{r_p}$ must be equal to or greater than $\frac{1}{M}\left(\frac{L_1}{r_p} + CR\right)$. The term $u \div r_p$, which is the mutual conductance of the tube, is proportional to the plate voltage. The term $\frac{1}{M}\left(\frac{L_1}{r_p} + CR\right)$ also is proportional to plate voltage. Then, since $u \div r_p$ must be at least equal to $\frac{1}{M}\left(\frac{L_1}{r_p} + CR\right)$, oscillations will not be generated if the plate voltage is below a value which is determined by the quantities L_1, C, R, r_p, and M.

Practical Arrangement of Circuits.—The position of generators or batteries in a transmitting circuit introduces several matters which must receive consideration. A diagram of a simple "Colpitts" circuit is shown in Fig. 405. No direct current can pass through the oscillating circuit from plate to filament because of the blocking action of condensers C_1 and C_2. The choke coil L_p passes the direct current of the plate battery but blocks the high-frequency portion of the plate current which flows through the oscillating circuit and maintains the oscillations. The inductance of the choke coil is made high so that its impedance may be several times the plate resistance of the tube. The filament is insulated from the plate voltage by the fixed condenser C_g. The capacity of C_g is chosen large enough so that it does not have much effect on the operation of the oscillating circuit. An accumulation of negative charges on the grid is prevented because of the leakage path provided by the grid-leak resistance R_g and the choke coil L_g. The antenna is represented by C_1 with the ground connection near the filament. The coupling to the grid circuit is obtained by the condenser C_2, increased capacity giving decreased coupling. Adjustment of the load is accomplished by moving the tap on the coil L.

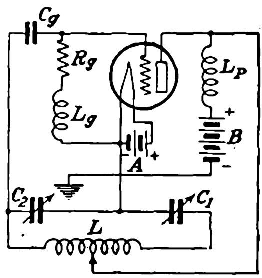


Fig. 405.—Colpitts oscillating circuit arranged for practical operation.

The source of power should be grounded to the same point which is used for grounding the tube circuit. If a ground at another point is used in connection with the generators or the batteries, another circuit due to the capacity between the power source and the ground will be set up parallel to the oscillating circuit with consequent loss of power and a possible reduction of oscillations.

Circuits for the generation of currents of high frequencies of the order of several hundred million cycles per second are simplified considerably: Sufficient inductance for such circuits is provided by the inductance of the connecting wires, and the internal grid-plate capacity of the tube constitutes the necessary capacity. In fact, the interelectrode capacities of a tube determine, for the most part, the upper limit of frequency which may be obtained.

A comprehensive study of the construction and operation of transmitters and receivers designed for use in amateur communication bands may be found in the current issues of *QST* published by The American Radio Relay League.

Conditions for Maximum Current.—The current in the oscillating circuit can be made a maximum when the load in the plate circuit is the proper one for the tube used. The load in the plate circuit of an arrangement such as that in Fig. 401, for instance, depends on the inductance L_1, the capacity C, and the resistance of the oscillating circuit to high-frequency currents. The *load* resistance has a high value when the inductance L_1 is large or when the capacity C and the circuit resistance are small; that is, if C is a low-capacity antenna and if the radio-frequency resistance of the circuit is small, the radio-frequency resistance of the load may be above the maximum for the tube in question. Under these conditions, oscillations will be generated but the current will not be a maximum. The load may be decreased by adjusting the tap on L_1 so that less inductance is included in the plate circuit. On the other hand, if the capacity of the antenna is high or if the radio-frequency resistance of the circuit is large, the current will be a maximum when the tap is adjusted so that more inductance is included in the plate circuit. If the filament voltage or plate voltage is changed, a readjustment of the plate inductance must be made to suit the load to the new operating conditions. Excessive grid voltage may be avoided by adjusting the control for the coupling of the inductance coils.

If the power output of a tube is plotted against the equivalent resistance of the oscillating circuit at the frequency of resonance, it will be observed that the power output is a maximum when the equivalent resistance is equal to the plate resistance of the tube. The ratio of inductance to capacity of the oscillating circuit can be determined, if the value of equivalent resistance is known. It is necessary to keep in mind the fact that a condition of maximum output power does not correspond to a condition of maximum efficiency.

Efficiency of Oscillator Tubes.—The efficiency of a vacuum tube oscillator may be expressed as the ratio of output power to input power. The power expended in heating the filament is not included; in high-power oscillator tubes this quantity is comparatively small, but in low-power tubes it may be greater than the output power. The output power, which usually defines the rating of a power tube, is the product of the square of the radio-frequency current and the radio-frequency resistance of the oscillating circuit. The input power, supplied by the plate circuit, is the product of the supply voltage and the current. Thus, in the case of the type 10 tube, which is rated at 7.5 watts, the plate current is 0.06 ampere at a plate voltage of 350 volts, when the tube is oscillating. The efficiency is

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{7.5}{0.06 \times 350} = 0.357 = 35.7 \text{ per cent.}$$

Under the best conditions of operation, and when the grid voltage varies about a point near the center of the characteristic curve, half the supply of power is taken in overcoming the internal resistance of the tube, and half is taken in overcoming the resistance losses in the oscillating circuit. Under these conditions, the tube as a transformer of direct current into *pure* alternating current has a theoretical limit of efficiency of 50 per cent. A negative grid-bias voltage may be applied, however, so that the grid voltage varies about a point on the lower bend of the curve. If the plate current flows only during that part of the cycle when the alternating grid voltage is positive, the average plate current is reduced. When the plate takes current, the plate voltage is reduced because of the voltage drop through the external load. Consequently, the amount of power dissipated in the tube itself is decreased. Input power, however, as used in determining tube efficiency, consists of the power dissipated in the tube and of the power supplied to the oscillating circuit. Under these conditions of operation, then, the input power and, in turn, the efficiency, is increased. But as efficiency increases the output power decreases.

The efficiency of low-power oscillator tubes is about 20 to 35 per cent; of medium-power tubes, about 40 to 60 per cent; and of high-power tubes about 85 per cent. It is obvious, of course, that efficiency varies, also, with the adjustment of the circuit.

Suppression of Oscillations in Multi-stage Amplifiers.— In an amplifier tube circuit the internal grid-plate capacity of the tube acts as a feed-back capacity and thus permits the generation of continuous oscillations. This action increases when the frequency of the oscillations generated is high, because then the reactance of the internal grid-to-plate capacity is small. Such feed-back interferes with the proper operation of the amplifier. Oscillations, of course, may be generated, also, because of the action of stray fields upon various parts of a receiver. In many cases, such oscillations may be avoided by shielding the apparatus properly, by placing the units so that their fields do not interlink, or by connecting them so that their fields are reversed.

Several methods of suppressing or minimizing the generation of oscillations due to the internal capacity of a tube have been mentioned in Chap. X. It will be of advantage to review these briefly, keeping in mind the action of the tube as an oscillator.

The first general method consists of increasing the resistance of the grid circuit, the plate circuit, or both, by inserting a resistance unit. When the resistance thus introduced is greater than the negative resistance due to the feed-back action, the generation of oscillations is suppressed.

Another method, which is similar, depends upon the application of a small positive grid-bias voltage to the grid of the tube. This allows a current to flow in the grid circuit, resulting in an energy loss to counterbalance the introduction of energy into the circuit through feed-back. The disadvantages of this general method are (1) increase of losses in the circuit, and (2) decrease in selectivity.

Another method has the effect of neutralizing the oscillations. The generation of oscillations is favored when the coupling between the grid and the plate circuits is negative; that is, when the equivalent resistance of the grid circuit is less than the resistance of the actual circuit. If, however, a coupling of the opposite kind, referred to as a *positive coupling*, is established between the grid and the plate circuits, its value may be chosen so as to neutralize the effect of the negative coupling. Several variations of this method have been mentioned previously.

The grid-to-plate capacity of the tube is reduced to a minimum by the use of a fourth electrode, placed between the plate and the grid, as in the screen-grid tube. The stability of this type of tube is due to the fact that small changes of plate voltage have very little effect on plate current because the flow of current is determined mostly by the screen voltage. The screen voltage is positive and is less in value than the plate voltage. The screen is connected to the cathode through a by-pass condenser which grounds the screen for currents of high frequency and acts to reduce the grid-plate capacity. Other types of multi-element tubes (page 130) utilizing this form of construction have the same general advantages.

Frequency Conversion in Superheterodyne Receivers.—The *frequency-converter stage* in a superheterodyne receiver (page 449), as considered here, refers to that portion of the equipment in which the local frequency-signal current is generated and "mixed" with the incoming broadcast-signal current. The two functions of local signal-current generation and of "mixing" may be performed by separate tubes or by a multi-unit tube. When separate tubes are used, the tube which generates the local frequency-signal current is known as an oscillator tube, and the one which performs the "mixing" is known by various names such as a *mixer*, a *modulator*, a *first detector*, or a *frequency changer*. When a multi-unit tube is used, it is termed a *mixer-oscillator*, a *modulator-oscillator*, a *converter tube*, and so on. When a *single* tube acts as *both* a mixer and oscillator, the arrangement is termed an *autodyne circuit*.

Converter Circuits.—One general type of converter circuit is that in which one tube is used as an oscillation generator, and another tube as a frequency mixer. All such circuits are similar in principle but may show variations depending on the type of tube used, on the manner in which the local frequency is introduced into the circuit containing the mixer tube, and also on the frequency of the local current.

The second general type of converter circuit is that in which the tube elements required for the generation of oscillations and the tube elements required for mixing are combined in one envelope or bulb. The oscillator and mixer circuits are coupled by inductive or capacitive means, or by the use of electron coupling (page 147).

Types of Tubes for Frequency Converter Circuits.—Where separate tubes are used for frequency generation and for "mixing," the oscillator tube is commonly of the super triode type, and the mixer tube of the triple grid or in some designs the pentagrid type.

When the functions of frequency generation and mixing are performed by a multi-unit tube, the types commonly used are the triode pentode, the triple grid, the pentagrid, and in receiving sets of the older designs the screen-grid type of tube.

Superheterodyne receivers that are designed for operation over the standard broadcast band have generally been provided with frequency-converter tubes which perform the double function of oscillation and modulation (or detection). For reception on the short-wave bands this arrangement may introduce difficulties caused by coupling between the radio-frequency stages and the oscillator stage by way of the frequency-converter tube. All-wave receiving sets, if provided with separate oscillator tubes, do not have these difficulties for the reasons that the interstage coupling is reduced, the oscillator circuit is more stable, and the transconductance of the detector-oscillator stage is increased. Practice varies in this respect since some designers of multi-range receivers use the pentagrid converter alone, while others use an additional tube as an oscillator.

The term *conversion transconductance* is used to determine the performance of a frequency converter just as the term mutual conductance is used in connection with the performance of an amplifier operating on a single frequency. Conversion transconductance may be defined simply as the ratio of the intermediate-frequency current in the primary winding of the intermediate-frequency transformer to the applied radio-frequency voltage which produces that current.

A comparison of the mutual conductance of the oscillator sections of the type 1C6 and type 1A6 tubes shows the importance of this characteristic with regard to the operating range at short-wave lengths. The mutual conductance of the oscillator section of type 1C6 is high enough so that satisfactory operation is possible even at frequencies as high as 25 megacycles. With type 1A6, however, this range is obtained by the use of a triode connected in parallel with the oscillator section for frequencies above 10 megacycles. This feature of high mutual conductance is of value in the design of multi-range receivers which may be intended to cover frequencies from about 20 megacycles to 150 kilocycles.

Autodyne Frequency-converter Circuits.—In an autodyne circuit for frequency conversion a single tube acts both as a mixer and as an oscillator, which operates with energy feedback from the plate to the grid circuit. Different types of tubes, such as triodes, tetrodes, and so on have been used. Likewise there are many different circuit arrangements (see pages 485 to 488) in which a given tube will produce the required oscillations.

In the arrangement shown in Fig. 406 the output of the radio-frequency tube is applied through a radio-frequency transformer T to the input circuit of a detector-oscillator tube (screen-grid type 24A). The plate circuit of this tube contains the primary winding of the tuned intermediate-frequency transformer T_1 and the plate coil L. This plate coil is part of the feed-back circuit which is tuned by the unit C of the "ganged" tuning condensers and by the trimmer condenser C_1 (page 504). The primary circuit of transformer T_1 is tuned to the intermediate frequency and is designed to offer low impedance to the oscillatory current. The heterodyne frequency is introduced by means of transformer T_2 into the cathode circuit of the tube.

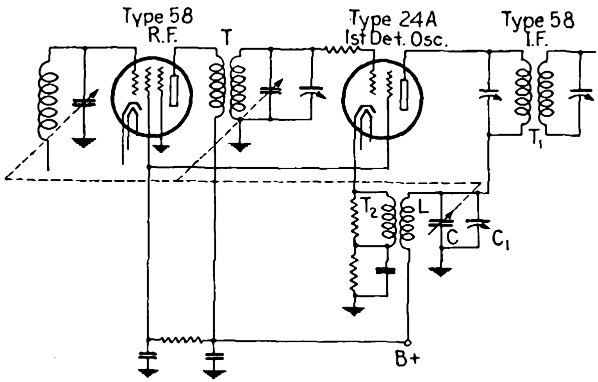


FIG. 406.—Autodyne frequency converter.

Separate Mixer and Oscillator Circuits.—The method commonly used for coupling the output circuit of the oscillator tube to its input circuit is that of inductance coupling but other forms of coupling (see page 485) are utilized in some designs.

The arrangement used for coupling the oscillator tube to the modulator or first detector tube also has several variations. In one form the coupling is accomplished through a series fixed condenser, one side of which is connected to a point on the grid winding of the oscillating circuit, and the other side to the cathode of the modulator tube. In another form a separate coil, coupled to the oscillating circuit, is connected into the cathode circuit of the modulator tube. In still another form the inductance coils in the oscillator stage are coupled by means of an intermediate tuned circuit, sometimes called a *tank* circuit, and another coil is used to couple the oscillator circuit and the circuit of the modulator tube.

In a multi-range receiver different coils are used for each tuning range, and a range switch is provided by means of which the proper coils are connected into the antenna and oscillator circuits. Each coil is connected to a trimmer condenser, in order that each circuit can be properly adjusted to

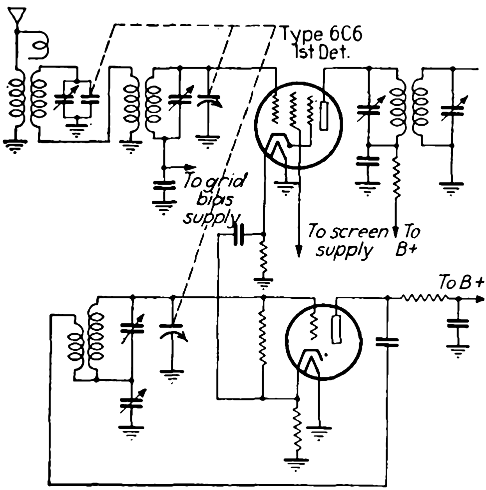


FIG. 407.—Typical all-wave superheterodyne oscillator circuit.

give the most satisfactory performance on the frequency range for which it is intended.

The receiver shown in Fig. 407 is a 7-tube all-wave superheterodyne design which has a frequency range from 530 kilocycles to 23 megacycles in four tuning ranges that can be selected by means of a range switch. For simplicity only the set of tuning coils and condensers for the broadcast range is shown in the diagram. The tuned pre-selector circuit is used only on this frequency range, to improve selectivity. After the radio-signal current passes through this circuit it is applied to the first detector tube where it is "mixed" with the output of the oscillator tube to produce the intermediate-frequency-signal current at 456 kilocycles.

Triode-pentode Tube as Oscillator Mixer for Superheterodyne Receivers.—In the application of a triode-pentode tube such as type 6F7 as combined oscillator and mixer (page 155) or frequency converter for superheterodyne receivers, the triode section is used as the oscillator, and the pentode section as the mixer. The circuit connections for this service are shown in Fig. 408. Since this type of tube consists of a triode, a pentode, and a common cathode in one envelope, the circuit arrangement does not differ fundamentally from that in which two separate tubes of similar types are used. In this arrangement R is the oscillator grid leak, R_1 is the self-biasing resistance for the pentode section of the tube, and R_2 is a voltage-dropping resistance. The oscillator voltage developed by the triode section is introduced into the cathode-to-ground circuit which is common to both sections of the tube. The oscillator voltage is transferred inductively from the coil L into the cathode circuit by the coil L_1. Another method of obtaining the voltage transfer is by direct connection to a tap as at A on the coil L, instead of by the use of another coil.

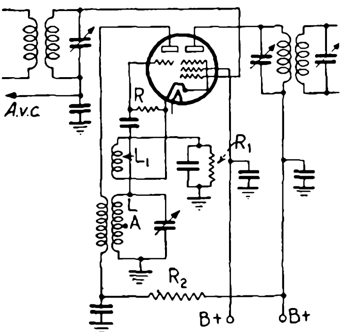


Fig. 408.—Triode-pentode tube in oscillator-mixer circuit.

Triple-grid Tube as Oscillator Mixer.—The application of a triple-grid type 6D6 tube (page 135) as an oscillator mixer for a superheterodyne receiver is shown in Fig. 409. Starting from the antenna, the broadcast signal is applied to the antenna coil T the secondary of which is tuned by the unit C of the "ganged" tuning condensers. The signal voltage then is impressed on the control grid (first grid) of the oscillator-modulator tube. This tube is so connected that the common cathode, the suppressor grid (third grid) and the plate, form a conventional triode oscillator (page 483). The oscillator frequency is determined by the setting of the unit C_1 of the "ganged" tuning condensers in conjunction with the oscillator coil of the transformer T_1. The intermediate-frequency signal voltage is applied to the intermediate-frequency transformer T_2 which is double-tuned by the condensers C_2 and C_3.

The grid-bias voltage for the input section of the tube is obtained from the voltage drop across the resistance R. The voltage drop across R and R_1 is used as the grid-bias

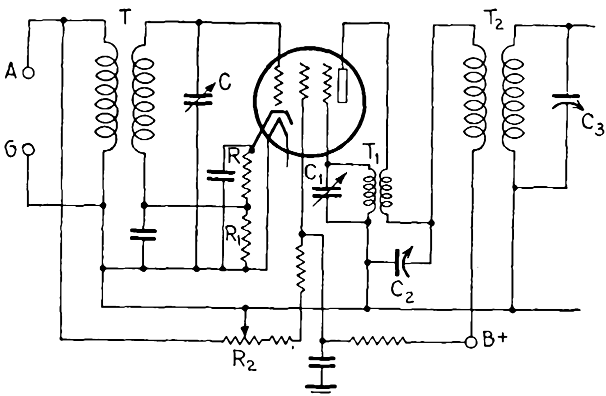


FIG. 409.—Triple-grid tube in oscillator-mixer circuit.

voltage for the suppressor grid oscillator section. The grid-bias voltage for the intermediate-frequency tube is obtained from the volume control resistance R_2.

Pentagrid Converter as Oscillator Mixer for Superheterodyne Receivers.—The application of a pentagrid converter type 6A7 tube (page 147) as an oscillator mixer is shown in Fig. 410. In operation, the cathode, with the first and second grids, forms the oscillator portion of the tube. Electrons emitted from the cathode are controlled in their flow to the oscillator anode (second grid) by the first grid. The electron stream in passing through the first grid is modulated at the frequency of oscillation of the oscillator-grid circuit. The incoming broadcast signal, applied to the fourth grid through radio-frequency transformer T, further modulates the electron stream, thus producing components of plate current, the frequencies of which are the various combinations of the oscillator and signal frequencies. Since the primary circuit of the first intermediate-frequency stage is designed for resonance at the intermediate frequency, only the desired intermediate frequency will be present in the secondary winding of the intermediate-frequency transformer.

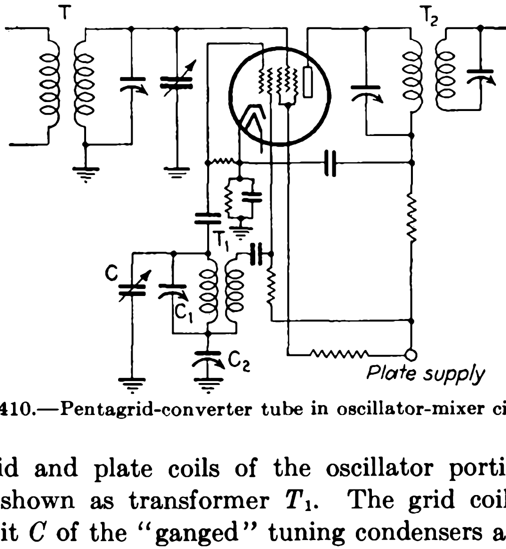


FIG. 410.—Pentagrid-converter tube in oscillator-mixer circuit.

The grid and plate coils of the oscillator portion of the tube are shown as transformer T_1. The grid coil is tuned by the unit C of the "ganged" tuning condensers and by the high-frequency trimmer condenser C_1, as well as by the low-frequency trimmer condenser C_2. The plate coil of the oscillator is connected to the second grid. A shunt arrangement is used for applying the plate voltage to the oscillator portion of the tube. The third and fifth grids are connected together and act as a screen. The primary winding of the intermediate-frequency transformer T_2 is connected to the plate of the tube. It should be noted that this receiver has four sets of tuning coils for the various frequency ranges, but only one set is shown in the diagram.

Oscillator-frequency Drift.—One of the troubles that may be experienced in connection with the operation of the oscillator is a shifting of the oscillator frequency from the value necessary to maintain the required frequency difference. A permanent shift can be corrected by a tuning adjustment, but the drift is more troublesome. If the frequency drift is slight, it will cause distortion. A more pronounced drift may produce an intermediate frequency to which the receiver will not respond. Another form of drift in which the frequency changes occur at a high rate may produce the effect of fading.

Frequency drift may be caused by the effects of atmospheric conditions on the components of the frequency-converter (page 497) stage, particularly the oscillator padding and series condensers. It may be caused also by the effects of vibration on the electrodes of the tubes, on the oscillator tuning condenser and on the position of coils and shields. Improvements have been made in circuit design, and in methods and materials of construction which tend to reduce or even to eliminate many of the causes of *frequency drift*. For example, a temperature-controlled trimmer condenser may be used in parallel with the oscillator tuning condenser to compensate for temperature effects.

Design of Superheterodyne Oscillator Circuit.—A superheterodyne receiver is tuned by means of one control which is arranged to adjust a gang of variable condensers that are connected in the *radio-frequency* and in the *oscillator* circuits. When the receiver is tuned to a certain signal frequency, the radio-frequency circuit must be adjusted for resonance at that frequency, and the frequency of the oscillator output must follow or "track" the signal frequency at a constant difference.

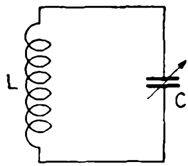


FIG. 411.—Typical radio-frequency circuit in superheterodyne receiver.

The radio-frequency circuit, shown in its essential form in Fig. 411, consists of a fixed inductance coil L and a variable tuning condenser C which must have sufficient capacity for the range of frequencies over which the receiver is to be operated. The values of inductance and capacity are determined from the relation $LC_0 = 25{,}330 \div f_0^2$* where L is the inductance in microhenrys, f_0 is the frequency in megacycles, and C_0 is the capacity in micromicrofarads of condenser C at frequency f_0.

The oscillator circuit shown in Fig. 412 consists of an inductance coil L_1, a variable tuning condenser C, a series tracking or padding condenser C_2, a shunt capacity C_3, and the distributed capacity C_4 of the inductance coil L_1. In the design of the oscillator circuit to obtain the required difference in frequency between the radio-frequency and oscillator circuits, the values of the oscillator inductance and minimum capacity are not the same as those of the radio-frequency circuit. It is, however, necessary that at any tuning adjustment the oscillator capacity must have the same value as the capacity in the radio-frequency circuit. The shunt condenser C_3 represents the difference in minimum capacity between the oscillator condenser C and the radio-frequency tuning condenser C in Fig. 411. The capacity of the condenser C_3 may have either a positive or a negative value depending on whether the minimum value of the oscillator tuning capacity is larger or smaller than the minimum capacity of the radio-frequency tuning condenser. Where the intermediate frequency is lower than the signal frequency, the condenser C_4, if small compared with C_2, may be considered as part of C_3.

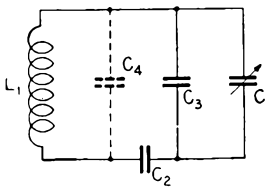


FIG. 412.—Typical oscillator circuit in superheterodyne receiver.

The frequencies which enter into the calculations for circuit design are the resonant frequency f_1 of the oscillator circuit, the resonant frequency f of the radio-frequency circuit, and the intermediate frequency f_0. The relation among these frequencies is stated as $f_1 = f + f_0$. With the circuit shown this relation is true only at three signal frequencies F_1, F_2, and F_3 called the "tracking frequencies."

* This relation is derived from Eq. (33), p. 78, which is $f_0 = 1 \div 2\pi\sqrt{LC_0}$.

For the design calculations for any frequency band, F_2 is selected near the center of the band, F_1 near one end of the band, and F_3 near the other end.

The circuit constants L_1, C_2, and C_3 or C_4 can be calculated by means of the formulas[1] given in the footnote. The values of f_0, F_1, F_2, F_3, the inductance L, or the capacity C_0 at frequency F_0, the capacity C_4, or the capacity C_3 must be known. In the following example a circuit is to be designed for a receiving range of 10 megacycles (30 meters) to 23 megacycles (13 meters) with an intermediate frequency of 0.465 megacycle (465 kilocycles). Several different cases[2] may be considered, but the one used here is the usual case in which $C_4 = 0$. The given values are $C_0 = 400$ micromicrofarads (for a frequency of 10 megacycles) and the tracking frequencies selected are 12, 16, and 20 megacycles. Then $f_0 = 0.465$, $2f_0 = 0.93$, $f_0^2 = 0.216$, $F_1 = 12$, $F_2 = 16$, $F_3 = 20$, $F_0 = 10$, $C_0 = 400$, and $C_0F_0^2 = 40{,}000$.

For this case
$$C_2 = C_0F_0^2(1 \div n^2 - 1 \div l^2)$$
$$C_3 = C_0F_0^2 \div l^2$$
$$L_1 = L(l^2 \div m^2)(C_2 + C_3) \div C_2$$
$$L = 25{,}330 \div C_0F_0^2$$

The quantities l, n, and m are introduced to simplify the equations, and have the following values:

[1] "Determination of Oscillator-circuit Constants in Superheterodyne Receivers," *Laboratory Series* UL-8, RCA Radiotron Company, Inc.

[2] When $C_3 = 0$; $C_2 = C_0F_0^2 \div n^2$; $C_4 = C_0F_0^2 \div (l^2 - n^2)$;

$$L_1 = L(l^2 \div m^2) \times C_2 \div (C_2 + C_4).$$

When C_4 is known; $A = C_0F_0^2(1 \div n^2 - 1 \div l^2)$;

$$C_2 = A(0.5 + \sqrt{0.25 + C_4 \div A});$$
$$C_3 = (C_0F_0^2 \div l^2) - C_2C_4 \div (C_2 + C_4);$$
$$L_1 = L(l^2 \div m^2)(C_2 + C_3) \div (C_2 + C_4).$$

When C_3 is known; $B = (C_0F_0^2 \div l^2) - C_3$; $C_2 = (C_0F_0^2 \div n^2) - C_3$;

$C_4 = C_2B \div (C_2 - B)$; $L_1 = L(l^2 \div m^2)(C_2 + C_3) \div (C_2 + C_4)$.

$$a = F_1 + F_2 + F_3 = 12 + 16 + 20 = 48$$
$$b^2 = F_1F_2 + F_1F_3 + F_2F_3 = 192 + 240 + 320 = 752$$
$$c^3 = F_1F_2F_3 = 12 \times 16 \times 20 = 3{,}840$$
$$d = a + 2f_0 = 48 + 0.93 = 48.93$$
$$l^2 = (b^2d - c^3) \div 2f_0 = (752 \times 48.93 - 3{,}840) \div 0.93 = 35{,}440$$
$$m^2 = l^2 + f_0{}^2 + ad - b^2 = 35{,}440 + 0.2 + 2{,}349 - 752 = 37{,}037$$
$$n^2 = (c^3d + f_0{}^2l^2) \div m^2 = (3{,}840 \times 48.93 + 0.216 \times 35{,}440) \div 37{,}037 = 5.28$$
$$C_2 = 40{,}000(1 \div 5.28 - 1 \div 35{,}440) = 7{,}575$$
$$C_3 = 40{,}000 \div 35{,}440 = 1.13$$
$$L_1 = L(35{,}400 \div 37{,}037)(7{,}575 + 1.13) \div 7{,}575 = 0.957L.$$

Here C_2 is so large in comparison with C that C_2 could be omitted; then L_1 would have to be corrected. If C_2 is retained, the resultant capacity of C and C_3 in series is 380 micromicrofarads. If C_2 is omitted the capacity is 400 as compared with 380 and hence L_1 must be reduced in proportion. The reduced value of L_1 is found from the relation $L_1 \div L = 0.957 \times 380 \div 400 = 0.91$. Finally the value of minimum capacity would have to be increased.

Beat-frequency Oscillator for Radio Receiver.—The beat-frequency oscillator shown in Fig. 413 is an integral part of the receiver so that continuous radio-wave signals can be received. The beat-oscillator circuit may be disconnected from operation by opening the switch in the plate circuit of the tube. The coil of the beat-frequency oscillator is tuned to give a 1,000-cycle note, but the condenser is adjustable in order that the beat note may be varied. In the reception of continuous waves the oscillator should not be tuned to the same frequency as the intermediate frequency because then, if the receiver is tuned exactly for the incoming signal, no beat note would be heard unless the receiver was detuned slightly.

This device may be utilized also as a means of accurately tuning the receiver in the broadcast range. For this purpose the frequency of the oscillator is adjusted so that a low-pitch whistle is obtained instead of the 1,000-cycle note mentioned before. When the receiver is to be tuned, the beat oscillator is connected up for operation. With this arrangement the radio-signal transmission as received is accompanied by a whistle. At some particular setting for a station the whistle is so low in pitch that it is not audible, but the pitch rises rapidly for settings on either side of the low point. When the receiver is tuned so that the lowest pitch of the whistle is obtained, the frequency to which the receiver is set matches accurately the transmitted frequency. Under these condi-

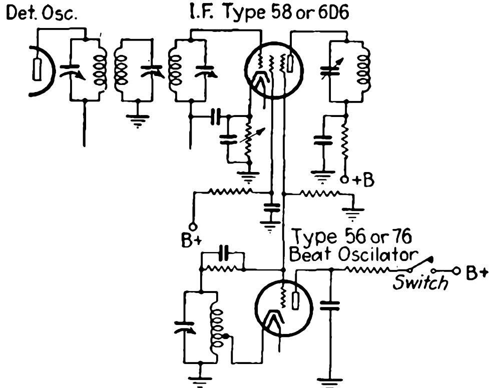


FIG. 413.—Beat-frequency oscillator circuit.

tions the receiver is accurately tuned and the beat-frequency oscillator then should be switched off.

Selection of Commercial Tubes for High-frequency Power Generation.—The high-vacuum, three-electrode tube is used for the generation of alternating currents having frequencies up to about 300 megacycles. Special types of tubes such as the split-anode magnetron (page 227) and the Barkhausen type of oscillator may be used for frequencies above 300 megacycles. Any given tube has a definite upper limit of frequency and a sharp drop in output near that limit. Consequently a careful selection must be made of the proper type and size of tube for a given combination of frequency and power output. The chart of Fig. 414 and the data in Table XXI are useful in this respect.

The values for power output and limiting frequency, except for the magnetron and Barkhausen types of tubes, are applicable only to the output per tube in a two-tube, push-pull circuit as shown in Fig. 415. In this circuit the resistance

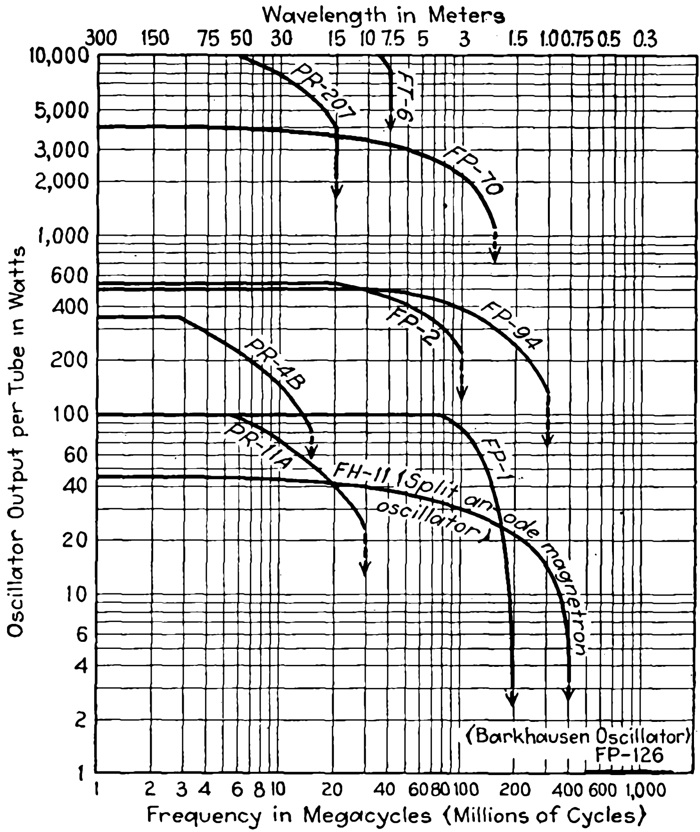


FIG. 414.—Frequency and power-output capacities of typical vacuum tubes

R_1 is used for the suppression of parasitic currents, C_1 is the condenser of the oscillating circuit, L_1 is the inductance coil of the oscillating circuit, L_2 are choke coils, R_2 is a grid-leak resistance, C_2 is a grid-leak condenser, C_3 includes several by-pass condensers, C_4 represents blocking condensers, and

TABLE XXI.—MAXIMUM VALUES OF PLATE VOLTAGES OF OSCILLATORS

Type of tube	Filament rating		Maximum operating anode voltage		Maximum anode dissipation (watts)	Cooling arrangement
	Volts	Amperes	Direct current	Alternating current		
PR-11A	10	3.25	1,250	1,250	100	air-cooled
FP-126	2.5*†	6.2†	300†	300†	20†	air-cooled
FP-1	10	3.25	3,000	3,000	100	air-cooled
FH-11	5	5.0	1,500	2,000	60‡	air-cooled
PR-4B	11	3.85	2,500	2,500	250	air-cooled
FP-94	7.5	26	4,000	3,000	500	water-cooled
FP-2	11	10	3,500	3,500	400	air-cooled
FP-70	11	51	7,500	6,000	2,500	water-cooled
PR-207	22	52	15,000	12,000	10,000	water-cooled
FT-6	22	52	20,000	18,000	20,000	water-cooled

* With the FP-126 tube, the output is controlled by filament temperature. The values given are the minimum values. The maximum values are about 3 volts and 6.9 amperes.

† With the FP-126, the grid is used as the anode while the "plate" has about 40 volts negative grid-bias voltage.

‡ Value applies to the pair of anodes of the tube.

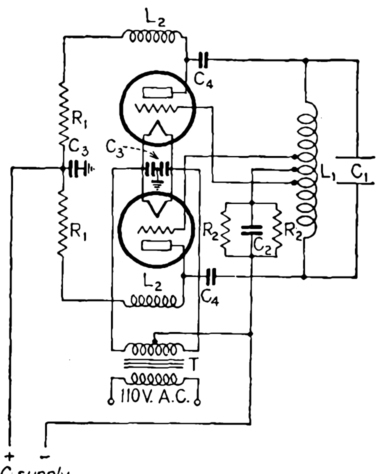


FIG. 415.—Oscillating push-pull circuit for three-electrode tubes.

T is a filament transformer. The circuit is operated from a direct-current-supply line.

The chart[1] of Fig. 414 shows the frequencies and power outputs which can be obtained with certain types of tubes. The chart is used by first locating the point which represents the required combination of frequency and power output.

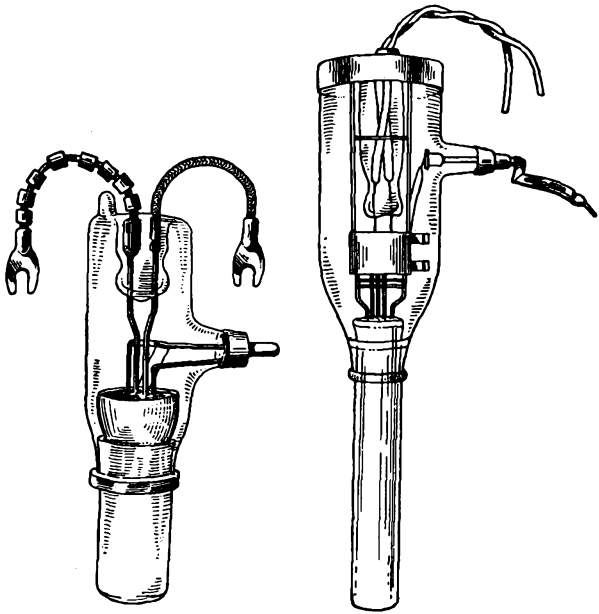


FIG. 416.—Type FP-70 and PR-207 tubes for high-frequency power generation.

Then the type of tube that should be used is the one whose curve is nearest but *above* the point. The region of recommended operation of a tube is the area to the left of and below the curve for the tube. Thus for a power output of 80 watts at 10 megacycles per second the FP-1 tube is suitable. Some of the tubes for which curves are given in the chart are illustrated in Fig. 416. These tubes range in length from 6 inches for type FP-126 to 24½ inches for type FT-6. The operating conditions for these tubes are given in Table XXI. Type

[1] *Gen. Elec. Rev.*, September, 1933.

FP-126 is a special tube for Barkhausen oscillations, type FH-11 is a split-anode magnetron, and the others are three-electrode tubes.

The average value of plate voltage must be such that consideration is given to fluctuations which occur in operation, and must not exceed the maximum value given in the table. When a tube is used at the higher frequencies near the drooping portion of the curve, the efficiency is decreased because the losses increase. For operation at these higher frequencies it is necessary to reduce both plate voltage and plate current in order that the plate dissipation may not exceed the rated value.

High-frequency Oscillator Tubes.—The types of oscillator tubes[1] used at frequencies in the range from 100 megacycles (3 meters) to 3,000 megacycles per second (0.1 meter) may be classified in three groups, namely, (1) negative-grid oscillators, (2) positive-grid or Barkhausen oscillators, and (3) magnetron oscillators.

Negative-grid Oscillator.—A standard three-electrode, high-vacuum tube will perform as an oscillator with no appreciable drop in efficiency or in power output over the frequency range from a few cycles per second to about 30 megacycles. Beyond this point the efficiency and output begin to decrease until at about 100 megacycles the tube will no longer oscillate.

The decreases in efficiency and output at higher frequencies are caused by increased energy losses, by unfavorable circuit requirements, by the effect of "transit time" (page 515), and by insufficient filament emission. The increased energy losses are due to dielectric hysteresis in the insulating materials used in parts of the tube such as the glass supporting stem, to eddy currents in the metal parts of the tube, to increased resistance of tube electrodes and lead-in wires caused by skin-effect, and to the increased charging current taken by the interelectrode capacities.

[1] Kelly and Samuel, "Vacuum Tubes as High-Frequency Oscillators," *Elect. Eng.*, November, 1934. This article includes a list of 27 references.

The effects of circuit conditions can be understood by reference to Fig. 417 which represents a *Colpitts oscillator*, the heavy lines indicating the main oscillating circuit, and the dotted portions representing the interelectrode capacities and lead inductances. In the lower frequency range the frequency of oscillation is determined by the product L_0C_0. As the frequency is increased, the capacity C_0 must be reduced and finally eliminated, and the external inductance L_0 must be reduced until finally it consists only of the circuit connections between the grid and the plate. The circuit as then constituted is shown in Fig. 418, in which the external tuning capacity is eliminated, and the external inductance is reduced to a wire connection between the grid and the plate leads. In this case the frequency is determined by the product L_tC_t in which $L_t = L_G + L_P$ and $C_t = C_{GP} + C_{FP}C_{FG} \div (C_{FP} + C_{FG})$, where L_t is the sum of the grid and the plate lead inductances, and C_t is the total grid-plate capacity. Control over the relative amplitude and phase of the alternating grid and plate voltages is obtained in the arrangement of Fig. 417 through adjustment of the condensers C_1 and C_2; but at higher frequencies the relation is determined by the fixed ratio of the grid-filament to the plate-filament interelectrode capacities.

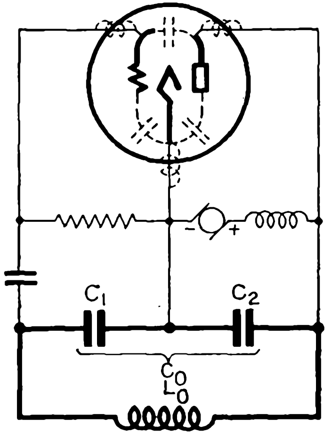


FIG. 417.—Modified Colpitts oscillator circuit.

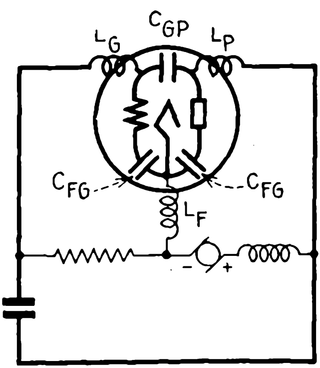


FIG. 418.—Limiting circuit of Colpitts oscillator.

The *transit time* is the time required for electrons emitted at the cathode to reach the plate of the tube. In commercial types of power tubes the transit time has a value of less than 1 microsecond. In the design of tubes used at high frequencies the relative phase of the alternating grid and plate voltages must be changed to compensate for the time required by an electron to move from the cathode to the plate. But even

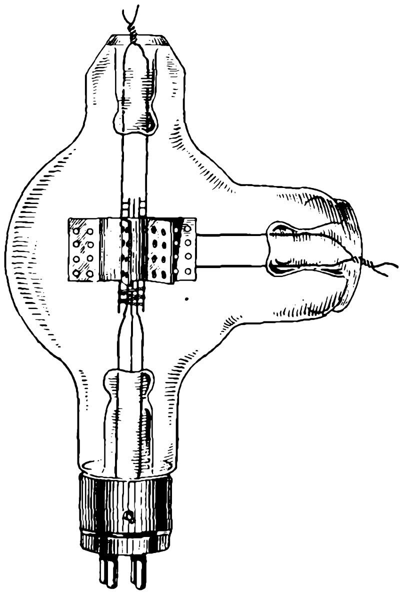


FIG. 419.—Typical air-cooled high-frequency oscillator.

with the best phase adjustment there is an efficiency loss caused by variation in grid and plate voltages during the period of transit. The effect of such variations is that the velocity of an electron arriving at the plate is greater than the velocity corresponding to the plate voltage at the time when the electron arrives. The extra energy due to the increased velocity is dissipated as heat at the plate. This extra energy must come through the oscillating circuit from the source which produces the change in grid voltage. As a result of this loss the useful frequency range of a tube is limited to values for which the oscillation period is long in comparison with the transit time. Consequently, a series of tubes must be designed, each tube being rated for a definite band of frequencies.

In high-frequency operation, in order that proper space-charge conditions near the filament may be maintained, the emission of electrons must be increased to take care of the charging currents required for the grid-filament and plate-filament capacities.

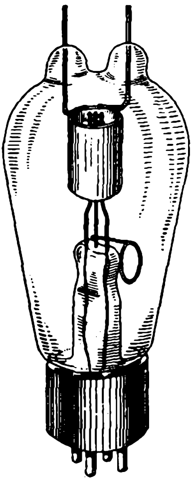


FIG. 420.—Air-cooled oscillator tube for frequencies up to 350 megacycles per second.

Illustrations of tubes designed for different frequency ranges can be used to indicate the necessary changes in construction as the frequency is increased. In the types shown, air cooling is adopted instead of water cooling. The tube shown in Fig. 419 is for use in the frequency range from 60 to 180 megacycles per second with a limiting frequency of 230 megacycles per second. The outstanding features of construction are the large ratio of plate diameter to plate length, the use of fins to increase the heat-radiating ability of the plate, the arrangement by which the electrodes are supported from their leads, and the large size of leads. The tube shown in Fig. 420 is for use up to 350 megacycles per second with a limiting frequency at about 400 megacycles per second as determined by circuit resonance. This type is designed for an increase in the diameter of the leads, a decrease in the length of the leads, and a shortened transit time.

The tube shown in Fig. 421 will oscillate at frequencies up to 740 megacycles per second. The features are, the method of electrode support, the close spacing of leads, the small size of the electrodes, and the shape of the grid which consists of straight wires parallel and equidistant from the axial filament. The plate of this tube can dissipate 40 watts safely. Extension of this type of construction indicates that closer interelectrode spacing and provision for grid cooling are necessary. Thus, the smaller of the tubes illustrated in Fig. 422 will oscillate at 1,200 megacycles per second. The "acorn" or midget type of tube for receiving purposes has been described on page 177. This latter type of tube will oscillate up to 1,000 megacycles per second.

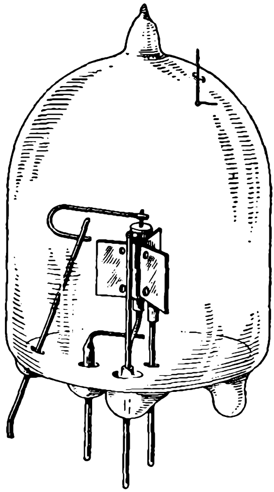


Fig. 421.—Oscillator tube for frequencies up to 740 megacycles per second.

With this type of design the use of the negative-grid oscillator for high frequencies is limited because the size of the tube and its output are dependent on the frequency range. The linear dimensions must be decreased in proportion to the operating wave length, the output decreasing as the square of the wave length.

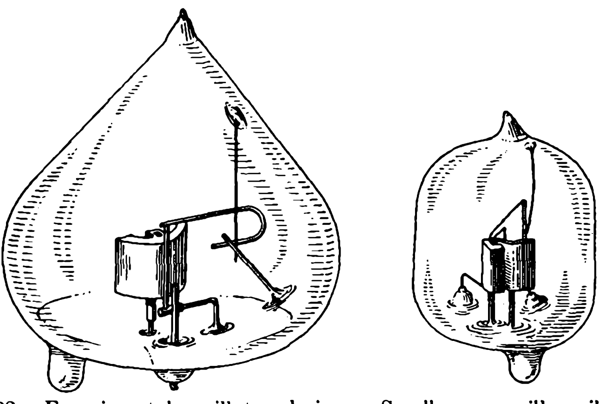


Fig. 422.—Experimental oscillator designs. Smaller one will oscillate at 1200 megacycles per second.

Thus at 3,000 megacycles per second an output of a few tenths of a watt might be obtained.

Positive-grid (Barkhausen) Oscillator.—A high-vacuum triode in which the electrodes are cylindrical in form and symmetrical, can be used as an oscillator at frequencies over 300 megacycles per second under special conditions of operation. In this tube a fairly high positive voltage is applied to the grid, and the plate is maintained at or near the cathode voltage. An oscillator of this type is called a *Barkhausen* or a *Gill-Morell oscillator* after the earliest experimenters, or a *positive-*

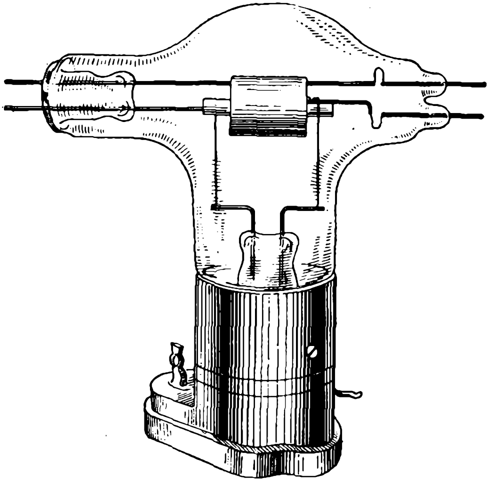


FIG. 423.—Typical positive-grid oscillator tube.

grid or *retarding-field* oscillator to indicate the relation between electrode voltages.

The construction of a positive grid type of oscillator is shown in Fig. 423. This tube is designed for use in the frequency range from 500 to 550 megacycles per second. The grid consists of parallel wires supported by cooling collars at each end. The diameter of the grid is fixed by the operating frequency and the applied grid voltage. The grid diameter varies directly with the wave length and the power output varies as the square of the wave length.

In the operation of this type of oscillator there are preferred frequencies which are fixed by the electrode spacings and voltages. For the lowest preferred frequency the period of one oscillation is approximately equal to the total transit time of an electron which fails to strike the grid on its first trip, is repelled by the plate, again misses the grid, and returns to the cathode. Maximum output is obtained when the tuning of the external circuit is adjusted to correspond to the preferred frequency fixed by the applied voltages. Critical adjustment of the cathode temperature is necessary because the most efficient operation of the oscillator is obtained when the space current is limited by the cathode emission.

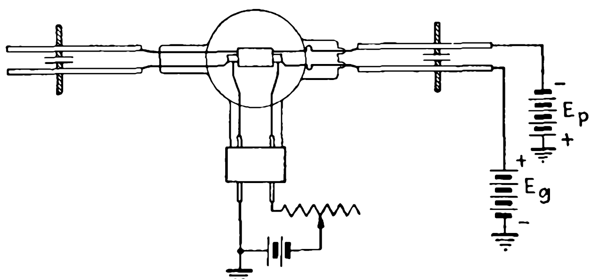


Fig. 424.—Typical positive-grid oscillator circuit.

A diagram of a positive-grid oscillator of the straight-wire grid type and its associated circuit is shown in Fig. 424. In this arrangement the tuned circuits which are connected between the grid and plate leads are in the form of the so-called *Lecher systems*, and extend about half a wave length (30 centimeters) beyond the glass seals of the lead wires. The length of the lead wires inside the tube is such that the seals are at or near the voltage *nodal points* for the Lecher systems of which the leads form a part. This arrangement is necessary to reduce dielectric losses in the glass. The effective paralleling of the two sets of leads reduces resistance losses, and the balanced arrangement reduces heat-radiation losses.

The curves of Fig. 425 show the dependence of efficiency and output on frequency. The efficiency reaches a maximum value at about 530 megacycles per second but the output increases with the frequency. The limit for output and frequency is determined by the safe grid dissipation. The positive-grid oscillator is at a disadvantage at the lower frequencies. Below 300 megacycles per second the negative grid type gives larger outputs with higher efficiencies. Above 600 megacycles per second the efficient operation of a positive-grid oscillator of the straight-wire grid type requires a power input which is beyond the capacity of the grid structure.

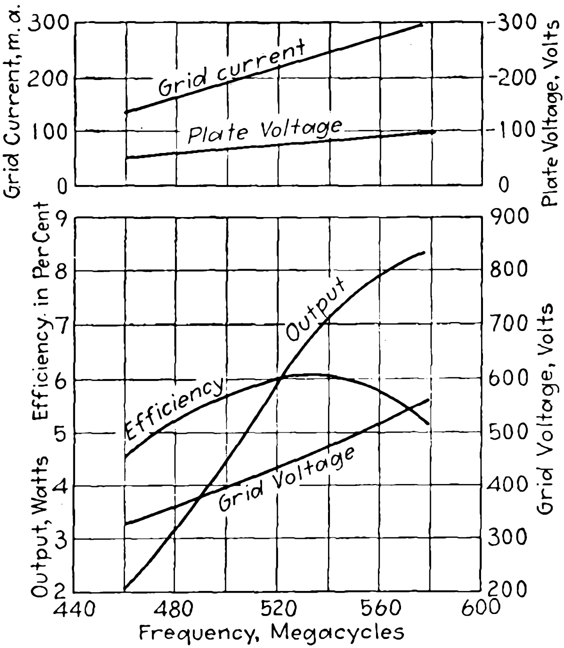


FIG. 425.—Output and efficiency curves for positive-grid oscillator tube in Fig. 423.

Spiral-grid Barkhausen oscillators such as the experimental models shown in Fig. 426 will oscillate at higher frequencies than the straight-wire grid types. The grid is constructed in the form of a simple helix. The advantage of this construction is that a rigid grid structure results which is capable of high energy dissipation in the higher frequency range. The smallest tube illustrated will oscillate at 2,500 megacycles per second, and tubes of this general type have been used at frequencies up to 3,000 megacycles per second. The *micro-ray-link between Lympe and St. Inglevert* utilizes tubes of this type. In the lower frequency ranges the efficiency and output are less than for the straight-wire grid type. The field for the spiral-grid type is in the frequency range of about 600 megacycles per second.

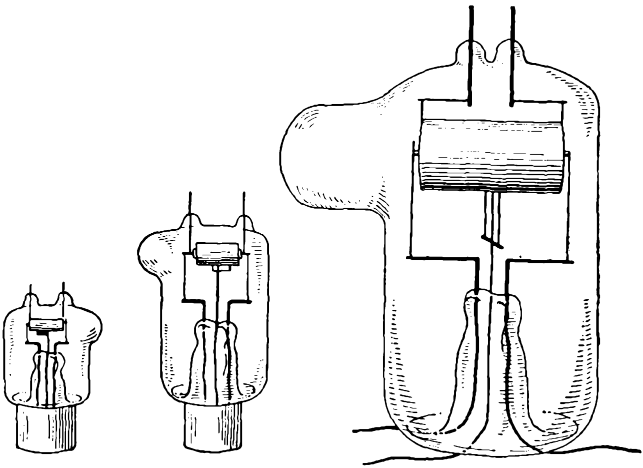


FIG. 426.—Three positive-grid oscillator tubes of spiral-grid type.

Magnetron Oscillator.—The action and applications of the magnetron tube have been described on page 509. For frequencies below 600 megacycles the magnetron compares favorably in output and efficiency with the negative-grid tube (page 513). For higher frequencies the output of a magnetron oscillator is larger than for any other type now used. The magnetron has been used at frequencies as high as 30,000 megacycles per second. The curves of efficiency and output against frequency of this tube show decreasing values as the frequency is increased. These decreases are due to resistance and radiation losses and to the effect of electron transit time.

CHAPTER XII

TELEVISION TUBES

Introduction.—Television tubes and other necessary accompanying equipment have now been so well perfected that so far as the technique of transmission and reception of pictures is concerned, there are no unusual difficulties in the way of the development and extension of broadcasting by photoelectric means. Television pictures when transmitted by good, practical equipment are clear in outline, and are as well illuminated as the kind of motion pictures that are usually shown in homes. Television is now being made available for radio broadcasting and reception.

In order to produce the illusion of continuity of vision, a large number of pictures must be transmitted in a second. In most television systems the rate of picture change is 24 per second, which is the standard rate of projection of motion pictures. Detail of the television image depends very largely on the number of scanning lines into which each picture is divided for transmission. In the relatively simple systems of television transmission, the number of scanning or division lines is 120, while in more complicated systems, as, for example, the cathode-ray-tube system (page 527), the number of scanning lines is 240.

The number of pictures to be transmitted per second, and the number of scanning lines for each picture determine the width of the band or radio channel that would be required for television transmission. Theoretically, a band or channel, about 2,000 kilocycles wide, would be necessary for the operation of each television broadcasting station, which is relatively, of course, an enormously wide band for a single station when one considers the fact that in present broadcasting of sound, each station is allowed for its broadcasting channel only 10 kilocycles. Satisfactory television broadcasting can, however, be accomplished with a band or channel that is 1,000 kilocycles wide. The size of the broadcasting band required for television is likely, therefore, to present some very difficult problems in the operation of television broadcasting stations, because the available wave bands for such use are confined to those frequencies between 30,000 kilocycles per second and 300,000 kilocycles per second, or in terms of wave length between 10 meters and 1 meter.

It is also obvious that the wires of telephone systems cannot be used for program distribution in television for a network of stations, as they are now used for the connecting together of sound broadcasting stations. Transmission of any kind at these high frequencies will suffer more than any of our present sound broadcasting from the interference that is caused by automobiles and airplanes that may be operated in the vicinity of the television receiver.

Characteristics of Typical Television Systems.—Several different systems have been developed in the last few years with very good success for television broadcasting. These systems differ from each other mainly in the methods of scanning the picture before it is transmitted and the methods used to recreate the picture after the appropriate television transmission has been received and amplified. The three television systems that have been most satisfactorily developed are the following, arranged according to relative simplicity, the first being the simplest:

1. Cathode-ray system.
2. Light-valve projector system.
3. Mechanical system.

Light-storage Method. Iconoscope.—The RCA Victor Company of Camden, New Jersey, has perfected a so-called *iconoscope* or *image observer*, which is intended to improve the methods used for scanning a picture by a method that permits the storage of light from each of the scanning lines of the picture, which is only a way of saying that it is a means for storing light from one scanning period to the next.

The iconoscope is the invention of V. K. Zworykin. It consists in essential parts of a glass tube from which the air has been removed to create a high vacuum. In the tube is a source of *cathode rays* called the *electron gun*, and also a sheet of mica on which very large numbers of drops of an alloy of caesium oxide and silver are deposited, each drop being isolated and insulated from every other one. These drops of silver alloy are very small, and are carefully arranged in line so as to give the appearance of a finely grained surface. Besides this finely grained mica plate with its silver-alloy covering, there is exactly opposite the mica plate a metallic coating which is called the *signal plate.* The first of these coatings is set up with respect to the second, so that the mica plate is between them and serves as a dielectric when the drops or particles of the coatings are charged. Opposite each drop or particle on the mica plate is a space on the signal plate, so that when charged, the drops or metallic particles and the signal plate act like small individual condensers, all having a common dielectric (mica).

In the operation of the iconoscope, the image that is to be transmitted by television is focused by means of a suitable lens on the silver-alloy coating on the mica plate. As the result of this focusing of the image, each element of the picture causes electrons to be discharged from the corresponding drops or particles of the silver-alloy coating on the mica. The number of electrons discharged will be obviously proportional to the intensity of the light reflected from the image that falls on a particular element of the coating. The electrons discharged from the drops or particles of the coating as a result of this light exposure pass easily through the rarefied atmosphere of the glass bulb to the other coating or the signal plate, the latter coating being the *anode for this emission.* This flow of electrons, as explained, has the effect of charging the drops or particles of silver alloy on the mica plate with a positive charge. In the operation of this device, as thus far explained, the drops or particles of the coating on the mica plate are positively charged, and the signal plate is negatively charged with a dielectric between them, so that each metallic drop or particle on one of the coatings constitutes with the space that is opposite it on the other coating, an individual condenser, of which the amount of charge is proportional to the amount of light received from the image that is to be transmitted through television. In the next operative step the large number of *individual condensers are discharged in the proper order corresponding to the scanning of the image;* the voltage of discharge across the individual condensers being used for the transmission of the television signal to the receiving apparatus. The discharge of the individual condensers in the proper order for image transmission is accomplished by an ingenious use of cathode rays, which are directed by the electron gun already mentioned to the surface of the silver-alloy particles on the sheet of mica. Condenser discharge is thus made to correspond to the movement of the *scanning device*, which is, of course, the cathode-ray beam. Since there are 24 images transmitted per second, the time between successive scannings is, of course, $1/24$ second. Since the reflected light from the image falls continuously on all the drops or particles on the sheet of mica, a positive charge collects on each drop or particle on the cathode, so that a relatively large voltage accumulates, and this built-up voltage is available at the proper time for the transmission of the signal corresponding to points in the image when the individual condensers are discharged by the movement of the cathode-ray beam. *Light storage*, as accomplished by this method, accounts for the superiority of this method of scanning over the more simple devices.

Farnsworth's Image Dissector.—P. T. Farnsworth of Philadelphia has invented a cathode-ray scanning device which he has called the *image dissector*. In many respects, this device in its operation is like that of a motion-picture camera. In its essential parts, this device, consists of a flat metallic plate with a uniform photosensitive coating, like an alloy of caesium oxide and silver. This photosensitive coating is placed at one end of a glass bulb in which a fairly good vacuum has been secured by air evacuation. Opposite this coating, at the other end of the tube, is a metallic plate which serves as the anode of the device.

The image of which a picture is to be transmitted by television is, in the operation of this device, focused by means of an ordinary camera lens on the photosensitive coating of the vacuum tube. The reflected light from the image, point for point, causes the discharge of electrons from the photosensitive plate in proportion to the amount of light reflected from the image. Very expressively the inventor of this device states that in this operation "the optical picture is thus transformed into a picture in electrons." Electrons discharged from the photosensitive coating find their way easily to the metallic surface of the other end of the tube which is the anode. Since, however, all the electrons are negatively charged and tend to repel one another, the "picture in electrons" diverges as it travels nearer and nearer to the anode. In order to counteract this tendency to divergence, a magnetic field is applied outside of the evacuated tube with the object of bringing the electrons into focus on the metallic plate (anode). Two more magnetic fields are used in this device, these latter magnetic fields being utilized to move the "picture in electrons" bodily through a small square aperture, which leads to a compartment in the tube, so that the electrons of the picture are received in the correct order corresponding to a scanning arrangement. At the other side of the small square aperture, but in another section of the vacuum tube, is a so-called *electron multiplier*.

With the help of this electron multiplier[1] it is possible to increase the electron emission to such an extent that outdoor scenes can be picked up by direct scanning for television transmission. This electron multiplier consists of two plates that have high secondary emission characteristics, so that the stream of electrons entering the multiplier through the aperture impinges on one of these plates, and there is then a

[1] A more detailed description of this apparatus is given in the article "An Electron Multiplier," in *Electronics*, August, 1934.

constant discharge of secondary electrons from this plate from 2 to 8 times as large as the number of electrons in the original stream, all of which find their way to the second plate to which they are attracted, and there repeat the process of secondary electron emission. On these two plates of the electron multiplier, the signal voltage is progressively amplified, until the output is about 1,000 times as large as the number of electrons in the original stream.

R.C.A. Victor Cathode-ray-type Television Receiver.—The kind of device that has gone through the most successful development for television reception is the *cathode-ray tube* which has become more or less standardized for this service by reason of its adoption by several of the large manufacturers specializing in television equipment. For example, the television receivers made by the R.C.A. Victor Company, the Philco Company, and Television Laboratories are applications of practically the same general principles, and they differ therefore in only minor details. In these television receivers applying the cathode-ray principle, the essentially important part is, of course, the cathode-ray tube, as developed for television service, which differs from the ordinary cathode-ray tube (page 221) in that it is complicated by the addition of auxiliary devices for controlling the flow of electrons that are discharged in the operation of this tube from an indirectly heated cathode or filament. The flow of electrons from this cathode must, of course, be modulated by some device that will be responsive to the reception of signal voltage as received from the transmitting station. This modulation of the electron flow is regulated by a control grid which influences the intensity of the electron beam according to the strength of the signal voltages that are applied between this grid and the cathode or filament. In the operation of this receiver, the next step after the modulation of the electron beam is to bring the beam within the range of two anodes, the first of which gives additional velocity to the electron beam, and the second serves to bring the electron beam to a close focus at the surface of a fluorescent screen which is also a part of this particular type of cathode-ray tube. This second anode thus used for focusing is operated at a higher voltage than the first and is nothing more than a conducting surface that has been applied to the inner walls of the tube.

For the practical application of the television receiver, provision for scanning in two directions is, of course, essential. Scanning lines are made by the influence of magnetic fields located outside the tube which deflect the modulated electron beam; in the horizontal direction for the scanning lines and in the vertical direction to correspond to the rate of picture transmission. The coils producing these magnetic fields around the cathode-ray tube are supplied with an alternating current which has an unusual, irregular-wave shape, the irregularity of the wave serving a very important function. The irregular wave is so shaped that it has a saw-tooth contour that deflects the modulated electron beam in such a way that a scanning line moves horizontally across the screen at the rate giving the proper number of scanning lines for the picture corresponding also, of course, to the rate of picture change. This velocity of movement of the modulated electron beam is practically constant from one side of the screen to the other. When, however, the modulated beam in its movement comes to the edge of the screen, the beam is extinguished by the influence of the magnetic fields and makes the return movement to the opposite side of the screen at a high velocity in comparison to its velocity across the screen in the first direction when making a scanning line of the image being transmitted. Thus, the beam has a quick return movement to the beginning of the next scanning line. During this quick return movement of the electron beam, provision is made for the sending from the transmission station to all the receivers taking its broadcast, a so-called *synchronizing signal*, which is intended, of course, as a guide to the operator of the receiving set for keeping his receiver in step with the transmitter.

Motion-picture Transmission by Television.—Transmission of pictures on standard-width motion-picture film at the standard rate of projection, that is, 24 pictures per second, has been made possible by the application of a suitable optical system, polarized light and a *Kerr-cell light valve.* In this system, in both the transmitter and the receiver, the scanning lines, which are horizontal, are obtained by the use of a disk having on its circumference a large number of glass lenses, each of which is coated on the back with a suitable amalgam to give mirror effect. The vertical scanning in the transmitter is accomplished by the movement at a constant rate of speed of the motion-picture film containing the pictures to be transmitted. In the transmitting equipment the source of light is a heated filament from which the light is directed by a suitable reflector to a collecting lens which directs into a beam practically all the light given off by the filament. This control beam of light is directed upon the edge of the disk with its multiple-mirrored lenses. From these lenses, the light beam is reflected through the motion-picture film to the light-sensitive element of a photoelectric cell (page 212), in which an electric current is modulated to correspond to the modulations of the light-intensity variation produced by the shading of the picture on the film that is being transmitted.

For this system, the television *receiver* has for its most important part a modified *Kerr cell,* which serves as a light valve. This cell consists of two parallel plates having a suitable liquid dielectric between them, so as to make a very simple condenser. The capacity is about 6 micromicrofarads. The liquid dielectric in this condenser is a solution of nitrobenzene which has the unusual property, when subjected to electric stress, of rotating the plane of polarized light that passes through it. Polarized light for transmission through the liquid is obtained from a filament light bulb similar to the one used in the transmitter and the light from the filament of the bulb is polarized by passing through a suitably designed prism, from which it goes through the liquid in the Kerr cell. The amount of voltage used to charge the two plates of the cell will control the amount of polarized light passing through the cell. Thus, if the voltage of an amplified television signal, as received from the transmitter, is applied to the plates of the Kerr cell, it will control the amount of polarized light passing through the liquid in proportion to the applied signal voltage. The beam of polarized light that emerges from the liquid in the Kerr cell is directed upon the edge of a disk which has the same number of mirrored lenses as there are scanning lines in the picture being transmitted. Provision is made for rotating this disk in synchronism with the disk of mirrored lenses in the transmitter. The mirrored lenses on the rim of the disk serve to reflect the polarized light upon a viewing screen in the proper sequence of the scanning lines, the number in this instance being 60.

Mechanical-optical System of Television.—Television transmission and reception by the application of mechanical and optical means have also been perfected. In this mechanical method, the image to be transmitted is scanned by a spot of light that is reflected from the filament of a light bulb, the reflection being accomplished by the application of a suitable mirror. This mirror is set up in this device in such a way that it can be moved on two axes at right angles to each other, usually one axis being vertical, and the other being horizontal. The mirror vibrates at the scanning frequency about its vertical axis, and about its horizontal axis at the standard projection rate of motion pictures, that is, 24 per second. The scanning frequency is very rapid, about 5,000 cycles per second, so that there is an enormous difference between the rates of movement about the vertical and the horizontal axis. Vibration of the mirror is produced by the effect of two magnetic fields. The excitation currents causing the magnetic fields needed for these two very different frequencies are obtained from small oscillator tubes. The mechanical resonance of the mirror about each axis can be very accurately adjusted, so that the entire system can be kept in synchronism.

The television receiver used in this system operates by the method of regulating the amount of polarized light from a Kerr cell. The modulated beam of polarized light from

TABLE XXII.—PRACTICAL TELEVISION SYSTEMS[1]

Name of system	Type of scanning device	Number of scanning lines in picture	Number of pictures per second	Type of light-sensitive device	Means of synchronization	Receiving light source and color	Method of light modulation
			Cathode-ray systems				
RCA-Victor	Cathode-ray iconoscope	240	24	Multiple-cell plate	Special signal	Fluorescence, green color	Control grid
Philco	Cathode-ray camera tube	240	24	Multiple-cell plate	Special signal	Fluorescence, green color	Control grid
Farnsworth	Cathode-ray image dissector	240	30	Single-cell plate	Special signal	Fluorescence, green color	Control grid
			Mechanical-optical systems				
Hogan	Mechanical (not disk)	120	24	Photocell	Transmitted signal	Glow lamp, white	Direct
Priess	Resonant mirror	60	24	Photocell	Transmitted signal plus resonance	Incandescent lamp, white	Kerr cell
Peck	Mirrored lens disk	60	24	Photocell	Power system	Incandescent lamp, white	Kerr cell

[1] Table abridged from one in *Electronics*, October, 1934.

the Kerr cell falls on a mirror set up in exactly the same way as the one in the transmitter with horizontal and vertical axis moving at the same frequencies as in the transmitter, with provision for adjustment of the mechanical resonance. The excitation current for the scanning and picture frequencies is supplied in the receiver by current from the amplified television signal.

A summary of the important features in television systems that are being developed by several manufacturers is given in Table XXII.

Iconoscope in Television.—The pictures that are printed in newspapers are reproduced by resolving the picture into a

Fig. 427.—Television pictures made with 60, 120, 180, and 240 lines.

number of dots, and the detail or definition of the picture is identified by the number of dots in a square inch. For ordinary work, about 4,000 picture elements are required, which corresponds to about 65 lines per inch. In the same manner, the reproduction of a television picture is referred to in terms of lines because the picture is broken up into a number of elements, one element being transmitted after another in a series of parallel lines. Thus, in television a reference to 30, 60, or 120 lines means that the picture when reproduced is made up of 30, 60, or 120 lines, each of which varies in density along its length. Much work has been carried on to determine the minimum number of lines that are necessary if the reproduced image is to be satisfactory. The definition of a picture does not change in direct proportion to the number of lines. This is shown by the pictures that are reproduced in Fig. 427 which gives a comparison of the same picture made by optical methods with 60, 120, 180, and 240 lines, respectively. This picture shows that if much detail is desired, a minimum of 240 lines is necessary.

The difficulties which must be considered in the development of television depend directly on the number of picture elements. The problem also involves the amount of light that is needed at both the transmitter and the receiver, the construction of the electrical equipment, and the limitations of the transmission channels. Table XXIII[1] gives the relation

TABLE XXIII.—LIMITING FACTORS IN TELEVISION

Number of scanning lines per picture	Number of elements in the picture	Maximum value of picture frequency,[1] cycles per second	Maximum width of communication band, cycles per second
20	4,798	63,970	127,900
120	19,200	256,000	512,000
180	43,190	576,000	1,152,000
240	76,780	1,024,000	2,048,000

[1] These values have been increased by 10 per cent to compensate for the loss of time when synchronizing signals.

between the number of scanning lines, the number of elements in the picture, and the maximum frequency of the communication band. This table is based on the condition that the *aspect ratio* of the picture is 3 to 4, and that there are 24 repetitions per second. It is clear that for a definition of more than 100 lines the communication band becomes so wide that the usual radio-broadcasting channels cannot be used. Such

[1] V. K. ZWORYKIN, *Jour. Franklin Inst.*, January, 1934.

transmission, therefore, must be carried out at ultra-high frequencies.

In the development of television systems depending on mechanical methods for scanning and for reconstructing the picture, the difficulties encountered are almost entirely mechanical in nature. These difficulties involve the construction of scanning devices having the necessary precision, methods for increasing the number of picture elements, and devices for obtaining sufficient light. The amount of light that can be obtained sets up a definite limitation, because it prevents the increase of resolution that is needed to give the desired quality. The difficulty with regard to light also practically eliminates the possible transmission of a picture of an outdoor scene.

The interval of time during which one element of the picture is illuminated is very short. Thus, for a picture of 240 lines or 76,780 picture elements, repeated 24 times a second, the time of transmission of one picture element is approximately 1/1,842,000 second. Since the output of the photocell to the amplifier is proportional to the light intensity and to the time (period) of illumination, it can be shown that the output of the photocell under the given conditions of operation is extremely small. This consideration is important because of the difficulties that are involved in the amplification of such small amounts of energy.

To avoid these difficulties a system of television has been devised in which the principle of operation would be the same as that of the human eye, so that the entire photosensitive surface would be affected by all the points of the picture throughout the period of exposure. In a system of this kind, the photoelectric output for each point of a picture with 76,000 elements would be theoretically 76,000 times greater than that in a mechanical system. However, since scanning is necessary in order to use only one communication channel, a system of this kind requires some means whereby the energy of the picture can be stored from one scanning period to the next.

Transmitter for Electrical Television.—The system of television to be described was developed *entirely along electrical lines* in order to obtain an adequate light supply and to avoid mechanical moving parts. Both the transmission and reception of the image are accompanied by the use of special electronic devices. The picture is translated by means of a vacuum tube called the *iconoscope,* and is reproduced by means of another vacuum tube called the *kinescope.*

The word "iconoscope" is taken from the Greek words for "image observer." The electrical circuit of the device is

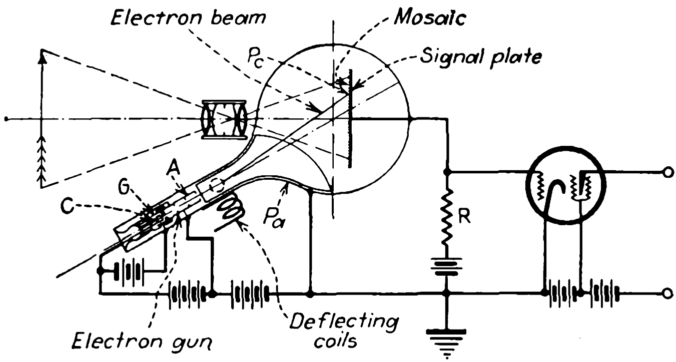


FIG. 428.—Iconoscope circuit.

shown in Fig. 428. As shown in this drawing, the vacuum tube consists of two main parts, (1) the *photosensitive surface,* and (2) the *electronic-beam scanner.* The photosensitive surface is made up of a metal plate, one side of which is covered with many tiny photoelectric cells which are insulated from the plate and from each other. The purpose of this combination is to change the light from the picture into charges of electricity and to allow these charges to accumulate until they can be changed into electrical impulses and transmitted. The transformation of the electrical charges into electrical impulses is accomplished by means of the electron-beam scanner.

The action of the photosensitive surface will be explained by a consideration of the circuit of one of the photoelectric elements. The electrical circuit of such an element is shown in Fig. 429. When light from the projected picture reaches the photosensitive surface, electrons are emitted from the cathode P_c of each element and the condenser C becomes

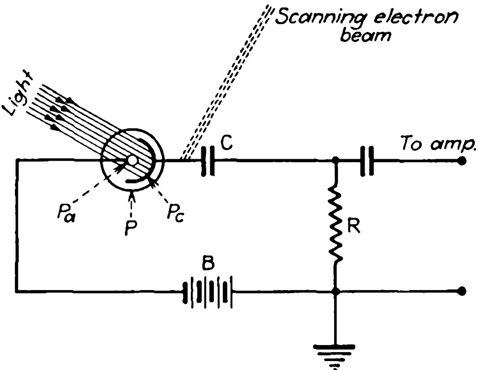


FIG. 429.—Circuit of photoelectric elements in iconoscope.

positively charged to a magnitude which depends on the intensity of the light. The condenser C represents the capacity between each element and a plate common to all the elements which is designated as the *signal plate*. When the beam of electrons from the scanner strikes an element P_cC, that element receives electrons from the beam and thus becomes discharged. The value of this discharge current depends on the value of the positive charge on the element.

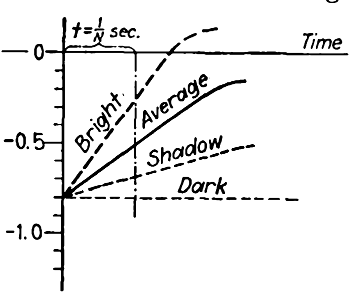


FIG. 430.—Rate of element charging for different degrees of brightness.

The rate at which a charge increases on an element P_cC is shown in Fig. 430 and depends directly on the brightness of the picture. This linear relation is maintained over the time interval during which the scanning takes place. Since the scanning operation proceeds at a constant rate this interval of time t, which is equal to $1 \div N$ where N is the frequency of repetition of the discharge per second, is also constant. Then, if the intensity of the scanning beam is constant, the current which flows through the resistance R and the voltage drop which it produces are proportional to the brightness of the picture. This voltage drop, representing the output of each photoelectric element, is then applied to an amplifier.

Voltage on Photoelectric Surface.—The electrical charges on the individual elements of the photoelectric surfaces are not

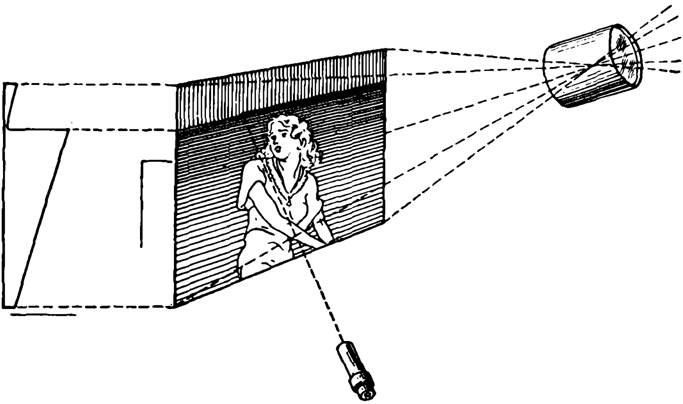


FIG. 431.—Charging conditions on photoelectric surface of iconoscope.

uniform but vary in value depending on the position of the scanning beam. The positive charge on a photoelement is overneutralized by the scanning beam, so that a negative charge results. Light reaching the element produces a positive charge which acts to reduce the value of the normal negative charge, but the effect of the scanning beam is to bring the charge back to a level known as the *equilibrium voltage.* The equilibrium voltage of an element depends on the velocity of the beam and on secondary emission from the photoemitting material. A normal iconoscope, in darkness, has an equilibrium voltage of about 1.0 volt negative. The charging conditions on the photoelectric surface are illustrated in Fig. 431.

The shaded portion of the picture represents the electrical charges produced on the elements of the photoelectric surface by the light of the projected picture. The density of the background of this picture is uniform, but the corresponding charges vary in the manner shown on the diagram at the left-hand side of the picture. As shown in this diagram, the charge is highest at the elements just in front of the approaching scanning beam. The charge drops to its equilibrium value after the beam passes and then begins to increase at the start of the next scanning period. It reaches its highest value again just before it is scanned by the beam.

The energy that is stored in an element of the surface during the interval between scanning repetitions is released *instantaneously* by the electron beam. It was stated before that the electrical impulse that is produced by each element is passed on to an amplifier. The ratio of the magnitude of this impulse to that produced in a system in which there is no storage effect is the same as the ratio of the time interval during which the light from the picture acts on the photosensitive element in the two systems. Under the conditions assumed, for a device which has an efficiency of 100 per cent, the theoretical ratio is 76,780, being equal to the number of picture elements. At the present stage of development, however, a gain of only about 10 per cent is possible.

Electrical Circuit of Iconoscope.—In the electrical circuit shown in Fig. 428 the representation of the photoelectric element differs from that of Fig. 429 because the two parts of the element are separated. In Fig. 428 the cathode P_c consists of the photosensitive elements on the surface of the signal plate. The anode P_a consists of a portion of the inside surface of the glass bulb which is covered with a coating of silver. It may be considered that each element with reference to its associated portion of the signal plates acts like a small condenser. The capacity C of this combination depends on the thickness and the dielectric constant of the layer of insulation between the element and the signal plate.

The electron beam that is used to discharge the photoelectric elements is produced by an electron gun. This electron gun is located in the small end of the vacuum tube and is inclined at an angle of 30 degrees from an axis perpendicular to the photoelectric surface at its central point. This arrangement is necessary in order that there may be room to project the picture on the photoelectric surface. The resolution of the iconoscope depends on the size of the scanning beam as well as on the size and number of picture elements in the element surface. From a practical consideration, however, the size of the scanning spot determines the number of picture elements, as shown in Fig. 432, and the number of elements in the photoelectric surface is much greater than the number of picture elements. The size of the scanning spot compared with that of a single element simplifies the "qualifications" for the elements to the requirement that there must be uniformity in the average distribution, surface sensitivity, and capacity of the elements in an area of the surface covered by the scanning spot. This requirement of uniformity is obtained by special forms of construction. The insulation between the photoelectric elements and the signal plate consists of a thin uniform sheet of mica, although the insulator may also be made of a thin film of vitreous enamel. The signal plate itself consists of a metallic coating on one side of the mica insulator. One method of making the photoelectric surface is by evaporating the photoelectric metal on the mica in a vacuum so that the metal forms small globules which are spaced uniformly and insulated from each other. The metal used is silver, and the globules are photosensitized by treating them with caesium.

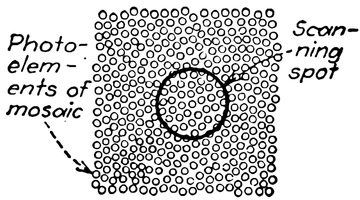


FIG. 432.—Scanning spot on photoelectric elements.

Characteristics of Photoelectric Surface.—The degree of sensitivity and of color response of the photoelectric surface is the same as that of a photocell of the caesium-oxide type (page 214) having the same vacuum. The response of the unit at the wave lengths of the spectrum is shown in Fig. 433. The cut-off shown in this figure in the blue-green part of the spectrum in the approximate region of 4,000 to 6,000 Angstrom units[1] is caused by the absorption effect of the glass. The photoelements by themselves have a color sensitivity which is indicated by the dotted line.

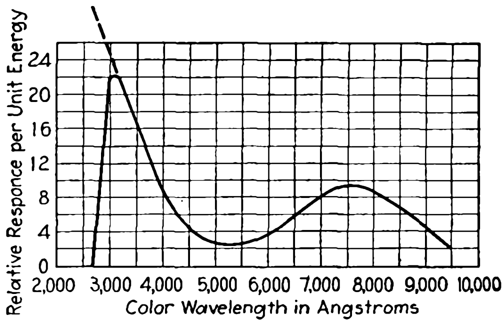


FIG. 433.—Relative response of iconoscope to color wave lengths.

Electron Gun.—An important factor in the design of the electron gun is that the size of the "cathode-ray spot" must correspond to the number of picture elements for which the system is constructed. For a photoelectric surface about 4 inches high, and for 76,780 picture elements, the distance between two adjacent lines is about 0.016 inch and the diameter of the cathode-ray spot is about half this size.

The various parts of the gun are shown in Fig. 434. These parts consist of a cathode *C*, a controlling element *G*, and two anodes *A* and *B*. The cathode *C* is of the directly heated type having the effective emitting area at the tip of the cathode sleeve. This cathode is placed so that it is near the hole *O* of the controlling element *G*. The anode *A* is a tube in which there are three holes centered on the axis of the cathode. The parts of the gun are placed in the stem of the

[1] The angstrom, a unit of light-wave length, is equal to one ten-billionth (10^{-10}) meter.

bulb which contains the photoelectric surface. The second anode, which serves also to collect photoelectrons from the photoelectric surface, consists of a metal covering on the inside surface of the stem and part of the bulb. The voltage

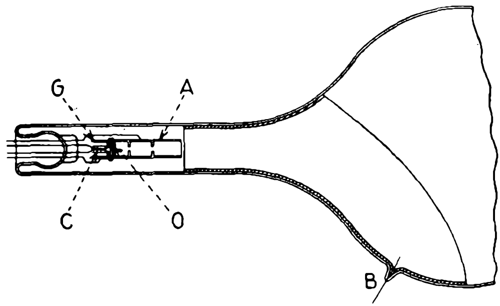


FIG. 434.—Electron gun of iconoscope.

on the second anode is about 1,000 volts, the voltage on the first anode being a small fraction of this value.

Focusing.—In this device the focusing or direction of the beam is controlled by an electrostatic field. This field is

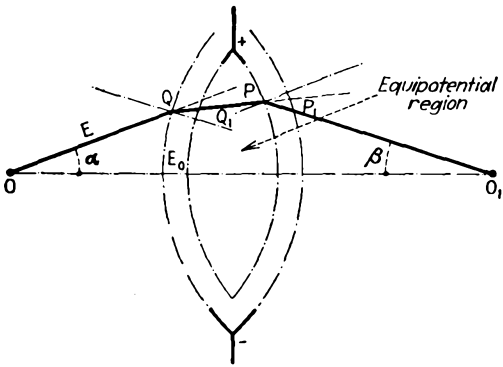


FIG. 435.—Converging and diverging effects of electrostatic field on electrons.

produced by the differences in voltage between the various parts of the electron gun, as well as by the voltage difference between the gun and the second anode *B* (Fig. 434). When an electron enters this field in a direction which is parallel to the lines of force, the velocity of the electron but not its direction will be changed. When, on the other hand, an electron enters the field at an angle, both the velocity and the direction of the electron will be changed. If the field is increasing in value, the direction of the electron is diverted toward the axis of symmetry of the field, but if the field is decreasing, the direction of the electron is diverted in the opposite direction. By means of this effect of the field, a stream of electrons can be made to change its direction. The action, as shown in Fig. 435, is somewhat like that of a lens and can be made to have either a converging or diverging effect by reversing the voltages.

Distribution of Electrostatic Fields.—A diagram showing the distribution of the electrostatic fields in the electron gun,

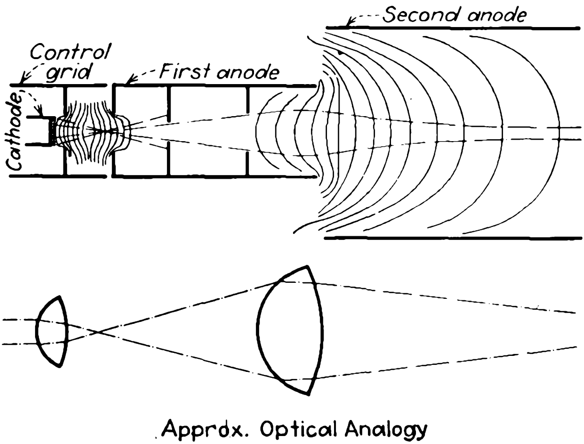


FIG. 436.—Distribution of electrostatic fields in electron gun.

and showing also the corresponding equivalent lens system, is given in Fig. 436. The first lens effect is at the cathode and shows how the electron stream is forced through the hole in the first anode under the control of the control element. Then the beam, constricted by the two other holes in the first anode, is focused by a second lens effect. This second effect is caused by the field that exists between the end of the gun and the stem of the glass bulb. Thus the factors which determine the size of the spot on the photoelectric surface are (1) the size of the active area of the cathode, and (2) the spacing between the cathode, the region of lens effect, and the photoelectric surface.

Deflection of Beam for Scanning.—In the scanning operation the direction of the electron beam must be varied both horizontally and vertically. This control is obtained by the effect of a magnetic field produced by deflection coils which fit over the stem of the glass bulb. To obtain a control of this kind it is necessary that the current producing the magnetic field be supplied by a generator of the vacuum-tube type which has a saw-toothed characteristic.

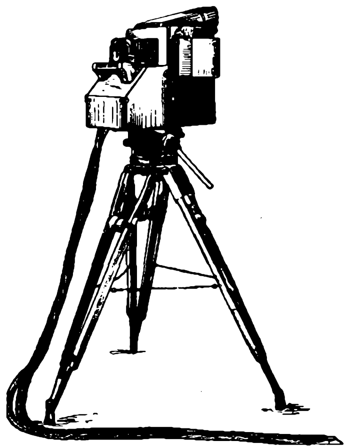


FIG. 437.—Portable iconoscope camera and pick-up equipment.

Iconoscope Camera.—For the reason that the iconoscope is sensitive to ultraviolet or infrared light as well as to the daylight spectrum (as shown in Fig. 433), it can be used for the transmission of pictures illuminated by such light and invisible to the eye.

At the present stage of development the sensitivity of the iconoscope is the same as that of a photographic film which is operated at the speed used in a camera designed for motion-picture use, assuming the same optical system for each. It is important to note that the resolution which the iconoscope possesses is higher than the requirement for transmission with 76,780 picture elements.

The iconoscope is essentially a complete pick-up unit. With this form of construction it is possible to design a portable camera which consists of the iconoscope and first amplifier stages. This camera may be connected by cables to the main units used for amplification and for beam deflection. The construction of one type of iconoscope camera is shown in Fig. 437.

Complete Transmitter.—The parts which have been described complete the apparatus in the transmitter up to the

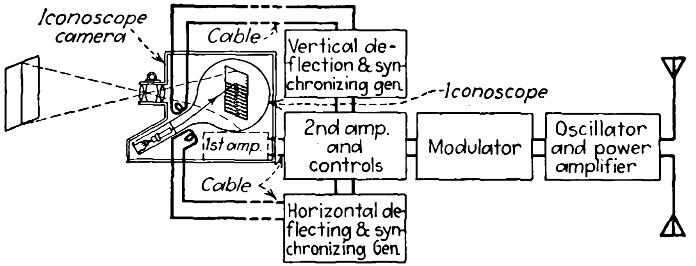


Fig. 438.—Iconoscope transmitting equipment.

point of connection with the modulator. The entire circuit of the transmitter, in diagram form, is shown in Fig. 438. It may be observed that the output of the iconoscope amplifier is passed to the modulator, to the oscillator and power amplifier, and finally is radiated from the antenna. The parts named

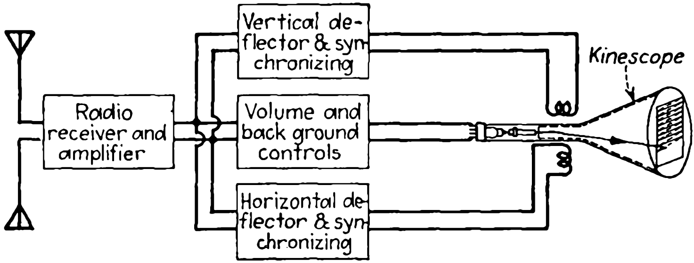


Fig. 439.—Iconoscope receiving equipment.

in order are: (1) the iconoscope camera, (2) the amplifiers for the picture-signal and for the synchronizing-signal voltage, (3) the equipment for control and adjustments, (4) the modulator, and (5) the radio transmitter.

Receivers for Electrical Television.—The circuit of the entire television receiver, in diagram form, is shown in Fig. 439. The parts of the television receiver are: (1) the radio-receiving and amplifying unit, (2) the equipment for control and adjustments, (3) the units for deflection and for synchronization, and (4) the cathode-ray unit or kinescope.

Kinescope.—The kinescope is essentially a cathode-ray tube. It differs from the oscilloscope type of the cathode-ray tube (page 221) in that it is provided with a control for adjusting the intensity of the electron beam. The tube illustrated in Fig. 440 has a flat end which is 9 inches in diameter and contains a screen that will show a 5½- by 6½-inch picture.

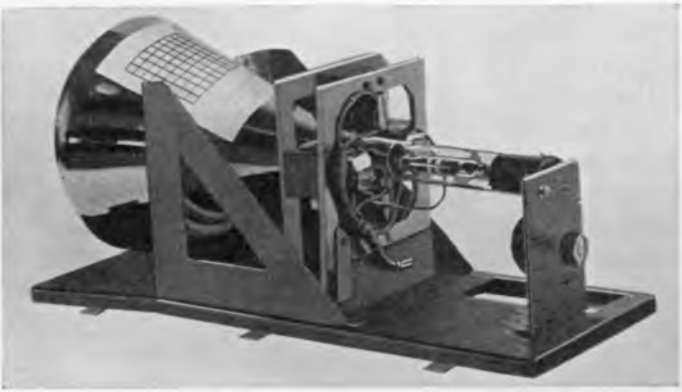


Fig. 440.—Kinescope.

The *electron gun* of the receiver is similar to the one used in the iconoscope (transmitter) and is likewise mounted in the stem of the bulb. The electrons emitted by the electron gun are accelerated and focused into a small beam by the effect of an electrostatic field that is produced by the second anode. The second anode of the kinescope, consisting of the metal coating on the inner surface of the glass stem, is operated at a voltage that is higher than the second-anode voltage of the iconoscope. The electron beam is directed so that it strikes the fluorescent screen in the flat end of the kinescope. This screen transforms electrical energy into light; consequently the action of the electron beam produces on the screen a spot of light having an area equal to that of the beam.

A means of control must be provided by which the intensity of the light on the screen can be changed. Such control is necessary for the reproduction of the changes in the intensity of light from the original picture. The device which gives this action is the control element of the electron gun. The design must be such that (1) the control effect is directly proportional to the input-signal voltage, (2) that the focusing of the spot of light is not changed, and (3) that the velocity of the electron beam is not affected. A slight change in beam velocity caused by picture modulation would produce considerable distortion of the image because the deflection of the beam is inversely proportional to the velocity of the electron beam.

Characteristic Curve of Kinescope.—The characteristic curve of the kinescope, as shown in Fig. 441, gives the relation between the input voltage, the second-anode current, and the brightness in candle-power units of the cathode-ray spot. This figure shows also the electrical circuit of the kinescope. Complete modulation of the cathode-ray beam, meaning a variation from one limit of brilliancy to the other, is obtained on an alternating-voltage input of about 10 volts.

The amount of light emitted from the fluorescent screen is directly proportional to the second-anode current. Because of this relation it is possible to reproduce all the shades between black and white that are needed for a satisfactory half-tone picture.

Fluorescent Screen of Kinescope.—The fluorescent screen is made of a manufactured zinc (ortho-silicate phosphor). This material was selected because it has suitable characteristics with regard to luminous efficiency, time lag, stability, and resistance to deterioration caused by the effect of the electron beam. The luminous efficiency is satisfactory because the peak of the light band in the spectrum is near the wave length of light to which the human eye is most sensitive. These relations are shown in Fig. 442. The spectral distribution of the zinc alloy lies in the visible region and has a peak at a wave length of 5,250 Angstrom units (page 540).

The dotted curve shows the range of wave lengths to which the human eye is sensitive. This curve has its peak at a wave length of about 5,550 Angstrom units.

The time decay curve of the light on the screen, for an ideal fluorescent material, would be such that the effective brilliancy

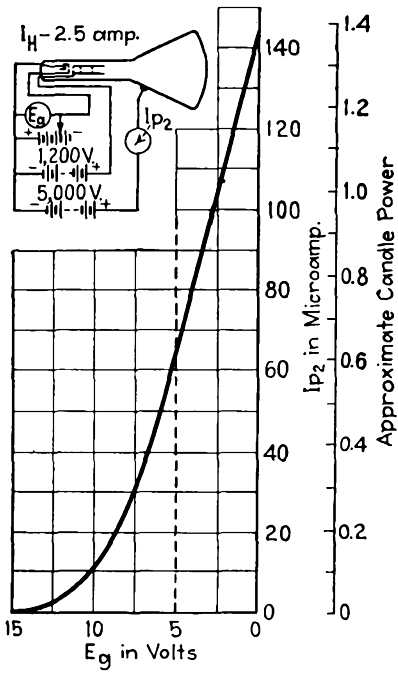


FIG. 441.—Characteristic curve of kinescope.

would be lost at the end of 1/24 second where 24 pictures are reproduced per second. The actual curve for zinc orthosilicate phosphor shows that the light intensity decreases from a maximum at excitation at such a rate that in 1/16 second the visible light is practically gone. In a time of 1/30 second the drop of light intensity in relative units is 10 to 1. If light is present for a longer time interval than 1/24 second, any element of the picture that is in motion will show in several positions—a thrown ball, for example, will appear to have a tail. If light is present for a shorter interval, the picture is black for a short period between consecutive excitations and a marked flicker is noticed.

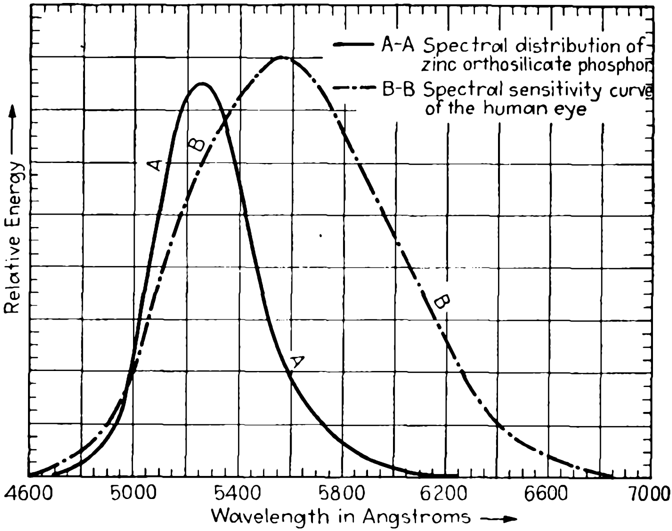


FIG. 442.—Relative energy over light band of (*A*) iconoscope, (*B*) human eye.

Electron-beam Scanner.—In this system of television the picture is scanned by an electron beam which passes over the picture, or over the fluorescent screen, in a succession of parallel horizontal lines which are equally spaced from each other. The motion of the beam is unidirectional. Thus the beam at the kinescope builds up the picture in the same manner as the beam at the iconoscope scans the picture. In this system the lines of motion travel down from the top, and the beam is turned back to the top for the next picture.

Deflection-current Generator.—The electron beam is caused to deflect in the required manner by the action of two variable magnetic fields, one for the horizontal movement, and one for the vertical movement.

In order to produce unidirectional scanning, the intensity of the two magnetic fields must vary as shown in Fig. 443.

Here the vertical scale is for field intensity, and the horizontal scale is for time. The curve *a* represents the field variations for the horizontal scanning period X, and the horizontal return period Y. The relation between the two values is

$$X + Y = 1 \div N\sqrt{nK} \text{ seconds}$$

where N = number of picture "frames" per second, n = number of picture elements per second, and K = the ratio of the dimensions of the picture. In the figure *b* represents the

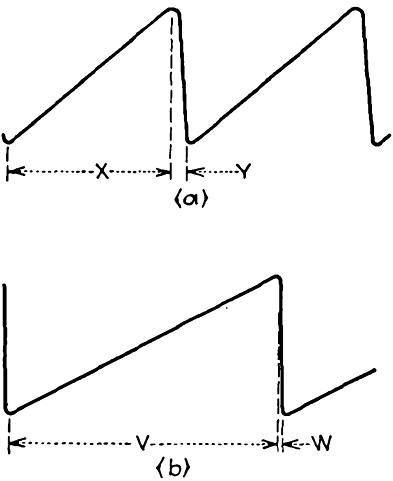


FIG. 443.—Intensity of magnetic fields for unidirectional scanning.

field variations for the vertical scanning period V, and the vertical return period W. The relation between these values is

$$V + W = 1 \div N \text{ seconds}$$

It is seen from the figure that the variation of field intensity follows a definite pattern consisting of equal cycles. The first part of a cycle shows the field variation during the linear movement of the beam in scanning, and the second or minor part of the cycle shows the variation during the return period.

The circuit for a generator which can produce a deflection current having the required "saw-tooth" form is shown in Fig. 444. The generator circuit consists of a dynatron oscillator (page 94), and amplifier discharge tubes. In the operation of this device the condenser *C* in the circuit for horizontal deflection is charged continuously by a current from resistance *R*. This condenser discharges periodically at the end of definite intervals through a discharge tube which is controlled by the dynatron oscillator. The current

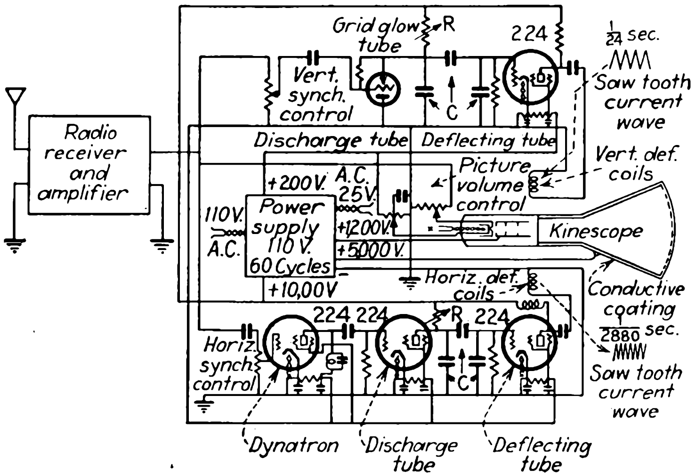


FIG. 444.—Generator for "saw-tooth" deflection current.

supplied by the oscillator has a distorted form, and a frequency equal to the scanning frequency of the transmitter. The resultant effect is that the voltage variations on the condenser, during charge and discharge, have the desired saw-tooth characteristic. These voltage variations are impressed on the grid of the deflecting tube, and the output of this tube passes to the deflecting coils. The action of the circuit that produces vertical deflection is similar to that of the horizontal deflection circuit, but it should be noted that the electrical constants of the two circuits are not similar because of the difference in operating frequencies.

Screen Pattern of Synchronization.—When picture signals are not applied to the kinescope, the screen shows a pattern which is made up of a number of parallel lines. The sharpness of the pattern may be taken as an indication that the deflection circuits are correctly adjusted and that exact synchronization with the transmitter has been obtained. The quality of the reproduced picture is dependent on these adjustments.

Synchronizing Signals.—The radio transmitter is modulated by three signals, namely, the picture signal, the horizontal

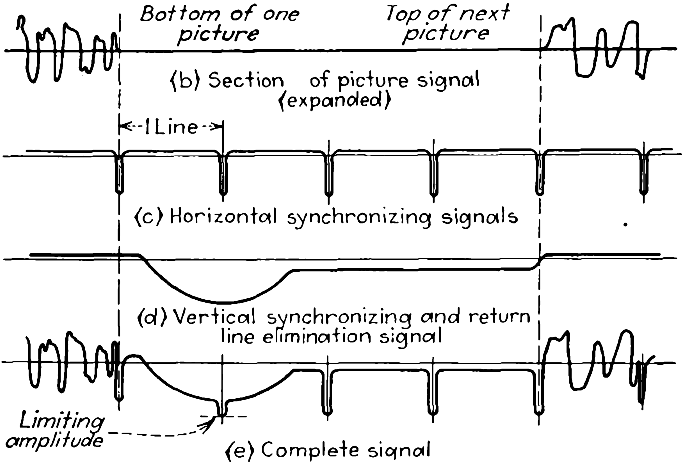


FIG. 445.—Diagram of synchronizing signals in iconoscope.

synchronizing signal, and the vertical synchronizing signal. The horizontal synchronizing signal is transmitted at the end of each line, and the vertical synchronizing signal at the end of each frame. The synchronizing signals, produced by the deflection generators, are applied to the amplifier and combined with the picture signal. This does not cause any interference because the synchronizing signals occur during the interval when a picture is not being transmitted. A diagram of these signals, separately and in combination to form the complete signal, is shown in Fig. 445. The complete signal is applied to the grid of the modulator in the receiving apparatus. It should be noted that the three signals differ in amplitude and frequency. The amplitudes of the two synchronizing signals are equal and their peaks are on the negative side of the axis. The peak of the picture signal is maintained at a value less than that of the synchronizing signals.

Separation of Signals at Receiver.—The receiving equipment is arranged so that the signals after passing through the radio receiver and amplifier, are applied to three units which are independent of each other. These units are the horizontal deflecting circuit, the kinescope, and the vertical deflecting circuit. Each unit must be so designed that it responds to its corresponding signal only.

The picture on the kinescope is not affected by the synchronizing signal voltages because they occur when the electron beam is extinguished, during its return period; and the deflecting circuits are not affected by the picture-signal voltage because the picture-signal amplitude is below the value to which the input tubes will respond. The input circuit of each deflecting unit contains a filter which admits the synchronizing signal intended for that unit but rejects the other. Additional selectivity in these units is obtained because the plate circuit of each dynatron input tube is designed to be resonant to the desired signal.

Voltage of Grid-bias Kinescope.—The *return line*, as it appears in the received picture, is produced when the electron beam is moved back to the position from which a new scanning line is begun. The return line can be eliminated if the electron beam is extinguished during its return swing. The negative grid-bias voltage that must be applied to the control electrode of the kinescope to produce this result is obtained by utilizing the negative impulses of the synchronizing signals. The grid-bias voltage thus applied to the kinescope affects the degree of contrast that appears in the picture through control of the background or average illumination. The most favorable condition is obtained when the grid-bias voltage is such that the picture signals have the maximum swing on the characteristic curve of Fig. 441.

Television Receiver and Reproducer.—The deflecting unit and kinescope of a television receiver based on this system are shown in Fig. 446. This chassis is designed for the cabinet of Fig. 447 which contains the complete recover consisting of a power unit, a television-reproducing unit, a receiving unit for picture signals, and an independent radio-broadcast receiver.

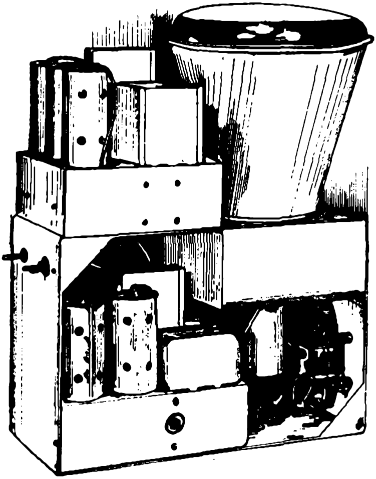


FIG. 446.—Deflecting unit of iconoscope.

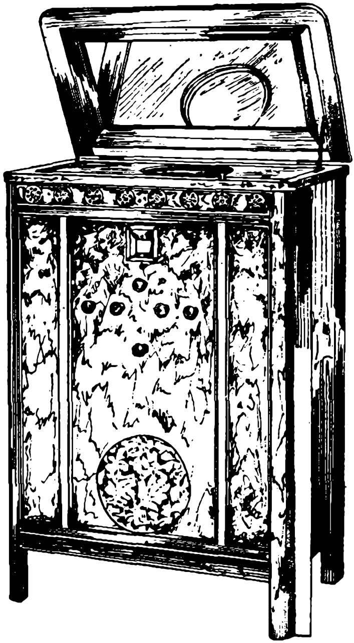


FIG. 447.—Iconoscope receiver and cabinet.

The underside of the cabinet lid is fitted with a mirror which reflects the picture on the screen located in the top panel of the cabinet. With this arrangement a greater and more convenient viewing angle is obtained, and the viewing surface is shielded from external illumination.

CHAPTER XIII

INDUSTRIAL APPLICATIONS OF VACUUM TUBES

The applications of electronic tubes for industrial-control purposes may be classified[1] in a few main groups. The applications described here include photoelectric control, electronic relays, electronic regulators, welding timers,[2] equipment for power services, indicating and measuring circuits, medical applications, communication systems, and aids to air navigation.

Photoelectric-control Applications.—The photoelectric tube is used instead of mechanical or electromagnetic equipment for many industrial-control applications in which the variations to be controlled cannot readily be changed into mechanical or electrical forces, or do not provide enough energy to operate the control devices.

Counting.—A simple type of photoelectric device can be used for the counting of movable objects, or to indicate a break in the continuity of a manufacturing process. Examples of the latter application are the *paper-break indicator*, and the *steel-mill shearing-machine operator*. A wiring diagram for this type of device is shown in Fig. 448. The photoelectric tube acts on a grid-controlled, glow-discharge tube which serves to amplify the weak photoelectric current. This amplified current then is used to operate relays and contactors. Two methods of connection are possible. In one the arrangement is such that the glow-discharge tube breaks down and supplies a current for the relay if the illumination on the photoelectric tube is increasing. In the other the relay

[1] A comprehensive list of 338 applications of electronic tubes, classified in 16 groups, is given in *Electronics*, January, 1935.

[2] GULLIKSEN and STODDARD, "Industrial Electronic Control Applications," *Elec. Eng.*, January, 1935.

is designed to operate if the illumination is decreasing. The equipment shown in Fig. 449 illustrates the use of a photo-

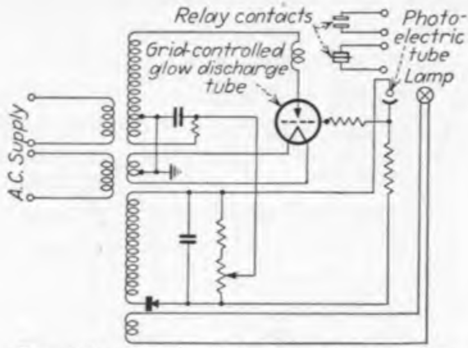


FIG. 448.—Circuit of photoelectric controller.

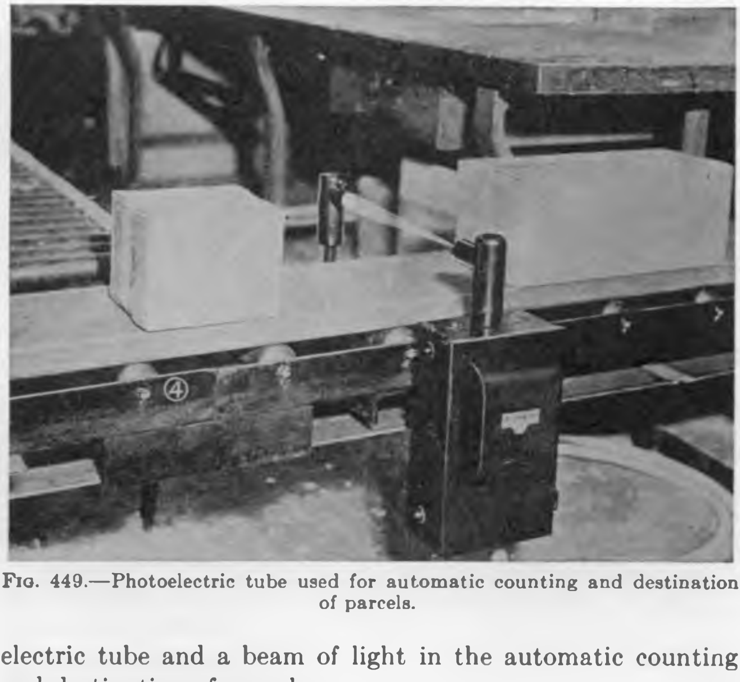


FIG. 449.—Photoelectric tube used for automatic counting and destination of parcels.

electric tube and a beam of light in the automatic counting and destination of parcels.

Inspection.—In some applications of such tubes for inspection purposes, the time available for inspection is so short that self-locking photoelectric equipment must be used. Apparatus of this type was developed in connection with a labeling machine for nail-polish bottles. The diagram of the circuit is shown in Fig. 450. The rate at which the

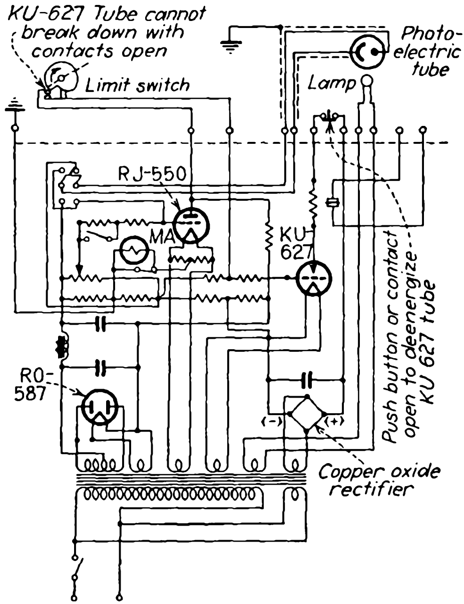


FIG. 450.—Lock-in type photoelectric controller with amplifier tube.

bottles pass through the labeling machine is one bottle per second. A different type of label is used for each shade of nail polish. The labels were received in sets of one thousand copies, and a set might contain a number of unmatched labels. It was found that the labels could be sorted more economically at the labeling machine than by the printer.

In the labeling operation, the bottles traveled intermittently on a conveyor past the label container. When the travel ceased, the label container moved horizontally towards the line of bottles. Each bottle previously had received a coat of glue on the side which was to be labeled. Thus, when the label container was moved up to a bottle and pressed against it, a label was attached to the bottle. Then the label container was moved away and remained stationary for 0.3 second while the labeled bottle passed on and a new one took its place. While the label container was in the stationary position for 0.3 second, a photoelectric scanning device was moved up to it to inspect the label that would be attached in the next operation.

The inspection was carried out with the aid of a special mark on the rear side of the label. This mark consisted of a black spot printed in a different position on each one of the eight labels corresponding to the eight shades of polish. In the operation of the scanning device a beam of light was directed to fall on the black spot of the label. If the proper label was in the container, the black spot would be correctly placed, no light would be reflected from the black spot to the photoelectric tube, and the photoelectric-control device would not operate. If, however, the proper label was not in the container or if the label was not in the right position, the black spot would be out of line with the light beam. Then light would be reflected to the photoelectric tube, and the photoelectric control would give a signal so that the machine operator could remove the bottle that would be labeled incorrectly.

Paper-cutter Control.—A control device for the intermittent type of paper-cutting machine has been developed which utilizes a spot printed on the paper as a means of stopping the travel of the paper while the cutting is performed. The action of the control device is used to deenergize a clutch between the driving mechanism and the rolls which cause the motion of the paper.

A circuit diagram of the device is shown in Fig. 451. This photoelectric controller is intended to supply a direct current to a relay, and to interrupt this current when there is a decrease in the intensity of illumination on a photoelectric tube in the device. The *anode circuit of tube A* is connected in such a way that when the anode current decreases, tube *B* will break down. A potentiometer and a resistance are connected in series with the *anode circuit of tube B.* The voltage drop across these units is applied to the grids of the tubes marked *C*. Before the tube *B* breaks down, the grid voltage on the tubes *C* has a zero value, and consequently the current flowing through

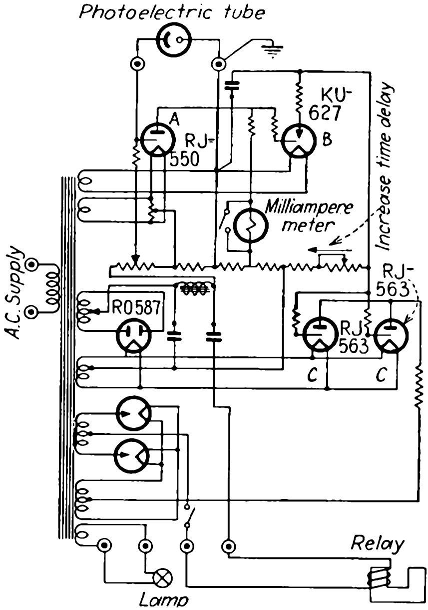


FIG. 451.—Photoelectric controller with time delay.

the tubes *C* and through the relay is at its maximum value. When the tube *B* breaks down, the condenser in parallel with the tube *B* discharges through the tube *B* until the voltage across the tube falls to about 15 volts, which is the value of the "arc drop" in the tube. At this value the discharge current ceases and the condenser begins to charge up through the resistance. Thus, when the tube *B* breaks down, a high negative voltage is applied to the grids of the tubes *C* and the relay current drops to zero. In the meantime, the condenser charge is increasing, the negative voltage on the grids of tubes

C is decreasing, and the relay current is increasing. After a certain period of time, determined by the setting of the *delay* potentiometer, the relay current will rise to its maximum value.

Lighting Control.—A photoelectric control device may be used to turn electric lights off and on depending on changes in the intensity of natural light. The applications range from the elimination of twilight-zone lighting, to the control of illuminated signs and display areas so as to produce a maximum of advertising value. Artificial light control devices have been installed for offices, industrial plants, show windows, schools, signs, flood lights, street lights, navigation lights, and airway and airport lighting.

In the operation of this device the variations in the intensity of light, acting on a photoelectric tube, produce a varying voltage which is impressed on an amplifier tube that is used to operate a relay. The relay in turn operates the main contactor. It was found necessary to introduce between the relay and the main contactor a *time-delay action* which would be effective in providing a delay of several seconds on both the opening and closing movements. With this provision the device is prevented from operating when someone walks in front of the unit or when there is a flash of lightning.

If there is a breakdown or failure of the amplifier or of the photoelectric tube during a period of darkness when the lights have been turned on, the lights will stay on, but the failure will not be indicated until there is a change in light intensity normally sufficient to cause the device to operate. A wiring diagram of the device is shown in Fig. 452. Two dials are provided for the necessary adjustments. One dial is used to set the intensity of light at which the device will close the lighting circuit, and the other dial to set the intensity at which the lighting circuit is opened.

Color Matcher.—A color-matching device, indicated schematically in Fig. 453, contains a "matching" circuit which consists of a photoelectric tube, an amplifier tube having low-grid-current characteristics, a coupling circuit, a means of adjustment for sensitivity, and a set of three color screens. The amplifier tube is connected to a meter or measuring device which serves to give an indication of the amount of

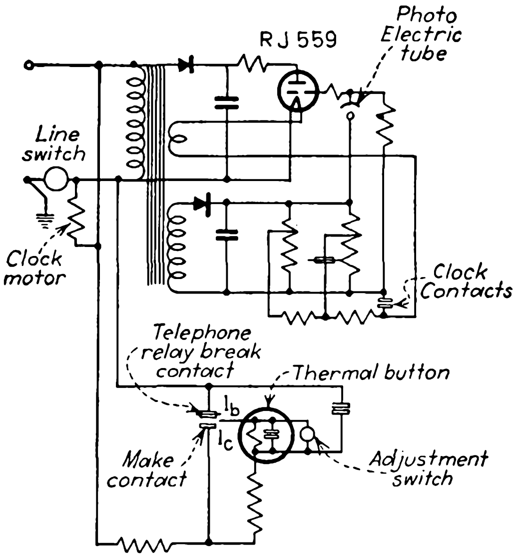


FIG. 452.—Circuit diagram for lighting control.

light reflected by a sample put into the device. The necessary voltages for the anode and grid circuits of the tubes are provided by a rectifier tube and filter. The illumination is furnished by an electric lamp of the incandescent-filament

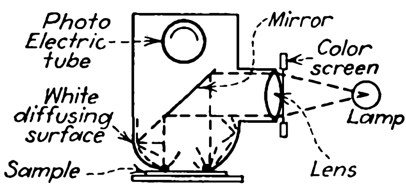


FIG. 453.—Arrangement of photoelectric tube and optical system for color matching.

type. The high degree of sensitivity makes necessary a provision for close regulation which is obtained by means of a voltage regulator. With the use of the color screens a comparison can be made between a sample and a standard in any one of three spectrum bands—blue, green, and red.

In the operation of the device, the light passing through the color screen is focused by a lens on the mirror and directed toward the sample. The light reflected by the sample is used to operate the photoelectric tube. Thus the indication of the measuring device or meter shows the amount of light of a given color that is reflected by the sample.

Temperature Control.—Another application of photoelectric equipment is in the pyrometric control of temperature. A

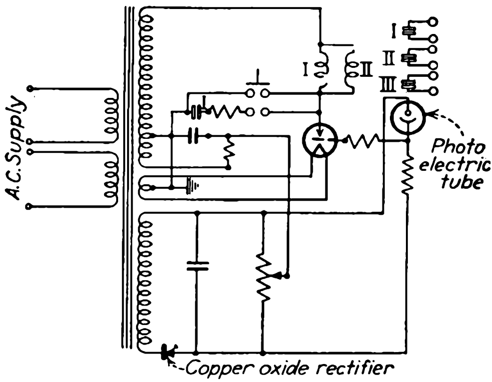


Fig. 454.—Circuit diagram for heater control.

device designed for the automatic control of an electric heating furnace is shown by the wiring diagram in Fig. 454, the device being operated from the light emitted by the metal being heated. In the operation of this apparatus, the light from the hot metal reaches a photoelectric tube, the output of which is sent directly to a grid-glow tube. The grid-glow tube operates a contactor which is arranged to control the power supply to the heater. The equipment is designed so that the power supply can be turned off when the metal being heated attains a brilliancy corresponding to any predetermined temperature. The power supply is turned on manually, and not automatically, by the control device.

Concentration Control.—In many electrochemical processes it is necessary to test the concentration of liquids at definite intervals for control purposes. This procedure, when carried out manually, is expensive, and the accuracy obtained depends on the human element. The photoelectric device for concentration control was developed primarily to serve as an indicator but can be used in a modified form as a regulator. A typical circuit diagram is shown in Fig. 455. The principle of operation depends on a comparison of the light reflected from a *standard* sample with the light reflected from the *process* sample. A light chamber is so arranged that the standard sample is located on one side, and the substance to be tested

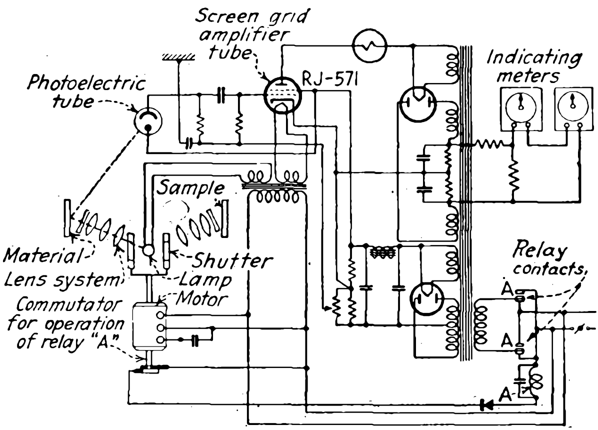


FIG. 455.—Circuit diagram of concentration indicator.

flows past the other side of the control device. A lamp and lens system is used to provide two beams of light, one of which is directed toward the standard sample and the other toward the process sample. The light reflected from the samples is directed to the photoelectric tube. The shutter surrounding the lamp is turned by a synchronous motor and acts to interrupt periodically the beams that light the samples. The voltage produced by the photoelectric tube is applied to the grid of the screen-grid amplifier tube. The output of the amplifier tube operates an indicating meter.

Thus a beam of light is directed alternately to the standard sample and to the process sample and the light that is reflected to the photoelectric tube comes alternately from the standard sample and from the process sample. If the color of the process sample is the same as that of the standard sample, the photoelectric tube will receive the same amount of illumination during each half of its voltage wave. Under these conditions the output of the amplifier produces a zero indication of the meter. But if the colors of the two samples do not match, the illumination on the photoelectric tube is greater in one cycle than in the other. Under these conditions the meter indicates how the color of the standard sample varies from that of the process sample.

Electronic Relays.—Another general group of devices utilizing electronic tubes is that known as electronic relays. The tube generally used in electronic relays is of the grid-controlled glow-discharge type (page 186). Electronic relays are being developed for control applications in industrial processes and in central-station work.

Synchronizing Relay.—Devices of this kind, because they possess superior operating characteristics, are replacing electromagnetic relays formerly used for the same applications. The equipment shown in Fig. 456 is a synchronizing relay with a low energy rating and is intended for operation from condenser bushing potential devices.

The feature of this design is the *proportional-advance* characteristic. The effect of this characteristic is that the relay which closes the circuit breaker is energized a definite time interval before the instant of phase coincidence corresponding to the breaker-closing time. Consequently when the contacts of the circuit breaker are closed, the value of the equalizing current, at the time when parallel operation goes into effect, is at a minimum. Further, this condition is obtained regardless of any difference in frequency.

Time-delay Relays.—In comparison with mechanical and electromagnetic relays, the electronic time-delay relay has the advantages of wide range, ease of adjustment for time delay, accuracy, and low cost of maintenance.

The equipment shown in Fig. 457 is designed so that the relay will stay closed during a definite time interval ranging

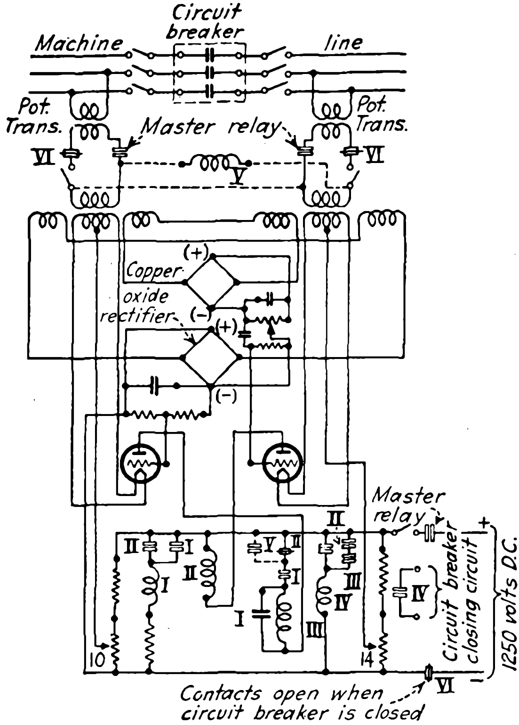


FIG. 456.—Circuit diagram of synchronizing relay.

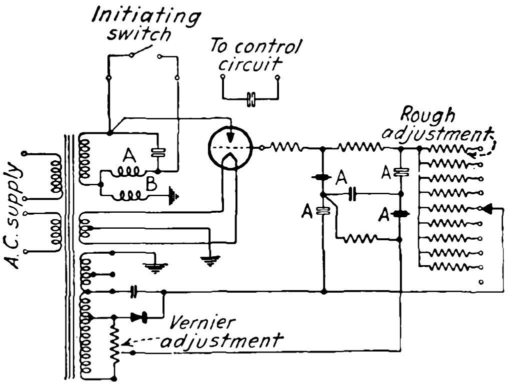


FIG. 457.—Circuit diagram of electronic timer.

from 0.1 to 40.0 seconds. The arrangement which provides the timing action is for all practical purposes independent of voltage variations and is not influenced by changes in the temperature of the surroundings.

Relay *A* is used for changing internal connections, and relay *B* for external connections. The timing effect is obtained by the use of a grid-controlled glow-discharge tube in connection with a condenser-discharge circuit. Under the condition when both relays are open, there is no current in the tube, but the condenser is being charged. The rise of charging voltage is controlled by the setting of a potentiometer. The

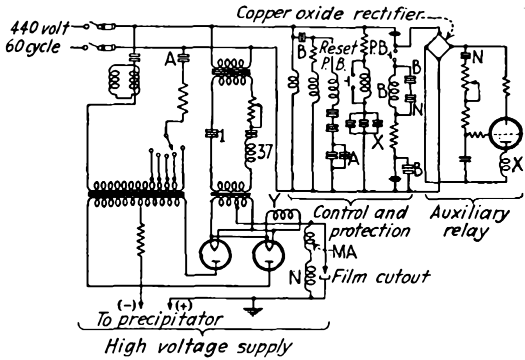


FIG. 458.—Circuit diagram of precipitation apparatus.

closing of the initiating switch causes relay *A* to close, thus reversing the connections of the condenser. Under these conditions there is a flow of current through the tube to relay *B* which will close. This relay stays closed during the interval in which the condenser is discharging. The discharge continues until the condenser voltage drops to the value at which the tube will not allow the flow of current.

Precipitation Control.—In the operation of precipitation equipment there is need for protection against short-circuit conditions. Such protection is provided by a special design of integrating time-delay relay. A circuit diagram of the control device is shown in Fig. 458. The device consists of a cold-cathode, grid-controlled, glow-discharge tube (page 563), a condenser, resistance units, and an auxiliary relay X.

In the operation of this device the master relay B is deenergized through one set of contacts of the overload relay N. At the same time the circuit containing the condenser and the resistances is energized through the *other* set of contacts of the overload relay N, so that the condenser voltage builds up to a certain value, but not to a value that is high enough to allow the tube to discharge. This condition, however, is temporary only, because when the plate-supply contactor A opens, the main current is cut off and the overload relay is reset. In the meantime the charge on the condenser is dissipating but at a very slow rate. Finally, after a short period of time the plate-supply contactor closes again. Then, if the condition which caused the short circuit is still present, the same sequence of events takes place. Now, however, the energy put into the condenser acts in addition to the energy still stored, and the condenser voltage increases. If the short-circuit condition persists, the repeated opening and closing of the circuit build up the condenser voltage to a value at which the grid-controlled glow-discharge tube will discharge between the anode and the cathode. This discharge energizes the auxiliary relay X. The lock-out relay is energized through the contacts of the auxiliary relay and seals its own circuit. The circuit of the plate-supply contactor A is kept deenergized through one of the contacts of the relay. Consequently the relay must be reset manually before the equipment can be put back into service.

Electronic Regulators.—A factor which must be considered in the design of automatic regulating equipment is the amount of energy available for operation. In this respect the energy requirement of most electromagnetic regulators is about 100 voltamperes, while that of electronic regulators is about 1 microwatt. Other advantages of the electronic regulator are: the wide variety of indicating elements that are available, a quick-response characteristic, and extremely high sensitivity. As compared with the electromagnetic regulator which is limited to the use of the electromagnetic solenoid as an indicating element, the electronic regulator has a choice of indicating circuits ranging from devices controlled by photoelectric tubes to those depending on resistance or capacity effects. The quick-response characteristic of the electronic regulator is due to the absence of moving parts with their attendant friction losses and inertia effects.

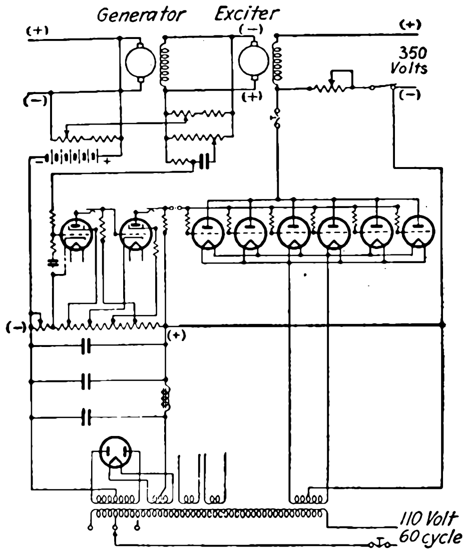


Fig. 459.—Circuit diagram of voltage regulator (electronic type) for direct-current generators.

Voltage Regulator for Direct-current Generators.—The standard voltage regulator of the electromechanical type is suitable for the regulation of the voltage of direct-current generators in applications where a sensitivity of 1 per cent is acceptable. In certain applications, however, a sensitivity of 0.1 per cent is needed. For such service a voltage regulator of the electronic type is used because of its high sensitivity and its quick-response characteristic.

A wiring diagram of a voltage regulator of the electronic type for direct-current generators is shown in Fig. 459.

Speed Regulator for Direct-current Motors.—A difficult problem of speed regulation occurs in the case of a paper machine driven by a single motor where a wide range of speed, for example, 12 to 1, is required. The difficulty arises because the characteristic of the drive is not the same at one end of the speed range as it is at the other end. For such service a regulator of the mechanical type may not be satisfactory, because if the device is adjusted at one speed, the regulation may be unstable at another. This difficulty does not apply

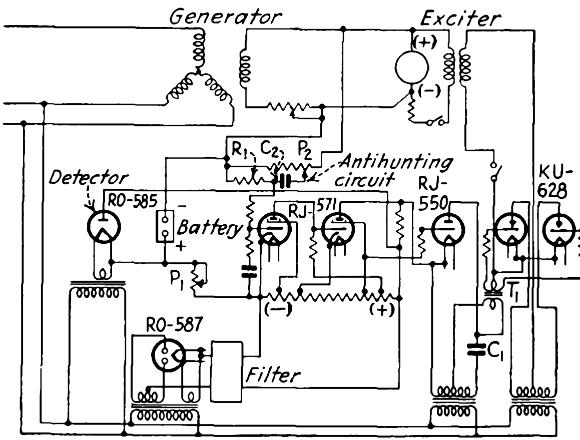


FIG. 460.—Circuit diagram of voltage regulator for alternating-current generators.

to the electronic regulator because this type can provide sufficient anti-hunting action to stabilize the equipment at any point in the range of operation.

The speed regulator of the electronic type consists essentially of a voltage regulator as designed for direct-current generators. In the operation of this device a pilot generator is coupled to the motor and the voltage produced by this pilot generator is applied to the regulator. The arrangement is such that when there is an increase in the voltage of the pilot generator, the armature voltage of the generator which supplies the motor power is decreased. Consequently the motor speed is decreased until the normal value is reached.

Voltage Regulator for Alternating-current Generators.—The wiring diagram shown in Fig. 460 is for a voltage regulator to be used with an alternating-current generator. In this case the generator is used for lamp-testing service in which a very high sensitivity is required. The sensitivity obtained with this device is about 0.1 per cent. For applications in which the sensitivity need not be so high it is possible to utilize a simpler type of regulator by eliminating the battery and by using only one control tube and two power tubes.

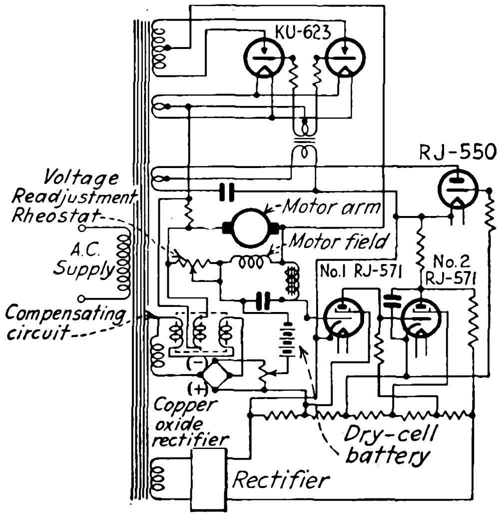


FIG. 461.—Circuit diagram of voltage-controlled rectifier for motor operation.

Supply-voltage Control for Motor Circuits.—In some industrial applications it is desirable to operate a motor of the direct-current type from an alternating-current source of supply. For this purpose it is necessary to rectify the alternating current and to maintain a supply of power at constant voltage.

A wiring diagram of a device developed for this application is shown in Fig. 461. This device is essentially a voltage regulator. Tubes of the grid-controlled, glow-discharge type (page 566) are used to provide a rectified voltage at a constant value. The design is such that the voltage level is maintained regardless of variations in the alternating-current supply. If a compound characteristic is desired so that the voltage applied to the motor will increase as the load is increased, a compensating circuit may be added to the regulating device.

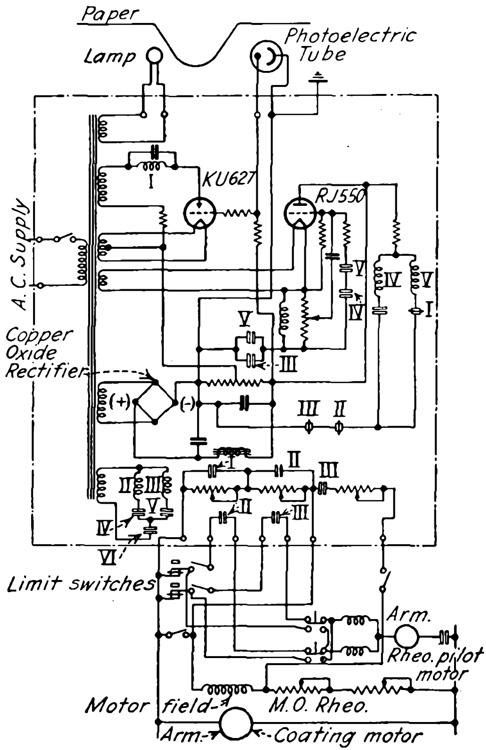


FIG. 462.—Circuit diagram of regulator of paper-coating machine.

Speed Regulator for Paper-coating Machine.—At a certain stage of operation in a paper mill, the paper in its travel between the coating machine and the drying oven must hang loosely in loop form. The paper as it leaves the coating machine is wet and will tear if too much tension is applied. The problem is to regulate the speed of the motor, which drives the coating machine, in order that the loop may be kept at the proper length. If the loop is too short, the paper may tear, and if the loop is too long the paper may drag on the floor. The use of a mechanical device to be operated by the paper is not practical because the paper lacks the necessary strength.

The device developed for this application consists of a photoelectric relay in connection with an electronic regulator of the vibrating type. The wiring diagram of the circuit is shown in Fig. 462. The circuit is connected to the field of the motor which drives the coating machine. The action is

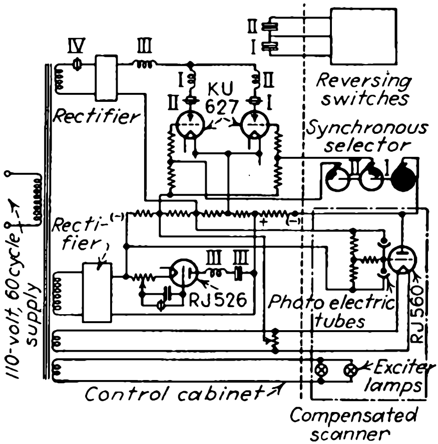


FIG. 463*a*.—Circuit diagram of regulator with compensated scanner.

such that when the loop of paper is too short, the light from a lamp reaches the photoelectric tube. Then the relays I, II, and IV are deenergized, and the speed of the motor is increased.

Automatic Register Regulator.—One operation in the paper-finishing industry involves the cutting of printed paper in such a manner that the cut will maintain a required register or position with respect to marks or designs on the paper. The control of the position of the paper with relation to the cutter is obtained by means of an electronic register regulator.

A wiring diagram of the circuit is shown in Fig. 463*a*. Spots are printed on the paper so that each spot is fixed with relation to the design on the paper. In the operation of this device a beam of light is directed toward the spot on the paper and is reflected to a photoelectric tube. The output of the photoelectric tube is applied to an amplifier tube which is arranged to act on a selector switch geared to the paper cutter, in order to give an indication of the position of the paper with relation to the cutter. The control relays are used to correct the paper speed by means of a mechanical differential.

Register Control.—The design on a printed web that is run into a processing machine must be kept in register with the cutter. To maintain the cut in proper register some provision must be made for controlling the feed of the web. The slightest error in the relation between the travel of the feed roll during one cycle of operation and the spacing of the printing on the web will accumulate so that in a short time the cut is made through the design. Errors of this kind may be caused by web stretch, by shrinkage due to atmospheric changes, or by variable tensions. Adequate control is obtained if there is provision for varying the angular relationship between the draw roll and the cutting roll.

In the application of photoelectric equipment for register control a small register mark is printed on the web. When the web is transparent the light source is mounted on one side of the web, and the photoelectric tube on the other side. When the web is opaque, both the light source and the photoelectric tube are on the same side of the web, and an optical system is used to project an image of the illuminated section of the web on the photoelectric tube. The register mark should be printed with dark-colored ink on a light background because the photoelectric tubes generally used are most sensitive to light at the red end of the spectrum and hence sufficient contrast might not be obtained with red or light brown marking. The length of the mark in the direction of the web travel need not be more than about 1/32 inch, but the width should be from 1/4 to 1/2 inch so that sidewise movement of the web will not remove the mark from the scanning region of the photoelectric tube.

When the mark passes beneath the photoelectric tube, an electrical impulse is produced which may be amplified and used to indicate the time of passage of the mark by means of the arrangement[1] shown in Fig. 463*b*. The amplified impulse from the photoelectric tube is impressed on the circuit of a timing or selector switch. This timing switch is driven from the cutter roll, and consists of two circuits designed to indicate whether the mark passes before or behind its proper point in the operating cycle. If the photoelectric tube impulse reaches the timing switch when both its circuits are open, no regulating action takes place. If the register mark arrives late, an impulse is applied to the grid of one of the thyratron tubes with the result that the web feed drive is speeded up. If the mark arrives early, the drive is slowed down.

The thyratron tube acts as a contactor in a direct-current circuit. When the grid of the tube is negative, there is no current flow between the anode and the cathode. When the grid becomes positive with respect to the cathode, the anode current is established, and thereafter the grid loses its control action. Thus a very quick impulse on the tube grid has a trigger effect in establishing a current flow. This action must take place in 0.0005 second in order to indicate an error of 0.05 inch with a web travel of 100 inches per second.

The thyratron anode current is used to energize relays in the anode circuits. These relays in turn act on motors, contactors, or other devices, which are needed to advance or to retard the position of the cut-off, and to make the required adjustment of speed. After the correction has been accomplished, a definite time relay or other circuit-opening device acts to open the thyratron anode circuits. Then the thyratron grids regain their control and no anode current flows until another photoelectric-tube impulse is applied through the timing switch.

Frequency Regulator.—A regulator of the electronic type for frequency control has been developed in which an electromagnetic indicating instrument is used in connection with a

[1] *General Electric Review,* April, 1934.

photoelectric amplifier. The frequency-indicating element is a resonant circuit meter with a fixed and a moving coil,

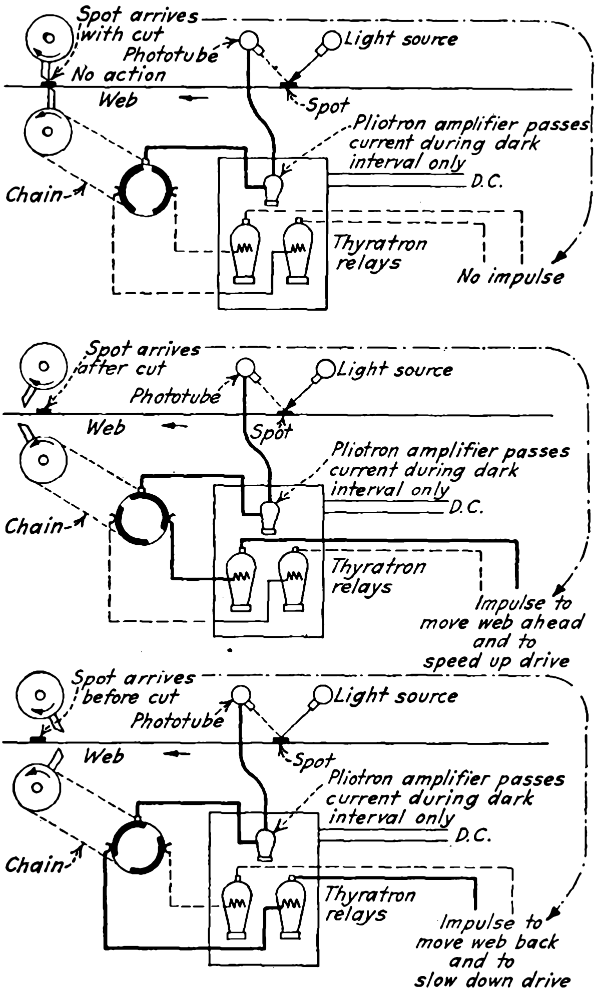


FIG. 463b.—Arrangement of apparatus for register control.

having a mirror mounted on the shaft connected to the pointer. Two light beams are directed toward this mirror and reflected to two photoelectric tubes. When the pointer of the meter is in the center position, corresponding to the frequency standard, there can be no light on the photoelectric tubes. But when the pointer moves, a beam of light reaches one of the photoelectric tubes which then produces a current flow in a grid-controlled glow-discharge tube. The current from this tube is passed through relays to control a speed-changer motor. Provision to prevent hunting is obtained by means of a rotating disk which is so placed that it will intercept the beams of light. The speed of the disk is such that the period of time, during which the photoelectric tube is illuminated, is proportional to the deflection of the meter pointer. Consequently the time of governor correction bears a definite proportion to the error in frequency regulation.

Electronic Timer for Spot Welding.[1]—In spot welding the required current is obtained by means of a transformer which reduces the commercial voltage to a value of a few volts. For a satisfactory weld both the magnitude and duration of the current must be under accurate control. If the time is short and the current high, a weld of small area is obtained which is weak under shear. If the time is long and the current low, the weld area is greater, but burning and warping of the metal may result. Because of these limitations a welding timer should be designed to afford control of both the magnitude and duration of the current in accordance with the physical and chemical properties of the metal.

With electromechanical contactors to make and break the current in the primary winding of the welding transformer the duty on the mechanical switch in high-speed service is severe and results in high maintenance costs. Also any inaccuracy in the timing obtained with a mechanical switch reduces seriously the strength of the weld.

The electronic timer developed for light-duty spot welding control is based on the action of the so-called "*ignitron*" tube. The function of the timer, as illustrated in Fig. 464, is that of

[1] Stoddard, R. N., "New Timer for Resistance Welding," *Elec. Eng.*, October, 1934.

a single-pole, single-throw switch placed in the primary winding of the welding transformer. Two ignitron tubes are connected in parallel and in inverse relation, and are also arranged to make and break the current. An *ignitron tube* is a rectifier of the cathode type with a mercury pool. It has the characteristics of the usual pool type but not the crest-current limitations of the hot-cathode type. In the ignitron tube an *ignition electrode* or crystal touches the mercury pool,

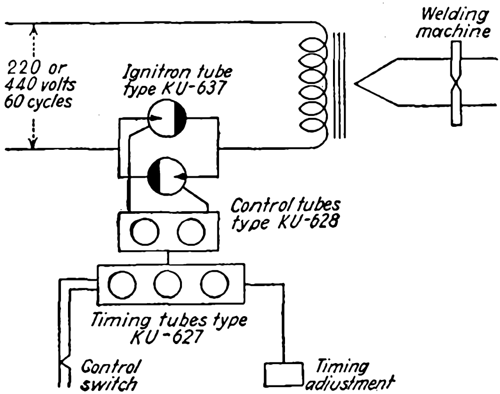


FIG. 464.—Layout of equipment using ignitron timer for spot welding.

and a small ignition current serves to put the tube into operation for a loop of welding current. If half a cycle of current is started in one of the tubes, the current will continue to flow until the arc is extinguished at the end of the loop. When the welding contacts are closed, either manually or automatically, the welding current starts at a predetermined point on the voltage wave and flows for a predetermined number of cycles.

The complete wiring diagram is shown in Fig. 465. The timing tubes are marked T, T_2, and T_3. The control tubes T_4 and T_5 control the ignition electrodes in the ignitron tubes A and B. The timing tubes and the control tubes are of the hot-cathode, grid-controlled mercury-vapor arc-discharge type and are provided with a time delay relay to protect the cathodes during the heating-up period. With this type of tube the application of a zero or positive voltage to the grid causes breakdown, and a negative voltage brings about "blocking." Power for the "initiating" tube T is obtained from a source of alternating-current supply which is in synchronism with the source of power for the welder. The phase of the voltage applied across the grid-cathode circuit of tube T may be varied by means of the resistor R_6 and the capacity C_1. When the grid of this tube is positive, breakdown occurs at a controllable point in the secondary winding of transformer E. Thus by the action of the tube T, the welding

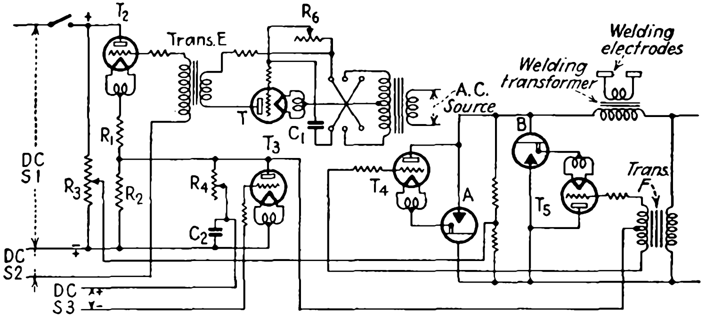


FIG. 465.—Circuit diagram of ignitron timer for spot welding.

current can be initiated at the zero point of current on the voltage wave, or at the correct value of power factor.

When the weld-initiating switch is closed, a surge of grid voltage on tube T is transmitted through the transformer E to the "starting" tube T_2 which breaks down and starts the flow of welding current. Before this action takes places the tube T_2 is kept blocked by the negative voltage applied to its grid through the connection at S_2. When tube T_2 breaks down, the flow of current in the circuit produces a voltage drop across R_2 which is applied as a positive grid-bias voltage to the grids of the tubes T_4 and T_5 to cause their breakdown. The flow of current from these tubes provides the ignition current for the ignitron tubes A and B which then cause the flow of the welding current.

Before the starting tube T_2 breaks down, the tubes T_4 and T_5 are blocked by means of a negative grid-bias voltage that is obtained through a connection to the cathode circuit of tube T_2. After tube T_2 breaks down, this grid-bias voltage for tubes T_4 and T_5 becomes positive. Transformer F and the potentiometer are used to counteract the alternating voltage which would otherwise act on the grids of tubes T_4 and T_5 because of their position in the circuit. The ignition current provided by tubes T_4 and T_5 for the ignitron tubes A and B continues to flow, increasing in magnitude, until the main ignitron anodes take the load. At that point the control tubes T_4 and T_5 are short-circuited and the flow of ignition current ceases.

The "stopping" tube T_3 normally is supplied with a negative grid-bias voltage through the connection at S_3. When the starting tube T_2 breaks down, a charge begins to build up on the timing condenser C_2 through the resistance R_4. The values of C_2 and R_4 can be selected so that after a predetermined interval of time the charge on C_2 will counteract the negative grid-bias voltage S_3 on the stopping tube T_3 which then breaks down. The effect of this breakdown is that R_2 is short-circuited, the grid-bias voltage on the control tubes becomes negative, and the flow of welding current ceases. Since the ignitron tube when once "ignited" will pass current to the end of the half cycle, the cut-off can occur within the last half of any desired cycle of welding current. Before the next weld the condenser C_2 must be discharged, and the control switch must be opened in order to block the tubes T_2 and T_3.

The various controls for adjustments are contained in a control box that may be mounted near the operator. Two controls are provided which act on the timing resistors and condensers to allow regulation of the cycle period over a range of 1 to 14 cycles. Another control is used to adjust the point on the voltage wave at which the weld is started.

Electronic Timer for Seam Welding.—The process of seam welding may be considered as a modified form of spot welding in which the spots *overlap* each other to form a continuous seam. In this operation a very high current at low voltage is discharged through two or more pieces of metal to form a spot at which the metal is heated to a fusing temperature. The pieces of metal are passed between low-resistance rollers which serve not only to conduct the current but also to apply the pressure needed to unite the metal pieces at the fused spot. The current flows for a period of several cycles only, then the metal piece is moved to a new position to provide an overlap of 50 per cent on adjacent spots. For this process a timer is needed which can operate within a period of a few cycles.

A timer of this kind consists of three main units: (1) a photo-timer driven by a synchronous motor; (2) a panel assembly for the control tubes and their circuits; and (3) the ignitron-tube assembly. The action of this timer is somewhat like that of an automobile-ignition system, the photo-timer corresponding to the distributor, the control panel to the ignition coil, the ignitron-tube assembly to the cylinders, and the ignition electrodes of the ignitron tubes to the spark plugs of the cylinders. The timer performs the service of a rapid-action single-pole, single-throw switch connected in series with the power source and the welding transformer.

The photo-timer is used to control the number of cycles of current for a weld, and also the number of cycles in the interval between welds. It consists of a revolving timing disk provided with slots along the outer edge and driven by a synchronous motor, a source of light, a system of lenses and apertures, photoelectric tubes, and amplifier tubes. There are 120 slots along the outer edge of the timing disk in order to allow for half-cycle control. Another disk, made of paper and fitted over the timing disk, is trimmed along its outer edge in such a way that it covers the slots of the timing disk for the interval in which no welding current is desired but leaves uncovered a series of groups of slots for the welding intervals. This slot arrangement interrupts a beam of light that is directed toward a photoelectric tube. With this arrangement it is possible to obtain various combinations of weld spacing and weld duration. Further, an adjustment made by shifting the position of the light beam with respect to the timing disk allows the operator to start the current at any desired point on the voltage wave. For assistance in making this adjustment the operator watches a zero-center direct-current meter connected to a shunt in the alternating-current-load circuit, the meter indicating the presence of unequal current loops by registering any direct-current component that exists in the welding current.

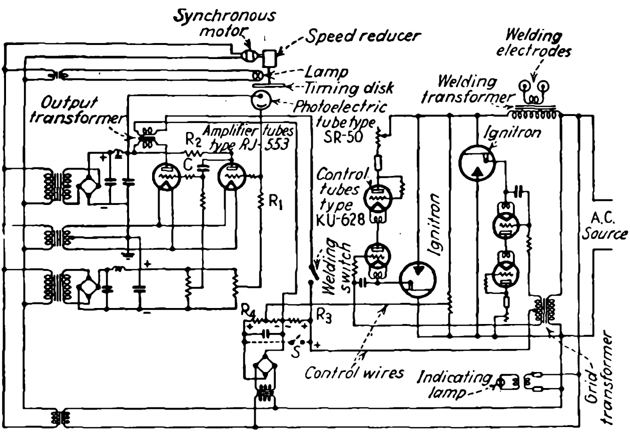


Fig. 466.—Circuit diagram of ignitron timer for seam welding.

A wiring diagram of the entire device is shown in Fig. 466. When the timing disk allows illumination of the photoelectric tube, a current will flow in the resistance R_1. Because of the voltage drop produced by this current flow, the grid-bias voltage on the amplifier tubes becomes more positive and the flow of plate current in resistance R_2 is increased. The plate current of the tube in the second stage of the amplifier, however, is decreased because the grid of the tube becomes more negative through the connection to the coupling condenser C. The plate current of the second amplifier tube, flowing in the primary winding of the output transformer, induces in the secondary winding a current which develops a voltage across the resistance R_3. Thus the flow of current from the phototimer produces a positive voltage across the control wires by neutralizing the constant negative voltage that normally exists across the resistance R_4. This positive grid-bias voltage is applied through the control wires and the secondary winding of the grid transformer to the grids of the control tubes.

It should be noted that the four control tubes are grouped in two pairs. The two tubes in a pair are in series and are connected between the anode and the ignition electrode of one ignitron tube. The ignitron tubes are connected into the circuit inversely with respect to each other. Consequently when the grids of the control tubes become positive, the anode of one of the ignitrons is positive. This ignitron then will pass a current and its low *arc-drop* voltage has the effect of short-circuiting the pair of control tubes associated with it, so that the ignition current ceases. The other ignitron goes into operation when the cycle of current reaches a zero value. Auxiliary relays are provided to protect the ignitrons against thermal overload. These relays are interlocked with the manually operated switches. The ignitrons used in this device are of the all-metal, steel-tank type with graphite anodes and provision for water-cooling.

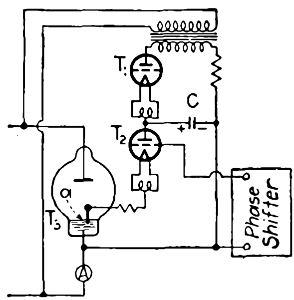


Fig. 467.—Circuit diagram of ignitron used for variable-speed controlled device.

Circuits for Variable Rectifier Output.—In many applications, such as motor-speed control, theater-light dimming, voltage regulation, and so on, the output of the rectifier must be varied. Control of this kind may be obtained by the use of an ignitron rectifier (page 377) with provision for shifting the phase of the control voltage.

A simple arrangement of this kind, as designed for direct-current motor-speed control, is shown in Fig. 467, although in practice full-wave rectification would be used. During the half cycle of inverse voltage the condenser C is charged with the polarity indicated. In the next half cycle the grid-glow tube T_2 breaks down and discharges the condenser through the igniter *a*. The point in the cycle at which this event occurs is controlled by the phase of the grid-bias voltage on the tube T_2. The rectifier T_1 serves to prevent the condenser charge from reversing during the positive half cycle. Thus a variable rectified output can be obtained and used to feed the armature of a direct-current motor.

The field for the applications of the ignitron tube includes rectification with or without control, conversion of current, control of motor speed, high-speed relays, welding, and circuit breaking.

Smoke Measurements.—The device shown in Fig. 468 is used to indicate the density of smoke in a flue or stack. It consists of a source of light, such as a spot light, mounted on a flue and arranged to throw a beam of light on a photoelectric cell that is located on the opposite side of the flue. The meter is calibrated to indicate "per cent smoke" or Ringelmann units.[1] A continuous recording device can be used in place of the meter, or may be connected into the circuit with the meter. If a bell alarm or a lamp signal is necessary, the circuit may be modified as indicated.

Water-level Indicator.—A simple and reliable water-level indicator utilizing a beam of light, several photoelectric cells, and an indicating meter may be constructed as shown in Fig. 469. The light sources are located so that each light beam is directed at an angle toward the gage glass used to indicate the water level. The circuit is connected so that when light strikes the photoelectric cell the meter needle moves, indicating the water level. If the gage glass contains water, the light beam is refracted, meaning that its direction is changed, and falls directly on the meter. If the gage glass is empty, the light beam does not change its direction and does not strike the cell. Where an alarm only is desired, one light

[1] For explanation of this method of determining smoke density, see "Power Plant Testing" by James A. Moyer, 4th ed., pp. 285–311, McGraw-Hill Book Company, Inc., New York.

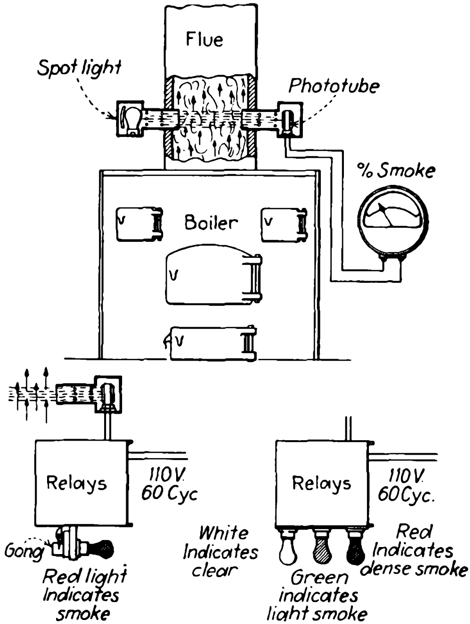


FIG. 468.—Photoelectric tube mounted in flue in boiler for smoke indication.

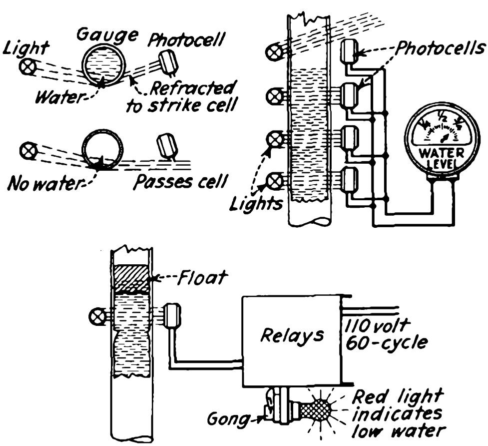


FIG. 469.—Photoelectric water-level indicator.

beam and one photoelectric cell are sufficient. In another alarm arrangement a float is used which blocks the light beam when a certain water level is reached in the gage glass, and thus causes a relay to ring a bell or to turn on a red light.

If indications of the height of water in the gage glass are required several photoelectric cells must be used. With this arrangement the movement of the meter needle is proportional to the number of cells illuminated.

Automatic Egg-candling Machine.—An egg is tested for edibility by its appearance when a strong light is made to shine through the egg. If a dark shadow is observed the egg has started to deteriorate and is not fit for food. Because deterioration may begin very quickly under certain atmospheric conditions, eggs sometimes are candled several times before they reach the consumer. When the testing is performed by persons who are experienced candlers, the eggs are separated for commercial purposes into grades designated as good, medium, and bad.

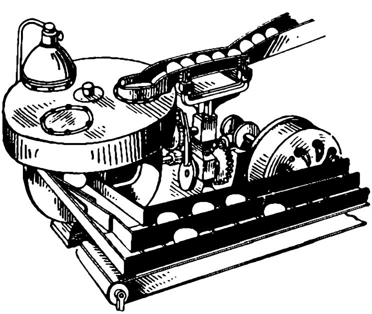


FIG. 470.—Automatic egg-candling machine.

The automatic egg-candling machine[1] shown in Fig. 470 utilizes for its action the effect of light on a photoelectric cell. The egg is handled in such a way that all the light passing through it reaches the photoelectric cell. When the egg reaches the cell it is supported by a rubber ring which is pressed gently against the egg by air pressure. By this method breakage is eliminated and the desired distribution of light is obtained.

Constant-current Direct-current High-voltage Transmission.—Interesting results in the transmission of high-voltage direct current have been obtained by the application of vacuum tubes for use with the large currents that are ordinarily

[1] A more complete description is given in *Electronics*, July, 1932.

handled in so-called *heavy* power transmission. For this kind of transmission, electricity is generated with constant-voltage alternating-current equipment and is converted in stationary apparatus equipped with radio-type vacuum tubes to constant-current direct-current power for transmission to distant points where, at the points of use, the power is changed back to

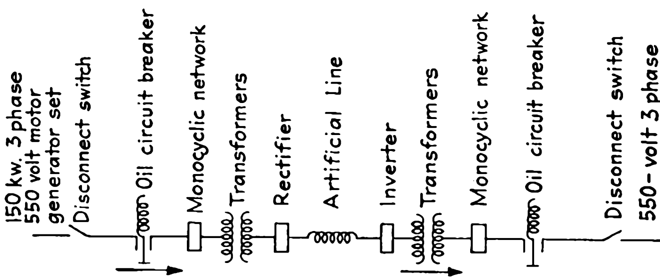


FIG. 471.—Direct-current constant-current transmission system.

constant-voltage alternating current. The promising features of a transmission system of this kind are its unusual stability and reliability. The simple elements of a transmission system of this kind are shown in Fig. 471. This diagram represents the simplified layout for an experimental transmission line intended for 10 amperes at 1,500 volts, the transmission being as shown by arrows from the left-hand to the right-hand side. A larger experimental system capable of actual service has, however, been constructed at Schenectady, New York, with the cooperation of the New York Power and Light Corporation.

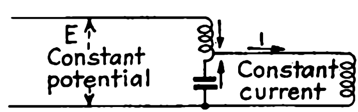


FIG. 472.—Simple monocyclic system of high-voltage transmission.

With this practical set-up, a constant direct current of 200 amperes has been transmitted at 15,000 volts when receiving three-phase, 60-cycle current at 13,800 volts. The wiring diagram of the monocyclic network used for this transmission system is shown in Fig. 472. This network is based on the principle of the series-resonant circuit invented by Boucherot more than 40 years ago when it was in practical use for transforming constant-voltage variable current into constant current for the arc lights in city streets. Naturally, the field of application of such a system depends largely on its efficiency in comparison with other systems. It is stated that the losses in this system are very small and that the commercial development of this direct-current transmission system would almost eliminate the present troubles with transmission systems due to lightning. There are, therefore, four principal advantages claimed for high-voltage transmission with direct rather than alternating current: (1) low transmission losses; (2) elimination of ordinary lightning troubles; (3) less cost for transmission lines; (4) extension of range of transmission. Calculations show that this system of direct-current high-voltage transmission is especially advantageous for application on a double, three-wire line, where the total saving may amount to from 40 to 50 per cent when direct-current transmission is substituted for alternating current. It is likely, further, that the direct-current system of transmission when fully developed will be applicable to the transmission of power at much higher voltages than are now possible on alternating-current lines; and this higher voltage of transmission will further increase the efficiency of the system.

Thyratron Electric Motor.—An electric motor has been developed by the General Electric Company in which electron tubes are used to perform a function similar to that of a commutator in a direct-current electric motor. This type of electric machine is called a *thyratron* motor for the reason that thyratron tubes (page 184) are used in its operation. This motor can be most advantageously applied for operation in places where variable speeds are required. It operates from a three-phase power system. There are two unique features embodied in this motor that are especially advantageous. The first is that it is possible to increase the operating speed from the minimum rating to 200 per cent of that rating, with no sacrifice of its best operating characteristics; and, secondly, the thyratron motor can be located at any point and the control devices may be set up a considerable distance away, as may be necessary.

The present designs of the thyratron motor are not suitable for operation at lower power voltages than about 440 volts, and motor ratings of less than 50 horsepower are not likely to be sufficiently advantageous to merit the large expense that is incurred for the expensive control apparatus that is required. Thyratron-tube replacements are, at the present time, a large

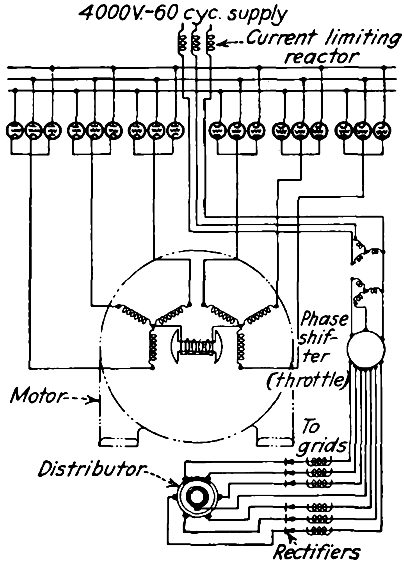


Fig. 473.—Circuit connections of thyratron motor with grid circuit omitted.

item of expense because of the limited demand; but when this motor has a sufficiently large commercial application, the cost for replacements will doubtless be reduced.

The action of a thyratron motor can be understood if it is considered as a type of direct-current motor. A direct-current motor assembly consists of a direct-current power supply, a commutator, an armature, and a field. In the thyratron motor the direct-current power supply can be identified, the thyratron tubes provide commutation, and a stationary armature is used with a rotating field. A simplified diagram[1] of connections for a thyratron motor with the grid circuit omitted is shown in Fig. 473, and the grid circuit in Fig. 474. The power supply of 60-cycle, three-phase current at 4,000 volts is rectified by the thyratron tubes and appears as direct current at 5,000 volts. These tubes act also as a commutator in applying the direct current successively to the different sections of the armature windings.

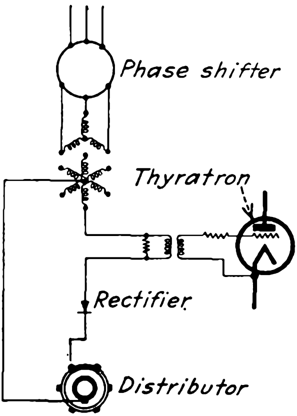


FIG. 474.—Circuit connections of thyratron motor with grid circuit.

Because the tubes are provided with grid control, the rectified output voltage can be adjusted to any value between zero and full voltage without any loss of power. The grid control functions also in such a way that electrical contact between the cathode and anode of a tube is permitted only when desired. In this action the cathode and anode of a tube may be considered as a commutator segment and a brush, respectively. The tubes are arranged in groups of three, with reference to the power supply. The double action of rectification and commutation is shown more clearly in the equivalent circuit of Fig. 475, where separate rectifying and commutating tubes are used. Each group of three tubes shown in Fig. 473 acts exactly like a single rectifier tube in Fig. 475. The tubes are arranged in groups of three also with reference to the motor, but each group acts like one of the commutator tubes in Fig. 475.

While there is but one grid for each tube in the arrangement of Fig. 473, two separate grid controls are provided, one for rectification and one for commutation. This grid control circuit as shown in Fig. 474 must be such that the two functions do not conflict. The rectifier control acts like a phase shifter (page 193), and the commutation control like a distributor.

[1] "The Thyratron Motor," *Elec. Eng.*, November, 1934.

When a positive voltage is delivered by the phase shifter and the distributor makes contact, the grid of the tube becomes positive and current flows through the tube. The tube is non-conducting if the distributor does not make contact, even though the phase shifter delivers a positive voltage, or if distributor contact is made when the phase shifter delivers a positive voltage, or if distributor contact is made when the phase shifter delivers a negative voltage. Thus the path for flow of current in the power-supply circuit is determined by the rectifier control and the path for current flow in the motor circuit is determined by the commutation control.

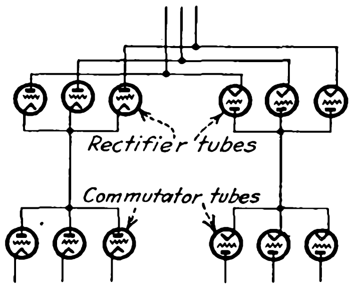


FIG. 475.—Arrangement of commutator tubes and rectifier tubes for grid control in thyratron motor.

Source of "Kilocycle Kilowatts."—Many manufacturing processes require the use of high-frequency alternating current ranging in frequency from about 1,000 to 100,000 cycles per second. Thus frequencies of 1,000 to 2,000 cycles are used in the smelting of scrap metal, 4,800 cycles in the manufacture of steel for razor blades, 30,000 cycles in the welding of pipe, and 50,000 cycles in the sterilization of milk.

Apparatus for the generation of *kilocycle-frequency power* may be classed in four groups: (1) rotating equipment, (2) high-vacuum tubes, (3) gaseous tubes, and (4) a recently developed tube known as the *arc-oscillator tube.* This tube as compared with the other types of apparatus has the advantages of low initial cost, low operating costs, simplicity, small weight, and ability to operate on industrial direct-current voltages.

The arc tube[1] consists of two electrodes closely spaced in inert gas under high pressure. Two typical tubes rated at

[1] "A New Source of Kilocycle Kilowatts," *Elec. Eng.*, March, 1935.

50, and 500 watts, respectively, are shown in Fig. 476. The arc-tube circuit shown in Fig. 477 consists of a choke coil, a stabilizing resistance *R*, a condenser *C*, and an inductance *L*. When voltage is applied to the input side, the condenser *C* begins to charge. The choke coil delays the flow of current at the start, but thereafter it maintains a steady continuous current. When the condenser is charged to a voltage which is high enough to produce breakdown between the electrodes of the tube, a current will begin to flow through the tube. The tube then becomes ionized and acts as a short circuit allowing the condenser to discharge through the *LC* circuit and the tube. The choke coil acts to prevent a rush of current into the circuit from the line, and is intended to maintain a continuous current input, even when there are high-frequency oscillations in the *LC* tube circuit. At the end of discharge

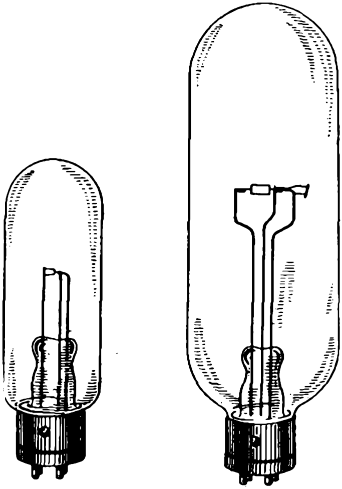


FIG. 476.—Typical arc-oscillator tubes.

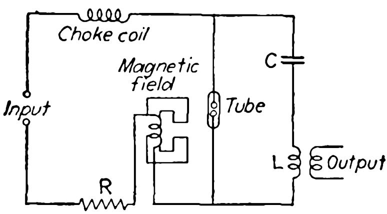


FIG. 477.—General purpose arc-tube circuit.

of the condenser a heavy current is flowing in the *LC* tube circuit. The energy existing in this circuit is stored in the magnetic field of the inductance *L*. When this field collapses, there is induced in the circuit a voltage which produces a continuation of the current flow and thereby charges the condenser in the opposite direction. The voltage on the tube now is negative and the arc is extinguished. After this the cycle of events is repeated.

The output is in the form of sinusoidal pulses (page 42) caused by each condenser discharge as shown in Fig. 478. In this figure V_C is the voltage across the condenser C and V_L is the voltage across the inductance L. The frequency of these pulses is varied by changing the condenser charging rate. If the charging periods are made short enough a sine-wave output as shown in Fig. 478 is obtained. Variable frequency is obtained by changing either the period of charge or the periods of both the charge and discharge of the condenser.

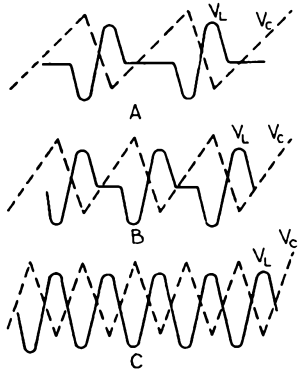


Fig. 478.—Wave shapes of output of arc-oscillator tube circuit in Fig. 477.

RADIO SURGERY

High-frequency electric current produces heat in animal tissues in much the same way that heat is produced by electric current flowing through resistance wires. In the case of the resistance wire, the relations between amperes, volts, and ohms are determined by Ohm's law; but this law does not hold for the relations of these units when high-frequency currents are passing through animal tissues, because of the *distributed capacity* in the cells of the tissues, so that temperatures that are destructive to tissues are easily obtained. For example, the temperature produced by even less than 1 ampere of high-frequency current flowing in a man's wrists will very quickly become unbearable. Because of the intensity of such heat when localized, it is often necessary to use electrodes of rather large area in order to avoid excessive heating. In the application of high-frequency current for surgical purposes, the electrodes intended for the hands of the surgeon are made very small in order to concentrate and localize the current density, and, therefore, also the heating effect. In fact, by this method, the heating of animal tissues becomes so intense that "cooking" may occur very quickly. The greatest heat concentration is, of course, at the points of the electrodes.

Now if the point of an electrode is an ordinary fine sewing needle, and this is applied to living animal tissues under the proper conditions, a boiling temperature is quickly obtained. As the result of the boiling of the tissues, the liquid in them is converted into water vapor so that minute steam explosions are continually occurring; these explosions tending to separate the tissues and thereby producing the equivalent of a clean cut with a knife.

The separation of the tissues by means of the radio needle has advantages, however, over the cutting of tissues with a knife or scalpel because the small capillary blood vessels are automatically sealed so that there is no bleeding where only small blood vessels are touched. There can be serious bleeding only when larger arteries or veins are severed.

This radio needle sterilizes as it separates the tissues. Besides the small blood vessels, the ends of the nerves in the tissues are "cooked" to such an extent that the so-called *surgical shock* of the patient is very much reduced. Operation on the tissues by this method produces much more rapid healing than when tissues are severed with a knife. The absence of bleeding in surgical work performed by this method makes it much safer than the ordinary method of removing the malignant tissues with a knife. When a knife is used for such surgical operations, there is always the danger that, because of the bleeding, the malignant cells will mingle with the main blood stream and will be carried elsewhere in the body where they may develop the same disorder that has produced them. In radio-needle cutting this does not happen, because the electrical surgery actually destroys the malignant cells, so that they may be conveniently removed as harmless refuse.

In radio-needle surgery, the electrodes may vary in size from a sharply pointed needle to one that is an inch or more in diameter, and may be in various shapes as needed for different kinds of surgery. In the operation of radio surgery, two electrodes, of course, are needed. One, called the "common" electrode, is usually of large area, so that it may be placed under the thighs of the patient without producing much heat. The other called the "active" electrode is relatively very small, and is intended to be applied to the place where concentrated and localized heat is to be applied. This arrangement is not necessarily the only one used, as in the treatment of some tumors, two "active" electrodes are used and are placed on each side of the tumor to be removed.

"Sparking" to Stop Bleeding.—A radio electrode may also be used only to stop the bleeding from broken tissues. In that case the radio electrode is held *near* the tissue from which the bleeding occurs and controlled sparks are permitted to pass through the thin layer of air between the needle and the tissue. This method is often applied by surgeons in the *removal of moles and warts.* For this service, the most satisfactory type of current is produced by an Oudin resonator or Tesla coil; and the apparatus is *mono-polar*, meaning that the capacity effect between the patient and the ground serves as the return circuit. This apparatus should generally be effectively grounded. It must be noted, however, that for such treatments with the radio needle the current used is relatively weak, for the reason that if the current were as strong as some of the high-frequency currents employed for other kinds of surgical work, they would be likely to seriously injure the patient.

Effects of Muscular Contraction.—The cells in animal tissues have such electrolytic properties that some muscular contraction occurs in the use of the radio needle. It should be noted, however, that this muscular contraction is lessened in proportion to the increase in frequency of the current that is used. As a rule, the frequency of the current for radio-needle work varies from 300 to 2,000 kilocycles per second. It is desirable, of course, that there should be as little muscular contraction as possible in the application of the radio needle, for the reason that twitching muscles may throw the radio needle too near to delicate internal organs and large blood vessels. Unfortunately, the effects of the radio needle during surgical operations in producing muscular contraction are quite varied. In some individuals, scarcely any muscular contraction results from its use, while in others, the muscular contraction is so great that the tissues are thrust upward toward the radio knife. Obviously, during a surgical operation the cutting implement must be absolutely under the control of the surgeon, and upward thrusts of the tissues may so much interfere with his work that it will become necessary to substitute a steel blade scalpel in order to complete the operation.

Types of Apparatus for Producing High-frequency Currents for Surgery.—When relatively large currents are required for use in radio surgery, the spark-gap type of oscillator is generally used, as the application of oscillating vacuum tubes for this service is almost prohibitive because of the high cost of the tubes. The vacuum-tube oscillator for such service has the advantage over the spark-gap type for cutting purposes because it produces much smoother operation of the radio needle, this greater smoothness being due to the continuous-wave output of the tube compared with the damped output of the spark-gap machine.

Typical Oscillating-tube Circuits for the Radio Knife.—One of the simplest types of circuits for the operation of the radio needle is shown in Fig. 479. For the operation of this circuit, a direct-current power supply at 1,000 volts is required. Because of this high-voltage direct-current requirement, this type of apparatus is not suitable for portable use. It is, however, possible to make a substitution of rectified and filtered current for the direct current. A suitable circuit for producing this rectified and filtered current from an alternating-current source is shown in Fig. 480. This device as shown uses only one rectifier tube, but is adaptable, of course, for the use of two rectifier tubes so as to utilize the two half-waves of each cycle of the alternating-current supply.

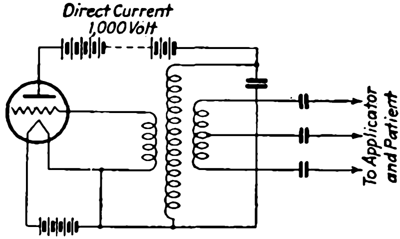


FIG. 479.—Circuit for radio surgical needle.

The circuit diagram in Fig. 481 shows an arrangement of one or two vacuum tubes which act both as rectifiers and as oscillators.

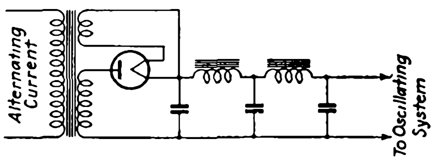


FIG. 480.—Circuit to provide direct current for surgical needle from alternating-current supply.

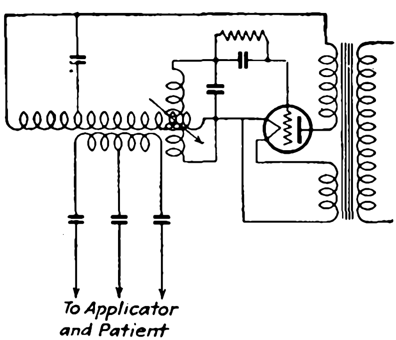


FIG. 481.—Vacuum tube for use as rectifier and oscillator.

In the circuits shown in Figs. 479, 480, and 481, the input currents are preferably regulated by reactances which are provided with a series of taps with corresponding suitable switches. The connections for the output current intended for the patient are made across suitably arranged taps on a main resonator or across a main oscillating-circuit condenser which may also be provided with a series of taps. As a rule, pilot lights are used to indicate when the apparatus is in operation.

Advantages of Radio Needle over Scalpel.—Even though there are advantages in the use of the radio needle for cutting tissues during surgical operations, mainly because of the very rapid coagulation of the blood that occurs with the electrical method, there are still many surgeons who contend that they can do their best work with a scalpel. By the electrical method of cutting, bleeding can be prevented or immediately stopped—in many cases without the delay that is necessary for tying up the ends of blood vessels with ligatures. In dealing with relatively large blood vessels, some surgeons entirely omit the use of clamps on the ends of arteries and veins, and, instead, take hold of the severed blood vessels with tweezers and touch them with the radio knife so as to cause the ends to be so thoroughly "cooked" that the tweezers can be immediately removed.

Description of Radio Needle.—The electrical cutting tool called the radio needle consists usually of a holding device into which a needle or some other special form of electrode is clamped. The circuit through the needle may be connected and disconnected by the pressure of a finger on a small switch or by a foot switch on the floor. The radio needle cuts without any pressure being exerted on it by the hand of the surgeon. In its operation there is usually very little observable sparking at the point. On the other hand, some sparking is, of course, necessary to do the cutting, as the tiny sparks produce the heat which causes the explosions of the tissue cells, which, by their bursting, produce a clean cut.

Other Uses of the Radio Needle.—There are a great many other applications of the radio needle which are practiced by surgeons, dermatologists, and similar practitioners. Among the simple applications in surgery may be mentioned the usual operation on the prostate gland where, it is claimed, the mortality following this operation has been reduced from 50 to 5 per cent. Electrical surgery is also used very successfully in the removal of tonsils.

Noise-measurement Instruments.—In practically all noise-measuring instruments, vacuum tubes of some kind are important features. Therefore, noise measurements for industrial, highway, or architectural purposes should be made by those who are well informed about the applications of such tubes. In other words, such measurements should be made by trained electronic engineers. The two principal types of noise-measuring instruments differ from each other largely in the method adopted for determining the evaluation of sounds. Some devices, especially those used in England, use the so-called subjective method by which the magnitude of sound is measured by an electrically operated meter. American engineers, on the other hand, as a rule favor the objective or acoustic method in which the human ear is used to determine the evaluation of noises. In this connection, it is important to keep in mind that there is a difference between hearing a sound with the human ear and measuring that sound with an electric meter. The reaction of sound on the human ear is very complex, and involves the coordination of a number of human organisms. Unfortunately, the two methods do not lead, in most cases, to the same results.

In the subjective method of noise measurement, there is a direct comparison between the noise to be measured and some standardized noise-making device so arranged that the noise to be measured can be tested by comparison by the ears of one or more observers. For example, in some of these devices, an ordinary tuning fork may be used as the standard, and when this tuning fork is sounded to a given intensity and held at a given distance from the ear, the time required for it to become inaudible can be used to determine the intensity of the noise to be measured. Such methods can be used to indicate relative noise intensities with fairly good accuracy if used by an experienced observer.

By adjusting the sound of the tuning fork or some other instrument selected for the standard so that the noise heard in an ear phone is first distinctly higher and then distinctly lower than the noise being measured, a set of successive tests can be made with some assurance of reliability. As an added precaution, however, the test should be made first with the ear phone in one of the ears of the observer and then in the other. The mean of the two results should be taken as the final evaluation of the sound. When using the services in this way of several different observers, it is reported that agreement within two decibels[1] can be readily obtained at the 100-decibel noise level and, similarly, an accuracy within 6 decibels is easily possible at the 50-decibel level. Such accuracy may be considered very satisfactory for this method of noise measurement.

A subjective method like the one described may be adversely criticized for several reasons: (1) the sound sensations in ears of different observers vary; (2) the sound response of the same individual will vary from hour to hour and also from day to day; (3) the human ear response is different for different kinds of noise. In individuals, the variation alone of sound response may be as much as 40 decibels.

It must be admitted, of course, in the final analysis of sounds by means of noise measurements, relative intensities must be interpreted in terms of the effective noise on the average normal ear. On the other hand, the average normal ear is hard to find; and, further, in all kinds of weather, it is difficult to maintain a normal standard in any person's ear. Accuracy of the subjective method, therefore, seems to be limited at best to 10 decibels with the average running possibly up to 25 decibels.

Acoustic Sound Measurement.—The so-called objective or acoustic sound-measuring devices consist essentially of the following four parts: (1) sound-translating device, such as a microphone or similar sound pick-up instrument; (2) attenuator for decreasing the output of the microphone or pick-up

[1] See p. 420.

device to the required input level of the amplifier to which it sends electric current corresponding to sound impulses; (3) audio-frequency amplifier and an indicating voltmeter, calibrated in decibels, so connected into the circuit that it measures the output of the audio-frequency amplifier. These four elements constitute the simplest form of acoustic noise meter, as sketched in outline in Fig. 482. This type of instrument will measure the total sound energy but makes no distinction between the different frequency components of the noise. The relative intensities of two noises of the same kind

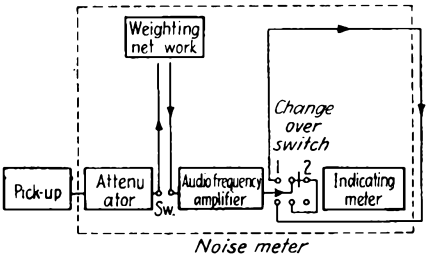


FIG. 482.—Acoustic noise meter.

can be compared by reference to a suitable *production standard*, but such a device is not altogether reliable when used for the comparison of two noises of a different character.

The *microphone* used with a device of this kind is usually either of the magnetic type or of the condenser type. The magnetic type of microphone is more rugged, and is cheaper than the condenser type, so that it is ordinarily used in industrial work. With either type of microphone, the frequency-response curve is not flat, and corrective filters are used to improve operating characteristics. Carbon-type microphones are not used for this type of service because their frequency response changes with use. The ideal noise-measuring instrument should be provided with a microphone that has a flat frequency-response curve for the reason that then any kind of response may be transmitted to the circuit of the instrument. For practical reasons, however, the frequency-response curve is usually slightly peaked in the middle range of the audio frequencies, so that its operation is more nearly like that of the human ear which is most sensitive, of course, to those frequencies that strongly affect the membranes of the ear.

Radio Compass.—Radio methods for course and position determination in air navigation include the use of range beacons, direction finding by ground stations, and direction finding on aircraft. The U. S. Department of Commerce has installed two types of radio-range beacon stations along federal airways. In the aural type an indication that a plane is on the course is given by the interlocking of the dash-dot and the dot-dash code signals into one long dash, and the course followed is determined by periodic code letters which identify a station. In the visual type which uses two modulation frequencies and a tuned reed indicator the direction of flight along the course is indicated by equal amplitude of the reed vibrations. There are also various improvements such as simultaneous telephone and range beacons, and the T-L type of antenna system to overcome *night effect.* Directive beacons may be supplemented by small marker beacons.

Direction finders which depend on the minimum signal current from loops may be successfully used for position determinations by triangulation, and for guidance toward or away from a transmitter, but not to show deviation from a course. Both direction finding and course-deviation indications may be obtained with a radio compass.

The usual type of radio compass for such services is provided with a synchronized switching device which rapidly switches the loop polarity with respect to the vertical antenna and simultaneously switches the rectified audio-frequency output into an indicating device having a zero-center scale. With this arrangement a sense of direction is obtained if the loop increases the vertical antenna voltage pick-up when connected for right-hand indication, and "bucks" when the indicator is connected for left-hand indication. The disadvantages are that this arrangement destroys the characteristic of the signal so far as use in communication is concerned, and that accuracy is affected by phase-angle shifts in the radio receiver such as may be caused by regeneration (page 149).

The radio compass[1] for air navigation as shown in Fig. 483 does not depend on synchronizing the input and output of the radio receiver and does not destroy any modulation on the radio signal. Because the loop has directional characteristics while the vertical antenna has none, the voltage from the loop may be used to buck or to boost the voltage induced in the vertical antenna. The combined radio-frequency

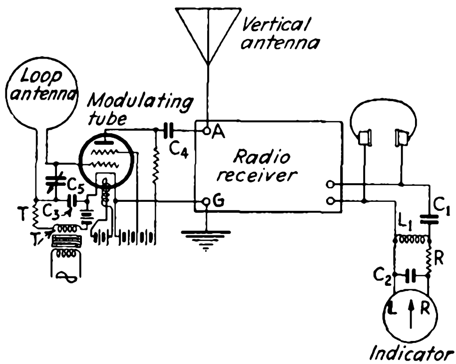


Fig. 483.—Circuit of radio compass for air navigation.

energy from the loop and the vertical antenna must be changed to direct-current which will reverse when the loop is turned from the bucking to the boosting position. This result is obtained by modulating the loop output with an audio-frequency voltage having the form shown in Fig. 484*A*. This wave form is applied to a nonlinear resistance[2] *R* in series with the usual indicator shown in Fig. 483. The current increase from one side of the wave produces in the direct-current indicator an indication which reverses if the alternating

[1] "Radio Aids to Air Navigation," *Elec. Eng.*, May, 1933.

[2] In a nonlinear resistance the current does not change in proportion to the applied voltage. Thus if a nonsymmetrical alternating current as in Fig. 484*a* is applied, the polarity of the wave with the highest peak causes more current flow than the opposite polarity even though the root-mean-square (p. 42) values of both sides are the same.

current is reversed. When the radio loop is moved from one side to the other of its zero position, the peak side of the audio-frequency output of the receiver appears on one side of the wave or the other.

When the loop is in a position that lies away from the normal to the direction of the radio wave, the output of the loop as shown in Fig. 484*B* is combined with the steady wave of Fig. 484*C* from the vertical antenna. The resultant appears as in

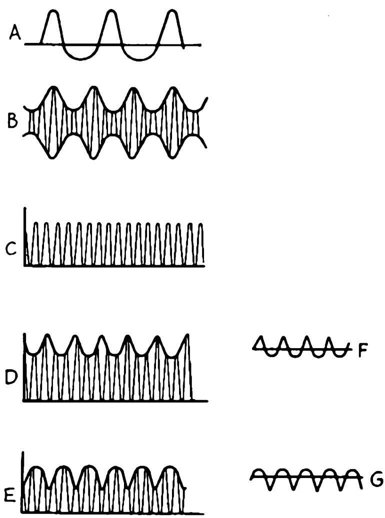


Fig. 484.—Output diagrams of radio compass when radio loop is away from normal to direction of radio wave, when combined with steady wave, when turned for boosting, and when in the position for bucking.

Fig. 484*D* when the loop is turned for boosting, and as in Fig. 484*E* for bucking. The resultant rectified currents in the two cases from the radio-receiver detector are shown in Figs. 484*F* and 484*G*. If the aircraft is on its course, the loop is normal to the radio wave and the loop voltage has a minimum value. In this condition the loop device does not react on the radio receiving set which is therefore available for communication purposes.

The compass effect of the loop apparatus is applied to the receiver through condenser C_4. The audio-frequency output is connected to the telephone headphones and to the indicator. The C_1L_1 combination acts to block excessive voice modulations from the indicator. A nonlinear resistance R, and a smoothing condenser C_2 are included in the equipment. The wave shape shown in Fig. 484G may be obtained by modulating the loop energy with an audio frequency f and combining it with a $2f$ frequency at the resistance R. Regeneration in the receiver up to the point of oscillation does not interfere with the accuracy of the compass device. The audio frequency f can have any value which will not be distorted in the receiver, and should be high to leave the lower range for continuous-wave (c.w.) telegraph signals. If f is over 1,500 cycles per second, a high-pass filter (page 64) is needed to block the voice effects from the indicator. The distance range of the compass attachment is limited to that of the radio receiver for headphone reception.

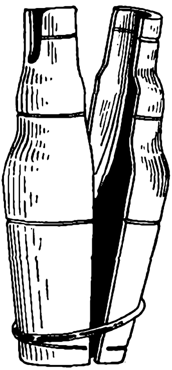


FIG. 485.—Metal shield for radio tubes made in halves.

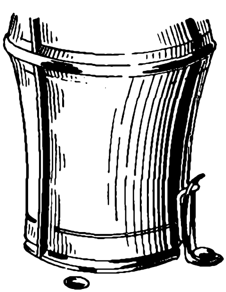


FIG. 486.—Method of grounding metal shield by single-contact spring clip.

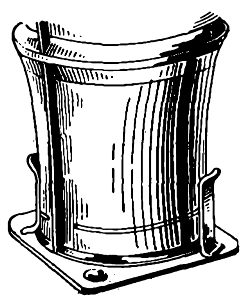


FIG. 487.—Method of grounding metal shield by double-contact spring clip.

Metal Shields for Tubes.—The necessity for economy in space requirements and in expense of chassis construction has led to the use of metal shields for radio tubes. These shields have been used also in connection with the replacement of tubes of the spray shield type in which the shield consists of a coating of metal sprayed on the glass bulb.

The type of metal shield shown in Fig. 485 is made in halves which are held together when mounted on the tube by a clamping ring. The shield may be grounded to the chassis by the use of a spring clip of either the single-contact (Fig. 486) or the double-contact type shown in Fig. 487.

APPENDIX

Abbreviations of Units

Unit	Abbreviation	Unit	Abbreviation
Amperes	amp.	Kilometers	km.
Ampere-hours	amp-hr.	Kilowatts	kw.
Centimeters	cm.	Kilowatt-hours	kw.-hr.
Cubic centimeters	$cm.^3$	Kilovolt-amperes	kva.
Cubic inches	cu. in.	Meters	m.
Cycles per second	~	Microfarads	m.f. or μf.
Degrees Centigrade	° C.	Micromicrofarads	m.m.f. or $\mu\mu$f.
Degrees Fahrenheit	° F.	Millihenries	mh.
Feet	ft.	Millimeters	mm.
Foot-pounds	ft-lb.	Pounds	lb.
Grams	g.	Seconds	sec.
Inches	in.	Square centimeters	$cm.^2$
Kilograms	kg.	Square inches	sq. in.

Explanation of Electrical Units

In connection with electrical units the prefixes given below are used to indicate smaller or larger units.

Micro-micro	$\mu\mu$	one-million-millionth	$\frac{1}{10^{12}}$ or 10^{-12}
Micro	μ	one-millionth	$\frac{1}{10^{6}}$ or 10^{-6}
Milli	m.	one-thousandth	$\frac{1}{10^{3}}$ or 10^{-3}
Centi	c.	one-hundredth	$\frac{1}{10^{2}}$ or 10^{-2}
Deci	d.	one-tenth	$\frac{1}{10}$ or 10^{-1}
Deka	dk.	ten	10
Hekto	h.	one hundred	10^2
Kilo	k.	one thousand	10^3
Mega	m.	one million	10^6

Notation Symbols

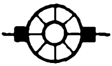
a = temperature coefficient.
A = area.
C = capacity.
de = electromotive force, instantaneous value.
di = current, instantaneous value.
E = electromotive force, effective value.
E_a = filament supply or "A" voltage.
E_b = plate supply or "B" voltage.
E_c = grid-bias voltage.
E_f = filament voltage.
E_g = grid voltage (with respect to negative filament terminal).
E_p = plate voltage (with respect to negative filament terminal).
f = frequency.
F = force.
G_m = mutual conductance (micromhos).
h = height.
H = magnetic field intensity.
I = current, effective value.
I_f = filament current.
I_g = grid current (usually measured in microamperes).
I_p = plate current (milliamperes).
I_s = emission current (milliamperes).
k = coupling coefficient.
l = length.
L = inductance, self.
M = mutual inductance.
n = number of revolutions.
θ = phase angle.
p = power, instantaneous value.
P = power, average value.
Q = quantity of electricity.
r_g = grid resistance.
r_p = load resistance (ohms).
R = resistance.
t = time.
T = period of a complete oscillation.
u = amplification factor.
v = velocity.
V = potential difference.
w = frequency $\times 2 \times 3.1416$.
W = energy.
X = reactance.
Z = impedance.
π = ratio circumference of circle to diameter, 3.1416.
ω = ohms.

Symbols of Wiring and Apparatus


Alternator (single phase)


Alternator (two phase)

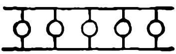

Alternator (three phase)


D.C. Generator

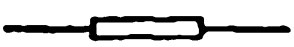

Ammeter Shunt


Circuit Breaker

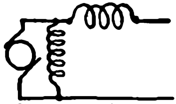
Frequency Meter

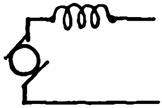

Lamp Bank

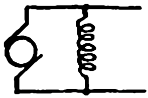

Link Fuse


Enclosed Fuse

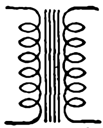

Plug Fuse

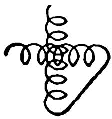

Compound Motor

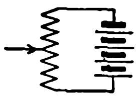

Series Motor


Shunt Motor


Filament Switch (S.P.S.T.)


Audio-frequency Transformer


Variometer


Voltage Divider (potentiometer)

Voltmeter

Wattmeter

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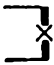
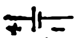
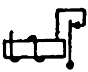
Ammeter


Antenna or Aerial


Arc


Battery


Battery (polarity indicated)


Buzzer


Coil Antenna

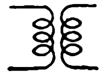

Condenser, Fixed

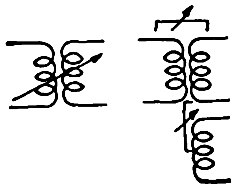

Condenser, Shielded


Condenser, Variable

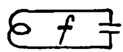

Condenser, Variable (with moving plate indicated)


Counterpoise


Coupler, Inductive (mutual inductor)


Coupler, Inductive (with variable coupling)


Crystal Detector



Frequency Meter (wavemeter)

Galvanometer


Ground


Inductor

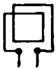

Inductor, Iron Core


Inductor, Variable


Inductor, Adjustable (by steps)

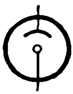

Jack

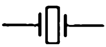

Key

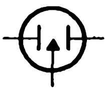

Loop Antenna

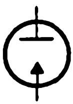

Loud-speaker


Microphone (Telephone Transmitter)


Phototube


Piezoelectric Plate


Rectifier Tube, Full-wave (with cold cathode)


Rectifier Tube, Half-wave (with cold cathode)


Resistor

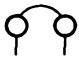

Resistor, Variable

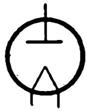

Resistor, Adjustable (by steps)

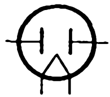

Spark Gap, Rotary

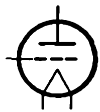

Spark Gap, Plain

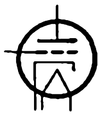

Spark Gap, Quenched

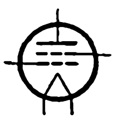

Telephone Receiver

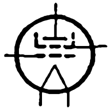

Thermionic Tubes
Diode (Half-wave Rectifier)
(with directly heated cathode)


Full-wave Rectifier
(with directly heated cathode)

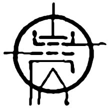

Triode
(with directly heated cathode)


Triode
(with indirectly heated cathode)

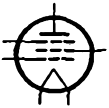

Tetrode
(with directly heated cathode)



Screen-grid Tube
(with directly heated cathode)

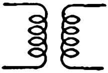


Screen-grid Tube
(with indirectly heated cathode)

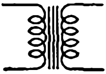


Pentode
(with directly heated cathode)

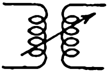
Thermoelement



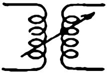
Transformer, Air Core



Transformer, Iron Core



Transformer, Variable Coupling



Transformer, Variable Coupling
(moving coil indicated)

Wires, Joined

Wires, Crossed, Not Joined

Specific Resistance of Metals

Material	Ohms per Circular Mil-foot at 20°C.
Aluminum	17.0
Copper, drawn	10.4
German silver	115 to 290
Iron, electrolytic	60.0
Iron, cast	450 to 570
Nichrome	600
Platinum	55 to 90
Silver	9.0 to 10.1
Steel, soft	95

Weight of Bare and Insulated Copper Wire

In pounds per 1,000 feet at 68°F. The sizes shown are American Wire Gage (Brown & Sharpe). Data on insulated wires supplied by Belden Manufacturing Co.

Size	Bare	Enamel	Single cotton	Double cotton	Single silk	Double silk
8	50.0	50.55	50.60	51.15		
9	39.63	40.15	40.15	40.60		
10	31.43	31.80	31.85	32.18		
11	24.92	25.25	25.30	25.60		
12	19.77	20.05	20.10	20.40		
13	15.68	15.90	15.99	16.20		
14	12.43	12.60	12.73	12.91		
15	9.858	10.00	10.10	10.33		
16	7.818	7.930	8.025	8.210	7.890	7.955
17	6.200	6.275	6.395	6.540	6.260	6.315
18	4.917	4.980	5.080	5.235	4.970	5.015
19	3.899	3.955	4.035	4.220	3.940	3.990
20	3.092	3.135	3.218	3.373	3.132	3.173
21	2.452	2.490	2.561	2.685	2.488	2.520
22	1.945	1.970	2.048	2.168	1.976	2.006
23	1.542	1.565	1.635	1.727	1.570	1.593
24	1.223	1.245	1.304	1.398	1.247	1.272
25	0.9699	0.988	1.039	1.129	0.994	1.018
26	0.7692	0.7845	0.8335	0.9140	0.7905	0.8100
27	0.6100	0.6220	0.6660	0.7560	0.6280	0.6450
28	0.4837	0.4940	0.5325	0.6075	0.4980	0.5140
29	0.3836	0.3915	0.4255	0.4890	0.3970	0.4130
30	0.3042	0.3105	0.3400	0.3955	0.3160	0.3330
31	0.2413	0.2465	0.2762	0.3257	0.2517	0.2678
32	0.1913	0.1960	0.2230	0.2700	0.2100	0.2170
33	0.1517	0.1550	0.1816	0.2270	0.1611	0.1750
34	0.1203	0.1230	0.1478	0.1928	0.1290	0.1412
35	0.09542	0.0980	0.1202	0.1600	0.1035	0.1130
36	0.07568	0.0776	0.0994	0.1361	0.0823	0.0920
37	0.0601	0.0616	0.0822	0.1204	0.0663	0.0740
38	0.04759	0.0488	0.0702	0.1049	0.0534	0.0623
39	0.03774	0.0387	0.0602	0.0937	0.0424	0.0504
40	0.02990	0.0307	0.0519	0.0838	0.0345	0.0429

Properties of Copper Wire

The resistance given in the table is that of pure copper wire; ordinary commercial copper has a resistance from 3 to 5 per cent greater

American or B. & S. Gage

Gage No.	Diameter in mils	Area in circular mils	Weight in pounds per 1,000 feet	Feet per pound	Resistance of pure copper in international ohms at 20° C. or 68°F.		
					Ohms per foot	Feet per ohm	Ohms per pound
0000	460.0	211,600	640.5	1.56	0.0000489	20,440	0.00007639
000	409.6	167,800	508.0	1.97	0.0000617	16,210	0.0001215
00	364.8	133,100	402.8	2.49	0.0000778	12,850	0.0001931
0	324.9	105,600	319.5	3.13	0.0000981	10,190	0.0003071
1	289.3	83,690	253.3	3.95	0.0001237	8,083	0.0004883
2	257.6	66,370	200.9	4.98	0.0001560	6,410	0.0007763
3	229.4	52,630	159.3	6.28	0.0001967	5,084	0.001235
4	204.3	41,740	126.4	7.91	0.0002480	4,031	0.001963
5	181.9	33,100	100.2	9.98	0.0003128	3,197	0.003122
6	162.0	26,250	79.46	12.58	0.0003944	2,535	0.004963
7	144.3	20,820	63.02	15.87	0.0004973	2,011	0.007892
8	128.5	16,510	49.98	20.01	0.0006271	1,595	0.01255
9	114.4	13,090	39.63	25.23	0.0007908	1,265	0.01995
10	101.9	10,380	31.43	31.85	0.0009972	1,003	0.03173
11	90.74	8,234	24.93	40.12	0.001257	795.5	0.05045
12	80.81	6,530	19.77	50.58	0.001586	630.5	0.08022
13	71.96	5,178	15.68	63.78	0.001999	500.1	0.1276
14	64.08	4,107	12.43	80.45	0.002521	396.6	0.2028
15	57.07	3,257	9.86	101.4	0.003179	314.5	0.3225
16	50.82	2,583	7.82	127.9	0.004009	249.4	0.5128
17	45.26	2,048	6.20	161.3	0.005055	197.8	0.8153
18	40.30	1,624	4.92	203.4	0.006374	156.9	1.296

19	35.89	1,288	3.90
20	31.96	1,022	3.09
21	28.46	810.1	2.45
22	25.35	642.6	1.95
23	22.57	509.5	1.54
24	20.10	404.0	1.22
25	17.90	320.4	0.97
26	15.94	254.1	0.77
27	14.20	201.5	0.61
28	12.64	159.8	0.48
29	11.26	126.7	0.38
30	10.03	100.5	0.30
31	8.928	79.71	0.24
32	7.950	63.20	0.19
33	7.080	50.13	0.15
34	6.305	39.75	0.12
35	5.615	31.52	0.10
36	5.000	25.00	0.08
37	4.453	19.83	0.06
38	3.965	15.72	0.05
39	3.531	12.47	0.04
40	3.145	9.89	0.03

256.5	0.008038	124.4	2.061
323.4	0.01014	98.62	3.278
407.8	0.01278	78.24	5.212
514.2	0.01612	62.05	8.287
648.4	0.02032	49.21	13.18
817.6	0.02563	39.02	20.95
1,031	0.03231	30.95	33.32
1,300	0.04075	24.54	52.97
1,639	0.05138	19.46	84.23
2,067	0.06479	15.43	133.9
2,607	0.08170	12.24	213.0
3,287	0.1030	9.707	338.6
4,145	0.1299	7.698	538.4
5,227	0.1638	6.105	856.2
6,591	0.2066	4.841	1,361
8,311	0.2605	3.839	2,165
10,840	0.3284	3.045	3,441
13,210	0.4142	2.414	5,473
16,660	0.5222	1.915	8,702
21,010	0.6585	1.519	13,870
26,500	0.8304	1.204	22,000
33,410	1.047	0.955	34,980

SPECIFIC INDUCTIVE CAPACITY

Substance	Dielectric Constant, k
Air	1.0
Glass	4.0 to 10.0
Mica	4.0 to 8.0
Hard rubber	2.0 to 4.0
Paraffin	2.0 to 3.0
Paper, dry	1.5 to 3.0
Paper (treated as used in cables)	2.5 to 4.0
Porcelain, unglazed	5.0 to 7.0
Shellac	3.0 to 3.7
Silk	4.6
Celluloid	7.0 to 10.0
Wood, dry	3.0 to 6.0
Molded insulating material like bakelite	5.0 to 7.5

Diameters of Bare Copper Wire and Outside Diameters of Insulated Wire

Sizes of wire are American Wire or Brown & Sharpe gage. Diameters in thousandths of an inch.

Size	Bare	Enamel	Single cotton	Double cotton	Single silk	Double silk
8	128.5	130.60	135.5	141.5		
9	114.4	116.50	121.4	127.4		
10	101.9	104.00	107.9	112.9		
11	90.74	92.70	96.7	101.7		
12	80.81	82.80	86.8	91.8		
13	71.96	74.00	78.0	83.0		
14	64.08	66.10	70.1	75.1		
15	57.07	59.10	63.1	68.1		
16	50.82	52.80	55.8	60.8	52.8	54.6
17	45.26	47.00	50.3	55.3	47.3	49.1
18	40.30	42.10	45.3	50.3	42.3	44.1
19	35.89	37.70	40.9	45.9	37.9	39.7
20	31.96	33.70	37.0	42.0	34.0	35.8
21	28.46	30.20	33.5	38.5	30.5	32.3
22	25.35	26.90	29.3	33.3	27.3	29.1
23	22.57	24.10	26.6	30.6	24.6	26.4
24	20.10	21.50	24.1	28.1	22.1	23.9
25	17.90	19.20	21.9	25.9	19.9	21.7
26	15.94	17.10	19.9	23.9	17.9	19.7
27	14.20	15.30	18.2	22.2	16.2	18.0
28	12.64	13.60	16.6	20.6	14.6	16.4
29	11.26	12.20	15.3	19.3	13.3	15.1
30	10.03	10.90	14.0	18.0	12.0	13.8
31	8.928	9.70	12.9	16.9	10.9	12.7
32	7.950	8.70	11.95	15.95	9.95	11.75
33	7.080	7.70	11.08	15.08	9.08	10.88
34	6.305	6.90	10.30	14.30	8.30	10.10
35	5.615	6.20	9.61	13.61	7.61	9.41
36	5.000	5.50	9.00	13.00	7.00	8.80
37	4.453	4.90	8.45	12.45	6.45	8.25
38	3.965	4.40	7.96	11.96	5.96	7.76
39	3.531	3.90	7.53	11.53	5.53	7.33
40	3.145	3.50	7.14	11.14	5.14	6.94

Color Code for Standard Resistors.—The Radio Manufacturers Association has adopted a system for indicating the resistance of standard resistors by means of three marks in color on the unit. The three color marks used are, (1) the color of the body, (2) the color of the tip or end of the unit, and (3) the color of a dot or band on the unit. These colors represent the value of the resistance of the unit in the following manner: The body color represents the first figure, the tip color the second figure, and the dot or band color the number of zeros after the two figures.

The figure corresponding to each color on each part of the unit is given in the following table:

Color	Body	Tip or end	Dot or band
Black	0	0	None
Brown	1	1	0
Red	2	2	00
Orange	3	3	000
Yellow	4	4	0000
Green	5	5	00000
Blue	6	6	000000
Violet	7	7	
Gray	8	8	
White	9	9	

Thus a resistor that is colored to have a green body, a black tip, and an orange dot or band is rated at a resistance of 50,000 ohms.

Color Code for Wires in Radio Receivers.—The National Electrical Manufacturers Association has adopted a system for indicating the use or application of wires in radio receivers by means of color markings on the braid or insulation of the wires. The color corresponding to a particular circuit application of a wire is given in the following table.

Yellow	A+	Green	C+
Black with yellow tracer	A−	Black and green	C−(low)
Red	B+(max.)	Black with green tracer	C−(max.)
Maroon and red	B+(int.)	Brown	Loud-speaker high side
Maroon	B+(det.)	Black with brown tracer	Loud-speaker low side
Black with red tracer	B−		

Radio-receiving-tube Average Characteristics

Reference footnotes are at end of table (page 626)

Tube	Use	Filament or heater, amperes	Plate, volts	Plate, milliamperes	Negative grid bias, volts D.C. on fil.	Negative grid bias, volts A.C. on fil.	Plate resistance, ohms	Screen voltage, volts	Screen, milliamperes	Mutual conductance, micromhos	Amplification factor	Power output, milliwatts	Load impedance, ohms
1.1-volt direct-current filament detector and amplifier tubes													
WD11*	Det. ampl.[a]	0.25	90	2.5	4.5	....	15,500	.....	...	425	6.6		
		0.25	135	3.0	10.5	....	15,000	.....	...	440	6.6		
WD12*	Det. ampl.[a]	0.25	90	2.5	4.5	....	15,500	.....	...	425	6.6		
		0.25	135	3.0	10.5	....	15,000	.....	...	440	6.6		
864*	Det. ampl.[a]	0.25	90	2.5	4.5	....	15,500	.....	...	425	6.6	Identical with WD11 and WD12, except that 864 is a non-microphonic tube	
1.5-volt alternating- or direct-current filament amplifier tubes													
26*	Ampl.	1.05	135	5.5	9.0	10.0	7,600	.....	...	1,100	8.3	80.0	8,800
2-volt direct-current filament detector, amplifier and converter tubes													
1A6*	Pentagrid converter[o]	0.06	180	1.3	3.0	....	500,000	.....	2.4	Conversion conductance 300[u]			
1C6*	Pentagrid converter	0.12	180	1.5	3.0	....	750,000	.....	2.0	Conversion conductance 325			
15†	Det.-osc	0.22	135	1.85	1.5	....	800,000	67.5	...	625	500		
30*	Det. ampl.[a]	0.06	90	2.5	4.5	....	11,000	.....	...	850			
		0.06	180	3.1	13.5	....	10,300	.....	...	900	9.3		
32*	Biased det. R.-F.	0.06	174[b]	....[c]	3.0	....	....	67.5					
	ampl.	0.06	180	1.7	6.0	....	1,200,000	67.5	...	650	780		
34*	Variable mu	0.06	135	2.8	3.0	....	600,000	67.5	1.0	600	360		

RADIO-RECEIVING-TUBE AVERAGE CHARACTERISTICS.—(*Continued*)

Tube	Use	Filament or heater, amperes	Plate, volts	Plate, milliamperes	Negative grid bias, volts		Plate resistance, ohms	Screen voltage, volts	Screen, milliamperes	Mutual conductance, micromhos	Amplification factor	Power output, milliwatts	Load impedance, ohms
					D.C. on fil.	A.C. on fil.							
	2-volt direct-current filament power amplifier tubes												
19*	Pow. ampl. class B	0.26	•135	27.0[l]	0	....	....	.....	...	......	....	2,100	10,000[m]
31*	Power ampl	0.130	135	8.0	22.5	....	4,100	.....	...	925	....	185	7,000
		0.130	180	12.3	30.0	....	3,600	.....	...	1,050	3.8	375	5,700
33*	Power ampl	0.26	135	14.5	13.5	....	50,000	135	5.0	1,450	70.0	700	7,000
49*	Power ampl.												
	Class A	0.12	135	6.0	20.0	....	4,000	.....	...	1,125	4.5	170	8,000
	Class B	0.12	180	4–28	0	....	....	.....	...	......	....	3,000	9,000
	2.5-volt alternating- or direct-current filament detector and amplifier tubes												
24A†	Biased det. R.-F.	1.75	275[d]	....[e]	5.0	5.0	....	20–45	1.7				
	ampl.	1.75	180	4.0	3.0	3.0	400,000	90.0	1.7	1,000	400	....	100,000
27†	Ampl	1.75	180	5.0	13.5	13.5	9,000	.....	...	1,000	9.0	165	18,700
27†	Biased det.[a]	1.75	250	....[c]	30.0	30.0							
29†	Det	1.00	180	4.5	3.0	....	20,700	.....	...	1,450	30.0		
35†	Variable mu	1.75	250	6.5	3.0	3.0	400,000	90.0	2.5	1,050	420		
51†	Variable mu ampl.	1.75	250	6.3	3.0	3.0	360,000	90.0	...	1,110	400		
53†	Class B ampl	2.0	300	12–70	0	....	....	.....	...	......	....	10,000	10,000
55†	Diode triode	1.0	250	8.0	20.0	20.0	7,500	.....	...	1,100	8.3	350	20,000
56†	Biased det.[a] ampl.	1.0	250	....[c]	20.0								
		1.0	250[f]	5.0	13.5	....	9,500	.....	...	1,450	13.8		
57†	R.-F. ampl. biased	1.0	250	2.0	3.0	3.0	1,500,000	100	0.5	1,225	1,500		
	det.	1.0	250[d]	.....	2.0	....	....	.....	...	......	....	....	250,000
58†	Variable mu	1.0	250	8.2	3.0	3.0	800,000	100	2.0	1,600	1,280		
2A6†	Duplex diode triode[p]	0.8	250[k]	0.4	1.35	....	....	.....	...	......	Gain per stage = 50 to 60		
2A7†	Pentagrid det.-osc.	0.8	250	3.5	3.0	....	360,000	100	2.2	520[n]			
2B7†	Duplex diode pentode.	0.8	250	9.0	3.0	....	650,000	125	2.3	1,125	730	Conversion conductance, 325[z]	

45*	Power ampl......	1.5	250	34.0	50.0	50.0	1,610	.....	...	2,175	3.5	1,600	3,900
46*	Class A ampl.[g]...	1.75	250	22.0	31.5	33.0	2,380	.....	...	2,350	5.6	1,250	6,400
	Class B ampl.[h]...	1.75	300	8–70	0.0	0.0	....	.....	...	......	....	16,000	2,600
		1.75	400	12–75	0.0	0.0	....	.....	...	......	....	20,000[i]	2,900[j]
47*	Power pentode...	1.75	250	*31.0*	*15.0*	16.5	*60,000*	250	6.0	2,500	150	2,700	7,000
59†	3-grid pow. ampl.												
	Class A triode..	2.0	250	26.0	28	....	2,400	.....	...	2,600	6.0	1,250	5,000
	Class A pentode.	2.0	250	35.0	18	....	40,000	250	9.0	2,500	100	3,000	6,000
	Class B triode...	2.0	400	30–75	0	....	....	.....	...	......	....	20,000	6,000
2A3*	Triode power ampl. class A...	2.5	250	60.0	42	42.0	800	.....	...	5,250	4.2	3.5	2,500
95 2A5†	Power ampl. pentode........	1.75	250	34.0	16.5	16.5	100,000	250	0.5	2,200	220	3.0	7,000
3-volt filament detector and amplifier tubes													
401*d.c.	Det. ampl.......	1.5	90	4.2	4.5	....	9,400	.....	...	870	8.6		
485†a.c.	Det. ampl.......	1.25	90	5.0	*3.0*	....	10,800	.....	...	1,150	12.5		
		1.25	120	6.0	4.0	....	9,300	.....	...	1,350	12.5		
3.3-volt direct-current filament detector and amplifier tubes													
22*	R.-F. ampl......	0.132	135	3.7	1.5	....	325,000	67.5	1.3	500	160		
99*	Det.[a] ampl......	0.063	45	1.5	*+A*	....	17,000	.....	...	370	6.6		
			90	2.5	4.5	....	15,500	.....	...	425	6.6	7.0	15,500
3.3-volt direct-current filament power amplifier													
20*	Power ampl.....	0.132	135	6.5	22.5	....	6,300	.....	...	525	3.3	110	6,500

RADIO-RECEIVING-TUBE AVERAGE CHARACTERISTICS.—(*Continued*)

Tube	Use	Filament or heater, amperes	Plate, volts	Plate, milliamperes	Negative grid bias, volts		Plate resistance, ohms	Screen voltage, volts	Screen, milliamperes	Mutual conductance, micromhos	Amplification factor	Power output, milliwatts	Load impedance, ohms
					D.C. on fil.	A.C. on fil.							
5-volt direct-current filament detector and amplifier tubes													
00A*	Det.	0.25	45	1.5	−A	....	30,000	.....	...	666	20.0		
01A*	Det.[a] ampl.	0.25	90	2.5	4.5	....	11,000	.....	...	725	8.0	15.0	11,000
		0.25	135	3.0	9.0	....	10,000	.....	...	800	8.0	55.0	20,000
12A*	Det.[a] ampl.	0.25	90	5.2	4.5	....	5,600	.....	...	1,500	8.5	30.0	5,600
		0.25	135	6.2	9.0	....	5,300	.....	...	1,600	8.5	115	8,700
		0.25	180	7.6	13.5	....	5,000	.....	...	1,700	8.5	260	10,800
40*	Voltage ampl.	0.25	180[k]	0.2	3.0	....	150,000	.....	...	200	30.0	....	250,000
5-volt alternating- or direct-current filament power amplifiers													
71A*	Power ampl.	0.25	180	20.0	40.5	43.0	1,750	.....	...	1,700	3.0	790	4,800
GA*	Power pentode	0.25	180	25.0	10.0	....	30,000	180	...	2,000	60.0	800	7,000
182B*	Power ampl.	1.25	200	20.0	45.0	....	2,000	.....	...	1,500	3.0		
183*	Power ampl.	1.25	250	26.0	65.0	....	1,500	.....	...	2,000	3.0		
6.3-volt alternating- or direct-current filament detector, amplifier and converter tubes													
36†	R.-F. ampl.	0.3	180	3.1	3.0	....	500,000	90.0	1.7	1,050	525		
	Biased det.	0.3	135[d]	....[e]	6.0	....	....	67.5					
37†	Ampl.	0.3	180	4.7	13.5	....	10,000	.....	...	900	9.0	75.0	20,000
	Biased det.[a]	0.3	135	....[c]	15.5								
39/44	Variable mu	0.3	180	5.8	3.0	....	750,000	90.0	1.4	1,000	750		
69†	Det.	0.30	180	4.5	3.0	....	20,700	.....	...	1,450	30.0		
75†	Duplex diode triode	0.3	250	0.8	2.0	....	91,000	.....	...	1,100	100		
76†	Super triode class			5.0	13.5	....	9,500	.....	...	1,450	13.8		
	A ampl detector[a]	0.3	250	....[c]	20.0								
77†	R.-F. pentode	0.3	250	2.3	3.0	....	1,500,000	100	0.5	1,250	1,500		
78†	R.-F. ampl.	0.3	250	10.5	3.0	....	600,000	125	2.6	1,650	990		
85†	Duplex diode triode	0.3	180	6.0	13.5	....	8,500	.....	...	975	8.3	160	20,000
92†	2-grid det.	0.4	250	3.5	0	....	10,000	.....	...	1,400	14.0	....	100,000

6A7†	Pentagrid det.-osc.	0.8	250	3.5	3.0	....	360,000	100	2.2	520[n]	....	conversion conductance, 520[z]	
6B7†	Duplex diode pentode........	0.3	250	6.0	3.0	....	800,000	100	...	1,000	800		
6C6†	Triple-grid det. ampl.[q].........	0.3	250	2.0	7.0	....	1,500,000	100	...	1,225	1,500		
6D6†	Triple-grid variable mu[r].......	0.3	250	8.2	3.0	....	800,000	100	2.0	1,600	1,280		
954†	Det.[y]..........	0.15	250	....[c]	6.0	....	....	100	...	......	....	....	250,000
	Ampl.[z]..........	0.15	250	2.0	3.0	....	1,500,000	100	0.7	1,400	2,000		
955†	Class A ampl....	0.16	180	4.5	5.0	....	12,500	.....	...	2,000	....	135	20,000
	Class C ampl.-osc.	0.16	180	7.0	35.	....	D.c. grid current 1.5 ma.					500	
	6.3-volt alternating- or direct-current filament power amplifier tubes												
38†	Power ampl.....	0.30	250	22	25	....	100,000	250	3.8	1,200	120	2,500	10,000
41†	Power pentode...	0.40	250	32	18	....	68,000	250	5.5	2,200	150	3,400	7,600
42†	Power pentode...	0.70	250	34	16.5	....	100,000	250	6.5	2,200	220	3,000	7,000
52*	Power ampl.												
	Class A........	0.3	100	42.0	0	....	....	.....	...	......	5.0	1,500	2,000
	Class B........		180	6–40	0	....	....	.....	...	......	....	6,000	9,000
79†	Class B ampl....	0.6	180	44.0[l]	0	....	....	.....	...	......	....	5,500	7,000[m]
89†	Class A triode...	0.4	160	17.0	20.0	....	3,300	.....	...	1,425	4.7	300	7,000
	Class A pentode.		180	20.0	18.0	....	80,000	180	3.0	1,550	125	1,500	8,000
	Class B triode...		180	.....	0	....	....	.....	...	......	....	3,500	9,400
6A4*	Power ampl. pentode[s]..........	0.3	180	22.0	12.0	....	45,500	180	3.9	2,200	100	1,400	8,000
6A6†	Twin triode class B ampl.......	0.8	250	.....	0	....	....	.....	...	......	....	8,000	8,000[m]
6F7†	Triode ampl.....	0.3	100	3.5	3.0	....	17,800	.....	...	450	8		
	Pentode ampl...	0.3	250	6.5	3.0	....	850,000	100	1.5	1,100	900		
	Pentode mixer[t]..	0.3	250	2.8	10.0	....	....	100	0.6				
	7.5-volt alternating- or direct-current filament power amplifier tubes												
10*	Power ampl.....	1.25	350	16.0	27.0	31.0	5,150	.....	...	1,550	8.0	900	11,000
		1.25	425	18.0	35.0	39.0	5,000	.....	...	1,600	8.0	1,600	10,200
50*	Power ampl.....	1.25	350	45.0	59.0	63.0	1,900	.....	...	2,000	3.8	2,400	4,100
		1.25	450	55.0	80.0	84.0	1,800	.....	...	2,100	3.8	4,600	4,350
	14-volt direct-current filament power amplifier tubes												
18†	Power pentode...	0.3	250	34.0	16.5	....	100,000	250	...	2,200	220	3,000	7,000

RADIO-RECEIVING-TUBE AVERAGE CHARACTERISTICS.—(*Concluded*)

Tube	Use	Filament or heater, amperes	Plate, volts	Plate, milliamperes	Negative grid bias, volts		Plate resistance, ohms	Screen voltage, volts	Screen, milliamperes	Mutual conductance, micromhos	Amplification factor	Power output, milliwatts	Load impedance, ohms
					D.C. on fil.	A.C. on fil.							
15-volt alternating-current filament detector and amplifier tubes													
22†	R.-F. ampl......	0.35	135	1.0	....	1.0	700,000	30.0	1.3	570	400		
26†	Det............	0.35	90	7.5	....	1.5	9,000	.....	...	1,165	10.5		
28†	Det. ampl.......	0.35	90	7.5	....	1.5	9,000	.....	...	1,165	10.5		
32†	Voltage ampl....	0.35	135	1.5	....	3.0	32,000	.....	0.4	940	30.0		
15-volt alternating-current filament power amplifier tubes													
30†	Power ampl.....	0.35	180	22.0	....	27.0	3,500	.....	...	1,085	3.8		
40†	Power ampl.....	0.35	180	21.0	....	40.5	2,000	.....	...	1,500	3.0		
25-volt alternating- or direct-current filament power amplifier tubes													
43†	Power pentode...	0.3	135	34.0	20.0	....	35,000	135	7.0	2,300	80.0	2,000	4,000
30-volt alternating- or direct-current filament power amplifier tubes													
48†	Power ampl. tetrode........	0.4	125	50.0	22.5	....	10,000	100	9.0	2,800	28.0	2,500	2,000

Metal Radio-receiving-tube Average Characteristics

6.3-volt alternating- or direct-current filament detector, amplifier, power, and converter tubes

6A8†	Pentagrid converter[1]	0.3	250	3.3	3.0	....	....	100	3.2				
6C5†	Triode det.-ampl.	0.3	250	8.0	8.0	....	10,000	.....	...	2,000	20.0		
6D6†	Triodepow.-ampl.												
	Class A	0.7	275	31.0	40.0	....	2,250	.....	...	2,100	4.7	1,400	7,200
	Class AB (2 tubes)	0.7	300	23.0[3]	50.0	....	....	.....	...	......	....	5,000	5,300[5]
6F5†	Triode high-mu	0.3	250	0.9	2.0	....	66,000	.....	...	1,500	100		
6F6†	Class A triode	0.7	250	31.0	20.0	....	2,600	.....	...	2,700	7	850	4,000
	Class A pentode	0.7	250	34.0	16.5	....	80,000	250	6.5	2,500	200	3,000	7,000
	Class AB pentode[2]	0.7	375	17.0[3]	26.0	....	....	250	2.5[4]	.....	....	19,000	10,000[5]
6H6†	Twin diode	0.3	A.c. plate voltage (R.M.S.) per plate, 100 volts. D.c. output current, 2.0 ma.										
6J7†	Triple-grid[6] det.-ampl.	0.3	250	2.0	3.0	....	1,500,000	100	0.5	1,225	1,500		
6K7†	Triple-grid[6] variable mu	0.3	250	7.0	3.0	....	800,000	100	1.7	1,450	1,160		
6L7†	Pentagrid mixer[7]	0.3	250	2.4	....	....	1,000,000	6.2	...	350[8]			

[1] Anode-grid voltage, 250 volts. Oscillator-grid resistor, 50,000 ohms.
[2] Push-pull connection, fixed bias.
[3] Zero-signal plate current per tube.
[4] Zero-signal screen current per tube.
[5] Plate to plate.
[6] Suppressor connected to cathode at socket.
[7] Signal-grid voltage, −3 volts. Oscillator-grid voltage, −10 volts.
[8] Conversion conductance.

Rectifier Tubes

Tube	Use	Maximum voltage ratings				Current ratings		
		Filament volts	R.M.S. volts per plate	Max. peak inverse volts	D.C. drop volts	Fil. amperes	Average output, milliamperes	Max. peak, milliamperes
2.5-volt alternating-current filament rectifier tubes								
82*	Full-wave mercury vapor	2.5	500	1,400	15	3.0	125	400
866*	Half-wave mercury vapor	2.5	...	7,500	..	5.0	...	600
5-volt alternating-current filament rectifier tubes								
80*	Full wave	5.0	450	.....	..	2.0	125	
80M*	Full-wave mercury vapor	5.0	450	1,250	15	2.0	125	250
83*	Full-wave mercury vapor	5.0	500	1,400	15	3.0	250	800
83-V†	Full wave	5.0	400	.....	..	3.0	...	200
5Z3†	Full wave	5.0	500	1,500	..	3.0	250	
6.3-volt direct-current filament rectifier tubes								
6Z3†	Half wave	6.3	350	1,500	..	0.3	50	
6.3-volt alternating- or direct-current filament rectifier tubes								
1V†	Half-wave mercury vapor	6.3	350	1,000	15	0.3	50	200
84†, 6Z4	Full wave	6.3	350	1,000	..	0.5	50	125 per plate
98†	Full-wave mercury vapor	6.3	350	1,500	15	0.5	50	100
7.5-volt alternating-current filament rectifier tubes								
81*	Half wave	7.5	700	.....	..	1.25	85	
81M*	Half-wave mercury vapor	7.5	750	1,050	15	1.25	85	175

RECTIFIER TUBES.—(*Concluded*)

Tube	Use	Maximum voltage ratings				Current ratings		
		Filament volts	R.M.S. volts per plate	Max. peak inverse volts	D.C. drop volts	Fil. amperes	Average output, milli-amperes	Max. peak, milliamperes
10-volt alternating- or direct-current filament rectifier tubes								
96†	Half-wave mercury vapor.	10.0	350	1,500	15	0.3	100	400
12-volt direct-current filament rectifier tubes								
12Z3†	Half wave.	12.6	250	. . . . .	. .	0.3	60	
25-volt alternating- or direct-current filament rectifier tubes								
25Z5*	Full wave.	25.0	125	. . . . .	. .	0.3	100	200 per plate
Gaseous-type rectifier tubes—no filament								
BA	Full wave.	. . . .	. . .	350	. .	. . . .	. . .	350
BH	Full wave.	. . . .	. . .	350	. .	. . . .	. . .	125
BR	Half wave.	. . . .	. . .	600	. .	. . . .	. . . .	50

METAL RECTIFIER TUBE

5-volt alternating-current filament

5Z4†	Full-wave high-vacuum.	5.0	400	1,100	. .	2.0	125	

Regulator Tubes (Glow Discharge Type)

Type	Use	Voltage		Current	
		Starting volts D.C.	Operating volts D.C.	Operating milliamperes D.C.	Maximum milliamperes D.C.
874	Volt reg	125	90	10–50	50
	Current regulator (ballast tube)				
876	Current reg	...	40–60	1,700	
886	Current reg	...	40–60	2,050	

* Filament cathode.
† Heater cathode.
[a] For grid-leak detection—plate volts 45, grid return to + filament.
[b] Applied through plate-coupling resistance of 100,000 ohms.
[c] Plate current to be adjusted to 0.2 milliampere with no signal.
[d] Applied through plate-coupling resistance of 250,000 ohms or 500-henry choke coil shunted by 0.25 megohm resistance.
[e] Plate current to be adjusted to 0.1 milliampere with no signal.
[f] Applied through plate-coupling resistance of 50,000 ohms.
[g] Grid next to plate tied to plate.
[h] Two grids tied together.
[i] For two tubes with 40 volts R.M.S. applied to each grid.
[j] Load resistance per tube.
[k] Applied through plate-coupling resistance of 250,000 ohms.
[l] 50 volts R.M.S. applied to two grids.
[m] Power output value is for one tube, at stated load, plate to plate.
[n] This value is the conversion conductance which is the ratio of the I.-F. component of the output current to the R.-F. component of the signal voltage.
[o] Third and fifth grids are screen. Fourth grid is signal-input control grid. Second (anode) grid 135 volts 2.3 ma.
[p] Same as type 75.
[q] Same as type 57. Values given are for class A amplifier service.
[r] Same as type 58. Values given are for class A amplifier service.
[s] Same as type LA.
[t] Conversion conductance = 300 micromhos. Oscillator peak volts = 7.0.
[u] Anode grid 135 max. volts, 2.3 ma.—oscillator grid resistor, 50,000 ohms.
[v] Anode grid 135 max. volts, 3.3 ma.—oscillator grid resistor, 50,000 ohms.
[w] Cathode connected to No. 4 base pin.
[x] Anode grid 200 max. volts, 4.0 ma.—oscillator grid resistor, 50,000 ohms.
[y] For operation as biased detector, suppressor is connected to cathode at socket.
[z] Suppressor connected to cathode at socket.

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