Electronic Engineering

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PREFACE

"Electronic Engineering" and "Radio Electronics" have been written as companion volumes, though they have been produced as independent textbooks. Together they represent a revision and extension of the author's "Electron-tube Circuits." It has been necessary to include a certain amount of material that is common to both books in order to ensure completeness and continuity of text material. Moreover, the common material is the same in each book, in the interests of economy of production. However, the amount of duplicated material has been kept to a minimum, consistent with the desire to have these books independent, and also to provide a complete and continuous development.

This book has as its objective a detailed discussion of a large variety of electronic circuits which are important in such diverse fields as radar, television, electronic control and instrumentation, and computers. Those circuits which have found applications principally in the field of radio are not included in this book, though a number of circuits of interest both in nonradio and in radio applications are included. Most of the text is devoted to the analysis of circuit operation. However, some of the factors that must be considered in circuit and system synthesis are discussed.

Wherever possible, the analysis proceeds in two stages. An effort is made first to present a physical explanation of the operation of the circuits. If feasible, a mathematical analysis of the operation of the circuit is given. Such mathematical analyses have a threefold objective: (1) To illustrate the techniques of analysis. Often, in fact, alternative developments have been included to demonstrate different methods of analysis. (2) To deduce a solution which yields a description of the operation of the circuit. (3) To examine the effects of the various parameters on the operation of the circuit.

In all analyses considerable care has been taken to include the requisite reference conditions for potential polarities, current directions, and transformer-winding sense. These are an essential part of any circuit diagram, and without them the ultimate choice of a positive or negative sign would require a major decision.

Representative types of circuits of widespread use and importance have been discussed and analyzed. It is not possible, of course, to include a discussion of every possible type of circuit of a given class. In fact, a review of the literature will disclose almost as many choices of circuit parameters or tube types as there are groups engaged in this work. In general, the principle of operation is deemed to be of the essence, rather than the choice of a particular set of parameters, and most attention is paid to a discussion of these principles of operation.

Much of the material in this book has been used in courses in electronic circuits and applications at Syracuse University. A considerable amount of new material has been added to that previously available in "Electron-tube Circuits." Thus, not only has there been an addition to the content of the chapters originally available, but an introduction to solid-state theory, the transistor, and the transistor as a circuit element is now available.

To provide the proper acknowledgment of the source of much of this material is impossible. As noted in the preface to "Electron-tube Circuits," much of this material represented circuits in use at the MIT Radiation Laboratory during World War II. Some of the circuits were developed at this laboratory, but many of them were developments at a number of American and British laboratories. In only a few cases was the identity of the groups responsible for any given circuit known. Where direct sources of information have been used, reference is given to these.

The author wishes to acknowledge helpful discussions with many of his colleagues. He is particularly indebted to Dr. Herbert Hellerman for his helpful suggestions relating to Chaps. 15 and 16, and to Richard E. Gildersleeve for his assistance in proofreading the entire text.

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CONTENTS

CHAPTER 1

CHARACTERISTICS OF ELECTRON TUBES

1-1. Electronic Systems. A unique definition of an electronic system as it will be studied in this text is not possible, owing to the multiplicity and complexity of such systems. For the most part, no consideration will be given to communication systems, as these are covered in the companion volume, "Radio Electronics," although certain of the circuits which are of importance in communication applications are also of considerable importance in essentially noncommunication applications. This text will confine itself principally to a study of a variety of circuits which form the building blocks of a tremendous array of electronic systems for all manner of applications. As part of the study, some discussion will be included of the manner of connecting a variety of such building blocks to perform a specified sequence of operations.

A particular electronic system may impose a demand for electronic circuits to perform a wide diversity of operations. For example, a relatively simple system might easily require the generation of waves of sinusoidal waveshape, of square waveshape, of triangular waveshape, amplifiers which amplify with virtually no distortion, amplifiers which introduce controlled distortion, amplifiers which produce controlled blocking, and a host of others. Some building blocks may consist of relatively simple circuits, and others may require a relatively complex array of components to achieve the desired end.

In order to present the material in a reasonably logical manner, the following chapters present the analyses of the operation of a variety of classes of electronic circuits, without regard for the particular applications, but principally according to the manner of operation and analysis. For this reason, a given chapter may contain circuits which have altogether different applications. The choice of examples and problems will indicate in some measure representative applications. Some discussion will be included in such cases of practical reasons which might influence the preference for one circuit over another for achieving a specified requirement.

1-2. Fundamental Considerations in Electron Tubes. Before one undertakes a study of circuits that incorporate electron tubes, it will be well to examine certain of the physical principles which govern the operation of these tubes. There are two important basic questions that relate to such tubes. One relates to the actual source of the electrons and their liberation; the second relates to the control of the electron beam. A brief discussion of these matters follows.

EMISSION OF ELECTRONS

1-3. Source and Control of Electrons. According to modern theory, all matter is electrical in nature. The atom, which is one of the fundamental building blocks of all matter, consists of a central core or nucleus which is positively charged and which carries nearly all the mass of the atom. Enough negatively charged electrons surround the nucleus so that the atom is electrically neutral in its normal state. Since all chemical substances consist of groups of these atoms which are bound to each other, then all matter, whether it is in the solid, the liquid, or the gaseous state, is a potential source of electrons. All three states of matter do, in fact, serve as sources of electrons. A number of different processes serve to affect the release of electrons, those which are of importance in electron tubes being (1) thermionic emission, (2) secondary emission, (3) photoelectric emission, (4) high field emission, and (5) ionization. These processes will be considered in some detail in what follows.

With the release of the electrons, a means for their control must be provided. Such control is effected by means of externally controlled electric fields or magnetic fields, or both. These fields perform one or both of the following functions: (1) control of the number of electrons that leave the region near the emitter; (2) control of the paths of the electrons after they leave the emitter. Control method 1 is the more common, and such a control method is incorporated in almost all electron tubes, except those of the field-deflected variety. The cathode-ray tube is a very important example of a field-deflected tube. However, even in this latter case, a control of type 1 is incorporated to control the electron-tube current, even though the subsequent motion is controlled by means of electric or magnetic fields, or both.

1-4. Thermionic Emission. Consider matter in the metallic state. Metals are most generally employed in the form of a wire or ribbon filament. If such a filament contains electrons and if these are relatively free to move about in the metal (and this is the case since the application of a small potential difference between the ends of the wire will result in a current flow), it might be expected that some electrons might "leak" out of the metal of their own accord. This does not occur, however.

Consider what happens to an electron as it seeks to escape from a metal. The escaping, negatively charged electron will induce a positive charge on the metal. There will then be a force of attraction between the induced charge and the electron. Unless the escaping electron possesses sufficient energy to carry it out of the region of influence of this image force of attraction, it will be returned to the metal.* The minimum amount of energy that is required to release the electron against this attractive force is known as the *work function* of the metal. This requisite minimum amount of energy may be supplied by any one of a number of different methods. One of the most important methods is to heat the metal to a high temperature. In this way, some of the thermal energy supplied to the metal is transferred from the lattice of the heated metal crystals into kinetic energy of the electrons.

An explicit expression relating the thermionic-emission current density and the temperature of the metal can be derived.[1]† The expression so derived has the form

$$J_{th} = A_0 T^2 \epsilon^{-b_0/T} \tag{1-1}$$

where A_0 is a constant for all metals and has the value of 120×10^4 amp/(m²)(°K²) and b_0 is a constant that is characteristic of the metal. The quantity b_0 is related to the work function E_W of the metal by

$$b_0 = 11{,}600 E_W \quad \text{°K} \tag{1-2}$$

It has been found experimentally that Eq. (1-1) does represent the form of the variation of current with temperature for most metals, although the value obtained for A_0 may differ materially from the theoretical value of 120×10^4 amp/(m²)(°K²).

TABLE 1-1

THE IMPORTANT THERMIONIC EMITTERS AND THE THERMIONIC-EMISSION CONSTANTS

Emitter	A_0, amp/(m²)(°K²)	E_W, ev
Tungsten	60×10^4	4.52
Thoriated-tungsten	3×10^4	2.63
Oxide-coated	0.01×10^4	1

It follows from Eq. (1-1) that metals that have a low work function will provide copious emission at moderately low temperatures. Unfortunately, however, the low-work-function metals melt in some cases and boil in others, at the temperatures necessary for appreciable thermionic emission. The important emitters in present-day use are pure-tungsten, thoriated-tungsten, and oxide-coated cathodes. The thermionic-emission constants of these emitters are contained in Table 1-1.

* A somewhat more detailed discussion of the electron theory of metals is given in Chap. 15.

† Superior numbers refer to citations at the end of some chapters.

Tungsten is used extensively for thermionic filaments despite its relatively high work function. In fact, this material is particularly important because it is virtually the only material that can be used successfully as the filament in high-potential tubes. It is used in high-potential X-ray tubes, in high-potential rectifier tubes, and in the large power-amplifier tubes that are used in radio and communication applications. It has the disadvantage that the *cathode emission efficiency*, defined as the ratio of the emission current in milliamperes to the heating power in watts, is small. Despite this, it can be operated at a sufficiently high temperature, between 2600 and 2800°K, to provide an adequate emission.

It has been found that the application of a very thin layer of low-work-function material on filaments of tungsten will materially reduce the work function of the resulting surface. A thoriated-tungsten filament is obtained by adding a small amount of thorium oxide to the tungsten before it is drawn. Such filaments, when properly activated, will yield an efficient emitter at about 1800°K. It is found desirable to *carbonize* such an emitter, since the rate of evaporation of the thorium layer from the filament is thus reduced by about a factor of 6. Thoriated-tungsten filaments are limited in application to tubes that operate at intermediate potentials, say 10,000 volts or less. Higher-potential tubes use pure-tungsten filaments.

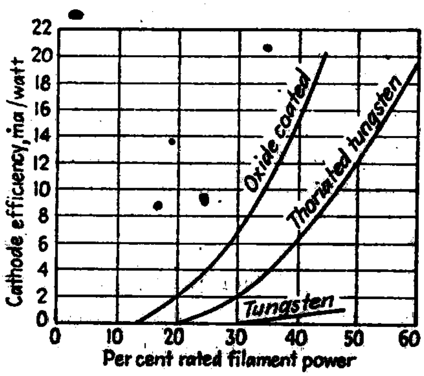


FIG. 1-1. Cathode efficiency curves of an oxide-coated, a thoriated-tungsten, and a pure-tungsten filament.

The oxide-coated cathode is very efficient (about twenty times as efficient as tungsten) and provides a high emission current at the relatively low temperature of 1000°K. It consists of a metal sleeve of konal (an alloy of nickel, cobalt, iron, and titanium) or some other metal, which is coated with the oxides of barium and strontium. These cathodes are limited for a number of reasons to use in the lower potential tubes, say about 1,000 volts or less, although they do operate satisfactorily at higher potentials under pulsed conditions at relatively low-duty cycle. They are used almost exclusively in receiving-type tubes and provide efficient operation with long life.

Curves showing the relative cathode efficiencies of tungsten, thoriated-tungsten, and oxide-coated cathodes are illustrated in Fig. 1-1. It will be seen that tungsten has a considerably lower efficiency than either of the other two emitters.

The thermionic emitters in their practical form in electron tubes may

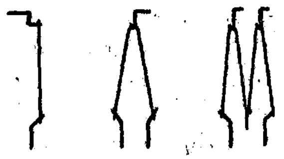


FIG. 1-2. Typical directly heated cathodes.

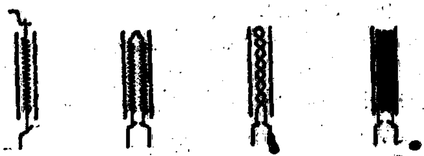
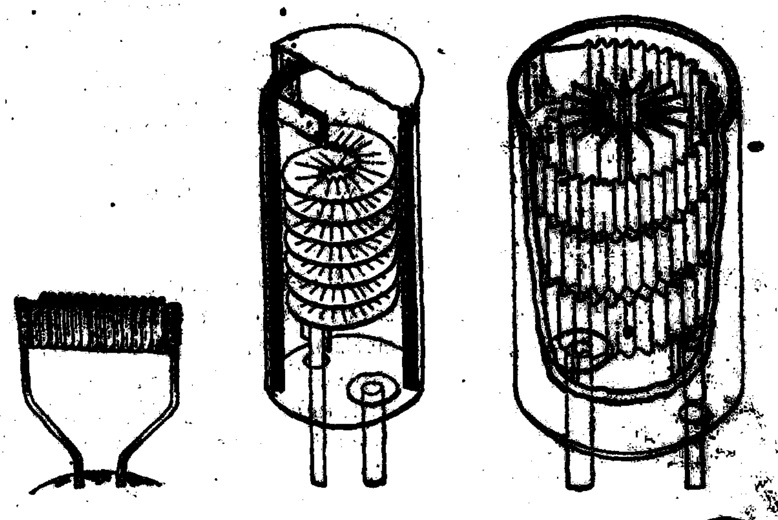


FIG. 1-3. Typical indirectly heated cathodes.



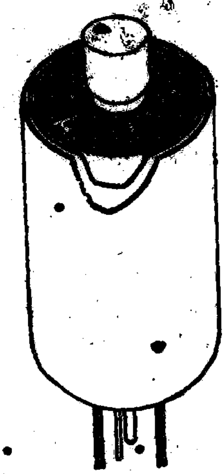


FIG. 1-4. Different types of heat-shielded cathodes. (*General Electric Co. and Lowry.*)

be of the directly heated or filamentary type, or of the indirectly heated type, and in the case of gas and vapor tubes the cathode may be of the heat-shielded type. Typical filamentary cathodes are illustrated in Fig. 1-2. These filamentary cathodes may be of the pure-tungsten, thoriated-tungsten, or oxide-coated type.

The indirectly heated cathode for use in vacuum tubes is illustrated in Fig. 1-3. The heater wire is contained in a ceramic insulator which is enclosed by the metal sleeve on which the oxide coating is placed. A cathode assembly of this type has such a high heat capacity that its temperature does not change with instantaneous variation in heater current when alternating current is used.

Heat-shielded cathodes, which can be used only in gas-filled electron tubes for reasons to be discussed in Sec. 1-25, are designed in such a way as to reduce the radiation of heat energy from the cathode. This materially increases the efficiency of the cathode. Several different types of heat-shielded cathodes are illustrated in Fig. 1-4.

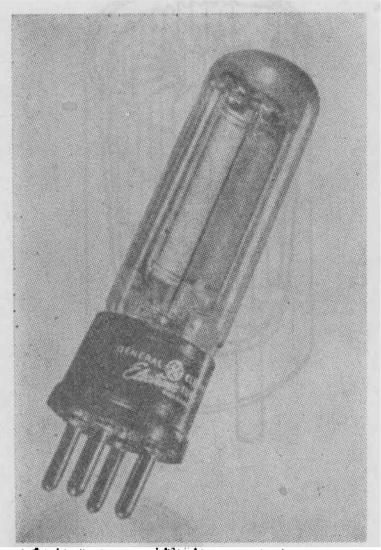


FIG. 1-5. A typical phototube.

1-5. Photoelectric Emission. The energy that is required to release an electron from a metal surface may be supplied by illuminating the surface with light. There are certain restrictions on the nature of the surface and the frequency of the impinging light for such electron emission to take place. That is, electron emission is possible only if the frequency of the impinging light exceeds a certain *threshold* value that depends on the work function E_W of the surface according to the equation

$$f_c = \frac{eE_W}{h} \tag{1-3}$$

where e is the charge of the electron and h is Planck's constant. The corresponding *threshold wavelength* beyond which photoelectric emission cannot take place is given by

$$\lambda_c = \frac{ch}{eE_W} = \frac{12{,}400\text{ A}}{E_W} \tag{1-4}$$

where A is the angstrom unit (10^{-8} cm). For response over the entire visible region, 4000 to 8000 A, the work function of the photosensitive surface must be less than 1.54 volts.

The essential elements of a phototube are the photosensitive cathode surface and a collecting electrode contained in a glass envelope that either is evacuated or contains an inert gas at low pressure. A photograph of such a phototube is shown in Fig. 1-5. The number of photoelectrons per square millimeter of area of a photocathode is small, and it is customary to use photocathodes of large area, as shown.

The current characteristics of such phototubes for different collecting potentials between the cathode and the collecting anode, with light intensity as a parameter, are illustrated. Figure 1-6 shows the curves of a

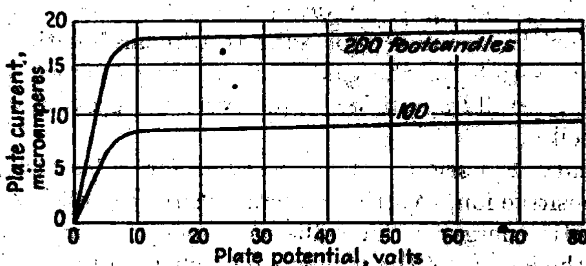


FIG. 1-6. The volt-ampere characteristics of a type PJ-22 vacuum phototube, with light intensity as a parameter.

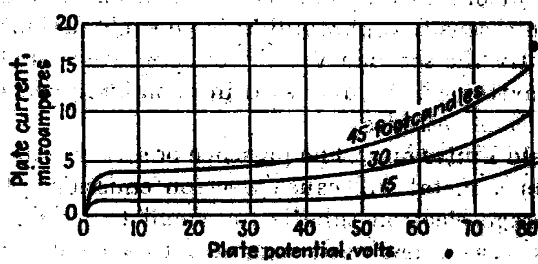


FIG. 1-7. The volt-ampere characteristics of a type PJ-23 gas-filled phototube, with light intensity as a parameter.

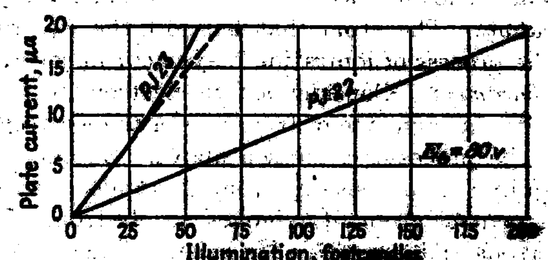


FIG. 1-8. Photocurrent as a function of illumination for a PJ-22 vacuum phototube and a PJ-23 gas-filled cell.

vacuum phototube with light intensity as a parameter. Note that the current reaches near saturation values for very low values of applied potential.

The presence in the glass envelope of an inert gas, such as neon or argon, at low pressure materially alters the volt-ampere curves. A set of characteristic curves for a gas phototube are given in Fig. 1-7. The presence of the gas in a phototube increases the sensitivity of the phototube, the current output for a given light intensity increasing with increased plate potential, whereas the output remains sensibly constant in the vacuum phototube.

A significant comparison of the output from two phototubes, one of the vacuum type and the other of the gas-filled type, other characteristics of the tubes being the same, is contained in Fig. 1-8. Note that the photocurrent for the vacuum phototube is a linear function of the illumination, whereas that for the gas-filled cell shows deviations from the linear at the higher illuminations. However, the greater sensitivity of the gas-filled cell is clearly evident.

1-6. Secondary Emission. It is possible for a particle, either an electron or a positive ion, to strike a metallic surface and transfer all or a part of its kinetic energy in this collision to one or more of the internal electrons. If the energy of the incident particle is sufficiently high, some of the internal electrons may be emitted. Several tubes have been designed which incorporate secondary-emission surfaces as part of the device, and highly sensitive phototubes have such auxiliary elements in them. Frequently the secondary emission that exists is of a deleterious nature. This matter will be discussed in explaining certain features of the characteristics of tetrodes.

1-7. High Field Emission. The presence of a very strong electric field at the surface of a metal will cause electron emission. Ordinarily the field in the average electron tube is too small to induce such electron emission. This process has been suggested to account for the electron emission from a mercury-pool cathode in a mercury rectifier.

1-8. Ionization. The process in which an atom loses an electron is known as *ionization*. The atom that has lost the electron is called a *positive ion*. The process of ionization may occur in several ways.

Electron Bombardment. Consider a free electron, which might have been released from the envelope or from any of the electrodes within the tube by any of the processes discussed above. Suppose that this free electron has acquired enough energy from an applied field so that, upon collision with a neutral atom, it removes an electron. Following this action, two electrons and a positive ion exist. Since there are now two electrons available, both may collide with gas particles and thus induce further ionization. Such a process as this may become cumulative, with consequent large electron release. This process is very important and accounts for the successful operation of gas- and vapor-filled rectifier tubes. It is also the basis of the gas amplification in gas-filled phototubes.

Photoelectric Emission. If the gas is exposed to light of the proper frequency, then this radiant energy may be absorbed by the atom, with resulting electron emission. This process is important in initiating certain discharges.

Positive-ion Bombardment. The collision between a positive ion and a neutral gas particle may result in electron release, in much the same manner as by electron bombardment. This process is very inefficient and is usually insignificant in normal gas tubes.

Thermal Emission. If the temperature of the gas is high enough, some electrons may become dislodged from the gas particles. However, the gas temperature in electron tubes is generally low, and this process is normally unimportant.

THE HIGH-VACUUM DIODE

1-9. The Potential Distribution between the Electrodes. Consider a thermionic source situated in a vacuum. This cathode will emit electrons, most of which have very little energy when they emerge. Those electrons which first escape will diffuse throughout the space within the envelope. An equilibrium condition will soon be reached when, because of the mutual repulsion between electrons, the free electrons in the space will prevent any additional electrons from leaving the cathode. The equilibrium state will be reached when the space charge of the electron cloud produces a strong enough electric field to prevent any subsequent emission.

The inclusion of a collecting plate near the thermionic cathode will allow the collection of electrons from the space charge when this plate is maintained at a positive potential with respect to the cathode; the higher the potential, the higher the current. Of course, if the thermionic emission is limited, then the maximum current possible is the temperature-saturated value.

In addition to such a simple two-element device, which is the diode, grids may be interposed between the cathode and plate. If a single grid is interposed, the tube is a triode. If two grids are present, the tube is a tetrode; three grids yield a pentode, etc. Details of the characteristics and operation of such devices will be considered in some detail in the following pages.

Consider a simple diode consisting of a plane cathode and a collecting plate, or anode, which is parallel to it. It is supposed that the cathode can be heated to any desired temperature and that the potential between the cathode and anode may be set at any desired value. It is desired to examine the potential distribution between the tube elements for various cathode temperatures and fixed anode-cathode applied potential.

Suppose that the temperature of the cathode is high enough to allow some electrons to be emitted. An electron space-charge cloud will be formed in the envelope. The density of the electrons and the potential at any point in the interelectrode space are related by Poisson's equation

$$\frac{d^2V}{dx^2} = \frac{\rho}{\epsilon_0} \tag{1-5}$$

where V is the potential in volts, ρ is the magnitude of the electronic-charge density in coulombs per cubic meter, and $\epsilon_0 = 10^{-9}/36\pi$ is the permittivity of space. A study of this expression will yield significant information.

It is supposed that the electrons that are emitted from the cathode have zero initial velocities. Under these conditions, the general character of the results will have the forms illustrated in Fig. 1-9. At the temperature T_1, which is too low for any emission, the potential distribution is a linear function of the distance from the cathode to the anode. This follows from Eq. (1-5), since, for zero-charge density,

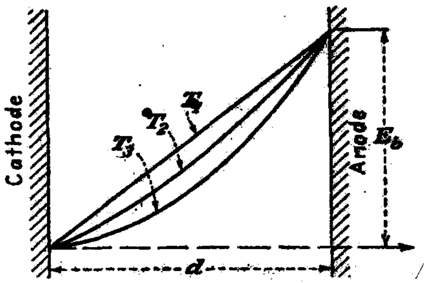


FIG. 1-9. The potential distribution between plane-parallel electrodes, for several values of cathode temperature.

$$\frac{d^2V}{dx^2} = 0 \qquad \text{or} \qquad \frac{dV}{dx} = \text{const}$$

This is the equation of a straight line.

At the higher temperature T_2, the charge density ρ is not zero. Clearly, the anode-cathode potential, which is externally controlled, will be independent of the temperature, and all curves must pass through the fixed end points. Suppose that the potential distribution is somewhat as illustrated by the curve marked T_2. All curves must be concave upward, since Eq. (1-5), which may be interpreted as a measure of the curvature, is positive. A positive curvature means that the change in slope dV/dx between two adjacent points must be positive. Moreover, the curvature is greater for larger values of ρ, corresponding to the higher temperatures. It is possible to justify that the maximum current that can be drawn from the diode for a fixed plate potential and any temperature is obtained under the condition of zero electric field at the surface of the cathode. Under these optimum conditions,

$$\frac{dV}{dx} = 0 \qquad \text{at } x = 0 \tag{1-6}$$

This condition is valid under the assumption of zero initial velocities of emission of the electrons.

1-10. Equations of Space Charge. An explicit relation between the urrent collected and the potential that is applied between the anode and cathode is possible. In general, the current density is a measure of the rate at which the electrons pass through unit area per unit time in the direction of the field. If v denotes the drift velocity in meters per second, N is the electron density in electrons per cubic meter, and e is the electronic charge in coulombs, then the current density in amperes per square meter is

$$J = Nev = \rho v \tag{1-7}$$

Also, neglecting the initial velocity, the velocity of the electron at any point in the interelectrode space is related to the potential through which it has fallen by the following expression, which is based on the conservation of energy:

$$\tfrac{1}{2}mv^2 = eV \tag{1-8}$$

By combining the foregoing expressions, there results

$$\frac{d^2V}{dx^2} = \frac{JV^{-\frac{1}{2}}}{\epsilon_0(2e/m)^{\frac{1}{2}}} \tag{1-9}$$

This is a differential equation in V as a function of x. The solution of it is given by

$$J = \frac{\epsilon_0}{2.25}\sqrt{2\frac{e}{m}}\,\frac{V^{\frac{3}{2}}}{x^2} \qquad \text{amp/m}^2 \tag{1-10}$$

For electrons, and in terms of the boundary conditions $V = E_b$ at the anode, there results

$$J = 2.33 \times 10^{-6}\,\frac{E_b^{\frac{3}{2}}}{d^2} \qquad \text{amp/m}^2 \tag{1-11}$$

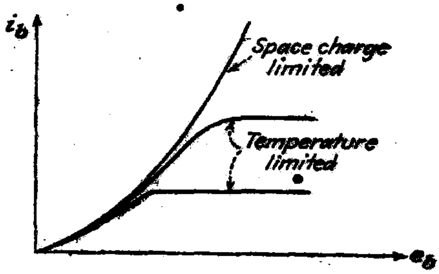


FIG. 1-10. The volt-ampere characteristics of a typical diode.

This equation is known as the *Langmuir-Childs*, or *three-halves-power, law*. It relates the current density, and so the current, with the applied potential and the geometry of the tube. It shows that the space-charge current is independent of the temperature and the work function of the cathode. Thus, no matter how many electrons a cathode may be able to supply, the geometry of the tube and the applied potential will determine the maximum current that can be collected by the anode. If the electron supply from the cathode is restricted, the current may be less than the value predicted by Eq. (1-11). The conditions are somewhat as represented graphically in Fig. 1-10.

For the case of a tube that possesses cylindrical symmetry, a similar analysis is possible. The results of such a calculation lead to the following expression for the current,

$$I_b = 14.6 \times 10^{-6} \frac{l}{r_a} \frac{E_b^{3/2}}{\beta^2} \quad \text{amp} \tag{1-12}$$

where l is the active length of the tube and β^2 is a quantity that is determined from the ratio r_a/r_k, the ratio of anode to cathode radius. For ratios r_a/r_k of 8 or more, β^2 may be taken as unity.

Attention is called to the fact that the plate current depends upon the three-halves power of the plate potential both for the plane parallel and also for a diode possessing cylindrical symmetry. This is a general relationship, and it is possible to demonstrate that an expression of the form $I_b = kE_b^{3/2}$ applies for any geometry, provided only that the same restrictions as imposed in the above developments are true. The specific

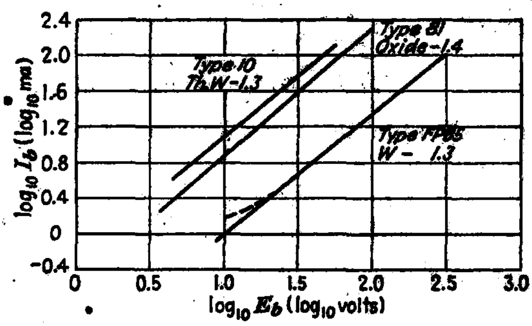


FIG. 1-11. Experimental results to verify the three-halves-power law for tubes with oxide-coated, thoriated-tungsten, and pure-tungsten filaments.

value of the constant k that exists in this expression cannot be analytically determined unless the geometry of the system is specified.

The dependence of the current on the potential for any tube may be determined by plotting the results obtained experimentally on a logarithmic scale. Theoretically one should find, if the expression $I_b = kE_b^{3/2}$ is valid, that

$$\log_{10} I_b = \log_{10} k + \tfrac{3}{2} \log_{10} E_b \tag{1-13}$$

The logarithmic plots for three commercial tubes are shown in Fig. 1-11. The type 10 tube is a triode and was converted into a diode by connecting grid and plate together. The other tubes are diodes. It will be observed that the logarithmic plots are straight lines, although the slopes of these lines are all slightly less than the theoretical 1.5.

1-11. Rating of Vacuum Diodes. The current and potential ratings of a diode, i.e., the maximum current that the tube may carry and the maximum potential difference that may be applied between anode and cathode, are influenced by a number of factors.

1. A limit is set to the tube current by the cathode efficiency of the emitter. Thus, for a given input power to the filament, a maximum current is specified.

2. There is a maximum temperature limit to which the glass envelope of the tube may be safely allowed to rise. This is the temperature to which the tube was raised during the outgassing process. This is about 400°C for soft glass and about 600°C for pyrex. For higher temperatures, the gases adsorbed by the glass walls may be liberated. Owing to this limitation, glass bulbs are seldom used for vacuum tubes of more than about 1 kw capacity.

3. A very important limitation is set by the temperature to which the anode may rise. In addition to the fraction of the heat radiated by the cathode that is intercepted by the anode, the anode is also heated by the energy carried by the anode current. The instantaneous power carried by the anode current and supplied to the anode is given by $e_b i_b$, where e_b is the anode-cathode potential and i_b is the anode current. The temperature to which the anode rises will depend upon the area of the anode and the material of its construction.

The most common metals used for anodes are nickel and iron for receiving tubes and tantalum, molybdenum, and graphite for transmitting tubes. The surfaces are often roughened or blackened in order to increase the thermal emissivity. The anodes of many transmitting tubes may be operated at a cherry-red heat without excessive gas emission. To allow for forced cooling of the anode, cooling coils may be provided, or the tube may be immersed in oil. The newer type of transmitting tubes are frequently provided with radiator fins for forced-air cooling. Two different types of transmitting tubes are illustrated in Fig. 1-12.

4. The potential limitation of a high-vacuum diode is also dependent on the type of its construction. If the filament and anode leads are brought out side by side through the same glass press, some conduction may take place between these leads through the glass. This effect is particularly marked if the glass is hot, and the resulting electrolysis will cause the glass to deteriorate and eventually to leak. The highest potential permissible between adjacent leads in glass depends upon the spacing and upon the type of glass but is generally kept below 1,000 volts. Higher-potential tubes are usually provided with filament leads at one end of the glass envelope, with the anode at the other end.

The glass envelope must be long enough so that flashover on the outside of the tube will not occur. In a diode as a rectifier, no current will exist during the time that the anode is negative with respect to the cathode. The maximum safe rating of a rectifying diode is known as the *peak-inverse-potential rating.*

Commercial vacuum diodes are made which will rectify current at high