GEPPERT

Basic Electron Tubes

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BASIC ELECTRON TUBES

DONOVAN V. GEPPERT, M.S.E.E.
General Electric Company
Syracuse, New York

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BASIC ELECTRON TUBES

PREFACE

A study of electronics involves a study of electron tubes and their associated circuit applications. Although there are many good electronics books on the market which cover the circuit applications thoroughly, the electron tubes themselves are all too often shoved into the background and neglected. Only by going into advanced graduate texts can a really good coverage of the tubes themselves be obtained. The undergraduate must be content, then, with an inadequate explanation of the complicated behavior of the various types of electron tubes.

In order to remedy this situation, the author has sought to write a book readable to the average undergraduate and yet advanced enough to give the student a really satisfying treatment of the physics and mathematics of electron tubes.

Each chapter is devoted to one specific type of electron tube. The student is first acquainted with the physical appearance of the particular tube. Then an experimental circuit diagram is given, along with the electrical characteristics to be obtained therefrom. The student can reproduce these results in the laboratory, of course, for himself. Then, and only then, is the physical theory presented to the student, whose curiosity should have been sufficiently aroused so that he is eager to learn the explanation for the peculiar electrical behavior. The theory is presented *without* mathematics, and mechanical analogies are judiciously applied. Then, finally, the mathematics is presented, again in as digestible a form as possible.

As each new tube type is discussed, the physical theory and mathematics are gradually enlarged and developed, so that the student's absorptive capacity is never severely taxed. Is this not better than expecting him to swallow two or three chapters of atomic theory and electron ballistics equations at the beginning of the course before he is convinced of the need for such material? The sequence of chapters has been carefully chosen so that this progression in the theory and mathematics is as logical and as orderly as possible.

No effort has been made to cover every conceivable type of high-vacuum tube. Microwave tubes have not been included because electromagnetic field theory is required for such study, and this book is intended to be a *first* course in electronics, possibly taken in parallel with a-c circuits. Or it could be used as a supplementary text with any text giving good coverage of circuit applications but incomplete treatment of the tubes themselves.

It is the author's hope that this book may be valuable not only to the undergraduate student for whom it was primarily written, but also may be helpful to practicing engineers and technicians who feel the need for a better understanding of electron tubes.

The author is deeply grateful for the helpful criticism and suggestions offered by Professor Newton H. Barnette and Professor Arthur S. Brown. The author is forever indebted to his wife, Doris, who typed the entire manuscript, and without whose forbearance and encouragement this volume would never have been produced.

DONOVAN V. GEPPERT

SYRACUSE, N. Y.
April, 1951

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CHAPTER 1

HIGH-VACUUM AND GAS PHOTOTUBES

PHOTOELECTRIC tubes allow control of electric currents through the medium of light. They are used for sound reproduction from film, counting moving objects, color sorting, flame-control work, opening doors, operating burglar alarms, and a host of other applications in the fields of measurement and control. Despite their tremendous importance in our present-day civilization, they are in many ways the simplest of all electron tubes and will be discussed first for this reason.

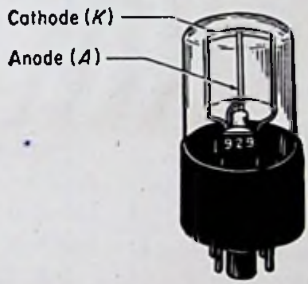

FIG. 1.1. Construction of a typical phototube. This is a vacuum tube used in relay and measurement work.

1.1. Physical Characteristics of Phototubes. A typical photoelectric tube, or simply phototube, as it is usually called, is shown in Fig. 1.1. K is a piece of sheet metal formed into a circular half cylinder. The letter K is the symbol for the word cathode. The inside surface of the cathode is specially treated, as described later. A is simply a stiff wire situated along the axis of the cylindrical cathode. The letter A is the symbol for the word anode. Symbols such as K and A are very frequently used to denote the internal elements of electron tubes. The electrodes are enclosed in a glass envelope, inside of which a good vacuum has been drawn.

In practice, the cathode is allowed to be illuminated by light from some source, such as an incandescent lamp. A large cathode is generally used so as to intercept as much light as possible. A small anode is necessary to avoid cutting off the light rays going to the cathode.

Another type of construction is shown in Fig. 1.2. The cathode is a circular cylinder containing numerous small holes. The inside surface is specially treated, as before. Light coming from any direction will pass through the holes and illuminate the inside surface of the cathode on the opposite side. The anode is a stiff wire situated along the axis of the cylinder, as before. The tube shown in Fig. 1.1 will respond to light from only one direction, whereas the tube shown in Fig 1.2 will respond to light from any direction. This tube also differs from the one shown in Fig. 1.1 in that it is not maintained at a high vacuum; instead, a small amount of argon gas has been admitted at a low pressure. Hence it is called a gas phototube.

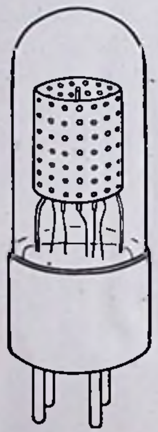

FIG. 1.2. A gas phototube used in relay work.

Figure 1.3 shows a gas tube which responds to light from the end of the bulb rather than from the side. The cathode is cup-shaped, and its inside surface is specially treated. The anode is a ring located just above the cathode. This tube has a screw-type base rather than a plug-in base. Figure 1.4 is a compact cartridge-type gas tube with the electrodes shaped as in Fig. 1.1. It will be noticed that all these different types of construction have one thing in common. The anode is located close to the *treated* surface of the cathode. The reason for this will become clear after the theory of operation has been explained in a later section.

1.2. Electrical Characteristics of Phototubes. The electrical characteristics of a phototube can be obtained by using the circuit shown in Fig. 1.5. The symbol shown for the phototube is standard. The curved line represents the cathode, and the dot represents the anode. Sometimes a short straight line is used for the anode, as in Fig. 1.6.

The potentiometer circuit shown in Fig. 1.5 allows the voltage applied to the anode to be varied from a high negative value to a high positive value relative to the cathode. The microammeter used in the circuit should be able to read currents below 20 μa, as this is the maximum amount of current that is ordinarily drawn through a phototube. The microammeter resistance should be low compared to the resistance of the phototube so that the voltmeter will read essentially the voltage drop across the tube. The phototube resistance varies according to the amount of light on the cathode but is ordinarily around 5 megohms or higher.

If desired, the circuit shown in Fig. 1.6 can be used instead. This circuit requires that the voltmeter have an extremely high internal resistance. A good vacuum-tube voltmeter should preferably be used. The value of the resistance R should be accurately determined. The current through the phototube is then

FIG. 1.3. A gas phototube used in relay work. (*Courtesy RCA*.

FIG. 1.4. A gas phototube used in sound reproduction. (*Courtesy RCA*.)

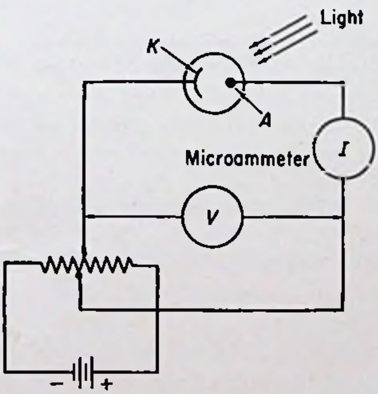

FIG. 1.5. Circuit for obtaining the electrical characteristics of a phototube.

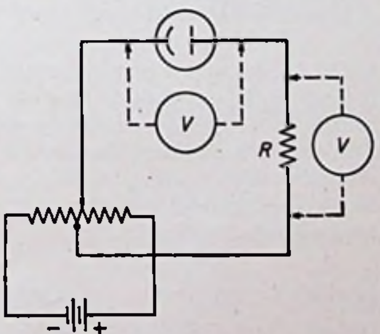

FIG. 1.6. An alternative circuit. Two vacuum-tube voltmeters or a single vacuum-tube voltmeter with traveling leads should be used to read the voltage drop across the tube and across R.

obtained by reading the voltage drop across R and calculating the current by Ohm's law.

A word of caution should be inserted here. Owing to the extremely high resistance of the phototube, the insulation resistance between the anode and cathode terminals should be kept as high as

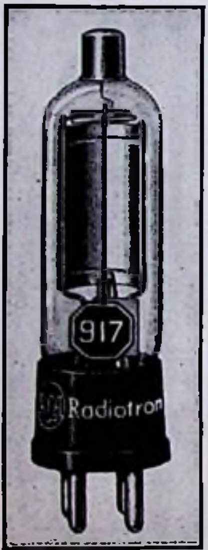

Fig. 1.7

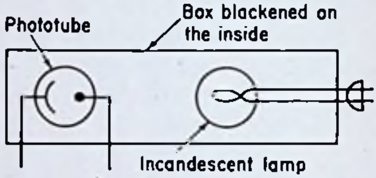

Fig. 1.8

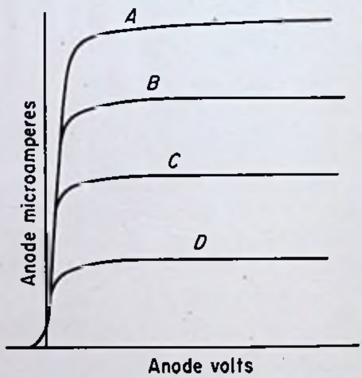

Fig. 1.9

Fig. 1.7. A vacuum phototube with the anode connection brought out at the top of the envelope to increase the length of the leakage path. This tube is used in relay and measurement work. (*Courtesy RCA.*)

Fig. 1.8. Arrangement of apparatus for obtaining electrical characteristics of a phototube.

Fig. 1.9. Curves of current vs. voltage for a vacuum phototube at different levels of cathode illumination.

possible. Some tubes are manufactured with either the cathode or the anode connection brought out to the top of the envelope in order to minimize leakage (see Fig. 1.7). A tube socket having good insulation should be used, and the surfaces of the insulation on both the tube and the socket should be very clean.

Suppose we insert a vacuum-type phototube in the circuit and study its electrical characteristics. Then the gas-type phototube can be studied and the two compared.

In order to obtain complete electrical characteristics, the phototube should be placed in a box which has been blackened on the inside to reduce light reflections. A light source should be placed so as to illuminate the cathode. A suitable source is a 75-watt incandescent lamp placed in the box. In order to vary the illumination of the cathode, and thus determine its influence on the current, the light source should be arranged so that the spacing between the phototube and the lamp is adjustable from about 1 ft up to several feet (see Fig. 1.8). The lamp current should be held constant, or otherwise its color as well as its brilliance would change, thus spoiling the characteristics. The illumination of the cathode varies inversely as the square of the spacing between the tube and lamp. (Actually, this is true only for a point light source. However, a good approximation to this law is obtained in practice by using a small incandescent lamp.)

Let us begin by setting the lamp close to the phototube. With a high negative potential on the anode, the current flowing in the circuit should be zero. As the voltage is reduced to zero and then made positive, a plot of current vs. voltage should look like curve A in Fig. 1.9. The currents shown flowing at low negative anode voltages are actually extremely small and have been exaggerated in Fig. 1.9 for clarity.

Curve B is obtained by increasing the spacing so that the illumination of the cathode is three-fourths the value used for curve A. Curves C and D are obtained by using one-half and one-fourth, respectively, of the illumination used for curve A. If the lamp is shut off completely, zero current, or *practically* zero current, should flow, regardless of the anode voltage. Actually, an extremely minute current would flow owing to the production of ions inside the tube by cosmic rays or radioactive materials nearby. However, the leakage current flowing in the insulation would ordinarily mask this current even if a meter sensitive enough to read it were available. [Special tubes are built to take advantage of this current produced by cosmic or radioactive radiations, the Geiger-Müller tube, for example. Also certain gas tubes require an outside source of radiation such as cosmic rays to initiate the current (see Sec. 7.3).]

Spectral Response. The amount of current obtained for a given impressed voltage and level of illumination depends largely on the manner in which the cathode surface has been prepared. One method is to deposit a layer of one of the alkali metals such as potassium, rubidium, or cesium, upon some ordinary metal base. One of the most important factors determining the choice of the alkali metal to be used is the manner in which the current varies with the wavelength, or color, of the light. If the wavelength could gradually be varied throughout all the colors of the rainbow, and even beyond into the infrared and ultraviolet regions at either

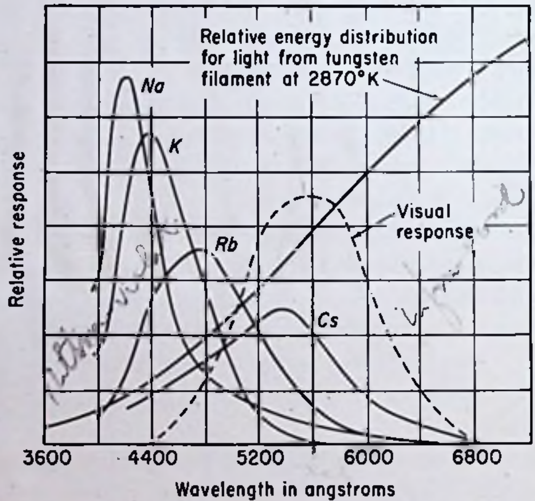

FIG. 1.10. Photoelectric color sensitivity of the alkali metals.

extreme end of the visible light range, the current through the tube would vary as shown in Fig. 1.10 for the different alkali metals.

The response of the human eye is dotted in for comparison. The relative energy distribution of the light from a tungsten filament, as might be used in an ordinary incandescent lamp, is also drawn in for comparison. The curves show that if a phototube is to respond to visible light, cesium would give the best results.

Most phototubes do not use cathodes of the simple type described above. The current is too low for a given amount of light, and the tubes do not respond well to red or infrared radiations. A much more sensitive cathode, and one which is highly responsive to red and infrared radiations as well, results from the following pro-

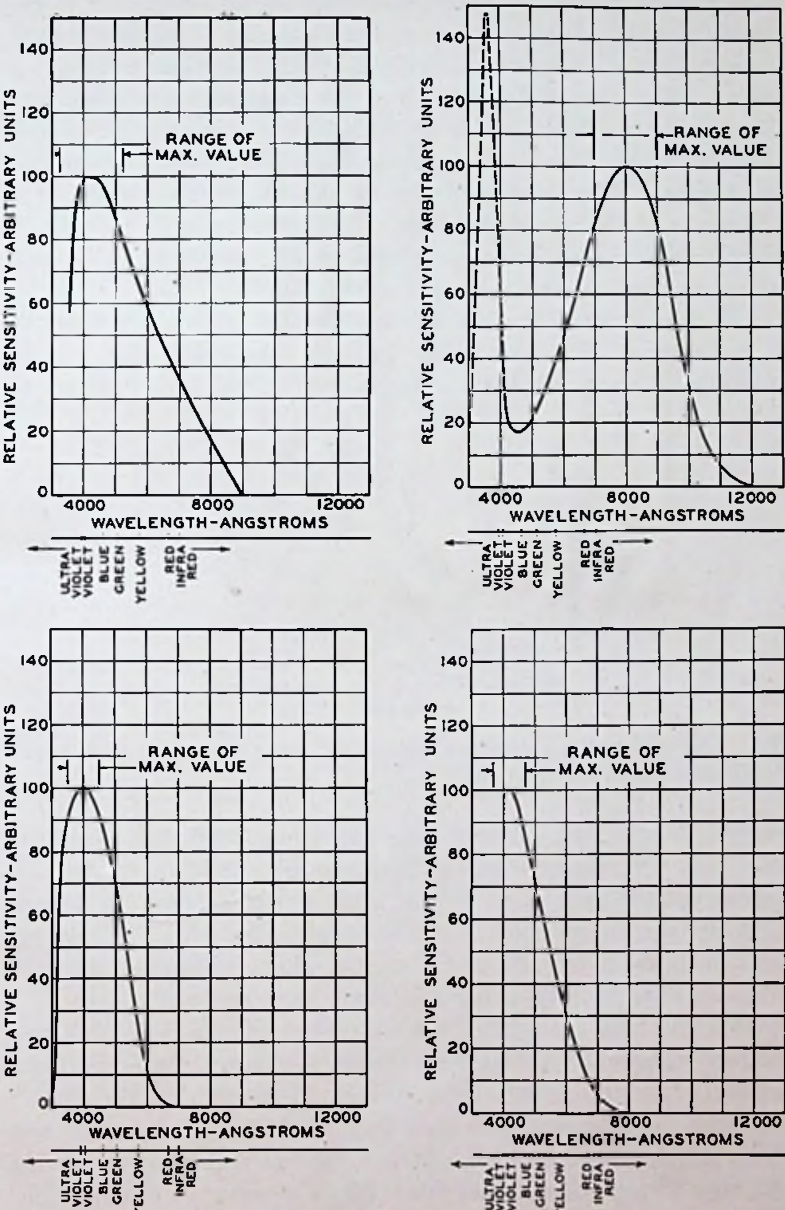

FIG. 1.11. Spectral-response curves of RCA phototubes.

cedure: The cathode is silver-plated and the silver allowed to become oxidized. The cathode is then exposed to cesium vapor, resulting in a composite cathode of cesium on cesium oxide on silver. Such a cathode gives 10 to 100 times as much current as an ordinary cathode, when illuminated by incandescent lamps. Figure 1.11 shows spectral-response curves of typical commercial phototubes. The type of glass used in the envelope of the tube influences the shape of the curve. When response to ultraviolet light is desired, a special type of glass such as Nonex must be used to prevent undue absorption of the radiation.

Gas Phototubes. The gas phototubes are constructed like the vacuum type. The main difference lies in the inclusion of a small amount of one of the inert gases, usually argon, at a pressure of

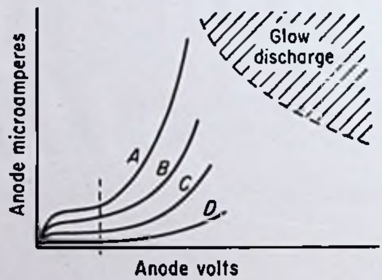

FIG. 1.12. Curves of current vs. voltage for a gas phototube at different levels of cathode illumination.

about 0.2 mm. Hg. Almost any gas would work, but chemical reactions with the sensitive cathode surface would occur for any gas except the inert gases helium, neon, argon, krypton, or xenon.

When a gas-type phototube is inserted in the circuit of Fig. 1.5 or Fig. 1.6 and curves taken in the manner described for the vacuum-type phototube, the results are as shown in Fig. 1.12.

It will be seen that the curves are very similar to those obtained using a vacuum phototube for voltages less than the amount indicated by the dotted line. For voltages to the right of the dotted line, the currents are *higher* than they would be if the gas had not been inserted into the tube. Hence, the gas is responsible for an increase in the current flow for a given amount of illumination. The ratio of the current obtained with the use of gas to the current that would flow without the gas is called the gas amplification factor and is commonly of the order of 7 to 10 for typical gas phototubes.

A word of caution should be inserted about gas phototubes. If the circuit of Fig. 1.5 is used, a protective resistance of about 5 megohms should be placed in series with the battery. In Fig. 1.6 the series resistor R should be at least 5 megohms. Furthermore, the battery voltage used should not be higher than 90 volts. In addition, the amount of illumination should be kept at the minimum value necessary to the proper operation of the circuit. Under no circumstances should the maximum anode current as stated by the manufacturer be exceeded. All of these precautions are essential to prevent damage to the cathode surface. If operation is ever caused to exist in the shaded zone in Fig. 1.12, a faint glow will be visible inside the tube and the current will be independent of the level of cathode illumination. This condition is called a glow discharge and may permanently ruin a gas phototube. [A glow discharge is, however, desirable in some types of electron tubes (see Sec. 7.1).]

The symbol for a gas phototube is the same as for a vacuum phototube except that a small black dot is placed inside the circle to denote the presence of gas. In the case of nearly every gaseous electron tube, a small dot is placed inside the symbol in order to distinguish it from a high-vacuum tube, which would otherwise have the same symbol.

The characteristics of vacuum phototubes are more stable over a long period of time than those of gas phototubes. The vacuum types are used for measurement and relay work. Gas phototubes are, in general, more sensitive and are used principally in relay work and sound reproduction from film.

1.3. Theories Used to Explain Electrical Characteristics. In order to understand photoelectric phenomena, several theories concerning the nature of matter and light must be considered.

All matter consists of about 100 chemical elements occurring either singly or in compounds. The smallest particle of each element is called an atom. A considerable amount of knowledge about the nature of atoms has been gained in recent years through the efforts of physicists, engineers, chemists, and mathematicians. Electronic devices and techniques have been of invaluable aid in much of this work.

According to the latest concepts, atoms are built up from three or possibly more fundamental particles: electrons, protons, and neutrons. Other particles are believed to exist, such as positrons, neutrinos, antineutrinos, and mesons. However, they play no part in ordinary electronic phenomena and hence will not be discussed further.

Each atom has a nucleus composed of protons and neutrons. Around this nucleus are several planetary electrons revolving in orbits of various sizes. This arrangement can be compared to our solar system consisting of the planets revolving around the sun.

The nucleus is extremely small, occupying only about $\frac{1}{1000}$ of one-billionth of the volume of an atom, but it contains over 99.95 per cent of the mass of the atom. The density of the nucleus is extremely high, being on the order of 100 million tons/cm^3. Any reaction involving only a change in the planetary electrons is an electronic phenomenon. Nuclear reactions change the chemical nature of the atom, whereas electronic reactions do not. The atomic number of the element is the same as the number of protons in the nucleus.

A proton has a mass of 1.65×10^{-24} g and a *positive* electric charge of 1.6×10^{-19} coulomb. A neutron weighs slightly more than a proton but is electrically neutral, hence its name, neutron. Isolated neutrons play no part in electronic phenomena because they have no electric charge. However, they influence the weight of the nucleus, which does have an electric charge.

An electron has a mass which is $\frac{1}{1840}$ times the mass of the proton. It has a *negative* electric charge equal to the positive electric charge of the proton. An electron has a density considerably lower than that of a proton and thus is much larger in spite of its light weight. If a proton were the size of a golf ball, an electron would nearly cover a football field. Yet a proton has about 1,840 times the mass of an electron! The outermost planetary electrons are called valence electrons, and they determine the chemical behavior of atoms.

The simplest atom is that of ordinary hydrogen. The nucleus has only one proton and no neutrons. This makes the hydrogen atom the lightest one in existence. There is one planetary electron spinning around the proton. Since the negative charge of the electron is equal to the positive charge of the proton, there is no net electrostatic field external to the atom; thus it is electrically neutral. The proton spins on its axis, much like the earth.

The next atom in complexity is the helium atom, the nucleus of which contains two protons and two neutrons. There are two planetary electrons in each helium atom, the radii of the two orbits being equal. The negative charges of the two electrons balance the positive charges of the two protons, thus making the helium atom electrically neutral.

Lithium has three protons and either three or four neutrons in its nucleus, depending on the isotope. There are three planetary electrons, two in the inner orbits as for helium, and one valence electron in a larger orbit.

For any atom, it may be said in general that the nucleus contains approximately as many neutrons as protons, the exact number depending on the isotope, but the number of planetary electrons always exactly equals the number of protons in the nucleus. Thus a normal atom of any element is electrically neutral.

Ionization, Excitation, and Radiation. In electronic work, we are particularly concerned with the orbital arrangement of the electrons spinning about the nucleus. The forces holding these electrons in their orbits are very complicated, but a simple physical picture can be obtained by assuming that the centrifugal force of an electron spinning around the nucleus exactly balances the inward pull due to the positive charge of the nucleus. This is an oversimplified picture, because there are also magnetic fields present, due to the revolving electrons and the spinning protons. However, it will serve for our present purpose.

The potential energy available due to the attractive force of two unlike charges depends on their separation. The farther apart the charges are placed, the greater the potential energy, just as the higher a weight is lifted above the earth's surface, the higher the potential energy. The electrons which are spinning close to the nucleus have *less* potential energy, therefore, than electrons revolving in larger orbits farther removed from the nucleus.

It is found that under certain conditions it is possible for an electron in the outer orbit of an atom to become detached, thus leaving the resultant particle with a net positive charge. Such a particle is called an ion, or more particularly, a positive ion. From the preceding paragraph we see that energy must be supplied from some outside source in order to ionize an atom. This energy could come from some high-speed particle which "bumped" into the atom. The process of producing ions is called ionization, and when it is caused by electrons or other high-speed particles colliding with an atom, it is called ionization by collision.

It is also possible to make an electron jump from its own orbit into a larger orbit, where it would have a higher potential energy. This might occur by a collision similar to that described above. This process of giving energy to an atom by forcing an electron to jump from its own orbit into a larger one is called excitation, and the resultant atom is said to be excited. Ordinarily, the electron quickly jumps back to its original orbit. But in so doing it loses potential energy. The question arises: Where does this energy go?

The answer is that energy is radiated in the form of electromagnetic waves, such as light or heat rays. Since the energy goes out in a spurt as the electron jumps back to its original orbit, a definite bundle or quantity of light energy is radiated. This spurt of light energy is propagated through space at the speed of 186,000 mi/sec and is called a photon. A photon is sometimes thought of as being a particle having zero mass when at rest. But light rays also exhibit the properties of electromagnetic radiations, as do radio waves. Hence, light has a dual nature. Sometimes it is more convenient to deal with the corpuscular nature of light, and at other times the wave nature is more convenient to use. In dealing with photoelectric phenomena, the particle concept is generally used.

Electron Gas. The atoms of a metal are arranged in a symmetrical lattice structure known as a crystal. The distance between atoms is small, which means that the valence electrons of adjacent atoms are very close together. Therefore an electron situated *between* two atoms does not have appreciably more energy than the valence electrons. Only a small amount of energy need be given an electron in one of the outer orbits to cause it to leave the atom. As a consequence, the atoms of a metal are constantly exchanging their outermost electrons, and at any one particular instant of time there are large numbers of these so-called "free" electrons existing in a piece of metal.

The free electrons moving about inside the metal constitute what is known as the "electron gas." They are in an almost constant state of agitation, colliding with each other and with the atoms and executing very erratic and chaotic motions. These motions are influenced only slightly by the temperature of the metal. They are not caused primarily by heat and would still exist even if the metal were reduced to 0°K (absolute temperature scale).

When a difference of potential is applied between two points of a metal, the resulting electrostatic field causes the average number of electrons moving toward the positive terminal to be greater than the average number moving toward the negative terminal. This difference in electron flow constitutes an ordinary electric current.

The difference in electron flow mentioned in the preceding paragraph is never anything more than a very minor modification of the already existing electron flow. If a metal rod 1 cm square were oriented east and west and all the eastbound electrons were stopped without disturbing the motion of the westbound electrons, and the westbound electrons were all counted, one by one, as they passed through a cross section of the rod, the resultant electric current flow would be approximately 10,000 billion amperes!

Potential Barrier at the Surface of a Metal. Let us imagine that we can take some particular electron in the electron gas and move it around to different points, and at each point determine the *average* force acting on that electron. If the electron is not brought near the surface of the metal but is kept well in the interior, the *average* force acting on the electron is zero (assuming there is no externally applied electric field). The *instantaneous* force acting on the electron due to the random and chaotic motion of the other electrons and the vibrations of the atoms may vary considerably with time, but since the electron is surrounded on all sides by essentially the same number of positive and negative charges, the *average force* is zero.

Now let us move the electron close to the surface of the metal. There are positive charges in the interior of the metal tending to keep the electron away from the surface, whereas there are few if any positive charges tending to draw the electron closer to the surface. The closer we take the electron to the surface, the greater this restraining force becomes. If we move the electron on out through the last atoms on the surface, the force becomes larger and larger until finally it reaches a maximum, after which it tapers off. Figure 1.13 is a plot of the force trying to pull the electron back into the metal vs. the position of the electron. The small circles represent atoms of the metal.

Work Function. As we push the electron, we find that we are doing work, since we are pushing through a distance against a force. The total amount of work necessary to move the electron out to an infinitely large distance is the area under the curve in Fig. 1.13. The work necessary to move it out to any point x is the area under the curve to the left of the point x. Hence a plot of the work vs. distance would appear as in Fig. 1.14.

On the average, the electrons moving in the electron gas of a

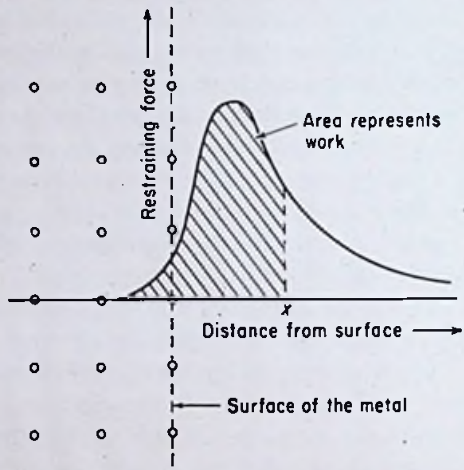

FIG. 1.13. The force on an electron leaving the surface of a metal.

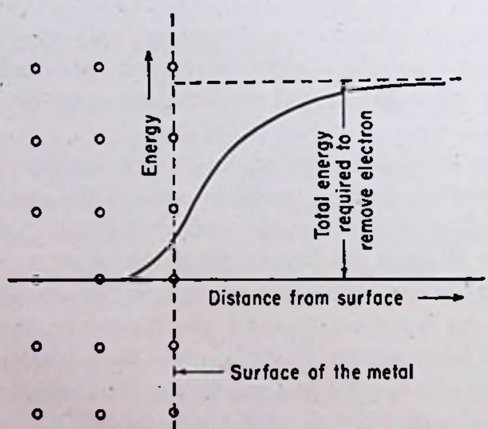

FIG. 1.14. The energy required to move an electron out to any point from the surface of a metal.

metal have velocities ranging from zero up to a maximum value. This maximum value is increased slightly when the temperature is raised. The maximum velocity that an electron can attain sets an upper limit on the kinetic energy of that particle. *The difference between the energy required to remove an electron out of a metal to an infinitely large distance and the maximum energy that the electron can have at 0°K is called the work function*

The principal factor determining the work function appears to be the spacing between the atoms in the metal. Wider spacings ordinarily give lower work functions. The work functions of several metals are listed in Table I. The unit of energy in the table is the electron volt (e-v), which is equal to 1.6×10^{-19} joule. This will be explained in a later section.

TABLE I

WORK FUNCTION OF VARIOUS METALS

Metal	Work function	Metal	Work function
Ag	4.6	Mg	2.43
Al	3.0	Mo	4.15
Au	4.78	Na	2.0
Ba	2.52	Ni	5.01
Bi	4.2	Pb	3.9
Ca	3.0	Pt	6.3
Cd	4.0	Rb	1.82
Cs	1.67	Sr	2.06
Cu	4.3	Ta	4.13
Fe	4.74	Th	3.50
Hg	4.53	W	4.61
K	1.90	Zn	3.44
Li	2.21	Zr	3.73

Electronic Emission. If an electron in the electron gas of a metal can be given an additional amount of kinetic energy equal to the work function, in addition to the maximum value it can have at 0°K, and if this speeded-up electron approaches the surface of the metal perpendicularly, it will escape from the metal.

The preceding sentence should be reread by the student as many times as is necessary for complete understanding, as it is one of the most important and significant facts in the whole field of electronics.

If an electron approaches the surface at an angle, it can still escape provided it has a component of kinetic energy perpendicular to the surface equal to the value it would require in order to escape perpendicularly.

It is a common observation that metals at ordinary room temperatures do not become positively charged. (One does not usually experience a shock every time he touches a dinner fork.) The reason for this is that almost none of the electrons in the electron gas of the metal have a kinetic energy equal to or greater than the amount necessary to overcome the "potential-energy barrier" represented by the curve in Fig. 1.14. Hence, they cannot leave the metal but are pulled back every time they approach the surface.

A mechanical analogy to this situation is a bowl of marbles being stirred with a stick. Some of the marbles receive enough kinetic energy to start up the sloping sides of the dish. But the sides are so high that none of the marbles is able to overcome the "potential-energy barrier" represented by the sides.

Similarly, the electrons in the metal do not have sufficient kinetic energy to overcome the potential-energy barrier represented by the work function of the metal.

Photoelectric Emission. When a beam of light falls on the surface of a piece of metal, millions of photons bombard the surface. As previously noted, photons are small bundles of energy. If a photon happens to hit an electron near the surface of the metal, it can transfer its energy to the electron. *If the sum of the original kinetic energy and the additional kinetic energy contributed by the photon is large enough, the electron may have a component of energy perpendicular to the surface equal to or greater than the amount necessary to overcome the potential-energy barrier, in which case it will escape from the metal.* Ejection of electrons by the above process is called photoelectric emission.

Returning to the analogy of the bowl of marbles being stirred with a stick, if blasts of air from an air hose were squirted into the bowl at random, some of the marbles might acquire enough *additional* energy over that already possessed by virtue of the stirring action so that they could climb all the way up the side of the dish and leave the bowl entirely. The blasts of air are analogous to the blasts of energy contained in the photons of light.

Plate Characteristics. Figure 1.15 is a sketch of a typical phototube. The inside surface of the cathode has been treated so that the work function of the surface is very low. This means that the electrons could escape very easily if given small additional boosts of energy. If light is allowed to fall on the cathode surface, it becomes bombarded by photons, which are small bundles of energy. If these bundles of energy are strong enough, electrons are emitted from the surface. A small fraction of these electrons hit the anode wire, thus causing an electric current to flow in the circuit of Fig. 1.5, even though the voltage applied to the phototube is zero. This is evidenced by the y intercept of the curves in Fig. 1.9. Most of the emitted electrons miss the small anode wire and eventually bombard either the glass envelope or the cathode.

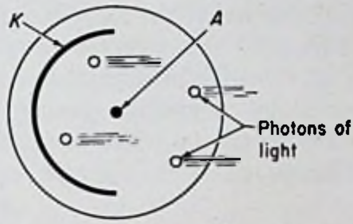

FIG. 1.15. A sketch of a typical phototube.

If a negative voltage is applied to the anode relative to the cathode, the negative charge on the anode repels the negatively charged electrons, thus decreasing the current flow. If this negative anode voltage is made high enough, none of the electrons has enough kinetic energy upon being emitted from the cathode to reach the anode, and the current is zero.

If, on the other hand, the anode is made positive, it attracts the emitted electrons, and more of them hit the anode. This situation is illustrated in Fig. 1.16. If the anode is made sufficiently posi-

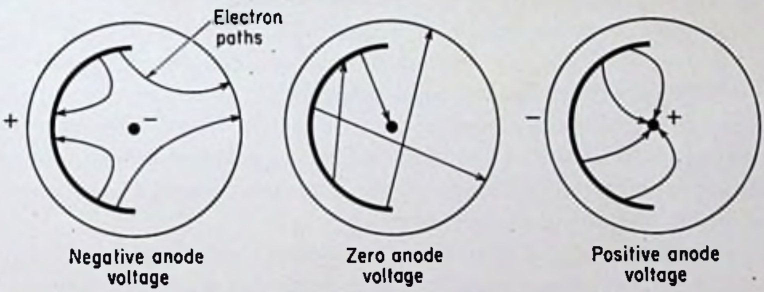

FIG. 1.16. Electron paths in a phototube.

tive, every single electron that is emitted from the cathode is drawn to the anode and contributes to the current flow. Any further voltage increase above this value does not increase the current, because every available electron is already being used. Thus the curves in Fig. 1.9 all saturate at some positive anode voltage.

Curve A in Fig. 1.9 saturates at a higher current than the rest because the high illumination of the cathode used in that case causes a larger number of photons to bombard the surface, and hence a larger number of electrons to be emitted. In fact, it will be seen that for any fixed value of plate voltage, provided it is sufficient to draw all the emitted electrons to the anode, the amount of current flowing in the circuit is directly proportional to the illumination of the cathode. Figure 1.17 illustrates this situation. This curve is obtainable experimentally from the circuit shown in Fig. 1.5. By holding the anode voltage constant at some high value and varying the spacing between the lamp and the phototube, readings can be taken of current and relative illumination of the cathode. However, if the curves in Fig. 1.9 have already been drawn, a simpler method of obtaining the data needed to plot a curve of current vs. illumination is to draw a vertical line on the current-voltage characteristics intersecting the horizontal axis at a point equal to the anode-to-cathode voltage. The intersections of this vertical line with the curves representing the current for various illuminations supply the data needed.

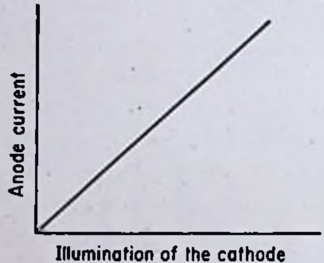

FIG. 1.17. Current through a vacuum phototube vs. the amount of light on the cathode.

Spectral Characteristics. The curves shown in Fig. 1.10 cannot be fully explained by any known theories. However, the falling off of the response of the cathode surface to zero as the wavelength of the light is increased to higher and higher values can be explained rather satisfactorily by means of the quantum theory of light, much of which has already been given.

This theory states that there is a definite relationship between the amount of energy contained in a particular photon of light and the frequency of the light; the higher the frequency of the radiation, the higher is the energy in each photon. Since the wavelength of a light wave is inversely proportional to the frequency, the photons contained in a beam of light of long wavelength have small amounts of energy, whereas the shorter wavelengths have more potent photons.

As the wavelength of the light is increased, therefore, the photons have less and less energy and are able to liberate fewer and fewer electrons from the cathode. Eventually the photons become so weak that even the most agile electron in the metal is unable to receive enough extra energy from a photon to allow it to leave the metal. The wavelength at which emission stops is termed the *threshold wavelength*, and the corresponding frequency the *threshold frequency*.

For most metals the threshold wavelength is much shorter than the shortest of the visible light waves, and hence special metals having very low work functions must be used. The alkali metals have the lowest work functions of all and are therefore used extensively in the construction of the cathode surfaces of phototubes.

Mean Free Path. Up to this point, we have not considered the speed of the electrons moving from the cathode to the anode inside the phototube. It is found that electrons behave like ordinary particles of matter in many respects. They obey Newton's laws of motion, for example. A constant force applied to an electron gives it an acceleration equal to the magnitude of the force divided by the mass of the electron. Hence the electrons which are emitted from the cathode move faster and faster as they are drawn toward the anode; the higher the anode-to-cathode voltage, the higher are the final and average velocities of the electrons in transit.

In vacuum-type phototubes, the number of gas molecules left inside the bulb is so small that only once in a great while does an electron ever bump into one on its way to the anode. There will be a few collisions, of course, since it is impossible to obtain a perfect vacuum. Even if a perfect vacuum could be obtained when a tube is first constructed, gas molecules would leak from the metal electrodes and wire supports inside the bulb and spoil the vacuum. The effects of residual gas in a tube are found to be negligible if the number of gas molecules is limited to a small enough value. If the average distance an electron travels before hitting a molecule is very large compared to the distance between the cathode and the anode, then very few electrons engage in a collision before reaching the anode and the current is essentially the same as for an absolutely perfect vacuum. The "average distance" spoken of above is termed the *mean free path*. The mean free path is ordinarily many times the spacing of the electrodes in good high-vacuum tubes.

Gas Amplification. In many cases it is found helpful to use a relatively high gas pressure, however. In gas-type phototubes, a small amount of argon gas serves to increase the sensitivity of the tube. Some of the electrons moving toward the anode collide with gas molecules and impart some or all of their kinetic energy to the molecules, causing them to become either ionized or excited. The excited atoms soon return to their normal state and emit photons of light in the process. Some of the photons may hit the cathode and release additional electrons. The positive ions produced by collision are attracted to the negative cathode, and the flow of these positive charges adds to the current. The positive ions may collide with atoms and produce additional ions. Furthermore, the electrons knocked out of the atoms which become ionized are drawn toward the anode, thus increasing the current. In addition, these electrons may attain a high enough speed before reaching the anode

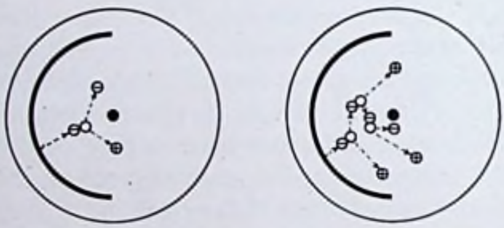

FIG. 1.18. Ionization by collision in a gas phototube. ⊖ represents an electron, O a neutral molecule, and ⊕ a positive ion.

to collide with additional atoms and produce additional ions. The positive ions hitting the cathode can impart kinetic energy to electrons in the metal and may cause emission. (This is called secondary emission and is discussed in greater detail in Chaps. 3 and 4.)

All of the above factors cause the current in a gas phototube to be higher than the current in the same tube at the same voltage without any gas. It will be observed in Fig. 1.12 that the current does not begin to increase appreciably until the voltage exceeds that indicated by the dotted line. The reason for this is that for voltages to the left of the dotted line, none of the electrons have a high enough speed to cause ionization, even when they do hit a gas molecule. For voltages to the right of the dotted line, the higher the voltage, the quicker an electron emerging from the cathode acquires enough energy to cause ionization, and the greater the number of ions that are produced by the chain-reaction process which follows (see Fig. 1.18, which illustrates this action).

As the anode voltage is raised to higher values, the positive ions traveling to the cathode produce more ionization by collision. The positive ions bombarding the cathode cause more secondary emission. The extra electrons thus produced flow toward the anode and produce more positive ions by collision, which in turn produce more electrons, which in turn produce more positive ions, etc. In other words, the process may become cumulative, in which case, the tube "breaks down," or a glow discharge occurs. This is undesirable in a gas phototube, as explained previously.

The relationship between current and illumination for a gas phototube is not so linear as for a vacuum phototube. For a high anode-to-cathode voltage, the curve is usually concave upward, as shown in Fig. 1.19. These curves are obtainable either experimentally or from the current-voltage characteristics of the tube, as previously described for vacuum phototubes. It should be noticed that several curves are necessary to represent the characteristics of a gas phototube completely, whereas one curve is usually sufficient for a vacuum phototube.

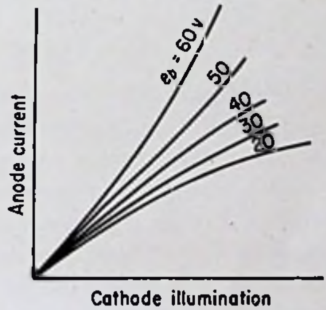

FIG. 1.19. Current through a gas phototube vs. cathode illumination for various cathode-to-anode voltages.

1.4. Mathematical Analysis of Phototubes. *Force on an Electron in an Electric Field.* An electron or other charged particle can be accelerated through space by placing it in an electric field. If the field has a strength $\mathcal{E}$ and the particle has a charge Q, the force F acting on the particle is

$$F = Q\mathcal{E} \tag{1}$$

The units in the cgs electrostatic system are dynes, statcoulombs, and statvolts per centimeter. The units in the mks practical system are newtons, coulombs, and volts per meter.

Example:

An electron is placed in an electric field having a strength of 3 statvolts/cm. Find the force acting on the particle.

Solution:

In the cgs system,

$$\begin{aligned} F &= Q\mathcal{E} \\ &= (1.6 \times 10^{-19})(3 \times 10^{9})(3) \\ &= 14.4 \times 10^{-10} \text{ dyne} \quad \textit{Ans.} \end{aligned}$$

The factor 3×10^9 converts coulombs into statcoulombs. In other words the charge of an electron is 4.8×10^{-10} esu, or statcoulombs.

In the mks system,

$$\begin{aligned} F &= Q\mathcal{E} \\ &= (1.6 \times 10^{-19})(3)(300)(100) \\ &= 14.4 \times 10^{-15} \text{ newton} \quad \textit{Ans.} \end{aligned}$$

The factor 300 converts statvolts into volts, and the factor 100 converts centimeters into meters.

The above answers are the same because 1 newton $= 10^5$ dynes.

This example illustrates two important systems of units used in electronic work. The cgs electrostatic and the mks practical systems of units should be thoroughly learned by students of electronics. The mks practical system has been adopted as the international standard, but the student should know both systems because the cgs system has been used extensively in the literature.

If the electron is free to move in the electric field, it experiences an acceleration a given by the equation

$$a = \frac{f}{m} \tag{2}$$

where f is the force on the electron and m is its mass. The acceleration is a space vector pointing in the same direction as the force, which is a space vector pointing in a direction *opposite* to that of the field-intensity vector. (The force on a *positive* charge, on the other hand, is a space vector pointing in the *same* direction as the field-intensity vector.)

As the electron gains speed, it always experiences a force opposite to the direction of the flux lines at any particular point. The magnitude of this force is always determined by the magnitude of the electric field strength at that point.

Acceleration of an Electron in a Uniform Field. If an electron is placed in a *uniform* field, *i.e.*, one in which the electrostatic flux lines are all straight, parallel, and equally spaced, then the field strength $\mathcal{E}$ is everywhere constant. Under such conditions the force acting on the electron at every point is constant and in the same direction. Thus the electron experiences a constant acceleration along a straight line.

Example:

Find the acceleration of an electron placed in a uniform electric field having a strength of 10 statvolts/cm.

Solution:

In the cgs system,

$$\begin{aligned} f &= Q\mathcal{E} \\ &= (4.8 \times 10^{-10})(10) \\ &= 4.8 \times 10^{-9} \text{ dyne} \\ a &= \frac{f}{m} \\ &= \frac{4.8 \times 10^{-9}}{(9.1 \times 10^{-31})(1{,}000)} \\ &= 5.27 \times 10^{18} \text{ cm/sec}^2 \quad \textit{Ans.} \end{aligned}$$

The factor 1,000 converts kilograms to grams. [9.1×10^{-31} is the mass of an electron in kilograms (see Table VI in the Appendix).]

In the mks system,

$$\begin{aligned} f &= Q\mathcal{E} \\ &= (1.6 \times 10^{-19})(10)(300)(100) \\ &= 4.8 \times 10^{-14} \text{ newton} \\ a &= \frac{f}{m} \\ &= \frac{4.8 \times 10^{-14}}{9.1 \times 10^{-31}} \\ &= 5.27 \times 10^{16} \text{ m/sec}^2 \quad \textit{Ans.} \end{aligned}$$

which checks the previous answer since 1 m = 100 cm.

An excellent analogy can be made between the motion of a marble rolling down an inclined plane and the motion of an electron moving in an electric field. If the plane is level, the marble does not move. This is because both ends of the plane are at the same elevation, or, in other words, the marble would not gain anything by moving to the other end since it would not lose potential energy in so doing. (Remember the case of the electron seeking the lowest potential-energy level in an atom.) A potential-energy difference must exist between the two ends of the plane before the marble will experience any force and move. The greater the slope of the plane, the greater the force acting on the marble, and the greater the resultant acceleration.

So far we have not discussed a means of obtaining a uniform electric field. Such a field is actually very difficult to obtain in practice but can be approximated within a limited volume by placing two large flat pieces of metal close together and parallel. If a potential difference is impressed between the two plates, an electron placed near the middle of the negative plate will experience a force toward the positive plate, which is the point of lowest potential energy. If the potential difference between the two plates is zero, the force acting on the electron is zero, just as the force acting on the marble is zero when there is no potential difference between the two ends of the inclined plane. The greater the potential difference between the two metal plates, the greater the force acting on the electron and the greater the resultant acceleration.

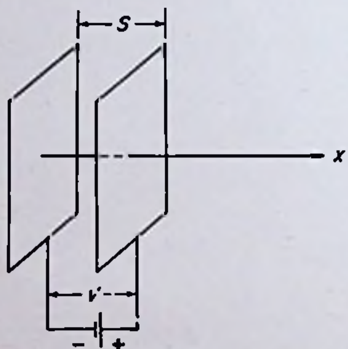

FIG. 1.20. A uniform electric field for illustrating the motion of an electron.

Velocity and Position of an Electron in a Uniform Field. In Fig. 1.20, let s represent the spacing between the two metal plates. If V is the potential difference between the two plates, then the electric field strength between the plates is uniform (neglecting fringing at the edges) and is found from the equation

$$\mathcal{E} = \frac{V}{s} \tag{3}$$

If an electron is placed at the center of the negative plate and released at time equal to zero, the instantaneous velocity v at any time t can be found as follows:

$$a = \frac{dv}{dt}$$

but

$$a = \frac{f}{m} = \frac{Q\mathcal{E}}{m}$$

Therefore

$$\frac{dv}{dt} = \frac{Q\mathcal{E}}{m}$$

Separating the variables, we obtain

$$dv = \frac{Q\mathcal{E}}{m}\,dt$$

Upon integrating,

$$v = \frac{Q\mathcal{E}}{m}\,t + K_1$$

At $t = 0$, $v = 0$, thus making $K_1 = 0$.

Therefore

$$v = \frac{Q\mathcal{E}}{m}\,t \tag{4}$$

Equation (4) applies only up to the time when the electron reaches the positive plate, at which point it stops if there are no holes in the plate.

The position in space of the electron at any time can be found as follows: Let the origin be at the center of the negative plate where the electron is released, and let the x axis be extended perpendicularly toward the positive plate.

$$v = \frac{dx}{dt} = \frac{Q\mathcal{E}}{m}\,t$$

Separating the variables,

$$dx = \frac{Q\mathcal{E}}{m}\,t\,dt$$

Upon integrating we obtain

$$x = \frac{Q\mathcal{E}}{2m}\,t^2 + K_2$$

At $t = 0$, $x = 0$. Therefore $K_2 = 0$.
Therefore

$$x = \frac{Q\mathcal{E}}{2m} t^2 = \frac{vt}{2} \tag{5}$$

where x is the distance from the cathode at any time t.

The equation just derived applies up to the time when the electron collides with the positive plate.

Transit Time. When the electron reaches the positive plate, x is equal to s. The time t in Eq. (5) is then the time it takes the electron to move from the negative to the positive plate. This time is called the "transit" time, because it is the length of time the electron is in transit between the two plates. Solving for the transit time,

$$t_t^2 = \frac{2ms}{Q\mathcal{E}}$$

$$t_t = \sqrt{\frac{2ms}{Q\mathcal{E}}} = \sqrt{\frac{2ms^2}{QV}} = s\sqrt{\frac{2m}{QV}} \tag{6}$$

where t_t is the transit time.

Example:

Find the velocity and position of an electron 10^{-9} sec after being released from the negative plate of a parallel-plate capacitor with a spacing of 2 cm and an impressed voltage of 600 volts. Find the total transit time.

Solution:

In the cgs system,

$$\begin{aligned}
\mathcal{E} &= \frac{V}{s} = \frac{600}{(300)(2)} \\
&= 1 \text{ statvolt/cm} \\
v &= \frac{Q\mathcal{E}t}{m} \\
&= \frac{(4.8 \times 10^{-10})(1)(10^{-9})}{9.1 \times 10^{-28}} \\
&= 5.27 \times 10^{8} \text{ cm/sec} \quad \textit{Ans.} \\
x &= \frac{vt}{2}
\end{aligned}$$

$$= \frac{(5.27 \times 10^{8})(10^{-9})}{2}$$

$$= 0.264 \text{ cm} \quad \textit{Ans.}$$

$$t_t = \sqrt{\frac{2ms}{Q\mathcal{E}}}$$

$$= \sqrt{\frac{(2)(9.1 \times 10^{-28})(2)}{(4.8 \times 10^{-10})(1)}}$$

$$= 2.75 \times 10^{-9} \text{ sec} \quad \textit{Ans.}$$

In the mks system,

$$\mathcal{E} = \frac{V}{s}$$

$$= \frac{600}{0.02}$$

$$= 30{,}000 \text{ volts/m}$$

$$v = \frac{Q\mathcal{E}t}{m}$$

$$= \frac{(1.6 \times 10^{-19})(30{,}000)(10^{-9})}{9.1 \times 10^{-31}}$$

$$= 5.27 \times 10^{6} \text{ m/sec} \quad \textit{Ans.}$$

$$x = \frac{vt}{2}$$

$$= \frac{(5.27 \times 10^{6})(10^{-9})}{2}$$

$$= 2.64 \times 10^{-3} \text{ m} \quad \textit{Ans.}$$

$$t_t = \sqrt{\frac{2ms}{Q\mathcal{E}}}$$

$$= \sqrt{\frac{(2)(9.1 \times 10^{-31})(0.02)}{(1.6 \times 10^{-19})(30{,}000)}}$$

$$= 2.75 \times 10^{-9} \text{ sec} \quad \textit{Ans.}$$

The final velocity of the electron as it hits the positive plate can be found by substituting for t in Eq. (4) the transit time t_t.

$$v_f = \frac{Q\mathcal{E}}{m} t_t$$

$$= \frac{Q\mathcal{E}}{m} \sqrt{\frac{2ms}{Q\mathcal{E}}}$$

$$= \sqrt{2 \frac{Q}{m} \mathcal{E}s}$$

Notice, however, that $\mathcal{E} = V/s$, whereupon

$$v_f = \sqrt{2 \frac{Q}{m} V} \tag{7}$$

Equation (7) shows that the final velocity depends only on the voltage V between the two plates. It does *not* depend on the spacing between the plates, nor, in fact, does it even depend on the maintenance of a uniform field between the two plates, as do the other quantities in Eqs. (4) to (6).

Thus an electron falling through a potential difference of 1 volt has the same final velocity regardless of the distance through which it has traveled, and regardless of the relative field strengths at any point along the way.

Electron Volts. For $V = 1$ volt, Eq. (7) gives for the final velocity,

$$\begin{aligned} v_f &= \sqrt{\frac{(2)(1.6 \times 10^{-19})(1)}{9.1 \times 10^{-31}}} \\ &= 5.93 \times 10^5 \text{ m/sec} \end{aligned}$$

The kinetic energy of an electron moving at this speed is

$$\begin{aligned} \text{K.E.} &= \tfrac{1}{2}mv^2 \\ &= \tfrac{1}{2}(9.1 \times 10^{-31})(5.93 \times 10^5)^2 \\ &= 1.6 \times 10^{-19} \text{ joule} \end{aligned}$$

The above amount of energy is by definition an *electron volt,* abbreviated e-v. It is a definite quantity of energy, just as ergs, joules, and kilowatthours are all definite quantities of energy. *An electron volt is the kinetic energy attained by an electron which has been accelerated by a potential difference of one volt.* It should be noticed that the above number is also numerically equal to the charge of an electron in coulombs. (In general, energy $W = QV$. For $V = 1$, $W = Q$.) "Electron volts" is sometimes shortened to "volts."

The advantage of using electron volts as units of energy in electronic calculations is the fact that the energy and the corresponding voltage can both be given in one number. Thus, in order to give an electron an energy of 4,000 e-v, the electron must be accelerated through a potential difference of 4,000 volts.

Energy Considerations. The velocity of an electron which has been accelerated in an electric field can also be found from energy considerations. The potential energy of the electron at the center of the negative plate in Fig. 1.20 is the force acting on the electron (which is constant throughout the space between the two plates) multiplied by the distance between the two plates. When the electron reaches the positive plate, its potential energy is zero, having all been converted into kinetic energy. From the law of conservation of energy, we can write at any point x,

$$fx = \tfrac{1}{2}mv^2$$

where v is the velocity at point x.

Substituting $f = Q\mathcal{E}$,

$$Q\mathcal{E}x = \tfrac{1}{2}mv^2$$

Solving for v,

$$v = \sqrt{\frac{2Q\mathcal{E}x}{m}} \tag{8}$$

Equation (8) gives the velocity of the electron as a function of the distance from the negative plate, x. The equation could have been worked out very easily from Eqs. (4) and (5) by eliminating the variable t. This makes an interesting exercise for the student, and it gives him practice in the handling of these simple equations.

In Eq. (8) if $x = s$, we obtain for the final velocity

$$v_f = \sqrt{\frac{2Q\mathcal{E}s}{m}} = \sqrt{\frac{2QV}{m}} \tag{9}$$

which checks Eq. (7).

The ratio Q/m for an electron can be considered constant for most engineering calculations. By substituting its numerical value into Eq. (7), a simplification results for use in practical calculations.

$$\begin{aligned} v_f &= \sqrt{\frac{2QV}{m}} \\ &= \sqrt{\frac{2(1.6 \times 10^{-19})V}{(9.1 \times 10^{-31})}} \\ &= 5.93 \times 10^5 \sqrt{V} \qquad \text{m/sec} \quad \textit{Ans.} \end{aligned}$$

where V is in volts.

As previously mentioned, Eqs. (7) and (9) apply even for a nonuniform field. However, the equations for transit time, velocity at any time t, velocity at any point x, or position x at any time t

all depend for their usefulness upon the assumption of a uniform field.

Mechanical Models. The average electron tube is not constructed with a uniform field between the cathode and anode. In fact, the field between the cathode and anode of most tubes is very nonuniform, so that a rigorous mathematical analysis for tubes of typical construction is out of the question. Furthermore, in most tubes the electrons are not released with zero velocity at the negative electrode, or cathode, but are emitted with finite velocities.

The above-mentioned complications have led to the development of mechanical models of vacuum tubes. Fairly accurate quantitative as well as qualitative results can be obtained from studies and tests made using the models.

A marble rolling down an inclined plane has already been mentioned as analogous to the motion of an electron in an electric field. In fact, there is more than an analogy here. There is an exact mathematical correspondence in the equations governing the position, velocity, etc., of the marble and the electron. If an electron is placed in a nonuniform field, then the marble must be placed on a warped plane with just the right slope at each point so that the marble will behave just the same as the electron. This may sound like an impossible task, but actually it is very simple.

Let us take the case of the phototube shown in Fig. 1.2. Since this tube has circular symmetry, it will be a fairly simple example with which to begin. An electron emitted with zero velocity or emitted with a finite velocity perpendicularly from the surface will travel straight toward the anode wire located at the axis of the cylinder (except near the top and bottom where the flux lines are curved owing to fringing). Let us assume that the holes in the cathode do not distort the field. There is some distortion, of course, near each hole. A two-dimensional model can be constructed to represent the motion of an electron inside such a tube. The height of the plane at any point must represent the *space potential difference* inside the phototube between that point and the anode.

The student may not have a full understanding of the meaning of the term *space potential.* He may have always thought of potential differences or voltage drops as existing only between two metal binding posts or across the leads of a resistor in a circuit. But a potential can exist in a space without regard to any physical metallic conductors whatsoever. When a voltage of 100 volts is impressed across the plates of a parallel-plate capacitor, the region between the two plates contains the difference of potential of 100 volts, and *the potential between the two plates must vary gradually.* The potential does not remain at zero all the way from the negative plate to the positive plate and then suddenly jump to 100 volts right at the positive plate. If it did, 100 volts potential difference would exist across an extremely thin layer of metal, which would yield a tremendous short-circuit flow.

In a parallel-plate capacitor, a plot of space potential vs. distance between the two plates yields a straight line (see Fig. 1.21). A general definition of field strength is the rate of change of the space

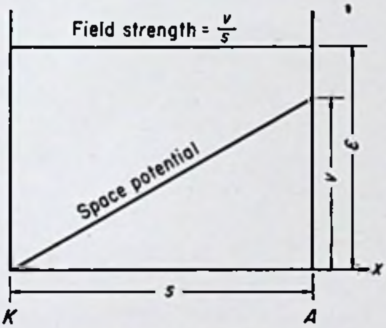

FIG. 1.21. Potential and field strength in a parallel-plate capacitor.

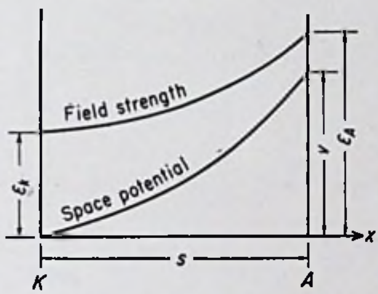

FIG. 1.22. Potential and field strength between two concentric cylinders.

potential with respect to distance. The field-strength vector always points in the direction in which the potential is *decreasing* most rapidly. The magnitude of the field strength can be found at any point by determining the slope of the potential curve at that point. For the case illustrated in Fig. 1.21, the slope of the potential curve is constant, and hence the field strength is constant.

For the case of a concentric-cylinder capacitor, which is what the phototube of Fig. 1.2 amounts to, the flux lines are crowded more closely together near the anode wire than at the cathode surface. Hence the field intensity is much greater near the anode than near the cathode for that particular tube. The field-strength curve is a hyperbola for the concentric-cylinder configuration, thus yielding a curved line for the potential function, as shown in Fig. 1.22.

In order to build a mechanical model, it is necessary to turn the potential curve upside down and construct a mechanical surface having the same shape as this inverted potential curve. (An electron released at the cathode K in either Fig. 1.21 or Fig. 1.22 would go "uphill," whereas a marble released at the mechanical cathode on the model must be allowed to go downhill by the pull of gravity.) Thus a mechanical model for Fig. 1.21 is a simple inclined plane, as already mentioned. For Fig. 1.22 a curved plane must be used. Figure 1.23 illustrates these two models.

The marble in Fig. 1.23(a) experiences a constant force giving it a constant acceleration, or a uniformly increasing velocity. The marble in Fig. 1.23(b), however, starts with a small force and acceleration, and as the marble rolls on down, the force and accelera-

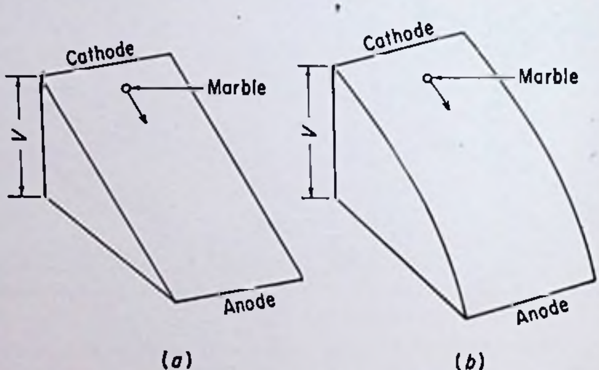

Fig. 1.23 (a). Mechanical model of a parallel-plane tube. (b). Mechanical model of a cylindrical tube.

tion both increase so that the velocity increases faster than a first-power function of time.

The usefulness of the mechanical models should already be apparent to the student, although their principal field of application, *i.e.*, extremely complex fields, has not yet even been touched upon.

In the above models, there are actually certain errors, such as the rolling friction of the marble, which have no counterpart in the electron tube, but these errors can generally be kept small enough so that the final results are not greatly in error.

Work Function. The criteria for determining whether or not an electron can be emitted by the photoelectric effect have already been determined. It is merely necessary now to define symbols to represent the various quantities and write the equations with the appropriate constants. If the student at this point is not absolutely sure that he understands Sec. 1.3, he should go back and restudy the entire section until he feels confident that he grasps the significance of the various statements made therein. Otherwise, he will be wasting his time in reading this section.

It has been determined by Fermi and Dirac that electrons in a constant-potential region have kinetic energies which can be represented graphically as in Fig. 1.24. The curve shows the *number* of electrons per cubic meter which have kinetic energies between any two values W_1 and W_2. The area under the curve between the limits W_1 and W_2 equals the *number* of electrons per cubic meter which have energies lying in the range from W_1 to W_2. The area under the whole curve between the limits zero and W_i gives the entire number n of electrons per cubic meter. The curve, which applies at a temperature of 0°K, shows that there are kinetic energies ranging all the way from zero up to a maximum limit W_i. None of the electrons has kinetic energy greater than W_i. Thus W_i is the *maximum* kinetic energy spoken of in Sec. 1.3 that an electron can have at 0°K.

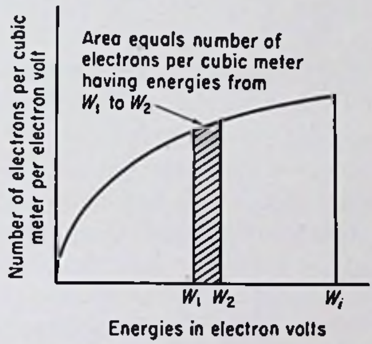

FIG. 1.24. Distribution of the kinetic energies among electrons in a constant-potential region at 0°K.

Strictly speaking, Fig. 1.24 does not truly represent the conditions existing in a piece of metal, since the curve applies only to electrons in a constant-potential region, whereas the potential in a piece of metal varies considerably from point to point owing to the presence of the atoms. However, an exact picture is almost impossible to obtain, thus justifying the use of the approximation.

The quantity W_i is given by the expression

$$W_i = 3.64 \times 10^{-19} n^{2/3} \qquad \text{e-v} \tag{10}$$

where n is the number of electrons per cubic meter. It is not possible in practice to obtain accurate results from Eq. (10) because of the difficulty in obtaining accurate values of n for different metals.

Example:

Assume a certain piece of metal contains 10^{30} electrons/m^3. Find the maximum energy which any electron in the piece of metal can attain at 0°K.

Solution:

$$
\begin{aligned}
W_i &= 3.64 \times 10^{-19} n^{2/3} \\
&= (3.64 \times 10^{-19})(10^{30})^{2/3} \\
&= 36.4 \text{ e-v} \quad \textit{Ans.}
\end{aligned}
$$

The total energy necessary to remove an electron from the metal out to an infinitely large distance has already been discussed qualitatively in Sec. 1.3. The symbol used for this total amount of energy is W_a. It is the total height of the potential-energy barrier in Fig. 1.14.

Reverting to the mechanical analogy of a bowl of marbles being stirred with a stick, W_i represents the maximum kinetic energy that any marble can ever attain by the stirring action, and W_a represents the total kinetic energy that a marble needs to surmount the sides of the dish and escape. The difference between these two amounts of energy is the additional energy which must be supplied to the marble in order to allow it to escape. This difference in W_a and W_i is called the *work function.*

It is very difficult to determine accurate values of W_a for the different metals because of the extremely complicated fields existing in a piece of metal which influence the restraining forces at any point. Thus, although it is theoretically possible to calculate the work function ϕ from the equation

$$\phi = W_a - W_i \qquad \text{e-v} \tag{11}$$

the results are not too accurate. The work function, as a consequence, is actually determined from experimental studies made on the emission of electrons from metals.

Example:

Assume that a certain piece of metal contains 2×10^{30} electrons/m^3. If the energy required to remove an electron from the metal out to an infinitely large distance is 60 e-v, find the work function of the metal.

Solution:

$$
\begin{aligned}
W_i &= 3.64 \times 10^{-19} n^{2/3} \\
&= (3.64 \times 10^{-19})(2 \times 10^{30})^{2/3} \\
&= 57.8 \text{ e-v} \\
\phi &= W_a - W_i \\
&= 60 - 57.8 \\
&= 2.2 \text{ e-v} \quad \textit{Ans.}
\end{aligned}
$$

If joules rather than electron volts are used as the units of energy for W_a and W_i, Eq. (11) becomes

$$\phi Q_e = W_a - W_i \tag{12}$$

where Q_e is the charge of an electron expressed in coulombs (which is also the number of joules in an electron volt).

Photoelectric Emission. The energy contained in a single photon of light, W_p, can be found from the equation

$$W_p = hf \qquad \text{joules} \tag{13}$$

where h is a universal constant known as Planck's constant, having a value of 6.624×10^{-34} joule-sec/cycle, and f is the frequency of the radiant energy in cycles per second.

Equation (13) can be written using electron volts as the units of energy, in which case the equation becomes

$$W_p = \frac{hf}{Q_e} \qquad \text{e-v} \tag{14}$$

Example:

Find the energy in each photon of light having a wavelength of 6,000 A. (1 A = 10^{-10} m.)

Solution:

$$f = \frac{c}{\lambda} \tag{15}$$

where c is the speed of light and has the value 3×10^8 m/sec, and λ is the wavelength expressed in meters.

$$f = \frac{3 \times 10^8}{(6{,}000)(10^{-10})}$$

$$= 5 \times 10^{14} \text{ cps}$$

$$W_p = hf$$

$$= (6.624 \times 10^{-34})(5 \times 10^{14})$$

$$= 33.12 \times 10^{-20} \text{ joule} \quad Ans.$$

$$W_p = \frac{hf}{Q_e}$$

$$= \frac{33.12 \times 10^{-20}}{1.6 \times 10^{-19}}$$

$$= 2.07 \text{ e-v} \quad Ans.$$

If one of the above photons strikes an electron in a piece of lithium, the electron is given an additional boost of energy, but it is not enough to allow the electron to escape from the metal, since the work function of lithium is about 2.21 e-v. If, however, the photon hits an electron in a piece of cesium, having a work function of only 1.67 e-v, the electron *can* escape. (Whether or not it actually does escape is determined by whether or not the electron happens to be moving *outward* from the piece of metal. If it were moving inward, it could not escape, of course.)

In both cases mentioned above, the photon disappears completely. It cannot lose a part of its energy and travel on with diminished strength. *All* of its energy is given to the electron with which it collides. Thus the electron gains an additional amount of kinetic energy equal to the energy contained in the photon. If the electron *does* escape from the metal, it must give up, when leaving, an amount of energy equal to the work function. Anything left over is represented by the finite velocity with which the electron is emitted from the cathode surface. The above ideas are incorporated in Einstein's photoelectric equation,

$$\tfrac{1}{2}m_e v^2 = hf - \phi Q_e \quad \text{joules} \tag{16}$$

where v is the emission velocity of the electron in meters per second and m_e is the mass of an electron in kilograms. Equation (16) gives the *maximum* velocity that an electron can attain upon being emitted from the cathode. It does not say that *all* electrons will be emitted with that velocity, but merely that the velocity can be no greater than that given by the equation.

Example:

Find the maximum energy an electron can have upon being emitted from a rubidium surface being illuminated with light having a wavelength of 5,000 A.

Solution:

$$f = \frac{c}{\lambda}$$

$$= \frac{3 \times 10^8}{(5{,}000 \times 10^{-10})}$$

$$= 6 \times 10^{14} \text{ cps}$$

$$W_p = hf$$

$$= (6.624 \times 10^{-34})(6 \times 10^{14})$$

$$= 39.74 \times 10^{-20} \text{ joule}$$

$$\phi = 1.82 \text{ e-v} \quad \text{(from Table I)}$$

Therefore

$$\tfrac{1}{2}m_e v^2 = hf - \phi Q_e$$

$$= 39.74 \times 10^{-20} - (1.82)(1.6 \times 10^{-19})$$

$$= 10.62 \times 10^{-20} \text{ joule} \quad \textit{Ans.}$$

$$= 0.664 \text{ e-v} \quad \textit{Ans.}$$

The above facts explain why current flows through a phototube even though the anode is at zero, or a slightly negative, potential relative to the cathode. Some of the electrons are emitted with enough kinetic energy that they can "coast" to the negative anode before they run out of energy.

Threshold Wavelength. By setting $\frac{1}{2}mv^2$ equal to zero in Eq. (16), we can obtain an expression for the threshold frequency f_0.

$$hf_0 - \phi Q_e = 0$$

$$f_0 = \frac{\phi Q_e}{h} \quad \text{cps} \qquad (17)$$

The threshold wavelength is

$$\lambda_0 = \frac{c}{f_0} = \frac{ch}{\phi Q_e} \quad \text{m} \qquad (18)$$

If the wavelength is expressed in angstroms (1 m = 10^{10} A),

$$\lambda_0 = \frac{(3 \times 10^8)(6.624 \times 10^{-34})}{(1.6 \times 10^{-19})\phi} \times 10^{10}$$

$$= \frac{12{,}400}{\phi} \quad \text{A} \tag{19}$$

Example:

Find the threshold wavelength for sodium.

Solution:

$$\phi = 2 \text{ e-v} \quad \text{for sodium (from Table I)}$$

$$\lambda_0 = \frac{12{,}400}{2}$$

$$= 6{,}200 \text{ A} \quad \textit{Ans.}$$

The above value can be approximately checked by referring to Fig. 1.10 and observing that the curve for sodium is dropping off to zero near the above wavelength.

Sensitivity of Phototubes. The amount of light flux falling upon the cathode surface of a phototube is measured in lumens. The number of lumens, L, of radiant flux falling upon a surface having a projected area A at a distance d from a point light source of candlepower C is

$$L = \frac{CA}{d^2} \tag{20}$$

Example:

Find the luminous flux on the cathode of a type 929 high-vacuum phototube located 10 ft from a light of 1,000-cp strength.

Solution:

The projected area of the cathode (called the window area) is 0.6 in.^{2} according to the manufacturer.

Therefore

$$L = \frac{CA}{d^2}.$$

$$= \frac{(1{,}000)(0.6)}{(10 \times 12)^2}$$

$$= 0.0416 \text{ lumen} \quad \textit{Ans.}$$

If the anode voltage and light flux are known, the anode current flowing in a phototube can readily be determined from the current-voltage characteristics. The ratio of this direct anode current to the steady incident flux received by the cathode is called the *luminous sensitivity.*

Example:

Compute the luminous sensitivity of the type 929 tube as used in the preceding example when the anode voltage is 180.

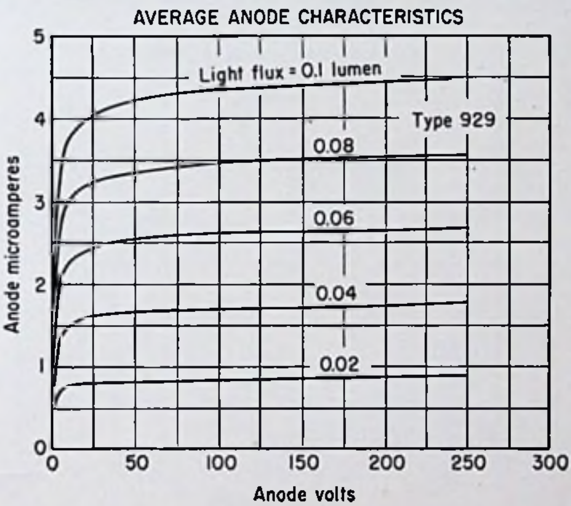

FIG. 1.25. Anode characteristics of type 929 high-vacuum phototube.

Solution:

The characteristics of a type 929 phototube are shown in Fig. 1.25. It is necessary to interpolate between the 0.04- and the 0.06-lumen curves.

$$I = 1.8\ \mu\text{a}$$

Therefore

$$\text{Luminous sensitivity} = \frac{I}{L}$$

$$= \frac{1.8}{0.0416}$$

$$= 43.2\ \mu\text{a/lumen}$$ *Ans.* (The manufacturer states 45.)

The sensitivity of high-vacuum phototubes is slightly higher for higher anode voltages but is almost independent of anode voltage.

The color of the light influences the sensitivity, and the characteristic curves of phototubes should always be accompanied by a description of the type of light source used to obtain the plotting data. Most curves are taken using a tungsten-filament lamp operated at 2870°K.

The characteristics of a type 918 gas phototube are shown in Fig. 1.26. The sensitivity of a gas-type phototube varies greatly with the anode voltage, because the curves are not almost hori-

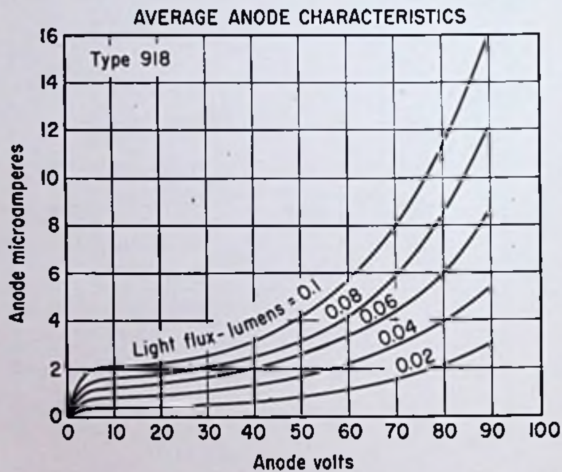

FIG. 1.26. Anode characteristics of type 918 gas phototube.

zontal as for a high-vacuum phototube. Also the current is not a linear function of cathode illumination as for a high-vacuum phototube.

Example:

Calculate the sensitivity of a type 918 gas phototube for fluxes of 0.04 and 0.1 lumen at anode voltages of 30 and 80.

Solution:

For 30 volts and 0.04 lumen,

$$\begin{aligned} \text{L.S.} &= \frac{I}{L} \\ &= \frac{1.1}{0.04} \\ &= 27.5\ \mu\text{a/lumen} \quad \textit{Ans.} \end{aligned}$$

For 30 volts and 0.1 lumen,

$$\text{L.S.} = \frac{I}{L}$$

$$= \frac{2.7}{0.1}$$

$$= 27.0\ \mu\text{a/lumen} \quad \textit{Ans.}$$

For 80 volts and 0.04 lumen,

$$\text{L.S.} = \frac{I}{L}$$

$$= \frac{3.95}{0.04}$$

$$= 98.75\ \mu\text{a/lumen} \quad \textit{Ans.}$$

For 80 volts and 0.1 lumen,

$$\text{L.S.} = \frac{I}{L}$$

$$= \frac{11.1}{0.1}$$

$$= 111\ \mu\text{a/lumen} \quad \textit{Ans.}$$ (The manufacturer gives 110.)

PROBLEMS

1. Find the force acting on an electron placed in an electric field having a strength of 2.3 statvolts/cm. Work the problem in both the cgs electrostatic and the mks practical systems of units.

2. Find the acceleration of a positive hydrogen ion placed in a uniform electric field having a strength of 15 statvolts/cm. Work the problem in both the cgs electrostatic and the mks practical systems of units.

3. Two parallel metal plates are placed 1.5 cm apart in a good vacuum. A voltage of 400 volts is impressed between the two plates. An electron is released at the center of the negative plate. Find the velocity and position of the electron 5×10^{-10} sec after being released.

4. Find the velocity of the electron in Prob. 3 midway between the two plates.

5. Find the transit time of the electron in Prob. 3.

6. Find the final velocity of the electron in Prob. 3 as it hits the positive plate. Find the kinetic energy of the electron as it hits the positive plate, expressing the answer both in joules and in electron volts.

7. Find the velocity of an electron which has a kinetic energy of 200 e-v.

8. Two parallel metal plates are 4 cm apart in a high vacuum. The impressed voltage is 1,000 volts. An electron is released at the center of the negative plate at the same instant that a positive argon ion is released at the center of the positive plate. (Atomic weight of argon = 39.9.) How far from the positive plate will the two particles meet? (Neglect the effect of the electric field of one particle on the motion of the other particle.)

9. Derive Eq. (8) from Eqs. (4) and (5) by eliminating the variable t.

10. Find the maximum velocity with which an electron can be emitted from a surface having a work function of 2 if the incident light has a wavelength of 5,500 A.

11. A type 929 high-vacuum phototube is to be operated at a distance of 15 ft from a light source. If a current of 3.5 μa is required and the anode voltage is 140 volts, find the candlepower required of the light source. (A = 0.6 in.^{2})

12. A type 918 gas phototube is to be used in place of the type 929 tube in Prob. 11. If 3.5 μa is required at 90 volts on the anode, find the required candlepower. (A = 1 in.^{2})

13. Find the luminous sensitivity of a type 918 gas phototube at 70 volts on the anode and 0.1 lumen of flux on the cathode.

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CHAPTER 2

HIGH-VACUUM THERMIONIC DIODES

THE HIGH-VACUUM thermionic diode was historically the first electron tube. Thomas A. Edison discovered the phenomenon of current flow through a diode while experimenting with incandescent lamps. Interested only in improving his lamps, he reported the discovery and passed on to other matters. Other workers applied the device to radio detection, and the field of electronics was born. The applications of high-vacuum diodes today are numerous, the most widely used ones probably being detection of radio signals and rectification of alternating current to supply d-c energy from an a-c source.

2.1. Physical Characteristics of High-vacuum Thermionic Diodes. A typical high-vacuum diode is shown in Fig. 2.1, the word diode signifying two elements. The elements are enclosed in an evacuated glass envelope. The cathode in this tube is a slender M-shaped filament of wire suspended at the top by two wire supports. The material of which the wire is composed and the method of preparing the wire for active service are both very important, as we shall later see. The anode A is a cylinder surrounding the cathode. Typical filament and anode shapes are illustrated in Figs. 2.2 and 2.3, respectively.

An electric current is passed through the filament when the tube is in operation. The I^2R loss in the filament heats it to a high temperature. When the filament becomes hot enough, an electric current can be passed through the tube from anode to cathode if the anode is made positive relative to the cathode. Since the operation depends on the high temperature of the cathode, the tube is called a *thermionic* diode. A cathode which is simply a filamentary wire is designated a filamentary cathode.

Another type of cathode which is used in some small receiving-type tubes is illustrated in Fig. 2.4. The cathode is a metal cylindrical sleeve, the outside surface of which is specially treated, as described later. Inside the cylinder is located a tungsten wire coated with a refractory insulating material. This inside wire is called the *heater*, because in operation an electric current is passed through it of sufficient strength to allow it to heat the cylindrical cathode surrounding it. This type of cathode is called an indirectly heated, or heater-type, cathode.

Some tubes are manufactured with two diodes located inside one bulb. In some cases of this type, the cathodes of the two diodes are connected together internally. Figure 2.5 illustrates this type

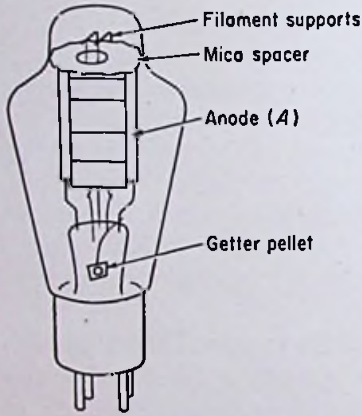


Fig. 2.1. Construction of a typical high-vacuum diode. This tube is designed for rectifier service.

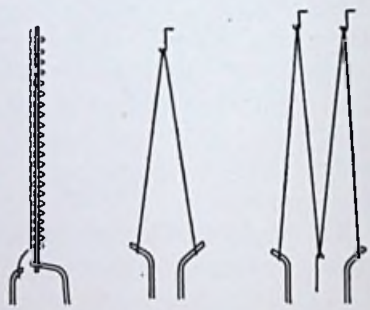


Fig. 2.2. Typical filamentary cathodes.

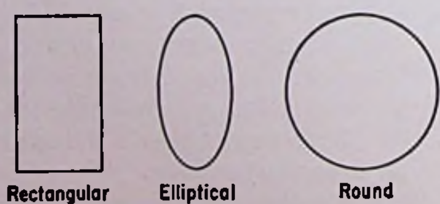


Fig. 2.3. Cross section of typical anodes.

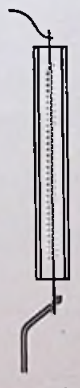
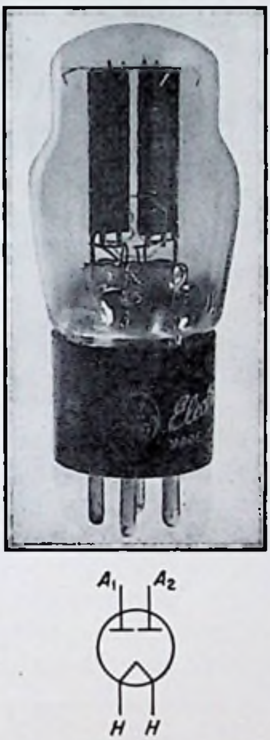


Fig. 2.4. An indirectly heated cathode.

of construction. It will be noticed that the cathodes are of the filamentary type.

In other cases, the two diodes are electrically separate. In tubes of this type having indirectly heated cathodes, the heaters for the



Symbol

FIG. 2.5. A duo-diode designed for full-wave-rectifier service. (*Courtesy General Electric Co.*)

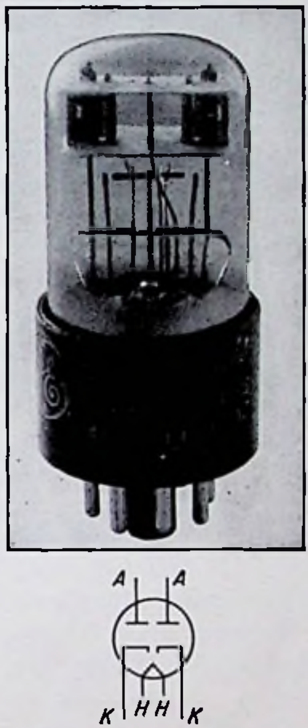


FIG. 2.6. A duo-diode designed for detector-automatic volume control service. (*Courtesy General Electric Co.*)

two cathodes are generally connected together inside the envelope and only two leads brought out to the base pins for the heater connections. Figure 2.6 illustrates a tube of this type.

Some of the smaller receiving-type diodes are made with metal instead of glass envelopes. In many cases, essentially the same tube is available with either a glass or a metal envelope.

Tubes built to operate at high voltages generally have their anode connections brought out at the opposite end of the bulb from the filament connections. This minimizes electrolysis of the glass, which may occur at high bulb temperatures, and also minimizes the possibility of spark-overs (see Fig. 2.7).

FIG. 2.7. A high-voltage, low-current vacuum-tube rectifier. (*Courtesy RCA.*)

2.2. Electrical Characteristics of High-vacuum Thermionic Diodes. A circuit which is suitable for obtaining the electrical characteristics of filamentary-cathode diodes is shown in Fig. 2.8. The symbol shown for the tube is standard. The straight line represents the anode, and the inverted V represents the cathode. Symbols for duo-diodes are shown in Figs. 2.5 and 2.6.

A circuit which is suitable for tubes having indirectly heated cathodes is shown in Fig. 2.9. The heater is represented by the inverted V and the cathode by the straight line with the sides folded down. The dotted connection between the cathode and heater is arbitrary. When the heater is operated by alternating current, the center tap of the filament transformer is usually connected to the cathode. However, if the heaters of several tubes are all being operated in parallel, this may not be permissible, and the center tap

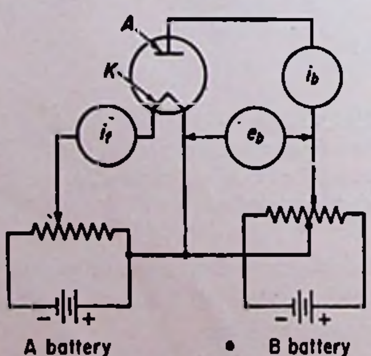


FIG. 2.8. A circuit for obtaining the electrical characteristics of filamentary-cathode diodes.

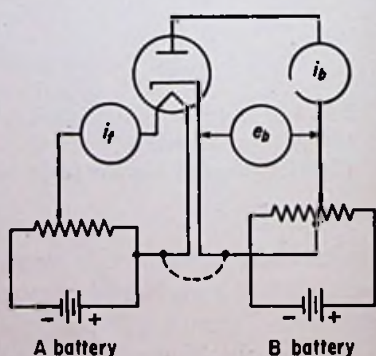


FIG. 2.9. A circuit for obtaining the electrical characteristics of diodes with heater-type cathodes.

of the filament transformer is then "grounded" to some common point in the circuit near cathode potential.

The battery used to heat the filament is termed the A battery, and the battery used to supply the anode voltage is called the B battery. An a-c operated power supply can be used in place of the B battery, in which case it is called the B supply, or the plate supply. The word plate is used interchangeably with the word anode, both terms meaning the same thing. The filaments or heaters of some tubes are designed to be operated on alternating current. In fact, nearly all tubes having cathodes of the indirectly

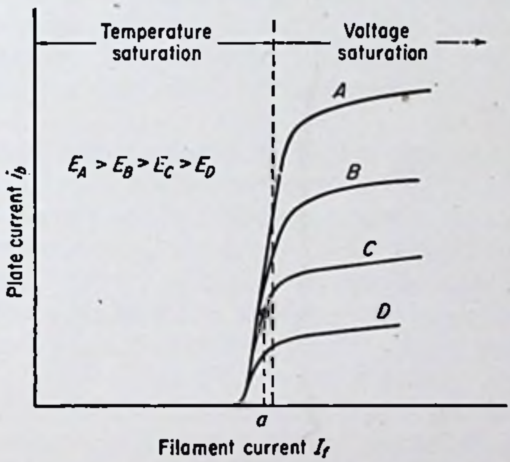


FIG. 2.10. Plate current as a function of filament or heater current for various plate voltages.

heated type are operated with alternating current through the heaters.

Let us start by setting the plate voltage at some high positive value. Then let us increase the filament current from zero up to the maximum value considered safe by the manufacturer. The plate voltage should be held constant as the filament current is varied. The curve obtained should look like curve A in Fig. 2.10. It will be observed that the plate current is essentially zero for all filament currents below a certain value. As the filament current is increased past this value, the plate current increases rapidly at first, but eventually levels off or saturates and is relatively constant for all higher filament currents.

Now let us reduce the plate voltage and repeat the measurements at the lower value. The resultant curve should almost follow the original one up to a certain point, but at the lower plate voltage the plate current should saturate at a lower value, as shown by curve B. Curves C and D are obtained by using successively lower and lower plate voltages.

Curves having essentially the same shape are obtained if the plate current is plotted as a function of the cathode temperature rather than the filament current. It is rather difficult to determine the temperature of the cathode, but it can be measured with an optical pyrometer. The temperature to be plotted is necessarily an average value, for not all parts of the cathode are at exactly the same temperature. The center portions of the cathode generally do not lose heat as fast as the ends and are therefore hotter.

Emission Characteristics. Plate currents to the *left* of the knees of the curves in Fig. 2.10 are called *emission* currents. The emission currents are almost independent of the plate voltage. For example, the current for $I_f = a$ is not changed appreciably by varying the plate voltage. The emission current is the *maximum* current that can be drawn through a tube at a given filament current or temperature. (Figure 2.10 shows a slight dependence on plate voltage. This will be explained later.)

The emission current depends on the materials used in the construction of the cathode and the manner in which the cathode has been prepared, or "activated," for service. Three different types of cathodes are in wide use at the present time. They are designated according to the active substance on the surface of the cathode as follows: pure-tungsten filaments, thoriated-tungsten filaments, and oxide-coated filaments (or cathodes).

Curves of emission current for the three different types of cathodes are shown in Fig. 2.11. It will be noticed that a higher temperature is required for the tungsten filament than for the thoriated tungsten, with the oxide-coated cathode requiring the lowest temperature of all. Thus for a given emission current, the tungsten filament requires the greatest expenditure of heat energy, with the thoriated tungsten next and the oxide-coated type the least of all. Since this filament or heater power is for all practical purposes wasted, in the sense that it does not contribute directly to the flow of current through the tube, it is desirable to use the most efficient type of cathode. Thus, at first glance, the oxide-coated cathode appears to be the most desirable. However, there are certain drawbacks to the use of oxide-coated cathodes. Certain portions of the cathode may become hotter than other portions while in operation because of the higher resistance of those portions to the flow of emission current. Since the curve in Fig. 2.11 shows that a higher temperature gives a greater emission, there is a possibility of a cumulative increase in temperature at such a "hot-spot." If the temperature becomes excessive, an arc may form at the hot-

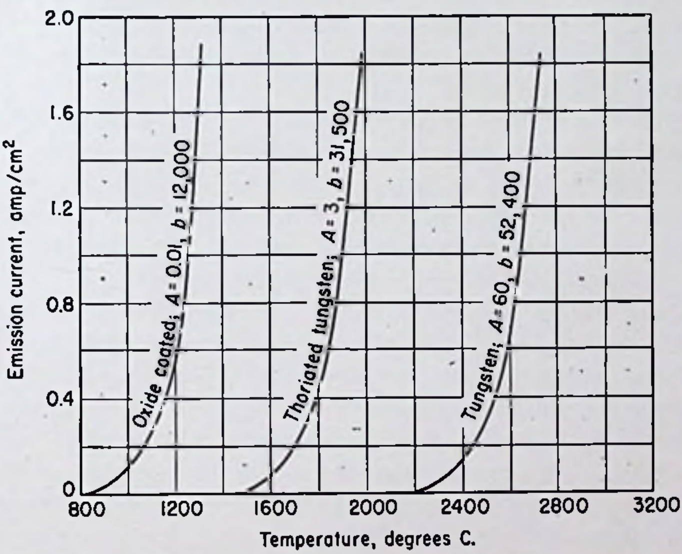


FIG. 2.11. Emission currents from various thermionic cathodes.

spot, causing the evolution of gas, which ruins the vacuum. A hot-spot is most likely to occur with high anode voltages or high anode currents, or both.

Another possible source of trouble with oxide-coated cathodes is their susceptibility to damage by positive-ion bombardment. All tubes contain some gas molecules, a few of which become ionized when the tube is in operation. The positive ions are drawn to the negative cathode and bombard the surface. This positive-ion bombardment, as it is called, is injurious to oxide-coated cathodes and, if the ions have sufficient energy, may permanently damage them. Such damage is most likely to occur with high anode-to-cathode voltages which accelerate the ions to higher speeds. These facts limit the field of application of oxide-coated cathodes to small receiving-type tubes (and certain types of gas tubes to be discussed in a later chapter) in which the anode voltages do not exceed a few hundred volts.

Indirectly heated cathodes are always of the oxide-coated type. The emission efficiencies of thoriated tungsten and pure tungsten are too low to allow their use as the active material in heater-type cathodes. Oxide-coated cathodes can also be of the filamentary type, however, this combination resulting in the highest possible cathode efficiency attainable. Battery-operated tubes generally are built with oxide-coated filamentary cathodes to reduce battery drain to a minimum.

Oxide-coated cathodes are prepared by coating a base metal with a 50-50 mixture of the carbonates of barium and strontium. The base metal is found to influence the emission properties to some extent. Either nickel or Konel metal, an alloy of nickel, iron, cobalt, and titanium, is generally used as the base metal. The activation process is begun by heating the cathode to a temperature of about 1500°K for a few minutes. During this time the carbonates are reduced to oxides with the evolution of oxygen gas. Then the temperature is reduced to about 1000°K, and a positive voltage of about 100 volts is applied to the anode (or all the elements other than the cathode in a multielement tube). The anode current slowly builds up, showing that the cathode is becoming activated.

When the anode voltage is too high to permit the use of an oxide-coated cathode, a thoriated-tungsten filament may be used. The emission efficiency is not so high, but voltages up to 4,000 or 5,000 volts may be used on the anode. For higher voltages than these, however, disintegration of the cathode occurs from excessive positive-ion bombardment, and a pure-tungsten filament must be used.

There are several methods of preparing a thoriated-tungsten type of filament, the most common method involving the mixing of about 1½ per cent of thorium oxide with the tungsten powder before it is sintered, swedged, and drawn into a wire. The filament is then carbonized by being heated at 2000°K in a hydrocarbon vapor at low pressure. This process decreases the emission current slightly but allows the tube to withstand more positive-ion bombardment. Also the life of the filament is materially increased because the rate of evaporation of thorium from the surface is reduced by a factor of about 6.

A thoriated-tungsten filament is activated by first heating the filament to a temperature above 2800°K for about a minute while the tube is being evacuated. The high temperature decomposes the thorium oxide into pure thorium metal and oxygen gas, the latter being removed by the vacuum pump. The temperature is then reduced to 2400°K for a few minutes, during which time a thin layer of pure metallic thorium is built up on the surface of the tungsten.

For anode voltages greater than about 5,000 volts, pure-tungsten filaments are generally used. Tubes using pure-tungsten filaments have been operated at plate voltages exceeding 350,000 volts. Tungsten is mechanically fragile because of crystallization but is extremely rugged electrically. X-ray and other high-voltage tubes generally use tungsten filaments.

The life of all thermionic cathodes is limited by evaporation of the active material. With oxide-coated cathodes, the barium apparently evaporates, leaving only the relatively inactive strontium oxide. With thoriated-tungsten filaments, the thorium, which is the active material, is gradually evaporated from the surface and replaced by more material diffusing out from the inside. Eventually all the thorium is evaporated, however. With tungsten filaments, the tungsten gradually evaporates, thus eventually terminating the life of the filament.

The evaporation of the active materials in all types of cathodes increases with the operating temperature. Hence the filament voltage and current should be maintained reasonably constant to ensure long life. This is particularly important in the case of thoriated tungsten. Operation at overvoltage or undervoltage may cause cessation of emission. If this occurs and the filament still contains some thorium, it can sometimes be reactivated, however.

The curves for oxide-coated and thoriated-tungsten cathodes shown in Fig. 2.11 should not be taken too literally. Slight differences in materials or method of activation may appreciably alter the emission characteristics. The curve for pure tungsten is, however, fairly reliable. More will be said about this subject in Sec. 2.4.

Diode Plate Characteristics. Normally the voltages applied to a tube are such that the operating conditions are to the right of the knees of the curves in Fig. 2.10. In this region the current through the tube is not being limited by the temperature of the filament. In other words the full emission current is not being drawn. Under normal operating conditions, a tube with a thoriated-tungsten filament is capable of passing about ten times as much current as it actually passes at the particular temperature being used. Some factor other than the filament temperature is limiting the current through the tube.

Another and perhaps more convenient way to express the electrical characteristics of a high-vacuum diode is illustrated in Fig. 2.12.

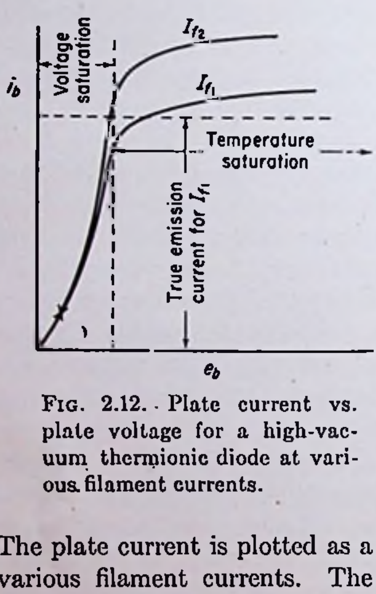


FIG. 2.12. Plate current vs. plate voltage for a high-vacuum thermionic diode at various filament currents.

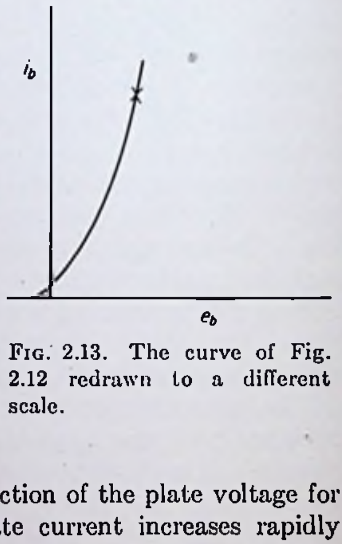


FIG. 2.13. The curve of Fig. 2.12 redrawn to a different scale.

The plate current is plotted as a function of the plate voltage for various filament currents. The plate current increases rapidly with the voltage until a certain value is reached, after which the current levels off, or almost levels off, to a constant value. This "saturation current," as it is called, is proportional to the filament temperature. The saturation current is approximately equal to the emission current of the cathode at the particular temperature being used.

A similarity will be noticed between these curves and the curves for a phototube of plate current vs. plate voltage for various values of cathode light flux. However, there are many differences which are very important. The presaturation currents in a phototube can be explained by failure of the emitted electrons to hit the small anode wire in the center of the tube. However, the anode in a thermionic diode almost entirely surrounds the cathode, thus eliminating this possibility. There is something else at work in a thermionic diode which, although perhaps present to a small extent, is not the current-limiting factor in phototubes.

Another important difference is the fact that phototubes are generally operated *above* the knees of the curves whereas thermionic tubes are nearly always operated *below* the knees of the curves. In this region the plate current is essentially independent of the filament current, as already noted. The filament current is simply set at a high enough value so that operation is never caused to exist above the knee of the curve. Figure 2.12 can be redrawn with more attention paid to the shape of the curve below the knee. Figure 2.13 is typical of the resultant curve.

The data to plot the curves of Figs. 2.12 and 2.13 can be obtained from the curves in Fig. 2.10 provided sufficient data are available at the lower anode voltages. Perhaps a more convenient method is to take the data experimentally, using the circuit of Fig. 2.8. The filament current is held constant and the plate current measured as the plate voltage is varied.

Plate Dissipation. A certain amount of power must be dissipated by the anode of a diode while in operation. The anode-to-cathode voltage multiplied by the anode current gives the power being lost in the tube. This power appears as heat at the anode; the reasons for this will be discussed in the following sections of this chapter. Also, a large percentage of the filament heat is intercepted by the anode and must be dissipated.

The temperature of the plate must not be allowed to become excessive. Gas may be evolved from the anode at high temperatures, thus spoiling the vacuum. If the anode gets too hot, conduction may occur through the tube even when the anode is negative relative to the cathode, the anode in this case acting as a cathode. In most circuits using diodes, it is the unidirectional current-flow properties which make the tube useful. Hence it is desirable to keep the anode temperature low to prevent conduction in the reverse direction. Too high a temperature may warp or even melt the anode.

The above facts are also true for a phototube. The amount of power involved in that case, however, is so small as to be negligible.

As larger and larger currents and voltages are handled by vacuum tubes, the anode dissipation becomes higher and higher. Larger anodes must be used, and more attention must be paid to the materials of which the anode is composed. Small low-power tubes generally use nickel anodes which are carbonized to improve the heat-radiation qualities. The low melting temperature of nickel, however, prevents its use in medium- or high-power tubes. Medium-power tubes use molybdenum or tantalum anodes, which can be operated at higher temperatures than nickel without causing gas evolution. In fact, some materials, including tantalum, actually "soak up" gas molecules at certain temperatures. Tubes using tantalum anodes are operated with their anodes at a cherry-red heat to maintain a high vacuum. Large tubes sometimes use graphite anodes, which have very high melting points. Some tubes have fins attached to the plates to increase the heat-radiating surface. The largest tubes have external anodes which are either water-cooled or forced-air-cooled. High-vacuum diodes are seldom large enough to warrant the use of external anodes, however. Figures 3.6 and 3.7 illustrate the external-anode type of construction.

2.3. Theories Used to Explain Electrical Characteristics of Diodes. Much of the theory given in Sec. 1.3 applies to thermionic diodes as well as to phototubes. It is merely necessary to make additions to the already developed theories which will cover all of the important aspects of the new subject.

Thermionic Emission. We saw in Chap. 1 that the "free" electrons in a piece of metal are free to move about in the metal, but not ordinarily free to leave the boundaries of the metal. An analogous situation would be an oriental harem in which the women are held captive inside the palace grounds. They are free to move about in the palace, but ordinarily prevented from leaving by the high surrounding walls. However, if an interloper should steal in and boost one of the lovely young ladies over the wall, she would thereby receive enough externally supplied energy to escape the confines of her "prison."

Similarly, the electrons in a piece of metal must be given additional boosts of energy to enable them to escape the confines of their metal boundaries. In a phototube, the additional energy comes from photons of light impinging upon the cathode surface. In a thermionic cathode, the necessary additional energy is imparted to the electrons through the medium of heat. As a metal becomes hotter and hotter, the average kinetic energies of the electrons increase, so that if the temperature becomes high enough, some of the electrons may attain sufficient energy to overcome the potential-energy barrier and escape.

It was seen in Chap. 1 that there is a *maximum* kinetic energy that the electrons in a metal can attain at 0°K. If the temperature is made higher than absolute zero, the maximum kinetic energy that the electrons can attain becomes greater. The number of electrons that can attain the energy required to leave the metal is rather difficult to determine analytically. However, it can be done if several simplifying assumptions are made. This will be discussed in some detail in Sec. 2.4.

The "bowl of marbles" analogy can be used with thermionic emission as well as with photoelectric emission. If the marbles are stirred with a stick, they are given random amounts of kinetic energy. The kinetic energies of the marbles represent the kinetic energies of the electrons at 0°K. If the bowl is shaken up and down (while the marbles are still being stirred), the maximum kinetic energy that a marble can attain will be increased. The shaking of the bowl represents the heat energy imparted to the metal. If the bowl is shaken violently enough, the energies of some marbles will be sufficient to enable them to travel all the way up the sloping sides of the dish and leave the bowl entirely. Any excess kinetic energy a marble has after climbing the sides of the bowl gives it an initial velocity upon leaving. Similarly, any excess kinetic energy an electron has after "climbing" the potential-energy barrier at the surface of the metal gives it an initial velocity upon leaving.

A thermionic cathode is therefore merely a piece of metal which has been heated to such a high temperature that electrons are literally being "boiled" from the surface. An analogy can be made to steam molecules being boiled from a pot of hot water. The hotter the water, the higher the energies of the water molecules, and the greater the number which are able to overcome the surface forces and penetrate the boundary of the liquid.

The work function of the metal used in a thermionic emitter should be as low as possible to allow operation at the lowest possible temperature. This is desirable in order to increase the efficiency of emission, or the milliamperes of emitted current per watt of heating power supplied to the cathode. This sounds simple enough, but when we begin examining the available materials, we find that most materials have a melting temperature lower than the value which gives effective thermionic emission. Or, the rate of evaporation of the metal at the required operating temperature is so great that the life of the filament is prohibitively short. As a matter of fact, there is only one pure metal that has a high enough melting point and a low enough evaporation rate to give satisfactory service as a thermionic emitter, that metal being tungsten. The work function of tungsten is rather high, however, being approximately 4.52 e-v. When this is compared with 1.67 e-v for cesium and about 1 e-v for cesium–cesium oxide–silver, some idea may be gained of the relative amount of energy needed to emit an electron from pure tungsten. However, its reliability and long life make the tungsten filament practical in large high-voltage tubes.

The work function of thorium is fairly low, at least compared to tungsten, being on the order of about 3.4 e-v. However, the rate of evaporation from the pure metal is high. It is found that a very thin layer of thorium deposited on the surface of an ordinary tungsten filament does not evaporate nearly so rapidly as does the pure metal. Hence, a high enough operating temperature to give satisfactory emission with reasonable life can be maintained. In fact, it is found that the work function of thoriated tungsten is lower than that of pure thorium, so that the emission efficiency of the former is higher than that of the latter. A monatomic layer of thorium on the surface of the tungsten appears to give the best results.

The emission from oxide-coated cathodes is difficult to explain. The core material is found to influence the amount of emission, but it is generally believed that most of the emission actually occurs from a thin layer of barium at the surface. Possibly the core metal reacts with the oxides chemically to produce the pure metal required for emission. There is also the possibility of electrolytic reduction of the oxide into the pure metal. Positive-ion bombardment also plays an important role in the reduction of the oxide, since a current must be passed through the tube during the activation period.

At any rate, the effective work function of the surface of typical oxide-coated cathodes is very low, being of the order of only 1 e-v. Thus a low temperature can be used, resulting in high emission efficiencies.

Edison Effect. Consider now what happens to the electrons which have been emitted from the cathode. If the anode voltage is zero, some of the electrons can reach the plate because of the initial velocities with which they are emitted. This is called the "Edison effect." A negative anode voltage is required to reduce the space current to zero. This condition has already been seen to exist for a phototube. It explains the reason for the y intercept in Fig. 2.13.

Contact Difference of Potential. When two metals having different work functions are brought into contact, a potential difference is found to exist between the ends of the two pieces not in contact. The metal with the lower work function becomes positively charged with respect to the other metal. The low-work-function metal has lost electrons, whereas the high-work-function metal has gained electrons.

Consider the direction in which an electron inserted at the boundary between the two metals is urged. It tends to go in the direction of the greatest force, or in the direction which enables the electron to *lose* the most energy and thus attain the lowest possible potential energy. This is in the direction of the metal with the higher work function, since it requires a greater expenditure of energy to remove an electron from a high-work-function metal than from a low-work-function metal.

Another way of looking at it is that the potential-energy barrier of each metal is removed at the boundary owing to the presence of the other metal. The potential-energy barrier of the low-work-function metal does not have to be lowered very much before electrons start leaving the metal of their own accord. On the other hand, the potential-energy barrier of the high-work-function metal must be lowered appreciably before electrons can leave. Thus, even though the potential-energy barriers at the surfaces of both metals are removed when the metals are brought into contact, the low-work-function metal loses more electrons than the high-work-function metal. In other words, more electrons cross the boundary going toward the high-work-function metal than in the other direction. This continues until a negative charge is built up on the high-work-function metal of sufficient strength to repel the incoming electrons and slow down their arrival. Eventually the number of electrons going one way becomes equal to the number going the other way, and an equilibrium condition is reached.

The voltage between the two metals is found to be equal to the difference in the work functions of the two metals and thus is ordinarily in the neighborhood of 1 e-v.

In order to illustrate the above situation, assume that we have two boxes of water, each having one side adjustable in height. Assume that one box is about 1½ times as deep as the other but that all the other dimensions are equal. Then assume that each box contains an equal amount of water, with the small box about three-fourths full. Furthermore assume that the tops of the two boxes are at the same elevation. The water in the small box is then nearer the top than the water in the large box. Now let us push the two boxes together with the adjustable sides in contact and lower the sides so that water will flow from the small box into the large box until the water levels are the same in both boxes. The small box, which is the one having the lower potential-energy barrier (the height of the box minus the original height of the water), has thus lost water molecules to the large box, which is the one having the higher potential-energy barrier. After lowering the sides in contact, the large box gains water, whereas the small box loses water. In a like manner, when two dissimilar metals are joined, electrons flow from the one having the lower potential-energy barrier into the one having the higher potential-energy barrier, allowing the latter to acquire more electrons or a more negative charge than the former.

If a third metal is inserted between the two original metals, the potential difference between the free ends of the original metals is the same as the original potential difference without the intermediate metal. This is like having a third box inserted between the two original boxes of water and allowing a free passage of water among all three. The middle box either contributes to or subtracts from the final water level in both the other boxes, but it does not change the *difference* in the amount of water in one box over that in the other.

Thus if a tantalum anode is electrically in contact with a tungsten filament, even though the electrical connection is made through a copper wire external to the tube, there is a difference of potential between the plate and filament equal to the difference in the work functions of tantalum and tungsten expressed in electron volts, or about $4.52 - 4.1 = 0.42$ e-v. Since tantalum has the lower work function, it becomes positively charged relative to the tungsten. Thus, even if the externally applied anode voltage were zero, there would still exist a positive voltage on the anode relative to the cathode. This has the effect of shifting the curve of anode current vs. anode voltage to the left by the amount of the contact difference of potential. If the plate has a higher work function than the cathode, however, the curve is shifted to the right. The effect is most noticeable, of course, at low anode voltages where the contact potential difference is a large percentage of the total anode voltage.

Space Charge. Let us find a solution to the problem of what limits the current flowing in the high-vacuum diode to the right of the knees of the curves in Fig. 2.10. It is not the filament temperature, because even if the filament were hot enough to emit 100 amp, the plate current would be determined almost entirely by the plate voltage.

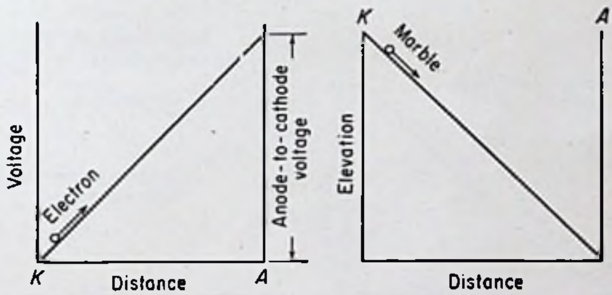


FIG. 2.14. Space potential in a parallel-plane diode with zero space current.

The answer can be found by considering the space potential distribution between the cathode and anode. The simplest configuration is a plane cathode parallel to a plane anode. In this case, the potential curve for zero current flow is a straight line (see Fig. 2.14). Electrons released at the cathode are accelerated to the anode. At any particular instant of time, a large number of electrons are present in the space between the cathode and the anode. This charge present in the interelectrode space is called *space charge.* Its effect is to depress the potential curve, since the electrons constituting the space charge are *negative* charges.

If there are a certain number of electrons on the cathode, there will be on the anode an equal number of positive charges (due to the protons in the atoms). The voltage between the anode and cathode is equal to the total charge on the plates (the number of electrons times the charge of one electron) divided by the capacitance of the plate and cathode acting as a parallel-plate capacitor. This is simply the well-known capacitor equation $V = Q/C$. If the cathode is emitting electrons, the emitted electrons move toward the plate. At the same time, however, electrons travel around the external circuit from the anode to the cathode to replace the ones lost from the cathode by emission. Hence the cathode does not become positively charged but merely stays at the same potential. However, the flux lines emanating from the positive charges on the anode do not all reach through to the cathode when the region contains numerous negative charges. Instead, many of the flux lines from the positive charges on the plate are intercepted by the negatively charged electrons in the space charge. *This means that fewer flux lines reach the cathode, and if fewer flux lines reach*

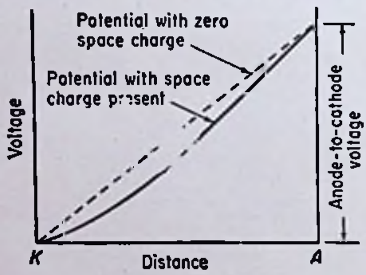


FIG. 2.15. Space potential in the presence of space charge.

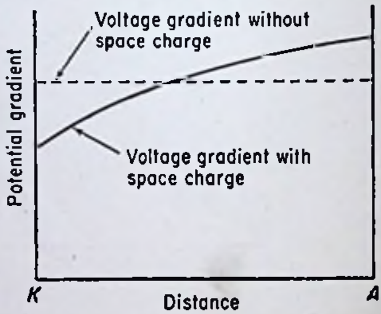


FIG. 2.16. Voltage gradient in the presence of space charge.

the cathode, the electric flux density D is decreased near the cathode. This reduction in flux density reduces the voltage gradient, or electric field intensity, near the cathode. A lower voltage gradient near the cathode surface means that the space potential near the cathode rises less rapidly.

Thus for a moderate amount of space current, the space potential curve is depressed, as shown in Fig. 2.15. The curves in Fig. 2.16 show the effects of space charge upon the voltage gradient in the interelectrode space. (Remember that the voltage gradient is the slope of the potential-distribution curve at each point.) The student should study the last few sentences until he is thoroughly familiar with their meaning.

In order to determine the effects of this new potential curve on an electron starting out at the cathode, let us invert the potential curve and imagine a marble rolling down the new configuration (see Fig. 2.17).

Notice that the marble will start off with a reduced velocity. This is a significant point, because it indicates that the electrons near the cathode will be crowded closer together because of their reduced speeds. (They are crowded closer together near the cathode than near the anode anyway because of their greater velocities as they approach the anode.)

If an *unlimited* supply of electrons is available at the cathode (owing to a very high temperature that is causing appreciable

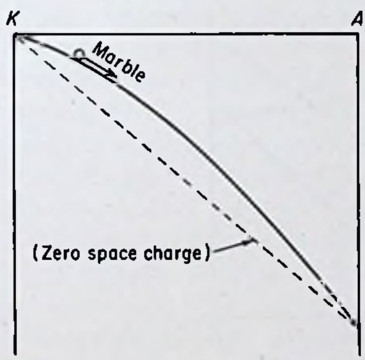


FIG. 2.17. Illustration showing the effects of space charge on the motion of an electron.

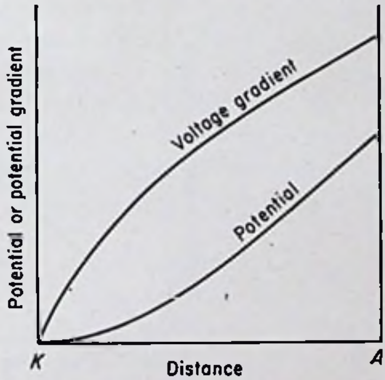


FIG. 2.18. Equilibrium conditions in a plane-electrode diode with zero initial electron velocities.

thermionic emission), the current continues to increase and the potential curve continues to be depressed, until an equilibrium point is reached when the voltage gradient at the cathode surface is zero, assuming that the electrons are released from the cathode surface with zero initial velocity. Thus an equilibrium point is reached, and the current reaches a stable value when the potential- and voltage-gradient curves have the shapes shown in Fig. 2.18.

The condition represented in Fig. 2.18 yields the highest current that can be drawn through the tube at the particular plate voltage being used. *For if the current were any higher, the potential curve would dip below the axis, the voltage gradient at the cathode surface would go negative, and the electrons at the cathode would be repelled* *rather than attracted, thus reducing the current until the potential gradient again became zero.*

Virtual Cathode. The above conditions assume that the electrons are emitted from the cathode with zero initial velocity. Actually, of course, the electrons are emitted with finite velocities ranging from zero up to a maximum value determined by the temperature of the cathode. The higher the temperature of the cathode, the higher the maximum velocity with which some of the electrons are emitted.

The conditions in an actual tube then are such that the voltage gradient at the surface can go negative, and in fact must go nega-

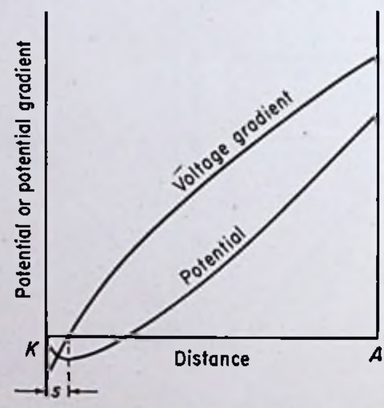


FIG. 2.19. The conditions existing in a parallel-plane diode under conditions of space-charge-limited current with the initial velocities of the emitted electrons considered.

tive to reach an equilibrium condition, provided of course that the current is not limited by the available cathode emission current. Thus the potential- and voltage-gradient curves in an actual diode are as shown in Fig. 2.19.

Electrons emitted from the cathode with zero initial velocity are met by a retarding field due to the negative voltage gradient at the surface and are turned and sent back into the cathode. Electrons emitted from the cathode with a low initial velocity are able to move out a short distance against the retarding field but eventually are slowed down to a standstill and sent back into the cathode. Some of the electrons are emitted with velocities high enough to enable them to reach the point s before losing all of their kinetic energy. At this point the voltage gradient is zero, and so these electrons are teetering on the edge, not knowing whether to go on toward the anode or back into the cathode. Still other electrons are emitted with velocities high enough to enable them to travel past the point s and still have some velocity left over. These electrons travel on to the anode, owing to the strong positive voltage gradient existing to the right of point s. This point of zero potential gradient in front of the cathode is a "virtual cathode," because the electrons are for all practical purposes "emitted" from this region.

In order to show that Fig. 2.19 represents an equilibrium condition, assume that the potential curve is caused by some external means to become momentarily depressed still further than it already is. The more negative voltage gradient at the cathode surface allows fewer electrons to penetrate past the point s, and the space current is correspondingly reduced. However, a reduced space current tends to *raise* the potential curve, and as soon as the external agency is removed, the potential curve rises until it assumes its original position.

On the other hand, suppose the potential curve is momentarily raised by some external means. This causes the voltage gradient at the cathode to become less negative and allows more electrons to penetrate past the point s. The increased space current tends to depress the potential curve, however, and as soon as the external agency is removed, the potential curve drops until it assumes its original position once again.

The above actions can be compared to a governor on a steam engine. If the speed starts to build up, the governor decreases the amount of steam entering the engine, which brings the speed back down. If the speed starts to go down, the governor lets more steam into the engine, which brings the speed back up. In the diode, if the plate current tries to increase, the voltage gradient at the cathode becomes more negative, which brings the current back down. If the current tries to decrease, the voltage gradient at the cathode becomes less negative, which brings the current back up.

Thermionic diodes are nearly always operated under the type of condition described above, which is sometimes spoken of as "voltage saturation," meaning that the plate voltage is too low to draw the full emission current through the tube. As the plate voltage is increased, the plate current also increases until it becomes equal to the full emission current from the cathode, after which it must saturate. This latter limitation of space current is usually termed "temperature saturation," meaning that the temperature is too low to allow the cathode to emit as many electrons as are needed to establish the equilibrium conditions required for space-charge-limited space current.

A marble analogy can be used again to help clarify the action taking place under conditions of temperature saturation and voltage saturation. Figure 2.20 illustrates the case for temperature saturation. The curve between points K and A is simply the

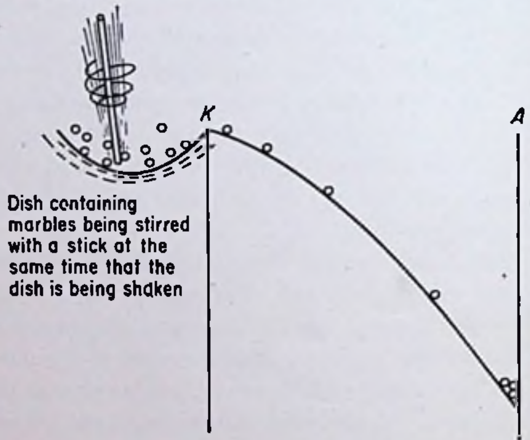


FIG. 2.20. Mechanical model of a thermionic diode under conditions of temperature saturation.

potential curve of Fig. 2.15 inverted. It should be noticed that every marble that is able to go past the top edge of the dish is drawn on to the anode.

The case for voltage saturation is illustrated in Fig. 2.21. The curve is the potential curve of Fig. 2.19 inverted. In this case, not every marble that reaches the top edge of the dish goes on to the anode, but only those having enough energy to get over the hump in the inverted potential curve as well.

If the plate voltage is increased under conditions of voltage saturation, the plate current must increase also. This can be reasoned as follows: When the plate voltage is first raised, the potential gradient at the surface of the cathode becomes less negative (or more positive). This is because more flux lines from the anode penetrate through the space charge. As the potential gradient at the cathode becomes less negative, however, the space current begins increasing. The increasing space current begins depressing the potential curve so that an equilibrium condition is soon reached at a higher value of plate current. The reverse situation occurs when the plate voltage is reduced. The lower plate voltage means a more negative potential gradient at the cathode surface, which

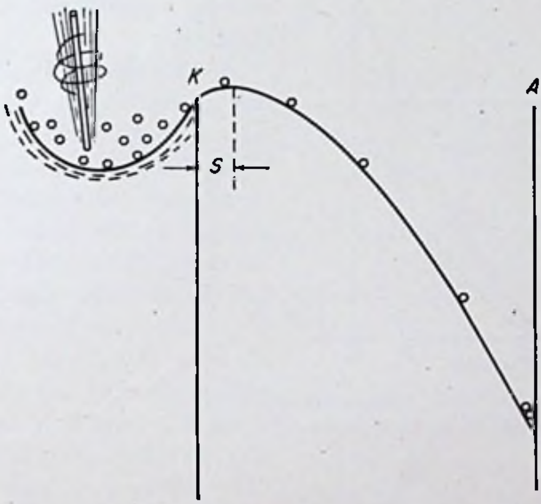


FIG. 2.21. Mechanical model of a thermionic diode under conditions of voltage saturation.

cuts down the plate current until a new equilibrium is reached at a lower value of plate current.

Figure 2.22 illustrates the effect of the spacing between the cathode and anode on the potential curve. When the anode is at position A_1 and the anode voltage is ab, the plate current has a certain value.. If the plate voltage is held constant and the anode moved farther away from the cathode to position A_2, the potential curve becomes depressed further. This is because the capacitance between the cathode and the anode is reduced when the spacing is increased, and for a constant voltage this gives a reduced charge on the plates. A lower charge means fewer flux lines traveling from the anode to the cathode, and hence a more depressed potential curve, owing to the space charge. At position A_2 the anode voltage must be increased to ac in order to draw the same plate current as when the anode was located at A_1. Thus, the voltage drop in a thermionic diode operated under conditions of voltage saturation is lower the closer the spacing between the cathode and the anode. In most cases, it is desirable to keep the voltage drop across the tube at a minimum in order to increase the efficiency of the circuit and allow the use of the smallest possible tube. This calls for a small anode-to-cathode distance.

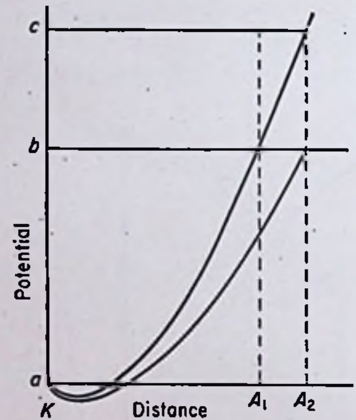


FIG. 2.22. Potential curves for different anode-to-cathode spacings.

Schottky Effect. It is found that under conditions of temperature saturation, the current is not actually constant and independent of the plate voltage but increases slightly as the plate voltage is increased. Thus, curve A in Fig. 2.10 is actually slightly higher to the left of the knees than curve B, even though the cathode is supposedly emitting all the electrons it is capable of emitting at any particular temperature. (The current is higher to the right of the knees for higher plate voltages because this is the region of voltage saturation.) The curves in Fig. 2.12 illustrate the above effect even more clearly. Theoretically, the plate current for a filament current equal to I_{f_1} should saturate at a value equal to the true emission current for I_{f_1}, indicated by the dotted line. However, the plate current continues to rise as the plate voltage is increased, and currents greater than the theoretical emission currents can be drawn through the tube.

The above effects are more pronounced with thoriated-tungsten filaments than with pure-tungsten filaments. The effect is so great with oxide-coated cathodes that a true saturation condition is almost impossible to obtain in practice. Schottky was the first to give a satisfactory explanation of the above phenomenon, and hence it is called the Schottky effect.

According to this theory, the potential-energy curve shown in Fig. 1.14 applies only when there is no external electric field at the surface of the metal. In the presence of a strong positive external field, such as exists at the cathode of a thermionic diode under conditions of temperature saturation, the potential-energy hump is *lowered*, as shown in Fig. 2.23. More electrons are able to get over the small "hump" than over the large one. In other words, the potential-energy barrier has been lowered by the application of a positive field to the surface of the metal.

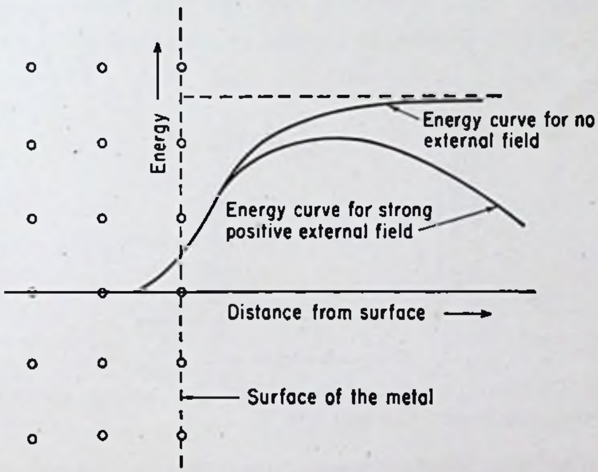


FIG. 2.23. Curves illustrating the Schottky effect, or the effect of an external electric field on the energy curves of an electron near a metallic surface.

Going back to the bowl of marbles, if some material were to be removed from the upper side of the dish, more marbles would have energy enough to reach the top and leave the bowl.

Effect of Cathode Temperature. It should be noticed that the plate currents in Fig. 2.10 do not saturate completely in the voltage-saturation region. The same effect is evidenced by the fact that the curve for the higher filament current I_{f_2} in Fig. 2.12 is higher in the voltage-saturation region than the curve for the lower filament current I_{f_1}. The reason for this increase of plate current with filament current, even when the plate current is space-charge-limited, is the fact that the higher the temperature of the cathode, the higher the initial velocities of the emitted electrons. Higher initial velocities push the virtual cathode closer to the anode. A smaller cathode-anode spacing has already been shown to give a greater plate current under conditions of voltage saturation. Therefore, as the temperature of the cathode is increased by increasing the filament or heater current, the virtual cathode moves a little closer to the plate and the plate current correspondingly goes up.

2.4. Mathematical Analysis of High-vacuum Thermionic Diodes. *Thermionic Emission.* Figure 1.24 shows the distribution of the kinetic energies among electrons in a constant-potential region at 0°K. In this case none of the electrons has energy

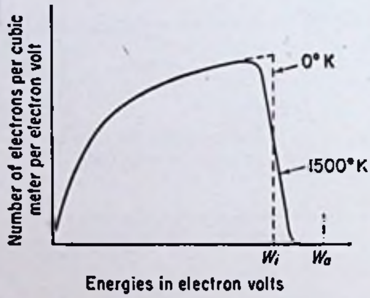


FIG. 2.24. Distribution of the kinetic energies among electrons in a constant-potential region at 0 and 1500°K.

greater than W_i. If the temperature is not zero, however, some of the electrons have energies greater than W_i. The curve for 1500°K is shown in Fig. 2.24.

Every electron which approaches the boundary with a perpendicular component of kinetic energy equal to or greater than W_a leaves the metal. (More exact analyses taking into account the wave nature of electrons show that not every electron leaves, even though the above conditions are satisfied. However, the number that are able to but do not leave is very small if the available energies at the boundary are more than a few hundredths of an electron volt.)

A determination of the number of electrons which leave a piece of metal at any particular temperature is a rather difficult task, in spite of all the simplifying assumptions that are made.

As the temperature is increased from 0°K, emission slowly increases. In other words, there is no "critical" temperature in the same sense that there exists a threshold wavelength for photoelectric emission. But at ordinary room temperatures, the amount of emission is very low. It has been estimated that only one electron in every 10^{14} years is emitted from every square centimeter of tungsten at room temperatures. Ordinarily the temperature must be increased to several hundred degrees Kelvin before emission of even a few microamperes per square centimeter takes place. As the temperature is increased, the curve in Fig. 2.24 moves farther out on the energy axis, thus showing that more electrons are attaining the necessary boosts of energy to escape from the surface.

The equation for emission current as a function of temperature can be derived, in spite of the difficulties, and is found to be

$$J = 4\pi m_e Q_e \frac{k^2}{h^3} T^2 \epsilon^{-Q_e\varphi/kT} \tag{1}$$

where J = emission current, amp/m²
m_e = mass of an electron
Q_e = charge of an electron
k = Boltzmann constant, 1.38×10^{-23} joule/°K
h = Planck's constant, 6.624×10^{-34} joule-sec
T = absolute temperature, °Kelvin (273° + °C)
ϕ = work function, e-v
ϵ = base of natural logarithms

By substitution of all the appropriate constants into the equation, we can simplify it as follows:

$$J = \frac{(4)(3.14)(9.1 \times 10^{-31})(1.6 \times 10^{-19})(1.38 \times 10^{-23})^2 T^2 \epsilon^{-(1.6\times10^{-19})\phi/(1.38\times10^{-23})T}}{(6.624 \times 10^{-34})^3}$$

$$= 120{,}400 T^2 \epsilon^{-11{,}600\phi/T} \quad \text{amp/m}^2 \tag{2}$$

If the current is expressed in amperes per square centimeter rather than per square meter, the equation is

$$J = 120.4 T^2 \epsilon^{-11{,}600\phi/T} \quad \text{amp/cm}^2 \tag{3}$$

Equation (3) is called the Richardson-Dushman equation, after the men who derived it. The equation is very frequently put into the form

$$J = AT^2\epsilon^{-b/T} \tag{4}$$

where A is theoretically a universal constant and b is a constant for any particular cathode material.

Example:

Find the emission current from a pure-tungsten filament 3 cm long and 1 mm in diameter at a temperature of 2000°K.

Solution:

$$\phi = 4.52 \text{ e-v}$$

$$\begin{aligned} \text{Area of filament surface} &= \pi Dl \\ &= (3.14)(0.1)(3) \\ &= 0.942 \text{ cm}^2 \\ I &= 120.4T^2\epsilon^{-11{,}600\phi/T} \times \text{area} \\ &= (120.4)(2{,}000)^2\epsilon^{-(11{,}600)(4.52)/2{,}000} \times 0.942 \\ &= 1.9 \times 10^{-3} \text{ amp} \\ &= 1.9 \text{ ma} \quad \textit{Ans.} \end{aligned}$$

It must be remembered that Richardson's equation gives the *emission* current obtainable at a particular cathode temperature. The actual current flowing in a diode under conditions of voltage saturation is less than the emission current but may be greater under conditions of temperature saturation, owing to the Schottky effect.

It has been found through carefully performed experiments that Eq. (3) cannot be used to compute with a high degree of accuracy the emission current from a particular cathode. There are several simplifying assumptions which were made in the derivation of the equation. Failure to take every factor into consideration makes the derived equation useful in a qualitative manner only. In the example above, the actual emission current would probably not be 1.9 ma at all, but might be about 1 ma.

It is found, however, that Eq. (4) can be used, provided that the constants A and b are arranged to make the equation fit the experimental curves of emission current vs. temperature, such as the curves shown in Fig. 2.11. When this is done, it is found that the constant A is about 60.2 for most pure metals, including tungsten. The constant b appears to check more closely with the theoretical value in Eq. (3). Thus, experimentally, b for tungsten is 52,400. If the work function is 4.52 e-v, b should theoretically be (11,600)(4.52) = 52,400, which checks exactly. The previous example can now be worked with the assurance of a more accurate answer.

Solution:

$$\begin{aligned} I &= 60.2T^2\epsilon^{-11,600\phi/T} \times \text{area} \\ &= (60.2)(2,000)^2(0.942)\epsilon^{-(11,600)(4.52)/2,000} \\ &= 0.95 \text{ ma} \quad \textit{Ans.} \end{aligned}$$

The values of A and b for oxide-coated cathodes and for thoriated-tungsten cathodes are rather indeterminate. This is because the amount of emission varies greatly with the exact composition of the cathode and with the method used in its activation. Also the Schottky effect influences the amount of current flowing under conditions of temperature saturation to such a large extent that the exact values of emission currents are difficult to measure experimentally. However, most tubes are never operated under conditions of temperature saturation, and hence the exact emission current is rather immaterial in most practical cases. A and b may vary anywhere from 0.001 to 0.01, and 10,000 to 12,000, respectively, for oxide-coated cathodes. For thoriated-tungsten filaments, A and b may range from 3 to 59, and 30,500 to 36,500, respectively.

Reference to Fig. 2.11 will quickly convince the student that the constant b in Richardson's equation is more important in determining the magnitude of the emission current than the constant A. Although A for tungsten is over 6,000 times A for oxide-coated cathodes, the emission current at the same temperature is immensely greater for oxide-coated than for pure-tungsten cathodes, and this in spite of the fact that b for oxide-coated cathodes is only less by a factor of about 4.5 than b for tungsten cathodes.

Perhaps another example will better illustrate the point. If A is increased by a factor of 10, the emission current is increased by the same factor. However, if b is *reduced* by a factor of 10, the current is increased by a factor of ϵ^{10}, or about 22,000 times!

Emission Efficiency. The amount of heating power required to raise the cathode to its operating temperature varies as the fourth power of that temperature. In spite of this fact, the higher the operating temperature, the higher the emission efficiency, which is defined as the ratio of the emission current to the heating power. This is because a given change in temperature produces a much larger increase in emission current than it does in heating power. For example, if the temperature is increased by a factor of 10, the new heating power is $10^4 = 10{,}000$ times the old heating power. However, the new emission current is $10^2 \times \epsilon^{10}$, or about 2,200,000 times the old emission current!

A more practical example is the fact that at 2400°K, the emission efficiency of pure tungsten is about 2.01, whereas at 2500°K, it is about 4.27, and at 2600°K, 8.56 ma/cm²/watt.

A practical limit to the operating temperature is reached when the evaporation rate of the metal becomes excessive. This is an economic problem, wherein the cost of replacement due to filament burnout must be weighed against the cost of heating the filament throughout its useful lifetime. In practice, an economical temperature for tungsten occurs around 2500°K. For thoriated-tungsten filaments, 2000°K gives a reasonable life, whereas 1000°K is commonly used for oxide-coated cathodes.

The emission efficiencies of thoriated-tungsten and oxide-coated cathodes depend on the effective values of A and b for the particular cathode under consideration. Typical values for all the common types of cathodes are as follows:

	Emission Efficiency, ma/cm²/watt
Oxide-coated filaments	200–1,000
Oxide-coated, indirectly heated cathodes	10– 200
Thoriated-tungsten filaments	5– 100
Pure-tungsten filaments	2– 10

Example:

Compute the emission current and the emission efficiency of an oxide-coated cathode 1 mm in diameter and 2 cm long if the heater voltage is 6.3 volts and the heater current is 0.3 amp.

Solution:

Assume $A = 0.01$, $b = 11{,}000$, and $T = 1000$°K. Therefore

$$\begin{aligned}
J &= AT^2\epsilon^{-b/T} \\
&= (0.01)(1{,}000)^2\epsilon^{-11{,}000/1{,}000} \\
&= 0.167 \text{ amp/cm}^2 \\
I &= J \times \text{area of cathode} \\
&= (0.167)(\pi)(0.1)(2) \\
&= 0.105 \text{ amp} \\
&= 105 \text{ ma} \quad \textit{Ans.}
\end{aligned}$$

$$
\begin{aligned}
P_f &= E_f I_f \\
&= (6.3)(0.3) \\
&= 1.89 \text{ watts}
\end{aligned}
$$

$$
\begin{aligned}
\text{Emission efficiency} &= \frac{I}{P_f} \\
&= \frac{105}{1.89} \\
&= 55.5 \text{ ma/watt} \quad \textit{Ans.}
\end{aligned}
$$

(The above example is fairly typical of small receiving tubes. Reference to any receiving-tube manual will show that 6.3 volts at 0.3 amp using a heater-type cathode is very common.)

The chances are that the rated direct current for the tube in the above example would not be over about 10 ma, thus allowing a large factor of safety in the available emission.

Equation for Space-charge-limited Current. The anode current in Fig. 2.13 is limited by the negative charges of the electrons in the interelectrode space between the cathode and anode. It is helpful to derive an equation for the magnitude of this current as a function of the anode voltage and the configuration of the electrodes. A general expression taking into account such factors as the initial velocities of the emitted electrons and the contact difference of potential would be extremely difficult to derive, and it would probably be so complicated as to be practically worthless. It is more informative to derive an expression under the following assumptions:

1. The anode and cathode are parallel planes.
2. There is no fringing of flux at the edges, and the flux lines are everywhere perpendicular to the electrodes.
3. The electrons are emitted from the cathode with zero initial velocity.
4. All parts of the cathode are at the same potential.
5. Contact difference of potential between electrodes is zero.

There are three equations which must be solved simultaneously to obtain the final answer for which we are looking. These three equations must first be obtained.

Let the origin be located at the center of the cathode, and let the x axis extend perpendicularly toward the anode. Consider an electron at a point x moving along the x axis to the anode (see Fig. 2.25). If its velocity is v, then its kinetic energy is $\frac{1}{2}m_ev^2$, and this must be equal to the loss of potential energy it has suffered since leaving the cathode. If the potential at point x is called V, this loss in potential energy is equal to Q_eV, where Q_e is the charge of an electron. Thus the first equation is

$$Q_eV = \tfrac{1}{2}m_ev^2 \tag{5}$$

[Equation (5) is the same as Eq. (8) in Sec. 1.4.]

The region between the anode and cathode is filled with negative charges. From the qualitative reasoning in Sec. 2.3 we know that the charge density ρ is higher near the cathode than near the anode owing to the lower electron velocities near the cathode. However, if a plane is passed through point x parallel to the electrodes, the charge density is uniform over that plane. Charge density means the charge contained in a very small volume divided by the volume.

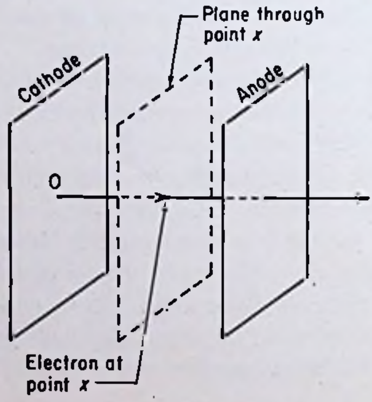


FIG. 2.25. A parallel-plane diode used in deriving Child's law.

The units for ρ in the cgs electrostatic system are statcoulombs per cubic centimeter.

The plate current i_b is equal to the number of charges moving through the plane per unit of time ($I = Q/t$). If the area of the electrodes is A cm², there are $-\rho A$ statcoulombs/cm in the plane through x. If these charges are moving at a velocity of v cm/sec, the total current passing through the plane is $-\rho Av$. Thus the second equation is

$$i_b = -\rho Av \tag{6}$$

The third equation can be obtained from Gauss's law, which states that the total number of flux lines emanating from a closed volume containing Q units of charge is $4\pi Q$. Consider a very small cube located at point x (see Fig. 2.26). If the volume of the cube is small enough, then to a first approximation the charge density ρ is uniform throughout the volume. If the sides are all Δx cm long, the total volume of the cube is $(\Delta x)^3$, which makes the total charge enclosed in the cube

$$Q = -\rho(\Delta x)^3 \tag{7}$$

There are more flux lines going *into* the box on the right side (the anode side) than there are coming *out* of the box on the left side (the cathode side). This is because some of the flux lines from the anode are intercepted inside the box by the negative charges enclosed therein. According to Gauss's law, the loss of flux lines must be equal to 4π times the enclosed charge. Therefore we can write

$$\Delta\phi = -4\pi\rho(\Delta x)^3 \tag{8}$$

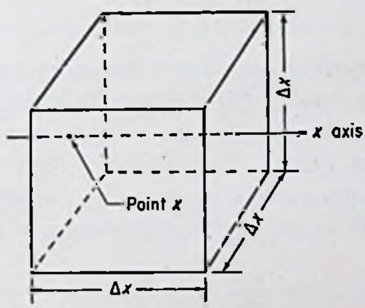


FIG. 2.26. A small cube of space charges.

where $\Delta\phi$ is the difference in the number of flux lines entering and leaving. If the electric flux density on the cathode side is designated D_x and the electric flux density on the anode side is designated $D_{x+\Delta x}$, we can write

$$D_{x+\Delta x} = D_x + \Delta D \tag{9}$$

where ΔD is the *increase* in flux density incurred by moving through the cube in the positive x direction. Equation (9) can be written as follows:

$$\frac{\phi_{x+\Delta x}}{(\Delta x)^2} = \frac{\phi_x}{(\Delta x)^2} + \Delta D \tag{10}$$

where $\phi_{x+\Delta x}$ is the total flux passing through the anode side of the box and ϕ_x is the total flux passing through the cathode side of the box. Solving for ΔD in Eq. (10) gives

$$\Delta D = \frac{\phi_{x+\Delta x} - \phi_x}{(\Delta x)^2} \tag{11}$$

But $\phi_{x+\Delta x} - \phi_x$ is the loss of flux lines after passing through the box, which we have already called $\Delta\phi$. Therefore

$$\Delta D = \frac{\Delta\phi}{(\Delta x)^2} \tag{12}$$

Substituting the value of $\Delta\phi$ from Eq. (8), we obtain

$$\Delta D = \frac{-4\pi\rho(\Delta x)^3}{(\Delta x)^2}$$

$$= -4\pi\rho\,\Delta x \tag{13}$$

Dividing both sides by Δx yields

$$\frac{\Delta D}{\Delta x} = -4\pi\rho \tag{14}$$

If the cube is shrunk to a smaller and smaller size, the assumption of uniform charge density throughout the volume becomes more and more accurate, and in the limit, as Δx approaches zero, the expression becomes exact. Therefore Eq. (14) can be written as follows: The derivative of the electric flux density with respect to distance is equal to 4π times the charge density at point x.

$$\frac{dD}{dx} = -4\pi\rho \tag{15}$$

The relation between the electric flux density and the voltage gradient is

$$D = \epsilon\mathcal{E} \tag{16}$$

which, in the cgs electrostatic system of units, reduces to

$$D = \mathcal{E}$$

since ϵ (the dielectric constant) is unity for air. Therefore Eq. (15) can be written as

$$\frac{d\mathcal{E}}{dx} = -4\pi\rho \tag{17}$$

The voltage gradient is related to the potential V by the equation

$$\mathcal{E} = \frac{dV}{dx} \tag{18}$$

Therefore Eq. (17) becomes

$$\frac{d^2V}{dx^2} = -4\pi\rho \tag{19}$$

which is the third equation we need. Solving for v in Eq. (5) gives

$$v = \left(\frac{2Q_eV}{m_e}\right)^{1/2} \tag{20}$$

Substitution of this value of v into Eq. (6) and solving for ρ yields

$$\rho = -\frac{i_b}{A}\sqrt{\frac{m_e}{2Q_e}}\,V^{-1/2} \tag{21}$$

Substitution of this value of ρ into Eq. (19) gives

$$\frac{d^2V}{dx^2} = \frac{4\pi i_b}{A}\sqrt{\frac{m_e}{2Q_e}}\,V^{-1/2} \tag{22}$$

Multiplying both sides of Eq. (22) by $2(dV/dx)\,dx$ gives

$$2\,\frac{dV}{dx}\,\frac{d^2V}{dx^2}\,dx = \frac{8\pi i_b}{A}\sqrt{\frac{m_e}{2Q_e}}\,V^{-1/2}\,\frac{dV}{dx}\,dx \tag{23}$$

Equation (23) may be written as

$$\frac{d(dV/dx)^2}{dx} = \frac{8\pi i_b}{A}\sqrt{\frac{m_e}{2Q_e}}\,V^{-1/2}\,dV \tag{24}$$

since

$$\frac{d(dV/dx)^2}{dx} = 2\,\frac{dV}{dx}\,\frac{d^2V}{dx^2} \tag{25}$$

Integrating both sides of Eq. (24) yields

$$\left(\frac{dV}{dx}\right)^2 = \frac{16\pi i_b}{A}\sqrt{\frac{m_e}{2Q_e}}\,V^{1/2} + C_1 \tag{26}$$

At the cathode, x is equal to zero, dV/dx is equal to zero (see Fig. 2.18), and V is equal to zero. Therefore the constant C_1 is equal to zero. Solving for dV/dx yields

$$\frac{dV}{dx} = 4\sqrt{\frac{\pi i_b}{A}}\,\sqrt[4]{\frac{m_e}{2Q_e}}\,V^{1/4} \tag{27}$$

Separating the variables gives

$$V^{-1/4}\,dV = 4\sqrt{\frac{\pi i_b}{A}}\,\sqrt[4]{\frac{m_e}{2Q_e}}\,dx \tag{28}$$

Integration of Eq. (28) gives

$$\tfrac{4}{3}V^{3/4} = 4\sqrt{\frac{\pi i_b}{A}}\sqrt[4]{\frac{m_e}{2Q_e}}\,x + C_2 \tag{29}$$

When x is zero, V is zero; therefore, C_2 is equal to zero. Solving for i_b gives

$$i_b = \frac{1}{9\pi}\sqrt{\frac{2Q_e}{m_e}}\frac{A}{x^2}V^{3/2} \tag{30}$$

Equation (30) gives the plate current as a function of the potential V at any distance x from the cathode. When x is equal to the spacing between the electrodes, s, V is equal to the plate voltage e_b. Thus

$$i_b = \frac{1}{9\pi}\sqrt{\frac{2Q_e}{m_e}}\frac{A}{s^2}e_b^{3/2} \tag{31}$$

Substitution of numerical values for the constants yields

$$i_b = (3.63 \times 10^7)\frac{A}{s^2}e_b^{3/2} \quad \text{statamperes} \tag{32}$$

where e_b is expressed in statvolts. Since 1 amp = 3×10^9 statamperes and 1 statvolt = 300 volts, we can write

$$i_b = (2.34 \times 10^{-6})\frac{A}{s^2}e_b^{3/2} \quad \text{amp} \tag{33}$$

where e_b is expressed in volts. It should be noticed that the area and spacing can be expressed in any units so long as they are the same for both. Equation (33) is known as the Child-Langmuir law, after the men who first derived it.

Example:

Find the plate current flowing in a diode if the anode and cathode are parallel metal plates 1 in. square and spaced $\frac{1}{8}$ in. apart, and the plate-to-cathode voltage is 200 volts.

Solution:

$$\begin{aligned} i_b &= (2.34 \times 10^{-6})\frac{A}{s^2}e_b^{3/2} \\ &= \frac{(2.34 \times 10^{-6})(1)(200)^{3/2}}{(\frac{1}{8})^2} \\ &= 0.419 \text{ amp} \\ &= 419 \text{ ma} \quad \textit{Ans.} \end{aligned}$$

Child's Law for Cylindrical Electrodes. The electrodes of most diodes are neither plane nor parallel. Hence Eq. (33) has limited application. Many tubes have cathodes and anodes which are coaxial cylinders, however. If simplifying assumptions are again

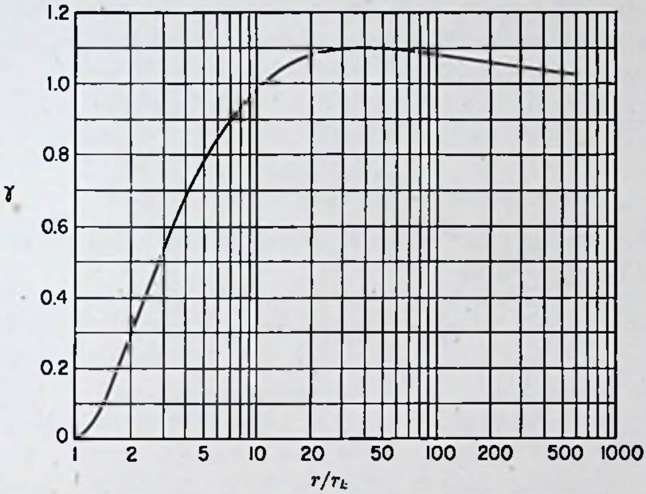


FIG. 2.27. Curve of γ vs. r/r_k.

made, the equation for cylindrical elements can be derived and is found to be

$$i_b = (14.67 \times 10^{-6}) \frac{l}{r} \frac{e_b^{3/2}}{\gamma} \quad \text{amp} \tag{34}$$

where e_b = plate voltage, volts
l = length of plate and cathode
r = radius of plate
γ = number determined by the ratio r/r_k, where r_k is cathode radius

Figure 2.27 is a plot of γ vs. the ratio r/r_k. It should be noticed that, for values of r/r_k greater than 7, the value of γ is within 10 per cent of unity. Hence an approximate expression for the plate current valid for large ratios of plate radius to cathode radius can be found by setting γ equal to unity. The expression then becomes

$$i_b = (14.67 \times 10^{-6}) \frac{l}{r} e_b^{3/2} \quad \text{amp} \tag{35}$$

Any units can be used for l and r so long as they are the same for both.

Example:

Find the plate current in a diode having a cylindrical anode and cathode. The anode is 2 cm in diameter, and the cathode is 4 mm in diameter. The elements are both 3.5 cm long, and the plate voltage is 550 volts.

Solution:

$$\frac{r}{r_k} = \frac{1}{0.2} = 5$$

Therefore the exact equation should be used. From Fig. 2.27, $\gamma = 0.77$. Therefore

$$\begin{aligned} i_b &= (14.67 \times 10^{-6}) \frac{l}{r} \frac{e_b^{3/2}}{\gamma} \\ &= \frac{(14.67 \times 10^{-6})(3.5)(550)^{3/2}}{(1)(0.77)} \\ &= 0.862 \text{ amp} \\ &= 862 \text{ ma} \quad \textit{Ans.} \end{aligned}$$

Departures from Theory. It must be remembered that the above expressions for plate current are approximate because of the assumptions made in their derivation. They are principally of interest because they show the dependence of plate current on the plate voltage and the geometry of the tube. In the case of plane electrodes, the current varies inversely as the square of the spacing for a given voltage. Hence, the elements should be spaced close together if a large current is desired at a low voltage drop. In the case of cylindrical electrodes, the current varies *approximately* inversely as the first power of the spacing provided the anode radius is large compared to the cathode radius. However, the factor γ depends on the spacing, and hence a simple statement for cylindrical electrodes is not possible.

For complicated geometries, such as V- or M-shaped filaments with elliptical or rectangular anodes, an analytical expression is very difficult to derive. For any geometry, however, it is permissible to write

$$i_b = Ke_b^{3/2} \tag{36}$$

where K, called the *perveance* of the tube, depends on the tube geometry.

Both the Child's law equations show that the plate current varies theoretically with the three-halves power of the plate voltage. In an actual tube, the exponent is usually neither constant nor three-halves. Initial velocities of the emitted electrons, contact difference of potential between electrodes, and the difference of potential existing along the length of a filamentary cathode all influence the exact value of the exponent. The last-mentioned effect may cause the exponent to be as high as five-halves. This occurs, however, only at low plate voltages comparable to the filament voltage. For high plate voltages, the drop of potential along the filament has little effect. Other factors causing an actual tube to deviate from the theoretical are the inevitable irregularities in construction, residual gas in the tube, and fringing of the flux lines at the edges of the electrodes.

Plate Dissipation in High-vacuum Diodes. The energy relationships involved in a high-vacuum diode should be clearly understood by the student. Consider an electron which is emitted from the cathode. In the case of a temperature-saturated diode, it is drawn to the anode regardless of its initial velocity. In the case of a voltage-saturated diode, it must have an initial velocity great enough to enable it to penetrate the virtual cathode before it is drawn to the anode. Suppose the electron we are considering does reach the anode. Before it leaves the virtual cathode, it has a certain potential energy with respect to the anode. As it accelerates toward the anode, it gains kinetic energy but only at the expense of its potential energy. While it is moving from the cathode to the anode, work is being performed on the electron. The energy comes from the stored energy of the electrostatic field of the capacitance formed by the anode and cathode. This energy comes, in turn, from the plate power supply, or B battery.

When the electron reaches the anode, it attains an amount of kinetic energy equal to the loss of potential energy it suffered by making the journey. Its kinetic energy at the instant of impact on the anode is equal to $\frac{1}{2}m_ev^2$, where m_e is the mass of the electron and v is its velocity on impact. The question arises: What happens to the energy? Most of it is usually converted into heat energy at the point of impact. This increases the temperature of the anode at that spot. In some cases, some of the energy is imparted to other electrons in the electron gas of the metal which are enabled thereby to overcome the potential-energy barrier of the metal and leave the metal. This is called secondary emission. In some cases, some of the energy of the bombarding electrons goes into high-frequency electromagnetic radiations known as X rays. X-ray tubes are specially constructed to utilize this principle. Many ordinary vacuum tubes, however, emit X rays, particularly high-voltage tubes. In some cases, these radiations are harmful, and such tubes should be adequately shielded.

In most cases, however, almost all the energy of the electrons is converted into heat energy at the anode. The temperature must not be allowed to become excessive, which means that the anode must be capable of dissipating the heat energy rapidly enough to limit its temperature to a safe value. All manufacturers make extensive tests with their anodes in order to determine the maximum amount of heat energy which they are capable of dissipating without an excessive temperature rise. This rating is called the *allowable plate dissipation*, and it is one of the most important ratings given a high-vacuum tube.

The plate dissipation is usually expressed in watts, and its magnitude can be found as follows: Each electron which bombards the plate contributes an amount of energy equal to $\frac{1}{2}m_ev^2$, which is also equal to Q_ee_b, the charge of the electron times the plate-to-cathode voltage. If N electrons bombard the plate in a time Δt, the power the plate is called upon to dissipate is

$$P_b = \frac{NQ_ee_b}{\Delta t} \tag{37}$$

The quantity $NQ_e/\Delta t$, however, is equal to the plate current i_b. Therefore, Eq. (37) can be written

$$P_b = e_bi_b \tag{38}$$

Equation (38) actually could have been written down immediately without going through the preliminary steps, because the power in any device is the voltage across the device times the current through the device. An electron tube is no exception. It consumes energy, just as does a resistor across which a voltage drop exists, whenever a current is sent through it. The important point about the manner of deriving Eq. (38) is the fact that it clearly shows that *all* the energy appears at the anode.

Furthermore, the anode must be capable of dissipating a considerable percentage of the cathode heating power. A more accurate expression than Eq. (38) for the total plate dissipation is

$$P_b = e_b i_b + fE_f I_f \tag{39}$$

where f is the fraction of the cathode heating power intercepted by the anode.

Example:

If the anode of a certain diode intercepts 70 per cent of the cathode heating power, and the plate current is given by the equation $i_b = 0.001 e_b^{3/2}$ amp, find the maximum allowable plate voltage and plate current. The ratings of the tube are

$$\begin{aligned} P_b \text{ (allowable)} &= 15 \text{ watts} \\ E_f &= 5 \text{ volts} \\ I_f &= 1 \text{ amp} \end{aligned}$$

Solution:

$$\begin{aligned} P_b &= e_b i_b + fE_f I_f \\ 15 &= 0.001 e_b^{3/2} e_b + (0.7)(5)(1) \\ e_b &= 42.1 \text{ volts} \quad \textit{Ans.} \\ i_b &= 0.273 \text{ amp} \quad \textit{Ans.} \end{aligned}$$

(The above problem illustrates the principles of plate dissipation. Actual tubes are seldom operated with *steady* plate currents and voltages.)

PROBLEMS

1. Find the emission current at 2400°K from a pure-tungsten filament 4 in. long and $\frac{1}{64}$ in. in diameter.

2. Find the emission current from a thoriated-tungsten filament having the same dimensions as the one in Prob. 1, but operated at a temperature of 2000°K. (Assume $A = 10$, $b = 33{,}000$.)

3. Find the emission current from an oxide-coated filament having the same dimensions as the one in Prob. 1, but operated at a temperature of 1000°K. (Assume $A = 0.005$, $b = 11{,}500$.)

4. If the filaments of Probs. 1 to 3 are all to be operated from a 10-volt source, find the required filament current for each filament. Assume emission efficiencies of 4, 40, and 400 ma/watt for tungsten, thoriated-tungsten, and oxide-coated filaments, respectively.

5. A parallel-plane diode has rectangular electrodes 2 cm wide and 3 cm long. What should the spacing be to limit the voltage drop to 50 volts at 100 ma plate current?

6. The voltage drop across a certain diode is found to be 75 volts at a plate current of 40 ma. Find the approximate voltage drop for a plate current of 120 ma.

7. A diode has a single-wire filament 5 cm long and 0.5 mm in diameter. The anode is 4 cm long and has an inside diameter of 3 cm. What current will flow for an anode voltage of 20 volts? What is the percentage error in using the approximate equation?

8. What should the diameter of the cylindrical anode be in order to limit the voltage drop in a diode to 100 volts at 300 ma? The cathode and anode are both 5 cm long, and the radius of the cylindrical cathode is 1.5 mm.

9. If the equation for the space current in a certain diode is $i_b = 2e_b^{3/2}$, in which i_b is expressed in milliamperes and e_b in volts, to what value should the plate voltage be limited in order to prevent exceeding the plate dissipation of 40 watts? Neglect cathode heating power.

10. What is the velocity in centimeters per second of an electron which hits the anode of a diode having a plate current of 375 ma at a plate voltage of 80 volts? What is its energy in ergs?

11. Find the perveance of a parallel-plane diode having electrodes 1.5 cm wide and 4 cm long spaced 0.5 cm apart.

12. Find the perveance of a cylindrical diode having a 0.5-mm-diameter single-wire filament and a 1-cm-diameter anode. Assume the length of both anode and cathode to be 3 cm.

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CHAPTER 3

HIGH-VACUUM TRIODES

WHILE the high-vacuum diode was historically the first electron tube, electronics would never have become anything more than a very minor branch of the electrical science had not the high-vacuum triode been invented. The introduction of a third electrode between the cathode and anode of the diode opened up almost unlimited areas of experimentation and research. Whereas the applications of diodes are by comparison rather limited, the applications of triodes are practically without bounds. Triodes are used for amplification of direct currents, amplification of alternating currents of frequencies ranging from near zero to over 1,000 megacycles/sec, oscillation over the same range of frequencies, modulation, detection, and a large number of special applications of such a diversified nature that it becomes difficult to classify them. Diodes were the doorway to electronics; triodes were the key that unlocked the door.

3.1. Physical Characteristics of Triodes. A cutaway sketch of a typical high-vacuum triode is shown in Fig. 3.1. The word triode signifies three elements, which in this case are a cathode, an anode, and a grid. The cathode is located in the center and is surrounded by the grid, which, in turn, is surrounded by the anode. The symbol for a triode is also shown in Fig. 3.1. It is the same as for a diode with the exception of the addition of a dotted line between the cathode and anode representing the grid.

The cathodes of all high-vacuum triodes are of the thermionic type. Small low-voltage tubes generally use oxide-coated cathodes, either filamentary or indirectly heated. Medium-power tubes operated at plate voltages up to several thousand volts are generally constructed with thoriated-tungsten filamentary cathodes, whereas very high power or very high voltage tubes are nearly always built with pure-tungsten filaments. Typical shapes for filamentary cathodes are shown in Fig. 2.2.

The grid can take the form of a helix, a squirrel cage, or a mesh structure. Figure 3.2 illustrates typical grid constructions. The grid in a triode is usually located fairly close to the cathode, and it is located so that no emitting portion of the cathode is exposed directly to the anode. The grid is always designed so that a free flow of electrons through its openings can be maintained.

The required anode shape is influenced by the shape of the cathode and grid and is usually round, elliptical, or rectangular. Figure 3.3 illustrates several triodes and shows the shape and arrangement of the cathode, grid, and plate for each.

Triodes designed to operate at high anode voltages usually have

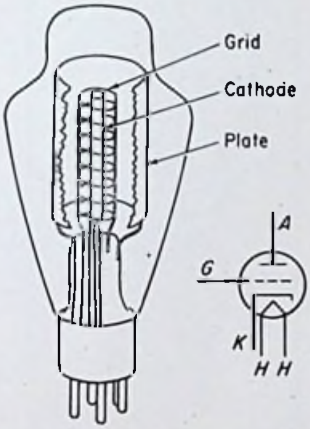

FIG. 3.1. Construction of a high-vacuum triode.

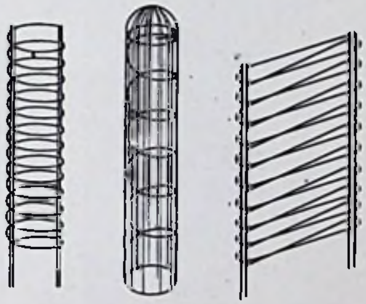

FIG. 3.2. Typical grid structures.

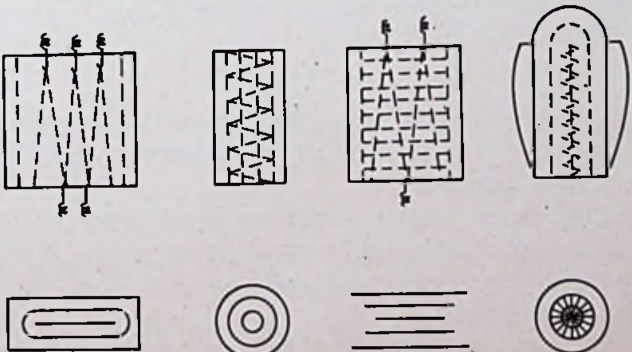

FIG 3.3. Typical triode structures showing the shape and arrangement of the electrodes.

their anode connections brought out at the opposite end of the envelope from their cathode connections, as shown in Fig. 3.4. This minimizes electrolysis of the glass at high temperatures, as mentioned in Chap. 2 in connection with diodes. It also allows better isolation of the grid and plate circuits, which is sometimes desirable.

Fig. 3.4. A medium-power transmitting-type triode designed to be used as an amplifier or modulator. The anode connection is made to the top of the envelope. (*Courtesy RCA.*)

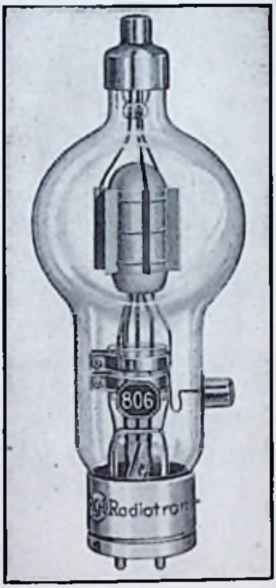

Fig. 3.5. A medium-power transmitting-type triode designed for amplifier and oscillator service. (*Courtesy RCA.*)

In some tubes the grid connection is made to the side of the bulb, as in Fig. 3.5. This is usually a convenience when the tube is used at high frequencies.

Large high-power triodes sometimes have copper anodes designed to be cooled either by forced air or by water. Figure 3.6 shows a typical forced-air-cooled triode, and Fig. 3.7 shows a typical water-cooled tube.

3.2. Electrical Characteristics of Triodes. A circuit suitable for obtaining the electrical characteristics of a triode vacuum tube is shown in Fig. 3.8. The filament circuit is shown dotted but is omitted in many circuit diagrams for the sake of simplicity.

Triodes are never operated under conditions of temperature saturation, *i.e.*, the plate current is limited always by space charge. Hence there is little to be gained by curves showing the variation of currents with variation of cathode temperature. (The temperature of the cathode actually does have a minor influence on the

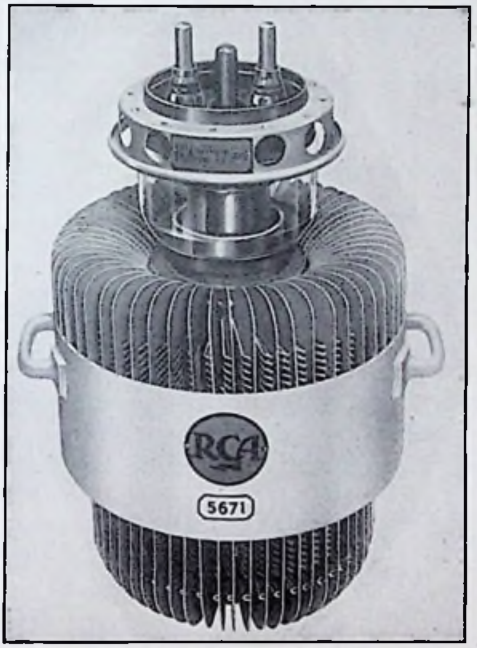

FIG. 3.6. A forced-air-cooled high-power transmitting triode. (*Courtesy RCA.*)

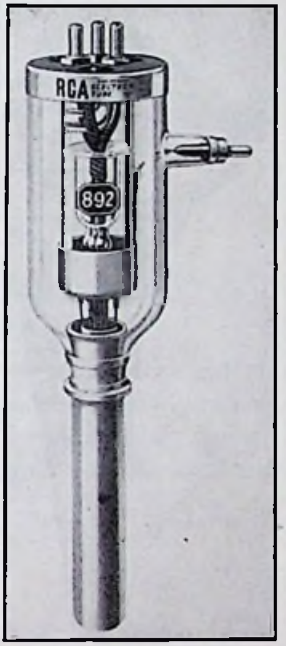

FIG. 3.7. A water-cooled high-power transmitting triode. (*Courtesy RCA.*)

curves, even though the tube is being operated under conditions of voltage saturation. This will be explained in a later section.)

The battery labeled C battery is for the purpose of applying a voltage between the cathode and grid of the tube. The center-tapped potentiometer allows the grid voltage to be made either positive or negative relative to the cathode. The subscript c is used to denote grid values of voltage and current, and the subscript b is used for the plate values, as in the diode.

Plate Characteristics. Suppose we begin by setting the grid voltage e_c at a high negative value relative to the cathode. Under this condition, the grid current i_c should be zero. If the anode voltage e_b is zero, the anode current i_b should also be zero. Now let us

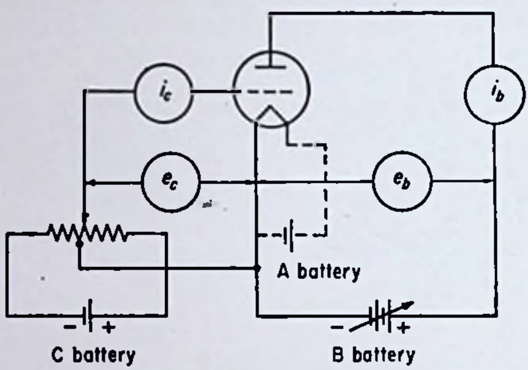

FIG. 3.8. Circuit for obtaining electrical characteristics of a high-vacuum triode.

slowly raise the plate voltage and observe the plate current meter. We should find that the plate current stays at zero until a certain value of plate voltage is reached. Beyond this point, the plate current rises with increasing plate voltage, as shown in Fig. 3.9.

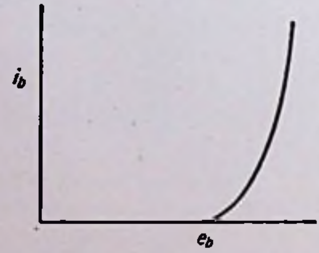

FIG. 3.9. Plate current vs. plate voltage for a triode with a high negative grid voltage.

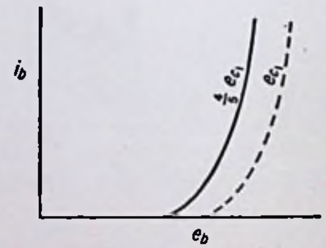

FIG. 3.10. Plate current vs. plate voltage for a lower negative grid voltage.

Now let us reduce the grid voltage to four-fifths of its original value and plot another curve of i_b vs. e_b. This second curve should be similar in shape to the first one, but the plate voltage at which the current begins increasing should be lower than for the first case, as shown in Fig. 3.10. The original curve is dotted in for comparison.

If the grid voltage is lowered in equal steps down to zero and curves of plate current vs. plate voltage taken at each value of grid voltage, the curves should move consecutively to the left until at $e_c = 0$, the curve should pass through the origin. (In some cases the curve does not pass exactly through the origin owing to the contact difference of potential and the initial velocities of the electrons emitted from the cathode.) Figure 3.11 shows a complete set of *plate characteristics*, as they are called, for an actual triode. Curves are shown only for negative grid voltages. In the majority of cases, triodes are operated so that their grids never become positive relative to their cathodes. Under these circumstances the grid current i_c is negligibly small. In some circuits, the

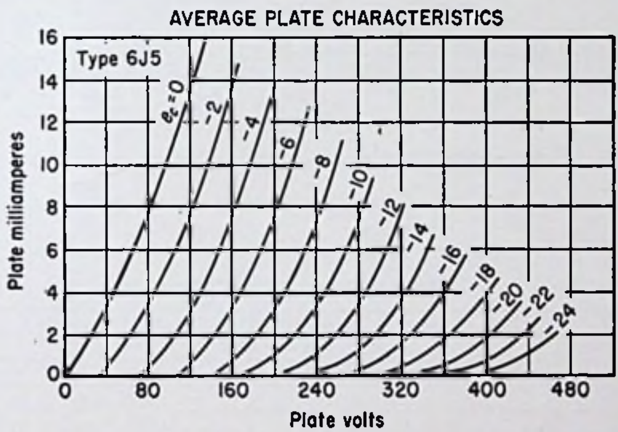

FIG. 3.11. Plate characteristics for a triode at negative grid voltages.

grid is made positive part of the time, however, in which case grid current does flow, so that curves of grid current vs. plate voltage for various values of grid voltage are necessary to specify the electrical characteristics completely.

Figure 3.12 shows the plate characteristics and Fig. 3.13 the corresponding grid-current curves for an actual triode. In some cases, it is more convenient to combine the two curves of Figs. 3.12 and 3.13 in a single graph, as in Fig. 3.14.

Transfer Characteristics. The plate characteristics describe completely the currents in a triode tube as a function of the applied voltages. However, the functions are for certain fixed values of grid voltage only. In some cases it becomes desirable to determine the currents corresponding to any possible value of grid volt-

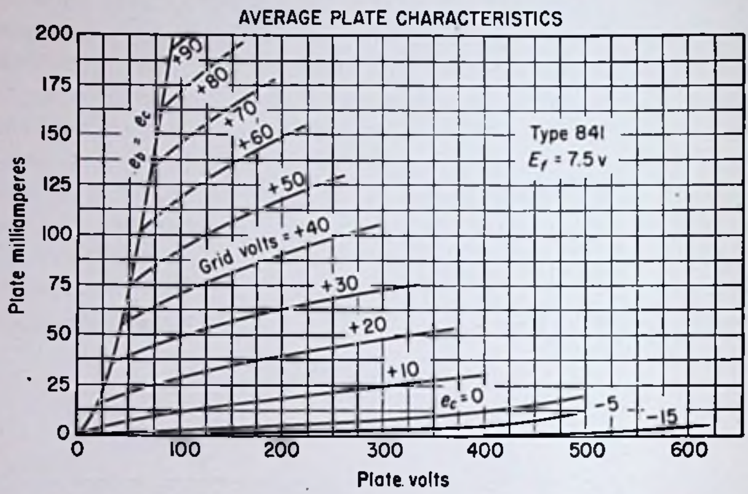

FIG. 3.12. Plate characteristics for both positive and negative grid voltages.

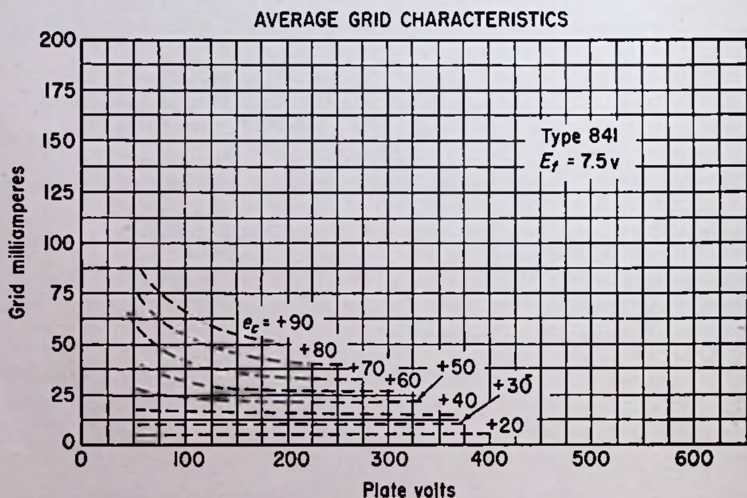

FIG. 3.13. Curves of grid current vs. plate voltage for a triode with various positive grid voltages.

age. This can be done for certain fixed values of plate voltage by means of curves of plate and grid currents vs. grid voltage, called *transfer characteristics.*

Data for the transfer characteristics can be obtained in two ways. The circuit shown in Fig. 3.8 can be used to obtain the data as follows: The plate voltage is set at some high value and held constant as the grid voltage is varied from a high negative value sufficient to reduce the plate current to zero up to as high a positive value as desired. The plate and grid currents are plotted as functions of the grid voltage. The plate voltage is then reduced

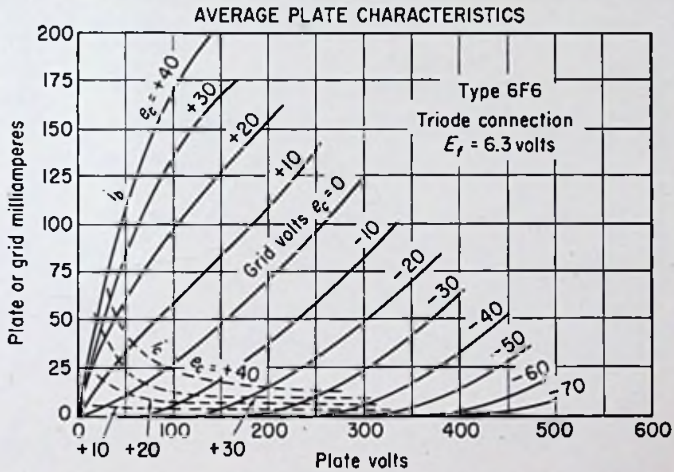

FIG. 3.14. Plate and grid characteristics of a triode tube with positive and negative grid voltages.

in steps to zero, and at each step is held constant while the grid voltage is varied and the plate and grid currents observed. Figure 3.15 shows the transfer characteristics of the tube whose plate characteristics are shown in Fig. 3.14.

It should be noticed that for each value of plate voltage there is a certain value of grid voltage at which the plate current is just reduced to zero. For example, at a plate voltage of 150 volts, Fig. 3.15 shows that the plate current is cut off at a grid voltage of -22 volts. This value of grid voltage is called the cutoff value for obvious reasons. The cutoff grid voltage depends on the plate voltage, being higher for higher plate voltages.

The curves also show that for positive grid voltages the grid current increases rapidly with increase of grid voltage, while the plate current rises less rapidly or even levels off. Some rather peculiar curves are sometimes obtained in the positive-grid-voltage regions of triodes. The reasons for these variations of currents with grid voltage will be discussed in Sec. 3.3.

If the plate characteristics have already been obtained for a given tube, it is not necessary to obtain any additional data in order to plot the transfer characteristics, because the required data can be

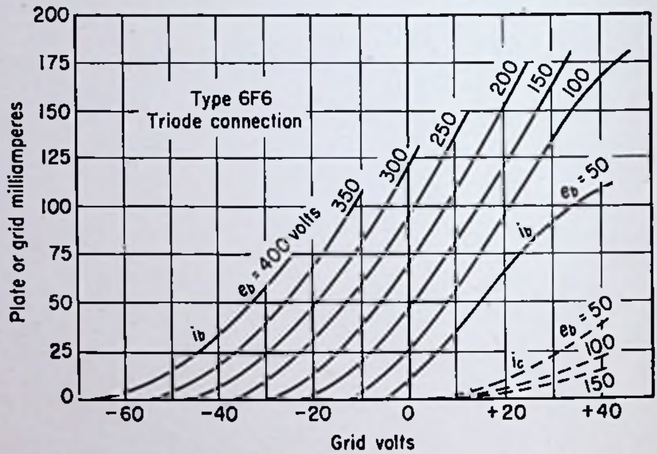

FIG. 3.15. Plate and grid currents as functions of grid voltages for various plate voltages.

secured very easily from the plate characteristic curves, provided a sufficient number of curves for different grid voltages are available. The procedure is to draw a series of vertical lines on the plate characteristics intersecting the abscissa at the plate voltages for which it is desired to obtain the transfer characteristics (refer to Fig. 3.16, which shows one such line and the curve obtained from it). The points of intersection of the vertical line with the i_b-e_b curves for various grid voltages determine values of i_b and e_c for that particular value of plate voltage. The main difficulty with this method is that enough points may not be available at the lower values of plate current to enable an accurate curve to be drawn all the way down to cutoff.

Constant-current Characteristics. Another method of representing the characteristics of a triode is by means of curves showing the variation of plate voltage with grid voltage for various values of constant plate current. Hence these curves are sometimes called *constant-current characteristics.*

Data for plotting the constant-current characteristics can be obtained experimentally using the circuit that was used for obtaining the data for the plate and transfer characteristics. The procedure is as follows: The various values of plate current for which it is desired to obtain the characteristics are first decided upon. Then the plate voltage is set at some high positive value and the grid voltage adjusted until the highest plate current for which it is desired to obtain the characteristics is drawn through the tube. The

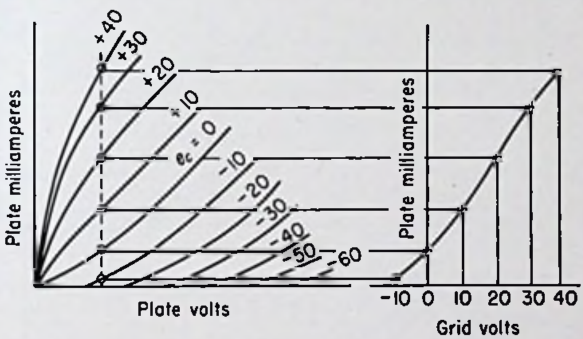

FIG. 3.16. A method of plotting the transfer characteristics from the plate characteristics.

plate voltage is then lowered in steps, and at each step the grid voltage is readjusted so that the same plate current is drawn through the tube as at the original point. After the plate voltage has been reduced to as low a value as practicable, the plate voltage is again set at some high positive value, but this time the grid voltage is adjusted so that the *next-to-the-highest* plate current for which it is desired to obtain the characteristics is drawn through the tube. For example, the highest current might be 100 ma, the next-to-the-highest current might be 90 ma, etc., down to zero. For each constant plate current, the data needed to plot a curve of plate voltage vs. grid voltage are recorded. The resultant constant-current characteristics should resemble the curves shown in Fig. 3.17, which are for the tube whose plate and transfer characteristics have already been given. The grid voltages are plotted

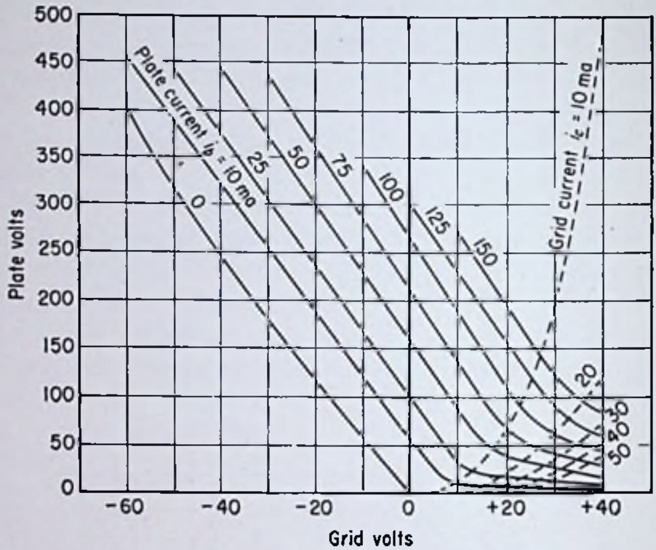

FIG. 3.17. Constant-current characteristics of a high-vacuum triode.

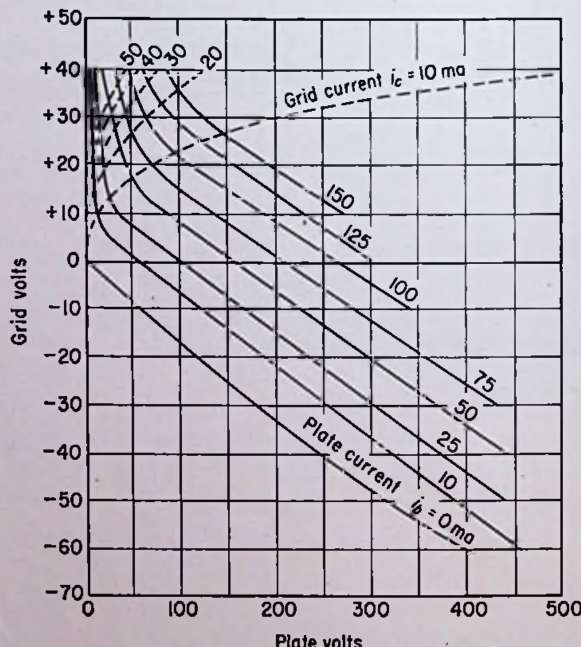

FIG. 3.18. Constant-current characteristics of a triode plotted with the grid voltages rather than the plate voltages as the ordinates.

along the horizontal axis, and the plate voltages along the vertical axis. Different scales are generally used for plate voltage and grid voltage because of the difference in the relative magnitudes involved.

In some cases, the constant-current characteristics are plotted with the plate voltages along the horizontal axis and the grid voltages along the vertical axis. The curves then appear as in Fig. 3.18.

If the plate characteristics of a tube are available, the constant-current characteristics can be plotted without any additional laboratory work. The procedure is similar to the one used in obtaining

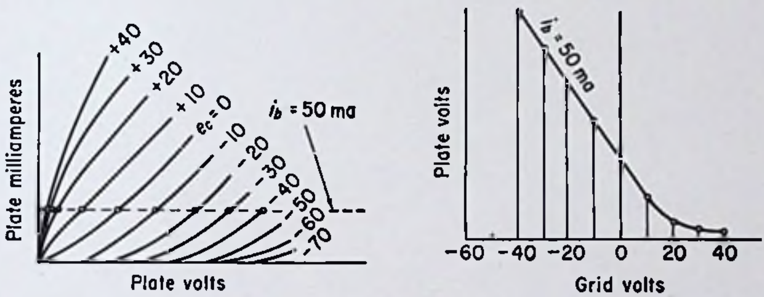

FIG. 3.19. A method of plotting the constant-current characteristics from the plate characteristics of a triode vacuum tube.

data for the transfer characteristics from the plate characteristics, except that in this case a series of horizontal lines are used rather than a series of vertical lines. The horizontal lines are drawn so that they intersect the ordinate at the various values of plate current for which it is desired to obtain the constant-current characteristics. Figure 3.19 illustrates the general procedure. A single horizontal line and the single constant-current curve obtained from it are shown. The intersections of the horizontal line with the various i_b-e_b curves are determined, and the plate voltages corresponding to these points are plotted vs. the grid voltages corresponding to the curves which pass through the same points.

If the transfer characteristics are available instead of the plate characteristics, they can be used just as well in obtaining the data needed to plot the constant-current characteristics. As a matter of fact, *if any one of the three sets of characteristics is available, the other two sets can be obtained therefrom.* For example, if the constant-current characteristics are available, the plate and transfer characteristics can both be determined from the available curves. The reason for this is the fact that each family of curves by itself contains all the information needed to describe the variation of currents with applied voltages.

Tube Coefficients. It should be noticed that none of the characteristic curves of a triode is linear. The curves having the greatest linearity are the constant-current characteristics, these being particularly linear in the negative-grid-voltage regions.

The analysis of circuits containing vacuum tubes is complicated because of the nonlinearity of the tubes' characteristic curves. In many cases, however, an approximate analysis can be made under

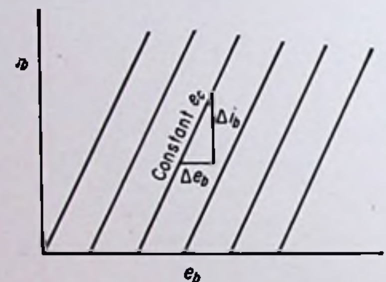

FIG. 3.20. Plate characteristics of an idealized triode.

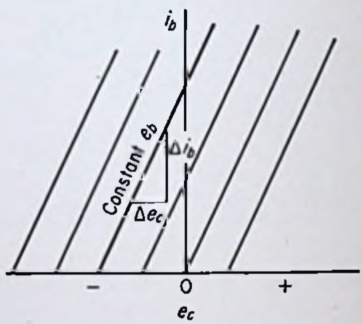

FIG. 3.21. Transfer characteristics of an idealized triode.

the assumption that the characteristic curves are all perfectly linear. In other words, an ideal tube, as far as the analysis of its operation is concerned, is one whose characteristic curves can be represented as in Figs. 3.20 to 3.22.

Although an analysis based on such assumptions is bound to be in error, the error is sometimes so small that the assumptions are fully justified because of the vast saving of time and effort effected thereby.

In many cases, the absolute *magnitudes* of the voltages and currents in a circuit are not so important as the *rates of change* of the quantities with respect to each other. In other words, the most important factors in determining the operating characteristics of tubes in some circuits are the *slopes* of the characteristic curves. Thus it becomes convenient to define three factors, or coefficients, of a tube. Each coefficient is simply the *slope* (or in one case the reciprocal of the slope) of one of the three sets of characteristic curves. Referring to Fig. 3.20, the reciprocal of the slope of the plate characteristic curves is the base of the small right triangle divided by the altitude, or $\Delta e_b/\Delta i_b$. This factor is known as the *dynamic plate resistance* and is denoted by the symbol r_p. (The subscript p stands for plate.) The units for r_p are ohms if Δe_b is expressed in volts and Δi_b in amperes.

In Fig. 3.21, the slope of the transfer curves is $\Delta i_b/\Delta e_c$. This factor is known as the *mutual conductance*, or *transconductance*, as it is sometimes called, the latter word being a composite of the two

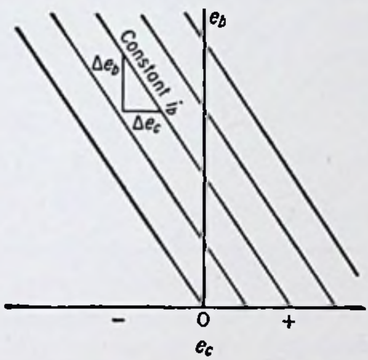

FIG. 3.22. Constant-current characteristics of an idealized triode.

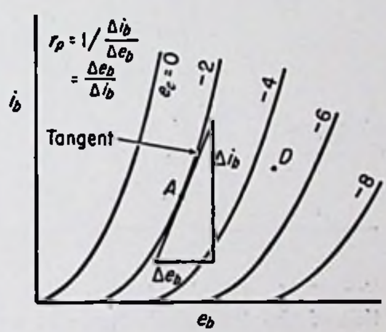

FIG. 3.23. Graphical determination of the dynamic plate resistance of a triode.

words "transfer" and "conductance." The symbol for transconductance is g_m, and the units are mhos if Δi_b is expressed in amperes and Δe_c in volts. (The subscript m in the symbol stands for mutual.) However, in most cases it is more convenient to express the transconductance in micromhos, or μmhos, a micromho being one-millionth of a mho.

Finally, the slope of the constant-current curves of Fig. 3.22 is $\Delta e_b/\Delta e_c$, this factor being known as the *amplification factor*. The symbol is the Greek letter μ, or mu, and this factor, unlike the other two, is simply a dimensionless number.

These three tube factors, or tube coefficients, are constants in the case of the idealized triode of Figs. 3.20 to 3.22. This is because the slopes of the curves are everywhere the same. In an actual tube, however, the slopes of the curves are not constant, but change with the applied potentials. Hence these coefficients cannot be regarded as constants, although this term is sometimes used in the literature.

The plate resistance of an actual triode at any one particular point can be found by constructing a tangent to the i_b-e_b curve at the particular point under consideration and determining the *reciprocal* of the slope of this tangent. For example, in Fig. 3.23, let the plate resistance at the point A be desired. A tangent to the

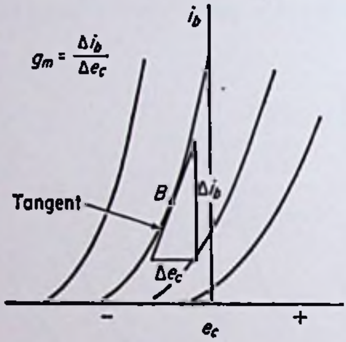

FIG. 3.24. Graphical determination of the transconductance of a triode.

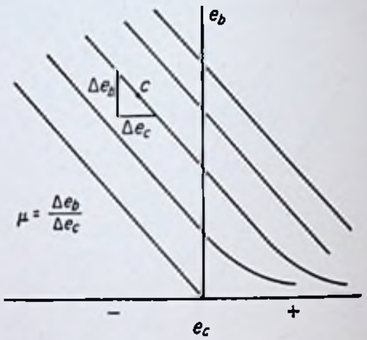

FIG. 3.25. Graphical determination of the amplification factor of a triode.

curve through point A is first drawn. Then the slope of this tangent is determined as for an idealized triode. The *reciprocal* of this slope is the desired plate resistance.

Figure 3.24 illustrates the procedure in determining the transconductance at a point B on one of the transfer curves, and Fig. 3.25 illustrates the procedure in computing the amplification factor at a point C on one of the constant-current curves.

These illustrations are designed principally to clarify the meaning of the tube coefficients. Actual determination of a factor at a particular point may prove to be more difficult than the examples seem to indicate. For instance, suppose the plate resistance at point D in Fig. 3.23 is desired. Or suppose the amplification factor at known grid and plate voltages is to be determined, but the only curves available are the plate characteristics. For these cases special techniques may have to be employed. The actual numerical calculation of tube coefficients will be discussed at length in Sec. 3.4.

Variation of Tube Coefficients with Plate Current. It is interesting and informative to consider how the tube coefficients vary with the plate current of a triode, assuming a constant plate voltage. The variation of plate resistance for any fixed value of plate voltage can be determined by constructing a vertical line on the plate characteristics intersecting the abscissa at the particular plate voltage under consideration. At each intersection of this vertical line with one of the constant-grid-voltage curves, the plate resistance can be determined graphically by the method previously outlined. These values of plate resistance can then be plotted vs. the plate currents corresponding to each of the intersection points used.

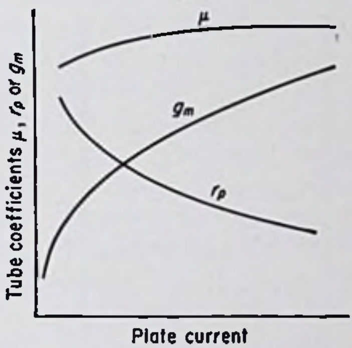

FIG. 3.26. Variations of tube coefficients with plate current at a constant plate voltage for a triode.

The variation of transconductance with plate current for a fixed plate voltage can be determined by selecting points along the transfer curve corresponding to the particular plate voltage under consideration and graphically computing the transconductance at each of the points by the method previously shown. These values of transconductance can then be plotted as a function of the plate currents corresponding to each of the selected points.

The variation of the amplification factor with plate current for a fixed plate voltage can be determined by constructing a horizontal line on the constant-current characteristics intersecting the ordinate at the particular plate voltage under consideration. At each intersection of this horizontal line with one of the constant-current curves, the amplification factor can be determined graphically by the method outlined previously. These values of amplification factor can then be plotted vs. the plate currents corresponding to each of the intersection points used.

Figure 3.26 is a typical example of the variation of r_p, g_m, and μ with plate current for constant plate voltage. It is seen that the amplification factor is fairly constant, decreasing slightly at the lower plate currents. The plate resistance and transconductance both vary considerably, however, the former decreasing and the latter increasing with increasing plate currents.

3.3. Theory of Operation of Triode Vacuum Tubes. Much of the theory needed to explain the behavior of triode vacuum tubes has already been discussed in preceding chapters. For instance, thermionic emission was taken up in Chap. 2. The motion of electrons in electrostatic fields has been briefly discussed in both Chaps. 1 and 2. The important subject of space-charge limitation of the space current flowing in a vacuum tube was discussed for diodes in Chap. 2.

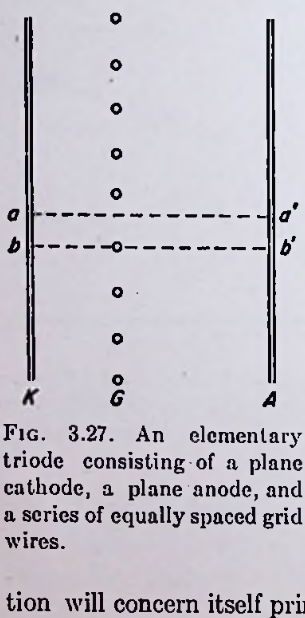

FIG. 3.27. An elementary triode consisting of a plane cathode, a plane anode, and a series of equally spaced grid wires.

In other words, the student at this point should already have a reasonable amount of knowledge concerning triodes merely by having studied the preceding chapters. There are, of course, several new and interesting factors present in the case of a triode which were absent or uninfluential in the case of either a phototube or a thermionic diode. Some of these new factors are responsible for the tremendous importance of triodes as compared with the tubes which have been discussed previously. This section will concern itself principally with these new factors and their influence in determining the characteristic curves of triodes.

An Idealized Triode. Consider an elementary triode composed of a plane cathode and anode separated by a row of parallel, equally spaced grid wires. Such a tube is seldom used in practice, but it serves well to illustrate the general principles involved. Figure 3.27 is a side view of the tube.

The behavior of the electrons emitted from the cathode is more complicated in the case of the triode than in the case of the diode because of the nonuniform potential distribution between the cathode and anode in the vicinity of the grid wires. The average electron emitted at point b in Fig. 3.27 will not behave the same as the average electron emitted at point a. An electron emitted at point a might be expected to be drawn to the positive plate toward the point a'. But an electron emitted at point b is certainly not going to travel a simple straight path toward point b' on the plate.

The motion of an electron emitted from any point on the cathode can be determined if the space potential at every point inside the tube is known. Determination of the space potential at each point is complicated, however, by the effects of space charge, which cannot be neglected if the plate current is to be space-charge-limited. Thus we have the paradoxical situation of the electron motions being determined by the potential distribution, which is determined to a large extent by the space charge, which in turn is controlled by the electron motions, which brings us back to the starting point.

In spite of the apparent difficulties, an understanding of the underlying principles governing the behavior of triodes can be obtained without too much difficulty. The problem can be simplified by noting that the three-dimensional tube of Fig. 3.27 can be reduced to a two-dimensional one. This is because there is no component of flux perpendicular to the paper. All the flux lines traveling between the three electrodes must be parallel to the plane of the paper. Hence an electron will always remain in a plane which is perpendicular to the electrodes (parallel to the plane of the paper), provided we assume that it is emitted from the cathode with no component of velocity perpendicular to the plane of the paper. In other words, an electron emitted from point m in Fig. 3.28 will behave exactly like an electron emitted from point n (provided the above assumptions are made).

Hence it is merely necessary to determine the behavior of electrons in a two-dimensional space such as is illustrated in Fig. 3.29. As a first step assume that the grid is negative and the plate is positive relative to the cathode. Assume furthermore that the grid is negative enough to cut the plate current completely off. With no space current flowing, the space charge is zero, thus making a determination of the potential distribution fairly simple. Such distributions can be obtained analytically, graphically, or mechanically. The mechanical method involves the construction of an electrolytic tank in which is immersed a large model of the vacuum tube. After impressing the correct voltages on the various electrodes, a voltmeter probe is moved about in the electrolyte and the potential at various points determined, usually in conjunction with a bridge circuit. The results of such measurements can be expressed by means of potential contours drawn on a sketch of the tube. A contour map of a vacuum tube is similar to a contour map of a plot of ground, except that the contour lines on the vacuum-tube map are lines of constant electric potential, whereas the contour lines on a map of a plot of ground are lines of constant elevation. Figure 3.30 shows a potential contour map of the

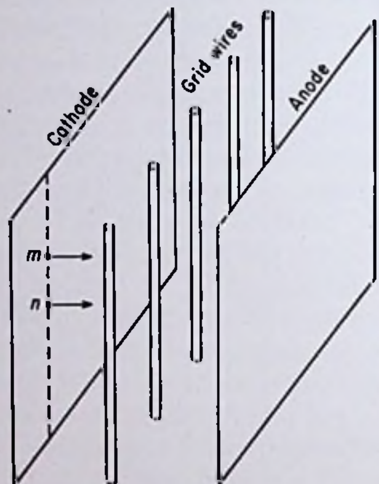

Fig. 3.28. A parallel-plane triode which has symmetry in the vertical direction.

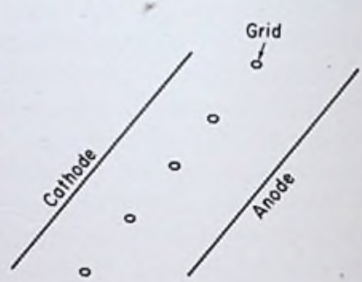

Fig. 3.29. A horizontal section of the tube shown in Fig. 3.28.

triode of Fig. 3.29 with −12 volts on the grid and +100 volts on the plate.

Potential Model of Idealized Triode. In order to visualize the potential distribution in a triode, it may be helpful to build a relief map wherein the elevation of a point is proportional to the potential at that point inside the actual tube. It is convenient to let the elevation of a point on such a map be proportional to the *negative* of its potential relative to the *anode*. In other words, the highest point on the relief map should represent the highest *negative* potential relative to the anode. Figure 3.31 shows a sketch for such a map.

Relief maps such as Fig. 3.31 are not so hypothetical as the student may imagine. They can be and actually are constructed in electronic laboratories for the purpose of studying the paths of electrons in complicated vacuum tubes. The construction of such a map is not too difficult. A piece of thin rubber is tightly stretched on a frame. Blocks of wood shaped like the electrodes are then inserted under the rubber. The height of a given block is made proportional to the negative of the potential on that particular electrode relative to the anode. For example, the map of

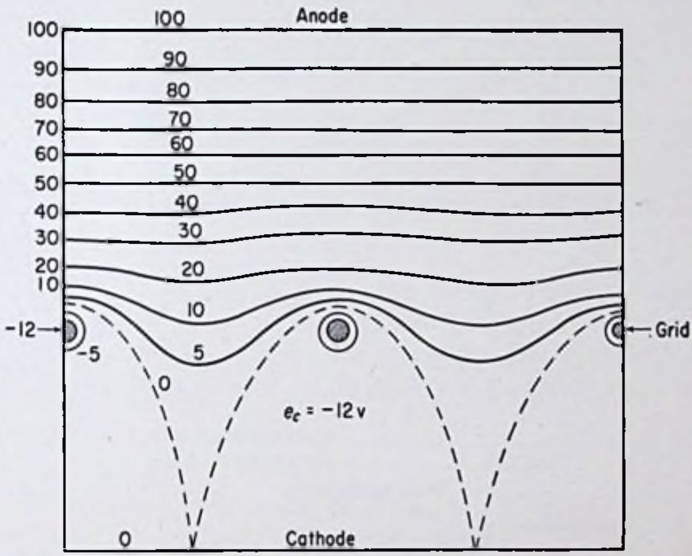

FIG. 3.30. Potential contours for a triode with $e_c = -12$ volts and $e_b = +100$ volts.

Fig. 3.31 could be constructed by using the blocks shown in Fig. 3.32. The blocks in an actual case are designed so that the slope of the rubber at any point does not exceed 6°deg. This is necessary in order to make the resultant map an accurate representation of the potential distribution inside the tube.

Figure 3.31 should be compared to the vacuum-tube models illustrated in Chap. 1. It was shown there that a marble released at the point representing the cathode would behave like an electron released at the actual cathode inside the tube. The same analogy holds for the map in Fig. 3.31. Hence we have a powerful means at our disposal for analyzing the seemingly complicated behavior of triodes.

If a marble is released anywhere at the cathode in Fig. 3.31, it will not be able to climb the hill toward the grid. To be strictly accurate, however, the marble should be given a little push repre-

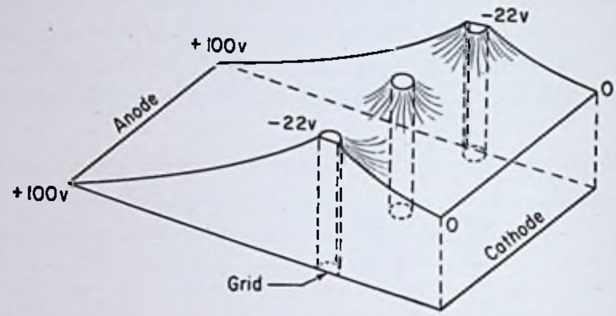

FIG. 3.31. A relief map of the potential distribution of a triode with $e_b = 100$, $e_c = -22$ volts.

senting the initial velocity with which an electron is emitted from the cathode. However, from Fig. 3.31, it can be seen that, for the case illustrated, the energy of the emitted electron must exceed 5 volts or so before it can climb all the way up the grid "hill" and

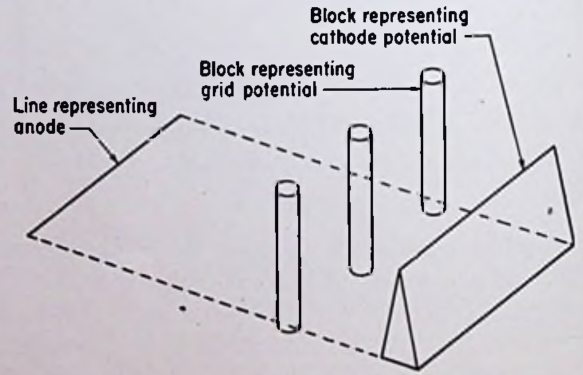

FIG. 3.32. Blocks suitable for use in constructing a rubber model of the potential distribution in a triode.

roll on down to the plate. Under ordinary circumstances, about 90 per cent of the emitted electrons have energies below ½ volt. An extremely small number of electrons have the energy required to overcome the high negative potentials in the vicinity of the grid wires, and hence for the case illustrated in Fig. 3.31, the plate current is essentially zero. In other words, the grid voltage is greater than "cutoff."

There are two ways of allowing the marble to reach the anode in Fig. 3.31. If the anode is made more positive, the potential *between* the grid wires becomes less negative. If the anode voltage is made high enough, the slope of the rubber immediately in front of the cathode can be reduced to zero. This situation is illustrated in Fig. 3.33, which is a side view of the contour map. It should be noted that the slope of the rubber represents the *voltage gradient* inside the actual tube. Hence, the voltage gradient at the cathode surface has been changed from a high negative value to zero.

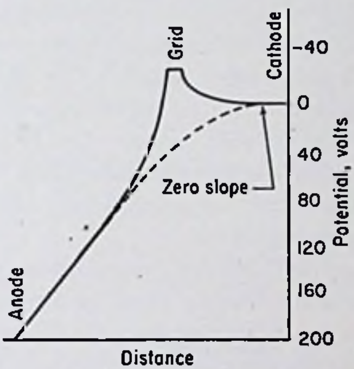

FIG. 3.33. Potential profiles in a triode at cutoff grid voltage.

Note that a marble located at a point on the cathode equidistant from two grid wires will roll all the way to the anode if given the slightest push in that direction. Hence, the condition shown in Fig. 3.33 is approximately the point at which plate current begins flowing in a triode as the plate voltage is made more positive. Actually, plate current begins flowing at a plate voltage slightly less than the value which gives zero voltage gradient at the cathode surface, owing to the initial velocities of the emitted electrons.

As soon as space current begins flowing, the potential distribution becomes modified by the presence of space charge. Were it not for space charge the current flowing in the triode of Fig. 3.33 would equal the full emission current from the cathode. Triodes are never operated under conditions of temperature saturation, however. The cathode is made so hot that it emits more electrons than the tube can draw to the anode with the particular combination of electrode voltages being used. The actual distribution inside a tube hence cannot be that shown in Fig. 3.33 under conditions of space-charge-limited current. The presence of the space charge makes the potential gradient near the cathode slightly negative, so that the space current is limited by the fact that not all electrons are emitted with enough velocity to overcome this negative force field.

Plate Control of Space Current. As the plate voltage is increased, the voltage gradient at the cathode tends to become less negative. This increases the space current, however, which keeps the potential gradient at the cathode negative. The process is exactly the same as for a diode. A curve of plate current vs. plate voltage for a triode at a constant grid voltage is remarkably similar in shape to the corresponding curve for a diode. The presence of the grid in a triode, in other words, does not radically alter the appearance of the i_b-e_b curve from its appearance for a tube without a grid. The chief difference is in the *position* of the i_b-e_b curve on the plate-characteristics graph. The more negative the grid voltage, the farther the i_b-e_b curve is moved over to the right. (This is an oversimplified picture but is sufficiently accurate to enable an understanding of triode action to be obtained.) The above statements hold for *negative* grid voltages. Positive-grid action will be explained later.

Grid Control of Space Current. Instead of making the plate more positive in order to allow current to flow in a triode, the grid can be made *less negative.* As the grid voltage is reduced, the potential *between* the grid wires becomes less negative also, so that by reducing the negative grid voltage sufficiently, the slope of the potential curve in front of the cathode can be made zero. For a grid voltage slightly more negative than the value which gives zero voltage gradient at the cathode surface, space current begins flowing, owing to the initial velocities of the emitted electrons. As the grid voltage is made less negative, the potential gradient at the cathode surface becomes less negative, which allows more of the emitted electrons to pass the potential minimum and travel on to the anode. Space charge, of course, prevents the voltage gradient at the cathode from ever becoming positive. The lower the negative voltage on the grid, however, the greater the space current must be in order to *prevent* the voltage gradient from going positive. Thus the negative voltage on the grid is able to influence the voltage gradient at the cathode surface, which in turn regulates the number of electrons which travel on to the plate.

As long as the grid is negative by more than about ½ volt, very few of the electrons will hit the grid wires. (For voltages less than this, some of the electrons have sufficient kinetic energy upon being emitted to hit the grid wires in spite of their negative polarity.) For high negative grid voltages, the electrons are repelled sufficiently from the grid wires to prevent grid current from flowing. This causes a focusing action of a sort. Figure 3.34 shows the paths of electrons emitted from various points on the virtual cathode. Such paths can be obtained by photographing the motion of marbles released on a rubber-membrane model of the triode.

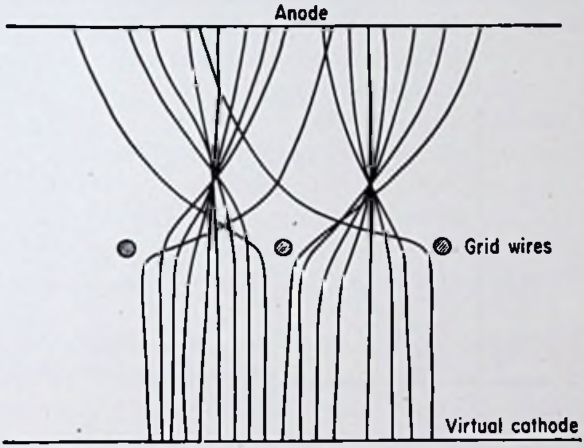

FIG. 3.34. Electron paths in a triode operated with a negative grid voltage.

It should be noted that the space current in a tube with a grid is less than the space current in a tube without a grid, unless the grid is made more positive than the positive potential which would exist at the point at which the grid is inserted in the absence of the grid. This statement is significant because it indicates that a triode is inherently less efficient than a diode having the same anode and cathode dimensions. A larger anode voltage, in other words, is required to draw the same space current through a negative-grid triode than through a diode. If the grid is made positive, the space current can be made higher, but at the expense of having grid current flow. When efficiency is of prime importance, as in class C amplifiers, the grid is made positive during part of the operating cycle.

When efficiency is relatively unimportant, however, the grid is seldom driven positive. Thus the grid is able to control the plate current without itself drawing any appreciable current. It gives the tube a "valve" action. By making the grid negative, the plate current can be stopped. By making the grid less negative, or positive, plate current can be made to flow. The *magnitude* of the grid voltage determines the *magnitude* of the plate current. The British actually use the term "valve" instead of the word "tube."

Secondary-emission Effects in a Triode. When the grid is made positive relative to the cathode, electrons are attracted to the grid wires. Hence, grid current flows, the magnitude of which depends

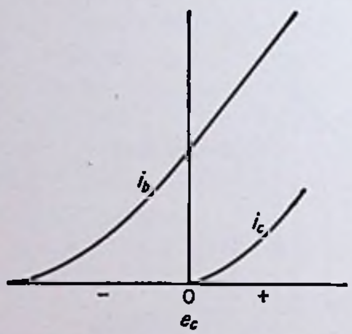

FIG. 3.35. Transfer curves for a tube with no secondary emission.

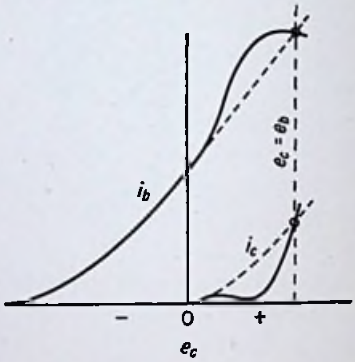

FIG. 3.36. Transfer curves for a tube having appreciable secondary emission.

on the magnitude of the grid-to-cathode voltage. As grid current begins flowing, the magnitude of the plate current is necessarily lessened by the amount of the grid current. For a negative grid, all the space current flowing from the virtual cathode goes to the anode, but for a positive grid, some of the space current flows to the grid, leaving the remainder for the plate.

The transfer characteristics show the plate and grid currents as functions of the grid voltage. It has been mentioned previously that these curves are sometimes peculiar in the positive-grid-voltage regions. A certain phenomenon is responsible for this peculiar behavior. Were it not for this phenomenon, the curves would look something like the curves shown in Fig. 3.35.

An actual tube, however, may have curves which look more like the ones shown in Fig. 3.36. The curves of Fig. 3.35 are dotted in for comparison. The grid current starts increasing at low voltages, but quickly levels off, then *decreases* with increase of positive grid voltage, *and may even go negative.* Further increase of grid voltage brings the grid current back up and causes it to *exceed* its normal value. The plate current does just the opposite of the grid current. While the grid current is decreasing below normal, the plate current is increasing above normal; and while the grid current is increasing, the plate current is decreasing.

The phenomenon responsible for the above behavior is *secondary emission.* Secondary emission is a process whereby electrons in the surface of a metal are given the energy they need to overcome the potential-energy barrier and escape by means of electron bombardment of the surface. Two methods of emission have already been discussed, photoelectric emission and thermionic emission. This third method is very important in the operation not only of triodes, but tetrodes, pentodes, cathode-ray tubes, glow-discharge tubes, and other important electron tubes as well. Hence it is essential that the student obtain a good understanding of this process.

When a high-speed electron bombards the surface of a metal, some of its kinetic energy may be transferred to electrons in the electron gas of the metal or to valence electrons in the atoms near the surface. If the additional energy given to an electron in the metal is great enough, it may have a component of velocity perpendicular to the surface great enough to allow it to leave the metal entirely.

An analogy to the above situation is a bowl of marbles being stirred with a stick. The energy given to the marbles by the stirring action is in itself insufficient to cause them to climb the sides of the dish and leave the bowl. However, if additional marbles were to be thrown into the bowl, the resultant collisions might give some of the marbles in the bowl the extra energy they need to escape. It should be noted that one marble thrown in with a considerable velocity might "splash" out *several* marbles from the bowl. Similarly, one high-speed electron bombarding the surface of a metal might "splash" out several electrons. These electrons which are knocked out of the metal are called "secondary" electrons to distinguish them from the bombarding, or "primary," electrons.

The ratio of secondary to primary electrons depends on the kind of metal, its surface condition, the speed of the primary electrons, and the angle at which the electrons hit the surface. In general, the lower the work function of the surface, the greater the secondary-emission ratio. However, there are exceptions to this rule caused by the rather complicated processes which occur during emission.

Slight impurities on the surface may greatly alter the secondary-emission ratio, usually increasing it. The ratio is usually about unity for pure metals, meaning that, on the average, one electron is emitted for each primary electron.

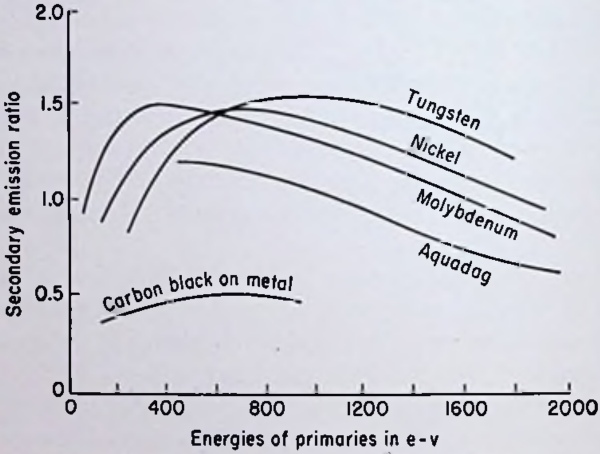

Fig. 3.37. The ratio of the number of secondary electrons to the number of primary electrons plotted as a function of the energy of the primary electrons.

The exact ratio depends on the speed of the bombarding electrons. As the velocity is increased from zero, secondary emission begins at about 10 volts of primary-electron energy. The ratio increases as the primary energy is increased, reaching a maximum at a few hundred volts, and then decreasing for higher energies. Figure 3.37 shows typical curves for several metals.

The secondary-emission ratio increases as the angle at which the electrons hit the surface becomes more nearly grazing. This is probably because more electrons are knocked out of the electron gas of the metal at low angles, whereas most of the electrons emitted at high angles come from the atoms near the surface.

A plausible explanation of the curves shown in Fig. 3.36 can now be given. As the grid is made positive, it becomes bombarded with electrons. Secondary emission from the grid wires occurs, and the resultant secondary electrons are attracted to the plate because it is more positive than the grid. Thus the plate current increases above its normal value, but since electrons are *leaving* the grid, the grid current *decreases*. If the number of secondaries from the grid exceeds the number of primaries, the grid current reverses direction.

As the grid is made more positive, however, it approaches the potential of the plate. As this occurs, fewer of the secondaries from the grid are attracted to the plate, thus increasing the grid current once again. When the grid voltage is made exactly equal to the plate voltage, none of the secondaries will be attracted to the plate, thus making the grid current equal to its normal value in the absence of secondary emission. This last statement is somewhat oversimplified, for it neglects the fact that the plate is also being bombarded by electrons and hence is emitting secondary electrons also. What actually happens, then, is that, when the grid is less positive than the plate, the secondaries from the grid go the plate, and the secondaries from the plate *return* to the plate. When the grid and plate voltages are made equal, the secondaries from the two electrodes are exchanged in about equal amounts, thus making the current flowing to each electrode equal to its normal value in the absence of secondary emission. When the grid is made more positive than the plate, the secondaries from the grid *return* to the grid, and the secondaries from the plate also go to the grid, as the grid is then the most positive electrode in the tube. Hence, for grid voltages higher than the plate voltage, the grid current is higher than normal, and the plate current is lower than normal.

Secondary emission from an electrode can be greatly reduced by coating its surface with some material such as graphite. Proper cleansing and degassing of the metal also aid in keeping down secondary emission. In most tubes, secondary emission is undesirable, and hence precautions such as those described above are necessary. Secondary emission, however, plays an important part in the operation of cathode-ray tubes, glow-discharge tubes, and gas-type phototubes. In the gas phototube, bombardment of the cathode by positive ions created by collision with electrons causes some secondary emission, which contributes to the gas amplification. However, ions are not nearly so effective in producing secondary emission as electrons. Another useful application of secondary emission is in the secondary-emission multiplier tube, wherein minute currents, usually resulting from photoelectric emission, are amplified thousands and even millions of times.

3.4. Mathematical Analysis of Triodes. Experimentally, it is found that the plate current in a triode can be represented by an equation of the form

$$i_b = K_1 \left(e_c + \frac{e_b}{\mu}\right)^{3/2} \tag{1}$$

where K_1 is a constant of proportionality.

If the natural logarithm of both sides of Eq. (1) is taken, the result is

$$\begin{aligned} \ln (i_b) &= \ln K_1 + \frac{3}{2} \ln \left(e_c + \frac{e_b}{\mu}\right) \\ &= K_2 + \frac{3}{2} \ln \left(e_c + \frac{e_b}{\mu}\right) \end{aligned} \tag{2}$$

where K_2 is a new constant $= \ln K_1$.

If the plate current of a triode, as read on a meter in the laboratory, is plotted on log-log paper as a function of the voltage $(e_c + e_b/\mu)$, as computed from the meter readings, the result is very nearly a straight line with a slope of $3/2$, thus verifying Eq. (1). For positive grid voltages, the sum of the grid and plate currents must be plotted against the equivalent voltage $(e_c + e_b/\mu)$ in order to yield a straight line.

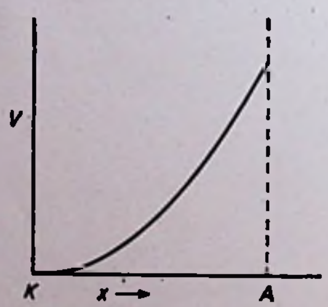

FIG. 3.38. Potential distribution in a parallel-plane diode under conditions of voltage saturation. The initial velocities of the electrons are neglected.

Plate Current in a Parallel-plane Triode. The constant K_1 in Eq. (1) (called the perveance) can be found as follows: If the grid voltage in a triode is made equal to the natural potential at the point of insertion of the grid, the potential distribution inside the tube is the same as for a diode. The natural potential at any point in the case of a parallel-plane diode can be found by solving Eq. (30) in Chap. 2 for the potential V.

$$V = \left(\frac{9\pi i_b}{A}\right)^{2/3} \left(\frac{m}{2Q}\right)^{1/3} x^{4/3} \tag{3}$$

The potential is thus seen to vary as the four-thirds power of the distance from the cathode x. The potential curve in Fig. 2.18 is a plot of Eq. (3). The curve is redrawn in Fig. 3.38 for convenience.

If a grid is inserted at some point between the cathode and anode and the grid voltage adjusted to the value corresponding to Eq. (3), we can write

$$e_c = \left(\frac{9\pi i_b}{A}\right)^{2/3} \left(\frac{m}{2Q}\right)^{1/3} (d_{kg})^{4/3} \tag{4}$$

where d_{kg} is the distance from the cathode to the grid.

When x is equal to d_{kp}, the distance from the cathode to the plate, the potential is equal to the plate voltage e_b. Thus we can write

$$e_b = \left(\frac{9\pi i_b}{A}\right)^{2/3} \left(\frac{m}{2Q}\right)^{1/3} (d_{kp})^{4/3} \tag{5}$$

Substituting Eq. (4) and (5) into Eq. (1) yields

$$i_b = K_1 \left[\left(\frac{9\pi i_b}{A}\right)^{2/3} \left(\frac{m}{2Q}\right)^{1/3}\right]^{3/2} \left(d_{kg}^{4/3} + \frac{d_{kp}^{4/3}}{\mu}\right)^{3/2} \tag{6}$$

Solving for K_1 yields

$$K_1 = \frac{A}{9\pi} \sqrt{\frac{2Q}{m}} \left(d_{kg}^{4/3} + \frac{d_{kp}^{4/3}}{\mu}\right)^{-3/2} \tag{7}$$

Substituting for K_1 in Eq. (1) gives

$$i_b = \frac{A}{9\pi} \sqrt{\frac{2Q}{m}} \left(d_{kg}^{4/3} + \frac{d_{kp}^{4/3}}{\mu}\right)^{-3/2} \left(e_c + \frac{e_b}{\mu}\right)^{3/2} \tag{8}$$

Equation (8) has been derived in the cgs electrostatic system of units. In practical units, the equation becomes

$$i_b = \frac{(2.34 \times 10^{-6})A \left(e_c + \dfrac{e_b}{\mu}\right)^{3/2}}{\left(d_{kg}^{4/3} + \dfrac{d_{kp}^{4/3}}{\mu}\right)^{3/2}} \quad \text{amp} \tag{9}$$

where the voltages are expressed in volts and the distances in the same units as for the area.

Example:

A parallel-plane triode has an amplification factor of 20. If the spacing between cathode and grid is 0.2 cm, and between cathode and plate 0.5 cm, find the plate current for a plate voltage of 150 volts and a grid voltage of -5 volts. The area of both the cathode and the plate is 4 cm².

Solution:

$$i_b = \frac{(2.34 \times 10^{-6})(4)(-5 + {}^{150}\!/_{20})^{3/2}}{\{(0.2)^{4/3} + [(0.5)^{4/3}/20]\}^{3/2}}$$

$$= 0.7275 \times 10^{-3} \text{ amp}$$

$$= 0.7275 \text{ ma} \quad \textit{Ans.}$$

The low value of plate current obtained in the above example should be noted. Even if the grid voltage were made zero, the plate current would still be only about 3.78 ma. It is interesting to see how much current would flow in a diode having the same cathode-to-plate spacing and the same electrode areas. Substitution of the above values into Eq. (33) of Chap. 2 gives a diode plate current of 67.8 ma with 150 volts on the plate. Thus it is clear that a heavy price is paid for the advantage of being able to control the space current by means of a grid. The heavy price is the greatly reduced plate current obtained for a given plate voltage.

Plate Current in a Cylindrical Triode. Very few actual triodes are of the parallel-plane type. Many triodes have electrodes which are circular cylinders, however. An analysis for cylindrical electrodes yields the following equation for the plate current in terms of the dimensions of the tube:

$$i_b = \frac{(14.67 \times 10^{-6})l(e_c + e_b/\mu)^{3/2}}{[(r_g\gamma_g)^{2/3} + (r\gamma)^{2/3}/\mu]^{3/2}} \tag{10}$$

where r_g is the grid radius, γ_g is a factor determined by the ratio r_g/r_k, and the other quantities are as defined for Eq. (34) in Chap. 2. Figure 2.27 can be used to determine γ_g in the same manner as for γ.

Example:

A certain triode with cylindrical electrodes has the following dimensions:

	In.
Cathode radius	0.015
Grid radius	0.15
Plate radius	0.4
Length of all electrodes	1.2

If the amplification factor is 30 and the plate and grid potentials are 180 and -2 volts, respectively, calculate the plate current.

Solution:

$$\frac{r}{r_k} = \frac{0.4}{0.015} = 26.7$$

$$\frac{r_g}{r_k} = \frac{0.15}{0.015} = 10$$

From Fig. 2.28, $\gamma = 1.08$ and $\gamma_g = 0.98$.

$$i_b = \frac{(14.67 \times 10^{-6})l(e_c + e_b/\mu)^{3/2}}{[(r_g\gamma_g)^{2/3} + (r\gamma)^{2/3}/\mu]^{3/2}}$$

$$= \frac{(14.67 \times 10^{-6})(1.2)(-2 + 180/30)^{3/2}}{[(0.15 \times 0.98)^{2/3} + (0.4 \times 1.08)^{2/3}/30]^{3/2}}$$

$$= 0.866 \text{ ma} \quad \textit{Ans.}$$

It is informative to compare this value with the current flowing in a diode having the same cathode and anode dimensions and the same plate voltage. From Eq. (34) in Chap. 2 this is found to be 98.5 ma, over 100 times the triode current!

Cutoff Grid Voltage. Equation (1) allows us to calculate the cutoff grid voltage for any particular plate voltage. Setting i_b equal to zero gives

$$e_c + \frac{e_b}{\mu} = 0$$

$$e_c = -\frac{e_b}{\mu} \tag{11}$$

Example:

Calculate the cutoff grid voltage of a triode which has 150 volts on the plate if the amplification factor is 20.

Solution:

$$e_c = -\frac{e_b}{\mu}$$
$$= -\frac{150}{20}$$
$$= -7.5 \text{ volts} \quad \textit{Ans.}$$

If a tube having the specifications called for in the example were actually built and the cutoff grid voltage measured in the laboratory for 150 volts on the plate, the chances are the voltage would be *greater* than -7.5 volts. It might possibly be -8 or -9 volts. In fact, the exact cutoff point is rather indeterminate. As the voltage is made more and more negative, the plate current becomes smaller and smaller. The reason for the error in Eq. (11) lies in the fact that the initial velocities of the electrons coming from the virtual cathode were neglected in deriving the equation. The velocities of the electrons range all the way from zero up to several volts. The low-speed electrons are stopped first, and then, as the grid voltage is made more and more negative, faster electrons are prevented from passing the plane of the grid wires. Thus, cutoff is a gradual process rather than a sharp one. The transfer characteristic curves of a triode illustrate this point well, as shown in Fig. 3.39.

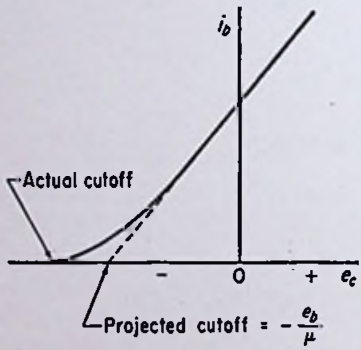

FIG. 3.39. Transfer curve illustrating the effect of initial electron velocities.

Another reason for the gradual cutoff is to be found in irregularities in the grid-wire spacing or in the grid-to-cathode spacing. If such irregularities exist, one portion of the grid may cut off the plate current through that portion of the grid at a different grid voltage from some other portion of the grid. Hence, geometrical tolerances should be held to a close value if sharp cutoff is desired (see Sec. 4.2).

The value of cutoff grid voltage calculated from Eq. (11) is called the *projected* cutoff grid voltage. The name stems from the fact that if the straight-line portion of the transfer curve in Fig. 3.39 is extended or projected, it intersects the abscissa at the value of grid voltage calculated from the equation.

Influence of Tube Geometry on Tube Coefficients. It is possible to derive equations for the amplification factor, plate resistance, and transconductance of a triode from the geometric dimensions of the tube. Such equations are fairly complex, however, and are used principally in the early stages of vacuum-tube design. The average engineer seldom has need to use the equations. It is instructive to consider some of the general conclusions which can be drawn from the equations. These may be summarized as follows:

1. The amplification factor increases as the spacing between the grid and plate is made larger.

2. The amplification factor increases as the diameter of the grid wires is increased.

3. The amplification factor increases as the spacing between the grid wires is *decreased.*

4. The amplification factor is independent of the spacing between the cathode and grid.

5. The transconductance increases as the spacing between the cathode and grid is *decreased.* (From item 4 notice that μ is independent of the cathode-grid spacing.)

6. The transconductance increases slightly as the ratio of the spacing between cathode and plate to the spacing between cathode and grid is *decreased.*

7. The transconductance increases with the one-third power of the plate current.

8. The transconductance increases as the equivalent voltage $(e_c + e_b/\mu)$ is increased.

9. The plate resistance is directly proportional to the amplification factor and inversely proportional to the transconductance.

Interrelation of Tube Coefficients. As has been pointed out previously, the tube coefficients can be calculated from the characteristic curves of the tube. Before proceeding with a thorough discussion of this subject, however, it is advisable at this point to give rigorous mathematical definitions of the three coefficients. The necessary equations can be written down immediately, because each tube factor has been related to the slope of one of the three sets of characteristic curves. Thus, the plate resistance at any point is the reciprocal of the slope of the plate characteristic curve at the point in question. Or stated mathematically,

$$r_p = \left(\frac{1}{\partial i_b/\partial e_b}\right)_{\text{constant } e_c} \tag{12}$$

The transconductance at any point is the slope of the transfer curve at the point in question. Stated mathematically,

$$g_m = \left(\frac{\partial i_b}{\partial e_c}\right)_{\text{constant } e_b} \tag{13}$$

The amplification factor at any point is the slope of the constant-current curve at the point in question. Stated mathematically,

$$\mu = -\left(\frac{\partial e_b}{\partial e_c}\right)_{\text{constant } i_b} \tag{14}$$

The plate current depends on both the grid and plate potentials. Thus a *change* in plate current may be expressed as the *rate* of change of the plate current with respect to the grid voltage *multiplied* by the change in grid voltage, *plus* the *rate* of change of the plate current with respect to the plate voltage *multiplied* by the change in plate voltage. Or stated mathematically,

$$di_b = \left(\frac{\partial i_b}{\partial e_c}\right) de_c + \left(\frac{\partial i_b}{\partial e_b}\right) de_b \tag{15}$$

Equation (15) can also be written as

$$di_b = g_m\, de_c + \frac{1}{r_p}\, de_b \tag{16}$$

If the change in plate current, di_b, is zero,

$$g_m\, de_c = -\frac{1}{r_p}\, de_b \tag{17}$$

Dividing both sides of the equation by de_c gives

$$g_m = -\frac{1}{r_p}\left(\frac{de_b}{de_c}\right)_{\text{constant } i_b} \tag{18}$$

Since $-(de_b/de_c)_{\text{constant } i_b}$ has already been defined as the amplification factor of the tube,

$$\mu = r_p g_m \tag{19}$$

The minus sign in front of Eq. (14) is necessary in order to make the amplification factor come out positive, since $\partial e_b/\partial e_c$ is negative in itself.

Example:

The type 6J5 triode has an amplification factor of 20 and a transconductance of 2,600 μmhos under typical conditions of operation. Find its plate resistance at this particular operating point.

Solution:

$$\begin{aligned} r_p &= \frac{\mu}{g_m} \\ &= \frac{20}{(2{,}600)(10^{-6})} \\ &= 7{,}690 \text{ ohms} \quad \textit{Ans.} \end{aligned}$$

The student should be cautioned against using the plate resistance in Ohm's law to calculate the plate current from the plate voltage. The plate current is *not* equal to the plate voltage divided by the plate resistance r_p. The reason for this is that the plate resistance r_p is a *dynamic* plate resistance and not a *static* plate resistance. The plate voltage divided by the plate current gives what might be termed the *static* resistance of the tube. But the dynamic plate resistance r_p is the ratio of an *incremental change* in plate voltage divided by the accompanying *incremental change* in plate current, for a constant grid voltage. The dynamic plate resistance enters into the analysis and design of many different electronic circuits, such as amplifiers, oscillators, and modulators. It is exceedingly important that the student obtain a clear understanding of the dynamic plate resistance, as distinguished from the static plate resistance. Unless otherwise specifically stated, the term "plate resistance" refers to the dynamic plate resistance and *not* the static resistance of the tube.

Graphical Determination of Tube Coefficients. The three tube coefficients can be graphically determined from any one of the three sets of characteristic curves. The accuracy of the results obtained by these methods depends on the accuracy with which the curves have been plotted, on the *size* of the curves, and on the manner in which the values are computed. Under ordinary circumstances, the accuracy is sufficient for all ordinary electronic engineering purposes. Another consideration is the fact that ordinary mass-produced tubes may vary somewhat in individual characteristics, even from the same manufacturer and assembly line. Thus, unless the characteristic curves are taken in the laboratory from the exact tube that is to be used, the resulting tube coefficients are *approximate* values. In other words, the errors involved in making graphical computations from characteristic curves *can* be made less than the probable errors involved in using *average* characteristic curves for a particular tube.

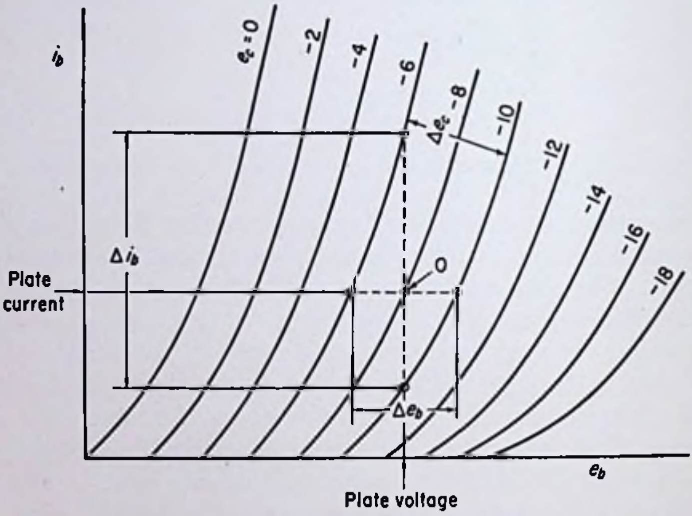

FIG. 3.40. Determination of the tube factors from the plate characteristics.

Figure 3.40 shows the method of computing the three coefficients from the plate characteristics. This method assumes that the operating point lies on one of the curves. The operating point is first determined by the intersection of the grid-voltage curve with either a horizontal line from the given plate current or a vertical line from the given plate voltage (point O in Fig. 3.40). Then horizontal and vertical lines are drawn through the operating point until they intersect the adjacent grid-voltage curves. These are the dotted lines shown in Fig. 3.40. The quantities Δi_b, Δe_b, and Δe_c, which are self-explanatory from the figure, are then determined. The desired coefficients can be found from the following equations,

$$r_p = \frac{\Delta e_b}{\Delta i_b} \tag{20}$$

$$g_m = \frac{\Delta i_b}{\Delta e_c} \tag{21}$$

$$\mu = \frac{\Delta e_b}{\Delta e_c} \tag{22}$$

More accurate results can probably be obtained, however, by proceeding as follows: Calculate the plate resistance by drawing a tangent to the curve at the operating point. Calculate its slope in amperes per volt. The reciprocal of this value is the plate resistance. Find the amplification factor as indicated above. Then *calculate* the transconductance from Eq. (19).

The procedure just given does not involve the quantity Δi_b, which in most cases would probably be too large an increment of current unless the curves are very close together. A fairly large increment of plate voltage Δe_b can ordinarily be used because the curves are very nearly parallel and equally spaced along a horizontal line.

If the operating point does not fall on one of the grid-voltage curves, there are two procedures which can be followed. A curve can be sketched through the operating point and the factors calculated as previously shown. A more desirable plan might be to draw a horizontal line through the operating point until it intersects the two grid-voltage curves on either side. The plate resistance at each of these two points should then be calculated by the slope method. Then the plate resistance at the operating point should be determined by interpolation. The amplification factor should be determined at the *closest* of the two points to the actual operating point (or interpolated between the two points as for the plate resistance). The transconductance should then be calculated from Eq. (19).

Figure 3.41 shows the method of computing the tube coefficients from the transfer characteristics. The operating point O is first determined. Horizontal and vertical lines through O allow determination of Δe_b, Δi_b, and Δe_c. The coefficients can then be calculated from Eqs. (20) to (22). Alternatively, the transconductance can be determined by the slope method, the amplification factor computed in the ordinary manner, and the plate resistance calculated from Eq. (19).

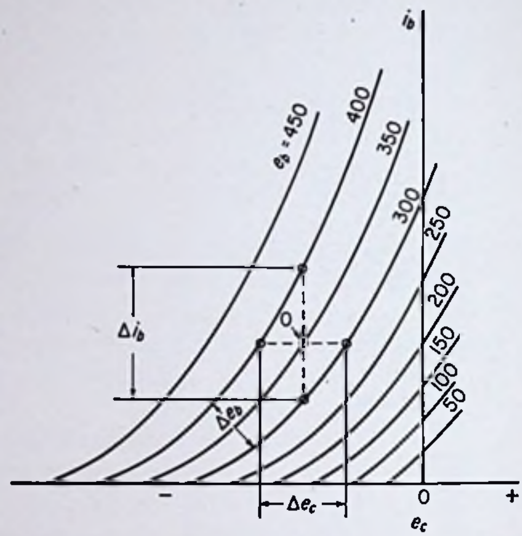

FIG. 3.41. Determination of the tube factors from the transfer characteristics.

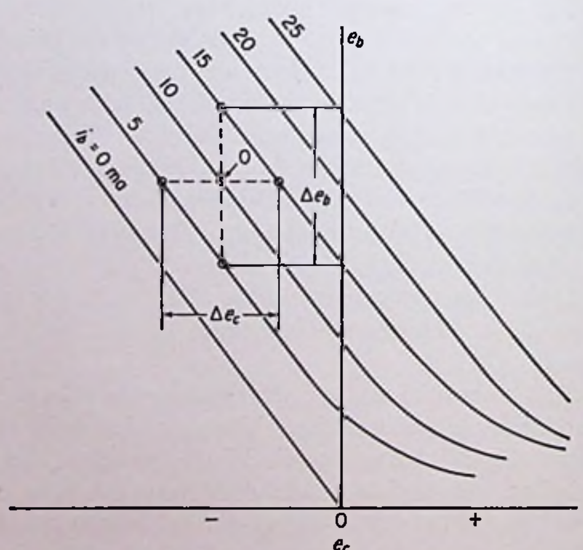

FIG. 3.42. Determination of the tube factors from the constant-current characteristics.

If the operating point does not lie on one of the plate-voltage curves, an interpolation procedure similar in principle to the one outlined for the plate characteristic curves should be followed.

Figure 3.42 shows the manner of computing the tube coefficients from the constant-current characteristics. The operating point O is determined as before, followed by a determination of the three increments Δe_b, Δi_b, and Δe_c. Equations (20) to (22) can be used as before to calculate the desired factors. Alternatively, the amplification factor can be determined by the slope method, either the transconductance or the plate resistance determined as indicated above, and the remaining factor calculated from Eq. (19).

PROBLEMS

1. Calculate the perveance [K_1 in Eq. (1)] of a parallel-plane triode having the following dimensions: spacing between cathode and plate, 0.25 in.; spacing between cathode and grid, 0.1 in.; cathode and plate both 1 in. square; and $\mu = 15$. Express the answer in amperes per volt to the three-halves power.

2. Calculate the plate current flowing in a cylindrical-electrode triode for grid and plate potentials of -40 and 1000 volts, respectively. The amplification factor is 7.5 and the dimensions are as follows:

	In.
Radius of cathode	0.04
Radius of grid	0.25
Radius of plate	0.50
Length of elements	2.3

3. Calculate the perveance of a type 304TH triode using the characteristic curves supplied by your instructor. The amplification factor of this tube is 20. Check it at three or four different points on the curves and compare the results.

4. Find the plate current in a tube having two plates and two grids disposed symmetrically on either side of a plane cathode. The dimensions of the plates and of the cathode are 1 by 2 in. The cathode-to-plate spacings are 0.65 in., and the cathode-to-grid spacings are 0.3 in. The amplification factor of the tube is 10, and the plate and grid voltages are 750 and -20 volts, respectively.

5. Calculate the perveance of a type 6J5 triode using the characteristic curves supplied by your instructor. Use a plate voltage of 150 volts and a grid voltage of -3 volts. Assume $\mu = 20$. What is the equation for the plate current in this tube as a function of the grid and plate potentials?

6. From the plate-current equation found in Prob. 4, calculate the transconductance and plate resistance of the type 6J5 triode at the operating point used in Prob. 4.

7. Calculate the projected cutoff grid voltage for a type 2A3 triode at plate voltages of 100, 200, and 300 volts. Assume $\mu = 4.2$. Check the calculated values by referring to the transfer curves for this tube supplied by your instructor.

8. From the plate characteristics for a type 6J5 triode supplied by your instructor, graphically compute μ, r_p, and g_m at plate and grid voltages of 150 and -3 volts, respectively. If Prob. 5 has been worked, compare the answers with the ones obtained there.

9. From the transfer characteristics for a type 2A3 triode supplied by your instructor, graphically compute μ, r_p, and g_m at plate and grid voltages of 250 and -40 volts, respectively.

10. From the constant-current characteristics of a type 304TH triode supplied by your instructor, graphically compute μ, r_p, and g_m at plate and grid voltages of 2,000 and -50 volts, respectively.

11. From the plate characteristics of a type 841 triode supplied by your instructor, plot transfer curves for $e_b = 200$, 400, and 600 volts. Plot grid current as well as plate current vs. grid voltage.

12. From the constant-current characteristics of a type 304TH triode supplied by your instructor, plot transfer curves for $e_b = 1{,}000$, 2,000 and 3,000 volts. Plot grid current as well as plate current vs. grid voltage.

13. From the plate characteristics of a type 833 triode supplied by your instructor, plot constant-current curves for $i_b = 200$, 400, and 600 ma.

14. From the transfer characteristics of a type 2A3 triode supplied by your instructor, plot e_b-i_b curves for $e_c = 0$, -20, -40, and -60 volts.

15. Compute the three tube coefficients of a type 833 triode at a sufficient number of points to enable curves of the three factors to be plotted vs. plate current at a constant plate voltage of 1,500 volts. Plot the curves starting all the scales at zero.

16. Explain why the amplification factor of a triode is independent of the grid-to-cathode spacing, whereas the transconductance depends to a large degree upon this spacing.

17. A certain tube has tube coefficients as follows: $\mu = 40$, $g_m = 2{,}000$ μmhos, and $r_p = 20{,}000$ ohms. If the plate current is to go *up* 0.2 ma when the grid voltage is increased 1 volt in the negative direction, in what direction and how much must the plate voltage be changed? (Assume the tube coefficients stay constant.)

18. A certain tube has an amplification factor of 12.5 and a transconductance of 600 μmhos. If the grid voltage is made *less* negative by 4 volts and the plate voltage *lowered* 60 volts, in what direction and how much does the plate current change? (Assume the tube factors remain constant.)

19. A certain tube has a dynamic plate resistance of 50,000 ohms. When the plate voltage is increased 100 volts, the grid voltage has to be increased 5 volts in the negative direction to bring the current back to its original value. What is the transconductance of the tube in micromhos?

20. A type 304TH triode has a rated maximum plate dissipation of 300 watts. The tube is to be used in a circuit with a voltage of 3,000 volts on the plate. If the only active voltage between the grid and cathode is the grid-voltage battery, how much voltage should this battery have in order to limit the plate dissipation to its rated maximum value? (Consult the characteristic curves supplied by your instructor. Neglect filament heating power in the calculations.)

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CHAPTER 4

TETRODES AND PENTODES

DESPITE their great importance and versatility, triode vacuum tubes give poor performance in many circuit applications. Specifically, the high grid-to-plate interelectrode capacitance provides a source of coupling between the grid and plate circuits. In many circuits this coupling causes instability and even oscillation. If an electrostatic shield, called the screen grid, is inserted between the control grid and plate, the undesired coupling can be greatly minimized. Difficulties with this new tube, known as the screen-grid tetrode, led to the development of the five-element tube, or pentode. Not only does the pentode permit a high degree of isolation between grid and plate circuits, but in many amplifier circuits greater amplification can be obtained using pentodes. The amplification of high-frequency signals in radio receivers is achieved almost exclusively with pentodes. Other important uses include power amplification of audio- and radio-frequency signals when small or moderate amounts of power are involved.

4.1. Physical Characteristics of Tetrodes and Pentodes. *Structure of Tetrodes.* The tetrode, or more precisely the screen-grid tetrode, is a four-element tube consisting of a cathode, an anode, a grid located adjacent to the cathode, called the *control* grid, or simply the grid, and a grid located between the control grid and anode, called the *screen* grid, or simply the screen. The tetrode is seldom used now because of its undesirable characteristics, except in a special form known as the beam-power tube (see Chap. 5). However, it will be discussed because a complete understanding of the operation of pentode tubes requires a knowledge of the limitations of tetrodes.

Figure 4.1 is a cutaway sketch of a screen-grid tetrode. It can be seen that the only difference between the screen-grid tetrode and the triode lies in the insertion of an additional grid, the screen grid, between the control grid and anode, the purpose being to shield the control grid electrostatically from the plate. In many cases the control grid was connected to the top of the bulb in order to minimize the grid-plate capacitance. In addition, a skirt was sometimes placed on the screen grid, almost totally enclosing the anode, as in Fig. 4.2.

The symbol for a screen-grid tetrode is shown in Fig. 4.1. The symbol is the same as for a triode with the exception of the additional dotted line between the control grid and anode representing the screen grid. The grids in a multigrid tube are customarily numbered in order starting from the cathode. Thus G_1 signifies

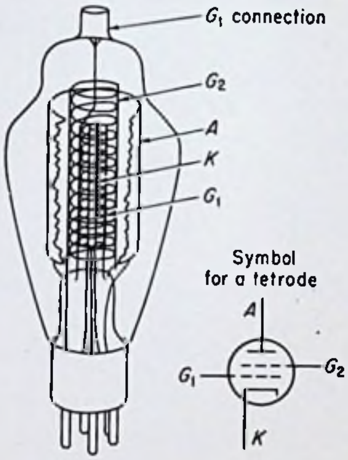

FIG. 4.1. Construction of a screen-grid tetrode.

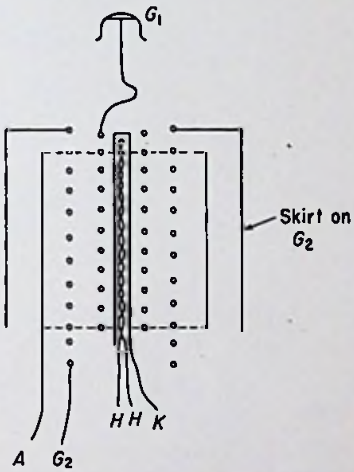

FIG. 4.2. Sectional sketch of a screen-grid tetrode showing the means of reducing the grid-to-plate capacitance.

the first grid from the cathode, G_2 the second grid from the cathode, etc.

Screen-grid tetrodes have been built in sizes ranging from the small receiving-type tubes up to large sizes suitable for handling several hundred watts of power. Such tubes are virtually obsolete now, however, having been replaced by either pentodes or beam-power tetrodes. About the only noteworthy feature of the screen-grid tetrode was the special treatment given to the electrodes to reduce secondary emission. As will be seen shortly, secondary emission proved to be the downfall of the screen-grid tetrode.

Structure of Pentodes. The pentode is a five-element tube consisting of a cathode surrounded by a control grid surrounded by a screen grid surrounded by a *suppressor* grid, or simply suppressor, surrounded by an anode. Thus the only difference between a pentode and a screen-grid tetrode is the extra grid, the suppressor, located between the screen grid and anode. This additional grid is responsible for the improvement in characteristics of the pentode over the tetrode.

Figure 4.3 is a sectional view of the elements of a pentode. The suppressor grid is ordinarily coarser than either the control grid

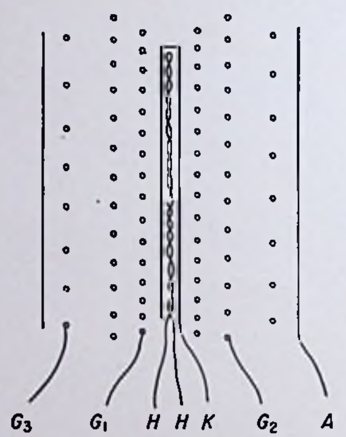

FIG. 4.3. A sectional sketch of a pentode. G_1 is the control grid; G_2 is the screen grid; and G_3 is the suppressor grid.

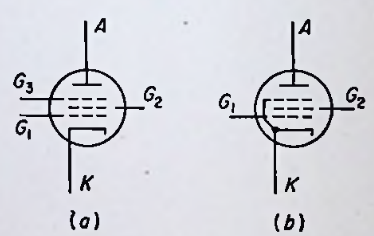

FIG. 4.4. Symbols for pentodes: (*a*) external suppressor-grid connection, (*b*) internal suppressor-grid connection.

or the screen grid and is generally placed very close to the anode. The suppressor grid in some tubes is connected internally to the cathode, as shown in Fig. 4.4(*b*), but in other tubes is brought out to a base pin for an external connection, as in Fig. 4.4(*a*).

Some pentodes are constructed with special attention paid to the minimizing of grid-to-plate capacitance. Internal shields are placed in the tube between the control-grid and plate leads. Metal envelopes are sometimes used, in which case the metal shell is grounded. Glass tubes can be enclosed in small metal cylinders to provide external shielding. Adequate shielding permits the tubes to be used at high frequencies without the need for special circuits and adjustments, which would otherwise be necessary to

FIG. 4.5. A miniature pentode designed for television amplifier service. (*Courtesy RCA.*)

FIG. 4.6. A metal-envelope pentode designed for radio-frequency voltage-amplifier service. (*Courtesy RCA.*)

FIG. 4.7. A low-power transmitter pentode designed for oscillator and amplifier service. (*Courtesy RCA.*)

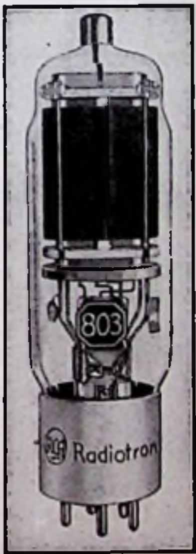

FIG. 4.8. A large transmitter pentode designed for oscillator and amplifier service. (*Courtesy RCA.*)

prevent instability and possible oscillation. (Oscillation is a process whereby a vacuum tube converts d-c energy into a-c energy. In most circuits this process interferes with the normal functioning of the tube and is very objectionable.)

On the other hand, some pentodes are not designed specifically for high-frequency service, and more attention is paid to some other aspect of the tube's characteristics. For example, tubes to be used as audio power amplifiers are designed so that a maximum amount of audio power output can be obtained with a minimum of distortion.

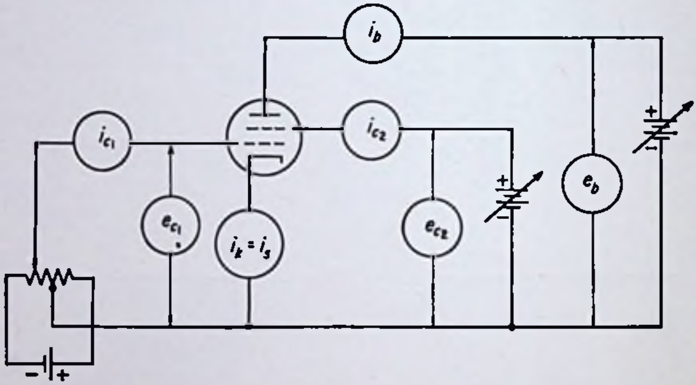

FIG. 4.9. Basic circuit for a screen-grid tetrode.

Figures 4.5 to 4.8 illustrate the general appearance of several pentodes, each of which is designed principally for some specific application.

4.2. Electrical Characteristics of Tetrodes and Pentodes. *Plate Characteristics of Tetrodes.* A circuit suitable for investigating the characteristics of screen-grid tetrodes is shown in Fig. 4.9. The control-grid circuit is arranged so that the grid-to-cathode voltage can be made positive in order to obtain the desired characteristics.

In most circuits, the screen-grid potential is set at some fixed value and held constant while the control-grid voltage is allowed to vary and determine the magnitude of the plate current. Therefore we are particularly concerned with the manner in which the electrode currents vary for a *fixed* value of screen voltage.

Figure 4.10 is a plot of plate current vs. plate voltage for fixed screen- and control-grid voltages. This graph is for a fictitious screen-grid tetrode having a negative control-grid voltage and a positive screen-grid voltage. The plate current starts essentially at zero at $e_b = 0$. As e_b is increased, i_b increases until point a is reached. Between points a and b, however, i_b *decreases.* Past point b, i_b increases again and levels off to an almost constant value for plate voltages greater than the screen-grid voltage.

At zero plate voltage, the screen current is fairly high. As e_b is increased from zero, i_{c_2} decreases until point a' is reached. From points a' to b', i_{c_2} *increases* with increasing plate voltage. Past point b', i_{c_2} decreases once more and levels off to an almost constant value for plate voltages greater than the screen voltage.

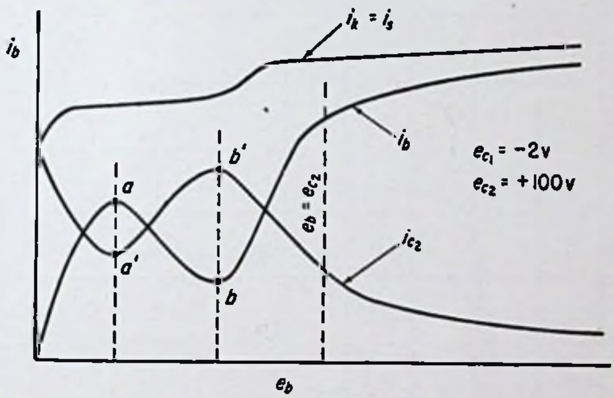

FIG. 4.10. Plate characteristics of a screen-grid tetrode for one value of control-grid voltage.

Secondary emission is responsible for the peculiar "up-and-down" variations of plate and screen currents.

The high screen currents flowing at low anode voltages may increase the screen temperature to excessive values. Therefore caution must always be exercised to avoid low plate voltages for prolonged time intervals.

The space current, or cathode current, which is the sum of the plate and screen currents, remains fairly constant as the plate voltage is varied over wide limits. There are two slight increases in cathode current at low and moderate plate voltages due to changes in the space charge near the screen-grid wires. However, the cathode current is almost independent of the plate voltage.

The plate characteristics of tetrodes consist of curves of plate current vs. plate voltage for various fixed values of control-grid voltage and a constant screen-grid voltage. In addition, the screen current is also sometimes plotted as a function of the plate voltage. For positive control-grid voltages, the control-grid current is also sometimes plotted vs. plate voltage.

Figure 4.11 shows the plate characteristics of a type 24 screen-grid tetrode (an obsolete type popular in the early days of radio). The dip in the plate current is so great that the current actually

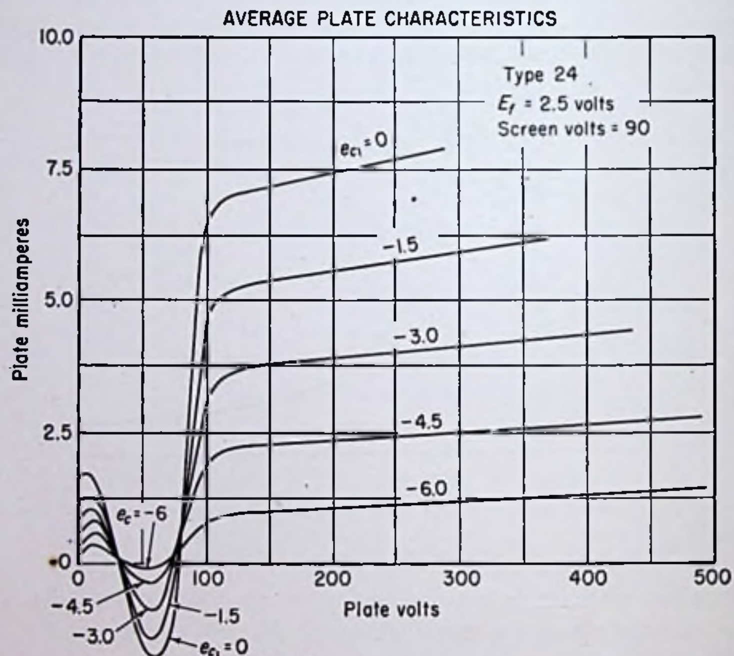

FIG. 4.11. Plate characteristics of a type 24 screen-grid tetrode.

goes to zero and reverses direction for plate voltages slightly less than the screen voltage. This indicates the presence of a large amount of secondary emission from the plate.

Figure 4.12 shows the plate characteristics of a type 24A screen-grid tetrode, a later version of the type 24 having a treated anode designed to reduce secondary emission. In this case, the dip in plate current is not so pronounced, which makes the characteristics somewhat superior to those of a type 24, although they still leave much to be desired.

Transfer Characteristics of Tetrodes. The plate characteristics are the most important of the three possible sets of curves that can be obtained for a fixed screen-grid voltage. The transfer characteristics of tetrodes and pentodes are seldom used. In the case of tetrodes, a set of transfer curves for various screen-grid voltages is helpful in obtaining an understanding of the operation of the tube. In the case of pentodes, two additional sets of curves

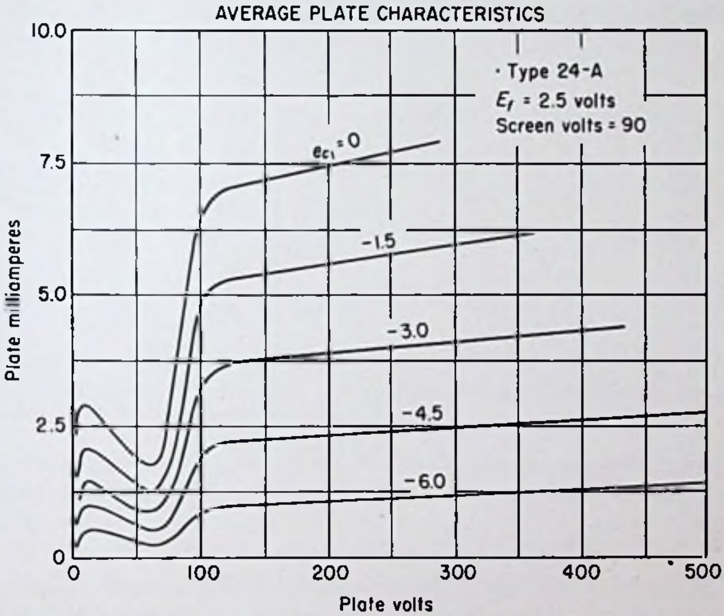

FIG. 4.12. Plate characteristics of a type 24-A screen-grid tetrode.

are helpful, one showing the influence of screen-grid voltage and the other showing the influence of suppressor-grid voltage.

The importance of screen-grid voltage can be seen from the curves in Fig. 4.13. They are very similar to the transfer curves of a triode for various values of plate voltage. The screen voltage is of major importance in determining the magnitude of the plate current. In particular, for plate voltages above the knees of the plate characteristic curves, the screen voltage has a much greater influence on the plate current than the plate voltage. The screen grid in a tetrode (or pentode) acts in place of the plate in a triode in drawing the space current from the cathode.

Limitations of Tetrodes. There are several objectionable features found in the characteristics of screen-grid tetrodes. The plate voltage must be kept above the screen voltage *at all times* if operation is to be maintained over the linear portion of the tube's characteristics. This requires a rather high plate voltage, and it severely restricts the *range* over which the plate voltage may vary. In power amplifiers this means low power output at low efficiency. If operation takes place over the nonlinear portions of the curves, excessive distortion occurs.

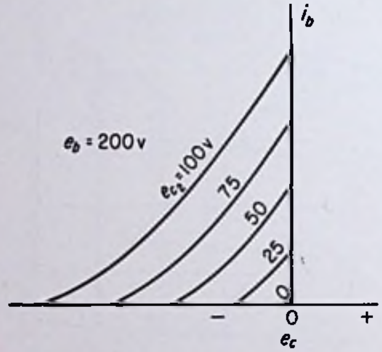

FIG. 4.13. Transfer curves of a tetrode showing the importance of screen voltage.

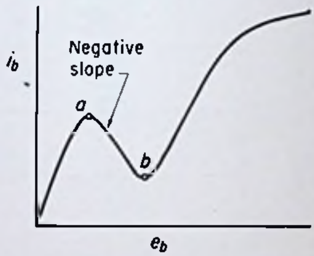

FIG. 4.14. Plate characteristics of a screen-grid tetrode illustrating the negative plate resistance.

A second objectionable feature is the fact that the plate resistance of the tube is negative over the *decreasing*-plate-current range. In Fig. 4.14, the slope of the curve is *negative* from point *a* to point *b*. The student may not be familiar with the concept of "negative resistance." A simple definition is "a circuit element through which the current varies *inversely* with the applied voltage." In other words, as the voltage is increased, the current decreases, and vice versa. Although this negative-resistance aspect of screen-grid tetrodes has practical application in a limited number of special circuits, it is highly undesirable in most cases. Instability and oscillation may occur in a circuit if operation is allowed to take place over the negative-resistance region.

A third but perhaps less important undesirable feature is the lack of stability in the tube's characteristics due to the changing influence of secondary emission as the tube ages.

Plate Characteristics of Pentodes. The characteristics of a pentode can be obtained by using the circuit shown in Fig. 4.15. A tube with an external suppressor connection is assumed, although many pentodes have no such connection, as mentioned earlier. It is included in this instance in order to show the influence of the suppressor-grid voltage on the characteristics of the tube.

Observe first the plate characteristics of a pentode, *i.e.*, plate, screen-grid, suppressor-grid, and control-grid currents plotted as functions of the plate voltage. Figure 4.16 shows such curves for a type 6J7 for negative control-grid voltages, a fixed screen-grid

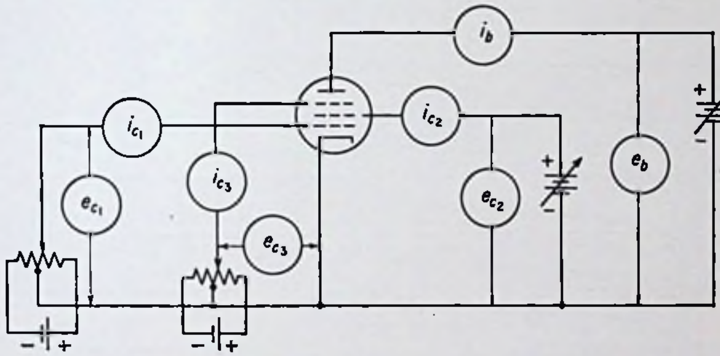

FIG. 4.15. Basic circuit for obtaining the electrical characteristics of pentodes.

voltage of 100 volts, and a suppressor-grid voltage of zero (relative to the cathode). Since the suppressor-grid and control-grid currents are essentially zero, only the plate and screen currents are plotted. The space current for $e_c = 0$ is also plotted to enable a comparison to be made with the space-current curve for a tetrode.

The plate characteristics are radically different from those of a tetrode. In particular, the effects of secondary emission are practically nil. The plate current rises rapidly as the plate voltage is increased from zero and levels off at almost a constant value for plate voltages higher than about 50 to 75 per cent of the screen voltage. The screen current varies inversely with the plate current, falling rapidly as the plate voltage is increased from zero. The space current increases by about 20 to 40 per cent as the plate voltage is increased from zero up to the screen-grid voltage but is almost constant for higher values.

The transfer curves of a pentode for various fixed screen-grid voltages are very similar to those of a tetrode. Figure 4.13 is typical of pentodes as well as tetrodes.

Suppressor-grid Characteristics. The importance of the suppressor-grid voltage in a pentode can be seen from the curves in Fig. 4.17, which are plate characteristics for fixed screen-grid and control-grid voltages and various suppressor-grid voltages. For high positive suppressor-grid voltages, secondary emission effects are pronounced, whereas for negative voltages the plate current is

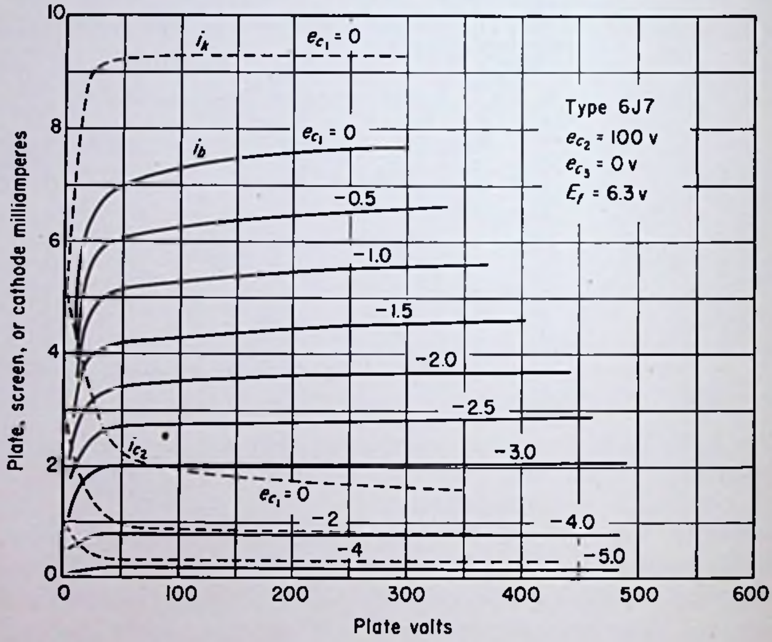

FIG. 4.16. Plate characteristics of a pentode with the suppressor-grid connected to the cathode.

reduced substantially. Zero suppressor voltage gives the best results in most cases. In transmitter-type pentodes which have external suppressor-grid connections, the suppressor grid is sometimes maintained at a low positive voltage in order to improve the characteristics. Figure 4.18 shows the improvement obtained in a type 804 pentode by making the suppressor positive by 45 volts. The plate current rises much faster as the plate voltage is increased from zero. Even at this positive voltage, however, the suppressor is still able to prevent secondary-emission effects in this particular tube.

In some circuits, a variable negative voltage is employed on the suppressor grid in order to vary the plate current. If the plate voltage is changed in steps and at each step the suppressor-grid voltage is varied while the other voltages are kept constant, curves such as those in Fig. 4.19 can be obtained. It is seen that the suppressor voltage has a considerable amount of control over the plate current. It is even possible to reduce the plate current to zero by using a high enough negative suppressor voltage.

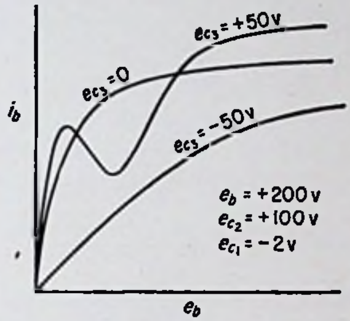

FIG. 4.17. Influence of suppressor voltage on the plate characteristics of a pentode.

Variable-mu Tubes. Pentodes are the only practical tubes to use in some circuits, particularly voltage amplifiers for high-frequency work. The radio-frequency amplifier stages in radio receivers invariably use well-shielded pentodes. It is found that in many cases the performance

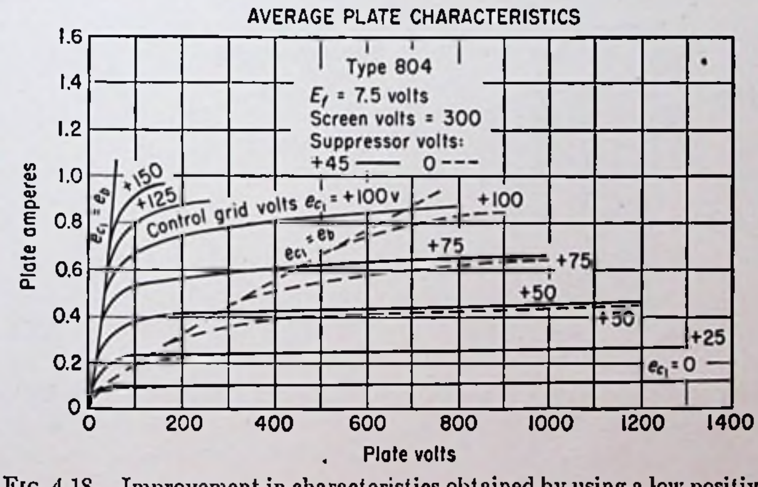

FIG. 4.18. Improvement in characteristics obtained by using a low positive suppressor voltage.

and usefulness of these tubes in such circuits can be greatly increased by constructing the control grids in a special manner. Ordinarily the grid wires are evenly spaced in a triode or pentode in order to make the plate current cut off sharply (see Sec. 3.4). However, in some radio-frequency receiving-type pentodes just the opposite construction is intentionally employed. The control-grid wires are spaced *unevenly* along the length of the tube. Or sometimes one or more turns of the helical grid, usually those near the middle, are omitted. Figure 4.20 shows the construction used in some tubes.

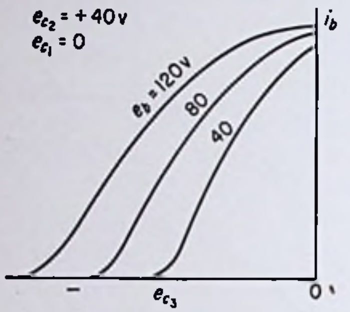

FIG. 4.19. Plate current as a function of suppressor-grid voltage for various plate voltages in a pentode.

The effect of the uneven control-grid structure is shown in Fig. 4.21. Two transfer curves are plotted, one for an ordinary pentode, or a "sharp-cutoff pentode," and one for the special type called a "remote-cutoff," or "supercontrol," pentode. The latter type is also called a "variable-mu tube" because the amplification factor, or mu, of the tube varies greatly as the control-grid

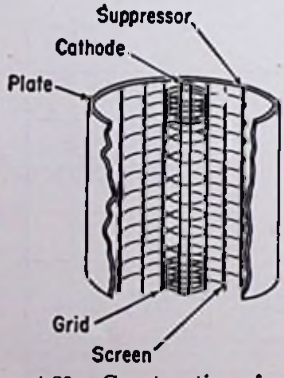

FIG. 4.20. Construction of a variable-mu pentode.

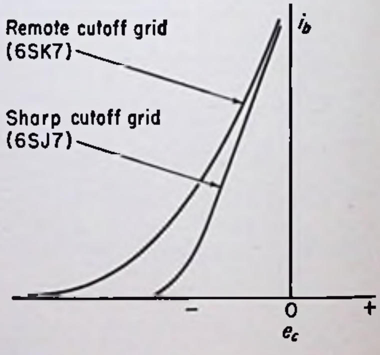

FIG. 4.21. Transfer curves for a sharp-cutoff pentode and a remote-cutoff pentode.

voltage is changed. Variable-mu tubes are superior to the sharp-cutoff types in radio-frequency voltage amplifiers, because automatic volume control can be employed without causing excessive distortion at low plate currents.

The remote-cutoff characteristics are also apparent in the plate characteristic curves of Fig. 4.22. The curves become spaced more closely together as the control-grid voltage is made more negative, indicating a gradual rather than a sharp decrease in plate current. Also higher negative grid voltages are necessary to reduce the plate current to small values as compared with a sharp-cutoff tube. Figure 4.23 shows the plate characteristics of a sharp-cutoff tube; these should be compared with the curves in Fig. 4.22.

Tube Coefficients of Tetrodes and Pentodes. The tube coefficients of tetrodes and pentodes can be defined graphically in the same

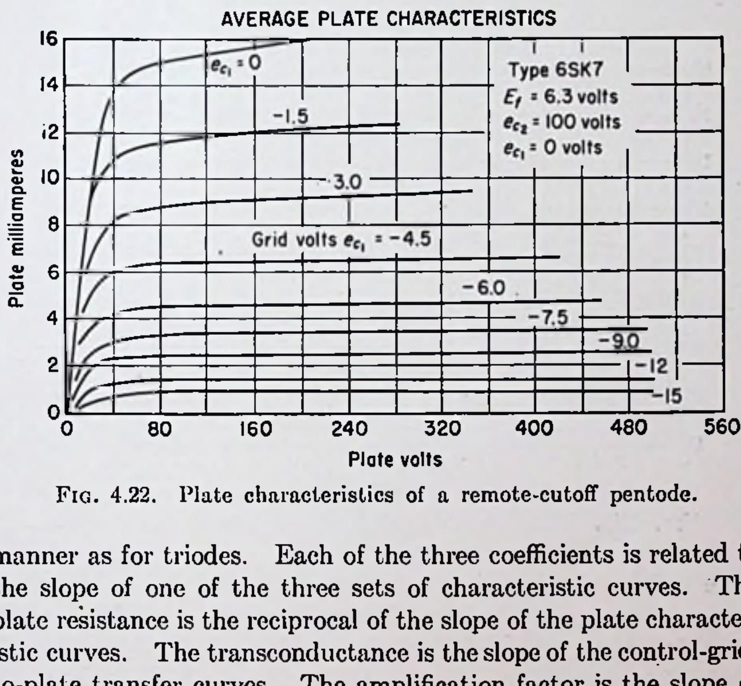

FIG. 4.22. Plate characteristics of a remote-cutoff pentode.

manner as for triodes. Each of the three coefficients is related to the slope of one of the three sets of characteristic curves. The plate resistance is the reciprocal of the slope of the plate characteristic curves. The transconductance is the slope of the control-grid-to-plate transfer curves. The amplification factor is the slope of the constant-plate-current curves. The latter curves are seldom used, however, so it is often more convenient to think of the amplification factor as the product of the plate resistance and the transconductance.

First of all, consider the relative magnitudes of the three coefficients of tetrodes and pentodes as compared with those of triodes. The transconductance of any tube is dependent primarily upon the ability of the grid to control the magnitude of the space current.

It does *not* depend upon the *inability* of the plate to control this current, as does the amplification factor. Since the control grids of triodes, tetrodes, and pentodes are similar in construction, the range of transconductances of these three different types of tubes is about the same. The above general statements apply only over the portions of the tubes' characteristics that are generally used. (They do not apply at *low* plate voltages for either tetrodes or pentodes.)

The plate resistance of any tube is a measure of the ability of a change in plate voltage to cause a change in plate current. In the case of either tetrodes or pentodes, however, a small change in

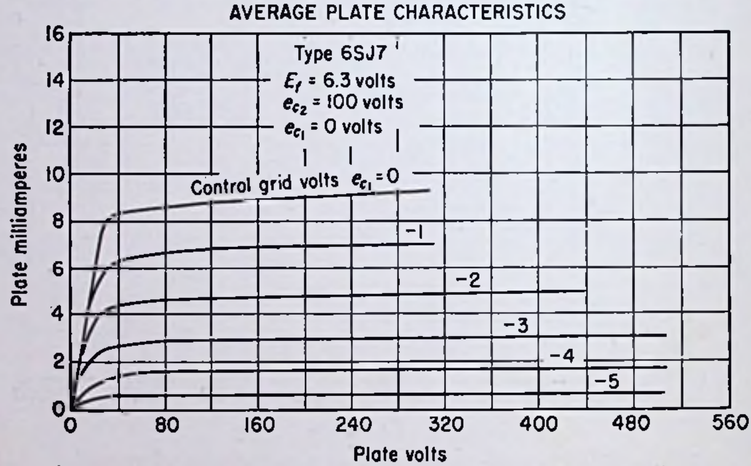

FIG. 4.23. Plate characteristics of a sharp-cutoff pentode.

plate voltage over the linear portions of the tube's characteristic curves causes only a relatively small change in plate current. Thus, in general, the plate resistance of tetrodes and pentodes is much *higher* than that of triodes.

Since the amplification factor of any tube is equal to the product of its plate resistance and transconductance, the amplification factor of tetrodes and pentodes is ordinarily much higher than that of triodes. The amplification factor of a tube is primarily a measure of the relative effectiveness of the grid and plate in controlling the plate current. The grid is about equally effective in any tube, but the plate is very ineffective in the case of tetrodes and pentodes; therefore the amplification factor of the latter types is very high.

Some idea of the relative magnitudes of the tube coefficients for the various tube types can be gained from a study of Fig. 4.24. Values for the plate resistance, transconductance, and amplification factor are given for typical triodes, pentodes, and beam-power tubes.

The values indicated in Fig. 4.24 are only average values over the normal range of operation of the tubes. None of the factors is actually constant for any tube. The variations in the coefficients for a fixed plate voltage have already been determined for a triode (see Fig. 3.26). Let us examine now the manner in which the

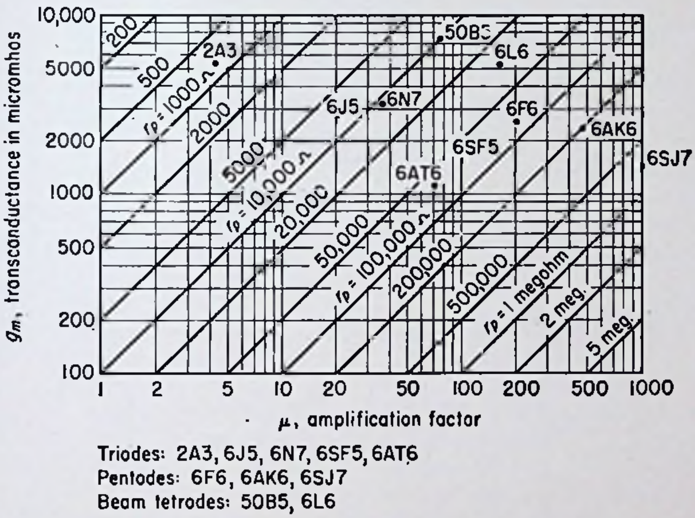

FIG. 4.24. Tube factors for typical vacuum tubes.

three coefficients of tetrodes and pentodes depend upon the applied potentials.

Figure 4.25 shows a single curve of plate current vs. plate voltage for a screen-grid tetrode and the corresponding plate-resistance curve obtained by computing the reciprocal of the slope of the i_b-e_b curve at various points. It is seen that the plate resistance may be positive or negative and reaches infinitely large values at the two inflection points.

If the plate current does not reverse direction owing to secondary emission, the transconductance of a tetrode remains positive. Therefore the amplification factor, being the product of g_m and r_p, goes negative for negative plate resistances.

On the other hand, if the plate current reverses direction, the transconductance goes negative over most of the negative-plate-current region. This makes the amplification factor negative when either r_p or g_m is negative, but positive when both or neither is negative.

The tube coefficients of pentodes are usually more nearly constant than those of tetrodes. For example, Fig. 4.26 shows a single i_b-e_b curve and the corresponding plate-resistance curve obtained from it. The plate resistance is seen to be relatively low

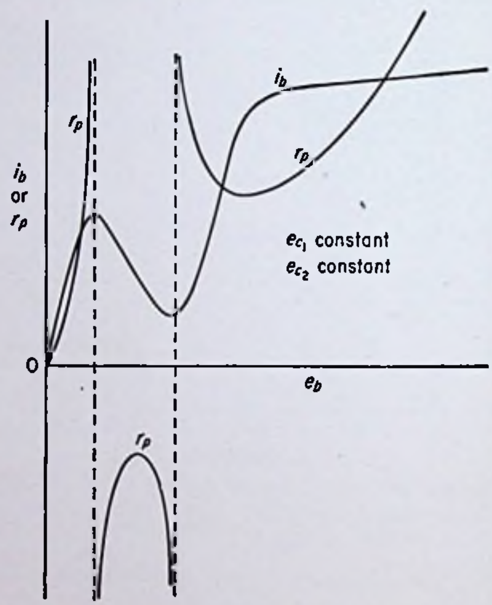

FIG. 4.25. Curves showing the manner in which the plate resistance of a screen-grid tetrode varies with the plate voltage for constant control-grid and screen-grid voltages.

for low plate voltages, but high and relatively constant for values of plate voltage higher than about 50 to 75 per cent of the screen voltage.

Figure 4.27 shows the manner in which the transconductance of a pentode varies with the plate voltage for constant grid and screen voltages. The curve also shows the variation of amplification factor, which is the product of the plate resistance and transconductance. For plate voltages in excess of about 50 to 75 per cent of the screen voltage, the tube coefficients of pentodes are high and relatively constant.

Screen-grid Amplification Factor. There is an additional tube coefficient for tetrodes and pentodes which is of major importance. This is the screen-grid amplification factor. Whereas the ordinary amplification factor measures the relative abilities of the plate and control grid to control the plate current, the screen-grid amplification factor measures the relative abilities of the screen grid and control grid to control the *space* current.

The screen-grid amplification factor is frequently called the "cutoff" amplification factor, because it determines the combination of screen-grid and control-grid voltages necessary to cut off the plate current, just as the amplification factor of a triode determines the

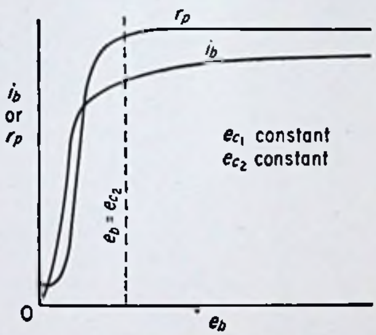

FIG. 4.26. Curves showing the manner in which the plate resistance of a pentode varies with the plate voltage for constant control-grid and screen-grid voltages.

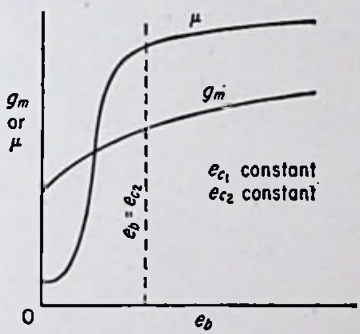

FIG. 4.27. Curves showing the variation of transconductance and amplification factor of a pentode with plate voltage for constant control-grid and screen-grid voltages.

combination of plate and control-grid voltages necessary to reduce the plate current to zero. There is an exact correspondence between the cutoff amplification factor of a pentode and the ordinary amplification factor of a triode. This is because the screen grid in a pentode acts like the plate of a triode as far as the space current is concerned.

The screen-grid amplification factor of a pentode is relatively constant for changes in electrode voltages and currents. It is much lower than the ordinary amplification factor, usually falling somewhere in the range from 5 to 25.

4.3. Theories Used to Explain the Electrical Characteristics of Tetrodes and Pentodes. A complete understanding of screen-grid tetrodes and pentodes requires a knowledge of the theories of thermionic emission, space-charge limitation of space current, and grid control of space current. All three of these very important matters have been taken up in some detail in preceding chapters. In addition, theories are needed to explain the effects of the screen grid and the suppressor grid on the characteristics of the tube.

The screen grid in either a tetrode or a pentode has about the same influence on the space current (or cathode current) as the plate in a triode. This can be seen from the transfer curves in Fig. 4.13, which are very similar to transfer curves for a triode for various fixed plate voltages. Reference to Fig. 4.10 shows that the

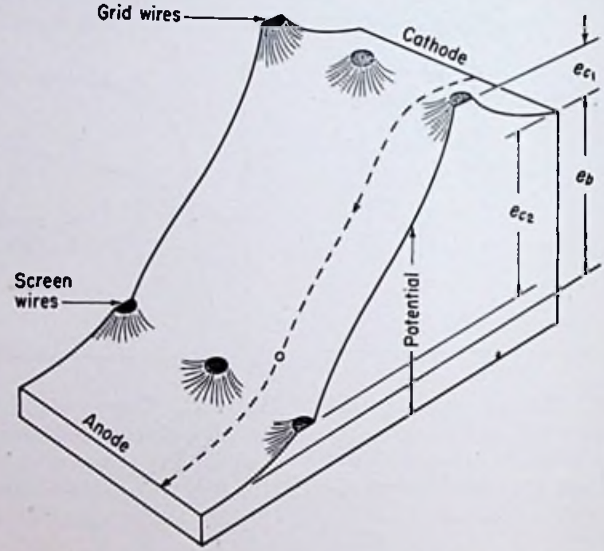

FIG. 4.28. Potential distribution in a screen-grid tetrode for $e_b > e_{c_2}$.

space current flowing from the cathode is practically independent of anode voltage. The reasons for the ineffectiveness of the plate in controlling the space current relative to the screen are twofold. First, the anode is *farther* from the cathode than the screen. In addition, the screen grid has a shielding effect, so that few flux lines from the plate reach through to the cathode, most of them terminating on the screen. The latter reason is by far the more important of the two.

Potential Model of a Tetrode. Perhaps a better way to illustrate the behavior of a screen-grid tetrode is by means of a potential model, which shows the space potential at any point inside the tube and allows a determination of electron paths to be made (see Sec. 3.3).

Figure 4.28 is a sketch of a potential model for a screen-grid tetrode. The plate voltage is assumed to be slightly higher than the screen voltage. Figure 4.29 shows the potential model for a plate voltage slightly lower than the screen voltage.

The first important fact which can be explained by these models is the inability of the anode potential to influence the potentials near the cathode. The potential distribution near the cathode is

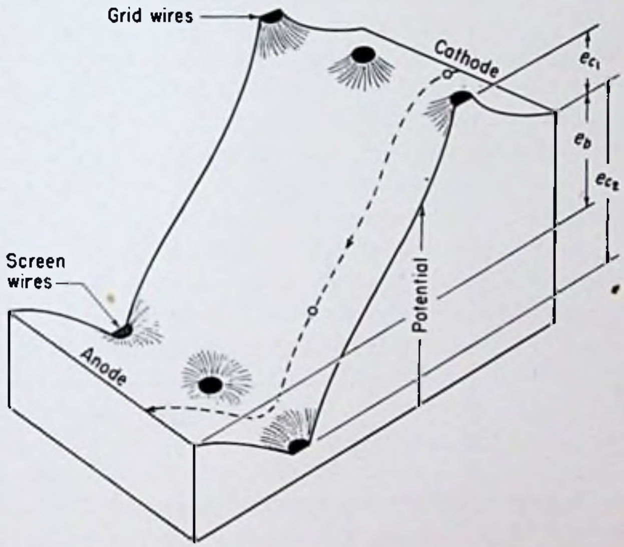

FIG. 4.29. Potential distribution in a screen-grid tetrode for $e_b < e_{c_2}$.

changed only to a very small extent as the anode voltage is varied. This is easy to visualize if the models are thought of as being of the rubber-membrane type. Imagine that the height of the line labeled "anode" is adjustable. Moving it up and down affects the membrane between the cathode and control grid only slightly. Since tetrodes are always operated under conditions of space-charge-limited current, the potential gradient near the cathode surface determines the magnitude of the space current. Therefore, the anode voltage has only a minor influence on the space current.

If the screen-grid-potential circles are moved up and down instead of the anode-potential line, the movement of the membrane near the cathode is considerable. If the screen voltage is lowered sufficiently (which corresponds to a *raising* of the circles representing the screen potentials in Figs. 4.28 and 4.29), the potential gradient at the cathode surface can be made negative, even in the absence of space charge, thereby reducing the space current to zero. Thus the screen voltage plays a very significant role in determining the space current.

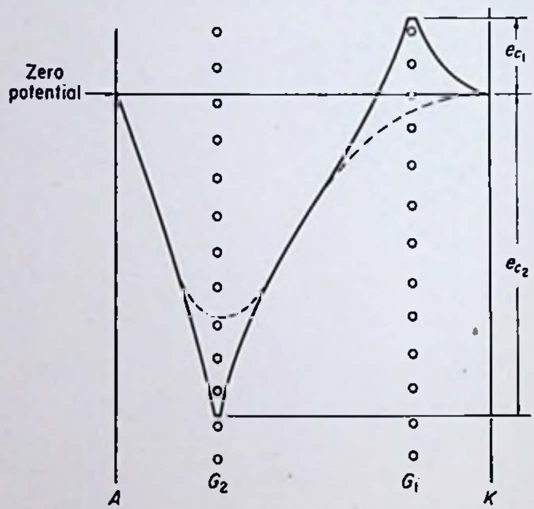

FIG. 4.30. Potential profiles in a screen-grid tetrode for $e_b = 0$. (The potential curves are inverted.)

The control grid is able to influence the potential gradient at the cathode surface, and thus the space current, even more effectively than the screen grid. This same situation exists in a triode, wherein the control grid is more influential than the plate. Thus each of the elements in a screen-grid tetrode affects the magnitude of the space current, but each to a different degree. The control grid is the most influential, with the screen grid next and the anode last.

The curves in Fig. 4.10 can be explained qualitatively by considering the action of marbles released at the cathode of a potential model of a screen-grid tetrode. For zero plate voltage, a side view of such a model appears as in Fig. 4.30. A high positive voltage on the screen with a negative voltage on the control grid near cutoff is assumed. The dotted lines represent the potentials along a line *between* the grid and screen wires, whereas the solid lines represent the potentials along a line *through* the wires. It is assumed for the sake of simplicity that the screen wires have the same spacing as the control-grid wires and that the two sets of wires are aligned. Such a construction is actually employed in beam-power tubes, as will be seen in the following chapter.

Oscillating Space Charge. A marble given a slight push at the cathode in Fig. 4.30 *might* travel along a straight-line path and hit the anode with a velocity equal to its initial velocity. This is very unlikely, however. Most electrons do not travel toward the anode along a straight-line path. Nearly every electron in any vacuum tube containing one or more grids is deflected somewhat upon passing through the grid structure. Figure 3.34 illustrates the deflection of electrons passing the control-grid wires in a triode. In screen-grid tetrodes, the electrons are deflected twice, first by the control-grid wires and then by the screen-grid wires.

After deflection by the grids the electrons have less energy directed toward the plate. For zero plate voltage, as in Fig. 4.30, almost every electron follows a curved path after deflection and eventually returns toward the positive screen. Some of these reflected electrons hit the screen-grid wires. Many miss the wires, however, and travel toward the control grid and cathode. There they are retarded by the negative potential gradient and are returned toward the screen. If they miss the screen-grid wires again they travel toward the plate and are reflected again. An electron may oscillate back and forth several times before finally hitting a screen wire.

The presence of the oscillating electrons about the screen-grid wires constitutes an additional space charge over and above the normal value that would exist without the oscillations. This lowers the space potential near the screen wires and reduces the voltage gradient near the cathode surface slightly, thereby lowering the space current from the cathode. As the anode is made a few volts positive, some of the electrons which were reflected for zero plate voltage become capable of reaching the anode. This reduces the number of electrons that return to the screen, and thus the oscillating space charge about the screen wires is reduced. The potential gradient near the cathode is correspondingly affected, with the result that the space current increases slightly. This accounts for the initial rise in space current in Fig. 4.10 as the plate voltage is increased from zero.

The rise in space current in the region where the plate voltage is made higher than the screen voltage is caused by the complete elimination of "reflected" electrons. For plate voltages higher than the screen voltage, none of the electrons which pass through the screen wires are turned back to the screen, regardless of how much they are deflected. Hence, the oscillating space charge is suddenly eliminated, and the potential gradient at the cathode is correspondingly affected, with the result that the space current is suddenly increased again.

Secondary-emission Effects in a Tetrode. Owing to its high positive potential, the screen grid in a tetrode is continuously emitting secondary electrons. As long as the screen is the most positive electrode in the tube, these secondary electrons are returned to its surface. As soon as the plate voltage reaches about 10 volts, secondary emission from the plate begins. The secondaries from the plate are drawn to the screen because of its high positive potential. The model in Fig. 4.30 can be used to illustrate these actions. If a marble is given a slight push from either the screen or the plate, it will travel to one of the screen wires.

As the plate voltage is increased, the speed of the primary electrons bombarding the plate increases, thereby increasing the secondary-emission ratio. The increased secondary-electron flow to the screen from the plate *subtracts* from the primary plate current. Thus the plate current decreases, and the screen current increases. This explains the negative-plate-resistance region of the plate characteristics.

As the plate voltage approaches the screen voltage, the plate begins losing fewer secondaries and the screen begins to lose a few of its own to the plate. For plate voltages higher than the screen voltage, all the secondaries emitted from the screen are drawn to the plate, and the plate's own secondaries are drawn back after being emitted.

Figure 4.31 shows the inverted potential curves for a screen-grid tetrode for a plate voltage higher than the screen voltage. A marble given a slight push from either the screen or the plate reaches the plate.

Potential Model of a Pentode. An understanding of the operation of pentodes can be gained from a study of the potential distribution for various electrode voltages. Figure 4.32 shows a potential model for a negative control-grid voltage and zero plate voltage. The wires of the three grids are assumed to be spaced equally for the sake of simplicity.

An electron starting from the cathode (or, actually, the virtual cathode) can theoretically reach the anode. However, as in a tetrode, the electrons are deflected when they pass between the grid wires. There are three grids in a pentode, each of which

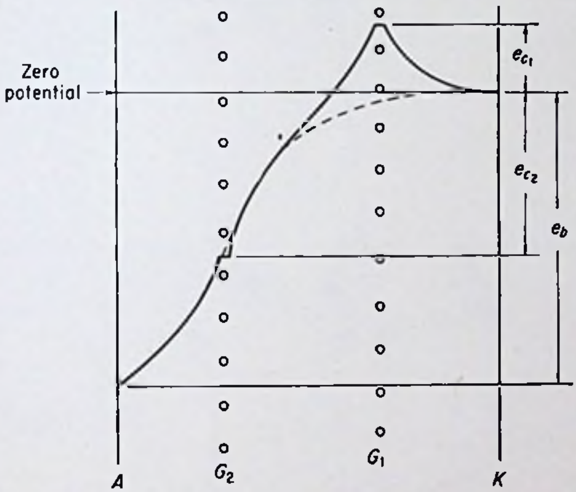

FIG. 4.31. Inverted potential curves for a screen-grid tetrode for $e_b > e_{c_2}$.

deflects the electrons and reduces their components of velocity directed toward the plate.

At zero plate voltage, most of the electrons are unable to reach the anode, but instead are drawn to the screen, possibly after a few oscillations about the screen wires. This oscillating space charge lowers the space current from the cathode as in the case of tetrodes. (The marble shown in Fig. 4.32 is assumed to reach the plate along a straight-line path in order to show the nature of the potential surface more clearly.)

As the plate voltage is increased from zero, a few electrons are able to "climb the potential hump" caused by the suppressor voltage and hit the plate. Figure 4.33 shows a potential model for a plate voltage a little lower than the screen voltage. Most of the marbles released at the cathode are able to reach the plate. A few hit the suppressor wires, and the rest return to the screen.

As the plate voltage is increased from zero, fewer and fewer electrons return to the screen. This reduces the oscillating space charge around the screen wires and permits the space current to increase. This explains the initial rise of space current in Fig. 4.16.

Notice that the plate voltage has very little influence on the potential gradient at the cathode surface. There is even less influ-

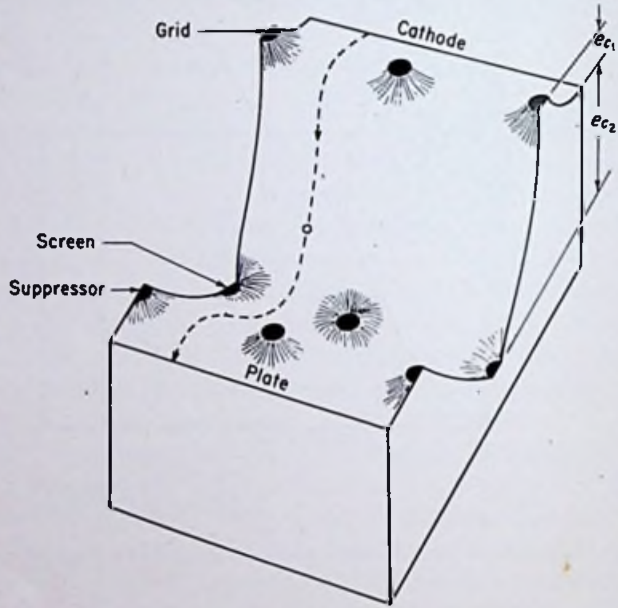

FIG. 4.32. A potential model of a pentode for zero plate voltage.

ence in a pentode than in a tetrode because of the additional screening imposed by the suppressor grid. This causes the tube coefficients of pentodes to be even higher than those of tetrodes.

Suppression of Secondary Electrons. The suppressor grid is able to prevent the interchange of secondary electrons between the screen and plate that distorts the characteristics of tetrodes. This is because a negative potential gradient is presented to electrons emanating from either the plate or the screen grid. The force on an electron between the suppressor and plate is toward the plate, whereas the force on an electron between the suppressor and screen is toward the screen. Figure 4.33 illustrates what happens to marbles that are ejected from the plate and screen to simulate secondary electrons.

About 90 per cent of all secondary electrons are emitted with velocities below 20 volts. Therefore if the most *positive* potential between two suppressor wires is more negative than either the plate or the screen by at least 20 volts, very few secondaries are exchanged between the two electrodes.

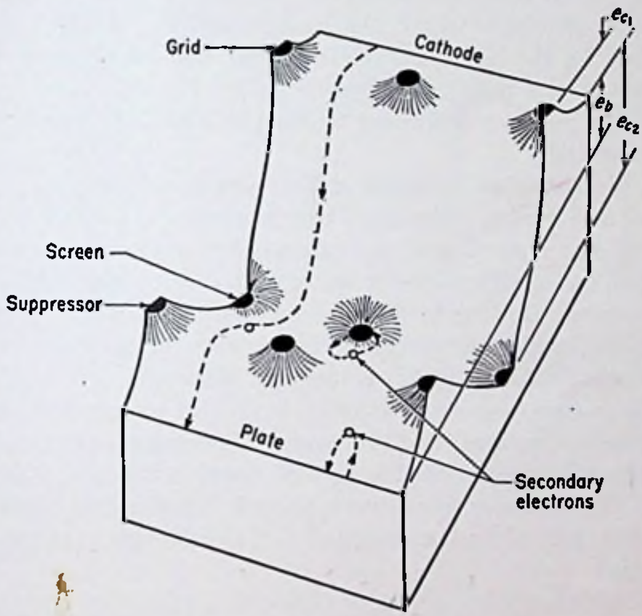

FIG. 4.33. Potential model of a pentode for $e_b < e_{c_2}$.

For negative suppressor-grid voltages, fewer electrons are able to reach the anode. This is because the suppressor-grid potential hump in Fig. 4.33 is higher, which stops electrons which have been deflected appreciably. If the suppressor grid is made negative enough, the potential hump can be made so high that none of the electrons have enough energy to "climb over" and reach the anode.

Furthermore, at high negative suppressor voltages, the velocities of the electrons approaching the suppressor are reduced considerably. This increases the charge density in front of the suppressor and consequently reduces the potential in the neighborhood still further. If the potential due to this space charge is reduced to zero, a *virtual cathode*, or a region of zero potential gradient, is formed.

In some pentodes, a virtual cathode tends to form immediately in front of the suppressor even for zero suppressor voltage. When a virtual cathode forms, the plate current is lowered, because more electrons are reflected back to the screen, owing to their low-velocity components directed toward the plate. A positive suppressor voltage tends to prevent the formation of a virtual cathode. In power pentodes where the current density is high, sharper shoulders on the plate characteristics can sometimes be obtained by employing a positive suppressor grid. Figure 4.18 shows the effect of a positive suppressor voltage on the curves of a transmitter pentode.

4.4. Mathematical Analysis of Tetrodes and Pentodes. *Space Current in Tetrodes.* The space current flowing in a triode divides between the control grid and plate. For negative control-grid voltages, essentially all the space current goes to the plate. The plate current flowing in a parallel-plane triode was derived in Chap. 3 by making the grid potential equal to the natural potential that would exist at the point of insertion of the grid.

In a tetrode, the space current is divided among the control grid, the screen grid, and the plate. For negative control-grid voltages, the space current is divided between the screen and the plate. The space current in a tetrode is found to vary with the electrode potentials according to the following approximate equation:

$$i_s = K\left(e_{c_1} + \frac{e_{c_2}}{\mu_{SG}} + \frac{e_b}{\mu}\right)^{3/2} \tag{1}$$

where K is the perveance of the tube and the other symbols are as defined previously. Ordinarily the amplification factor μ is very large compared to the screen-grid amplification factor μ_{SG}. The plate voltage e_b is usually not more than three or four times the screen voltage e_{c_2}, and in some circuits the two voltages are about equal. Therefore it is justifiable to drop the last term and obtain a simplification of the equation.

$$i_s = K\left(e_{c_1} + \frac{e_{c_2}}{\mu_{SG}}\right)^{3/2} \tag{2}$$

This equation should now be carefully compared with Eq. (1) in Chap. 3. The equations are identical if e_b is made equal to e_{c_2} and μ_{sg} is made equal to μ for the triode. In other words, as far as the *space* current is concerned, a tetrode is identical with a triode, with the screen grid in the tetrode taking the place of the plate in the triode.

This being the case, the perveance of a parallel-plane tetrode is equal to the perveance of the triode portion of the tube considering the screen grid as the plate. Therefore, the derivation of the perveance of a parallel-plane triode holds equally well for a parallel-plane tetrode, provided that the distances appearing in the perveance equation are properly interpreted. From Eq. (7) in Chap. 3 we can write

$$K = \frac{A}{9\pi}\sqrt{\frac{2Q}{m}}\left(d_{kg_1}{}^{4/3} + \frac{d_{kg_2}{}^{4/3}}{\mu_{sg}}\right)^{-3/2} \tag{3}$$

In the mks practical system of units, the equation for the space current in a tetrode becomes

$$i_s = (2.34 \times 10^{-6})\,\frac{A(e_{c_1} + e_{c_2}/\mu_{sg})^{3/2}}{(d_{kg_1}{}^{4/3} + d_{kg_2}{}^{4/3}/\mu_{sg})^{3/2}} \quad \text{amp} \tag{4}$$

where d_{kg_1} is the distance from the cathode to the control grid, d_{kg_2} is the distance from the cathode to the screen grid, and the other quantities are as defined previously.

Example:

A parallel-plane tetrode has electrodes which are equally spaced 0.5 cm apart. The area of the cathode is 10 cm², and the cutoff amplification factor is 10. Find the cathode current if the plate voltage is 300, the screen voltage is 250, and the control-grid voltage is −7.5 volts.

Solution:

$$i_s = (2.34 \times 10^{-6})\,\frac{(10)(-7.5 + 250/10)^{3/2}}{\left[(0.5)^{4/3} + \frac{(1.0)^{4/3}}{10}\right]^{3/2}}$$

$$= 4.29 \times 10^{-3}\text{ amp}$$

$$= 4.29\text{ ma} \quad \textit{Ans.}$$

Notice that, according to Eq. (4), the distance from the cathode to the plate has absolutely no bearing on the space current. This is in contrast to the triode, wherein the space current varies inversely with the cathode-to-anode spacing. It will be shown in the next chapter, however, that under certain circumstances the plate-cathode spacing *does* have a very important influence on the division of space current between the screen and the plate. In particular, if the spacing between the screen and the plate is made too great, a maximum limit is imposed on the plate current for a given plate voltage owing to the formation of a virtual cathode in the screen-anode region. In fact, this is the principle upon which a beam-power tube is based.

Screen Current in Tetrodes. The proportion of the space current going to the screen in the absence of secondary-emission effects is approximately equal to the ratio of the projected area of the screen wires to the total area in the plane of the screen wires through which the current travels. Under ordinary circumstances, this percentage is usually in the range from about 15 to 40. For any particular tube, the exact ratio of plate to screen current depends upon the applied potentials, but for plate voltages in excess of the screen voltage, the ratio is practically constant.

Example:

Assume that the screen wires in the preceding example are 0.1 mm in diameter and spaced 0.6 mm apart. Find the plate and screen currents flowing at the voltages used in the preceding example.

Solution:

$$A_p = \frac{lwD}{s} \qquad \text{cm}$$

where A_p = projected area of screen wires
l = length of wires, cm
w = width of entire grid, cm
D = diameter of wires, cm
s = spacing between wires, cm

This is true because lD is the projected area of each wire and w/s is the number of wires required. Notice that lw is simply the area of the whole screen plane.

$$A_p = \frac{(10)(0.01)}{0.06}$$

$$= 1.67 \text{ cm}^2$$

Therefore

$$i_{c_2} = \left(\frac{1.67}{10}\right)(4.29)$$

$$= 0.726 \text{ ma} \quad \textit{Ans.}$$

$$i_b = i_s - i_{c_2}$$

$$= 4.29 - 0.726$$

$$= 3.56 \text{ ma} \quad \textit{Ans.}$$

The actual screen current in the preceding example would probably be slightly higher, perhaps 0.8 ma instead of 0.726 ma. The exact value is influenced somewhat by the ratio of plate to screen voltage. As the plate voltage is increased, the electrons are pulled past the screen wires more rapidly and fewer are drawn in to the screen. Therefore the ratio of plate to screen current generally increases slightly as the plate voltage is made higher.

Notice that the plate voltage in the preceding example was higher than the screen voltage. Had the plate voltage been lower, the screen current would have been much higher than that calculated on the basis of areas owing to incomplete current transmission to the plate. The calculation of screen and plate currents at low plate voltages is possible, but the effects of secondary emission make the calculations difficult and the results inaccurate.

Cutoff Bias of Tetrodes. The screen-grid amplification factor can be used to determine the combination of screen and grid voltages necessary to reduce the plate current to zero, just as the ordinary amplification factor of a triode can be used to determine the combination of plate and grid voltages necessary to reduce the plate current to zero. The relationship among the three quantities is, from Eq. (2),

$$e_{c_1} = -\frac{e_{c_2}}{\mu_{sg}} \tag{5}$$

where e_{c_1} and e_{c_2} are the grid and screen voltages, respectively, giving zero plate current.

Example:

Compute the cutoff control-grid voltage of the tube in the preceding example for a screen voltage of 250 volts.

Solution:

$$\begin{aligned} e_{c_1} &= -\frac{e_{c_2}}{\mu_{sg}} \\ &= -{}^{250}\!/_{10} \\ &= -25 \text{ volts} \quad \textit{Ans.} \end{aligned}$$

The voltages specified in Eq. (5) are actually in error owing to the finite velocities with which the electrons are emitted from the cathode. The grid voltage calculated from Eq. (5) is the *projected* cutoff grid voltage. A slightly higher negative voltage is required in an actual tube. The same situation was shown in Chap. 3 to be true for triodes.

Space Current in Pentodes. The space current in a pentode must divide between four electrodes: the control grid, the screen grid, the suppressor grid, and the plate. The voltage on each of these electrodes affects the potential gradient at the cathode surface and therefore the total space current. Experimentally it can be shown that the space current in a pentode follows the approximate equation

$$i_s = K\left(e_{c_1} + \frac{e_{c_2}}{\mu_{sg}} + \frac{e_{c_3}}{\mu_{su}} + \frac{e_b}{\mu}\right)^{3/2} \tag{6}$$

where μ_{su} is the amplification factor of the control grid relative to the suppressor grid, and the other quantities are as previously defined. The suppressor-grid amplification factor μ_{su} measures the relative effectiveness of the suppressor grid and control grid in controlling the plate current. It is ordinarily much higher than the screen-grid amplification factor owing to the shielding effect of the screen grid. The ordinary amplification factor μ of pentodes is generally much higher than that of tetrodes. Therefore it is possible to simplify the equation by dropping the last two terms, giving

$$i_s = K\left(e_{c_1} + \frac{e_{c_2}}{\mu_{sg}}\right)^{3/2} \tag{7}$$

This equation is identical with the one for tetrodes. Therefore all the other equations which were given for tetrodes apply to pentodes. The suppressor grid in a pentode has relatively little influence on the characteristics of the tube at high plate voltages. The main effects occur at low plate voltages where secondary emission is most pronounced. However, the presence of the suppressor grid does make the plate resistance and amplification factor higher for pentodes than for tetrodes.

Tube Coefficients of Tetrodes and Pentodes. It is possible to derive equations for the amplification factor, plate resistance, and transconductance of tetrodes and pentodes from the geometries of the tubes. However, for the purposes of this book, it will be sufficient merely to indicate some of the important relationships governing the tube coefficients. These may be summarized as follows:

1. The screen-grid amplification factor increases as the spacing between the grid and screen is increased.

2. The screen-grid amplification factor increases as the diameter of the grid wires is increased.

3. The screen-grid amplification factor increases as the spacing between the control-grid wires is decreased.

4. The screen-grid amplification factor is independent of the spacing between the cathode and control grid.

5. The amplification factor of a tetrode is approximately equal to the screen-grid amplification factor multiplied by a fictitious amplification factor computed on the basis of the control grid acting as a cathode and the screen grid acting as a control grid. The same factors which influence the triode amplification factor and the screen-grid amplification factor also influence the fictitious amplification factor just cited.

6. The amplification factor of a pentode is approximately equal to the product of three amplification factors: the screen-grid amplification factor; the fictitious amplification factor computed on the basis of the control grid acting as a cathode, the screen grid acting as a control grid, and the suppressor grid acting as a plate; and the fictitious amplification factor computed on the basis of the screen grid acting as a cathode and the suppressor grid acting as a control grid.

7. For negative control-grid voltages, the transconductance of tetrodes is equal to the triode transconductance of the first three electrodes multiplied by the ratio of plate to total space current.

8. For zero or negative suppressor-grid voltages and negative control-grid voltages, the transconductance of pentodes is equal to

the triode transconductance of the first three electrodes multiplied by the ratio of plate to total space current.

9. The plate resistance of tetrodes and pentodes is the quotient of amplification factor divided by transconductance.

Graphical Determination of Tube Coefficients. The plate resistance, transconductance, and amplification factor of pentodes can be determined graphically from the characteristic curves, just as in the case of triodes. The plate characteristics are the only ones generally given for pentodes. Also the plate resistance and amplification factor are usually difficult to determine accurately from the plate characteristics because of the low slope of the curves over the

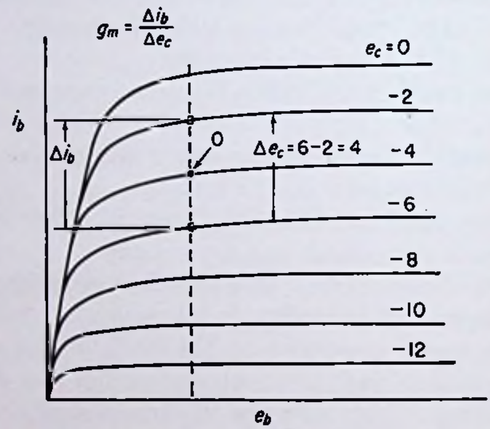

FIG. 4.34. Plate characteristics of a pentode showing the method of calculating the tube coefficients graphically.

usual operating range. However, it is desirable to be able to make the calculations because the tube coefficients are used quite extensively in the analysis and design of circuits using pentodes.

Figure 4.34 shows the plate characteristics of a hypothetical pentode with the suppressor at cathode potential and various negative control-grid voltages. The transconductance can usually be determined more accurately than either of the other two factors. This is in contrast to triodes in which case g_m is difficult to determine accurately from the plate characteristics.

The point of operation is first determined. Assume that the point lies on one of the available grid-voltage curves. A vertical line should be drawn through the point until it intersects the two adjacent grid-voltage curves. The transconductance is then calculated from the equation

$$g_m = \frac{\Delta i_b}{\Delta e_c} \tag{8}$$

where the increments are as shown in Fig. 4.34.

A more accurate method of determining the transconductance consists in plotting a transfer curve for the given plate voltage. A line should then be drawn through the operating point tangent to the transfer curve. The slope of this tangent gives the transconductance. This method is also convenient if the operating point falls between the available plate characteristic curves.

The plate resistance should be calculated by the slope method. For some pentodes the plate resistance is so high that the slope of the tangent drawn through the operating point is practically zero. If greater accuracy is desired, the plate curves should be replotted using a very exaggerated plate-current scale. If the operating point does not fall on one of the available curves, an interpolation method can be used, as explained in connection with triodes in the preceding chapter. Or, alternatively, a curve passing through the operating point can be sketched in and the plate resistance calculated directly by the slope method.

After the plate resistance has been determined, the amplification factor can be found from the relation

$$\mu = g_m r_p \tag{9}$$

PROBLEMS

1. Calculate the perveance of a parallel-plane pentode having the following dimensions: $d_{kg_1} = 2$ mm, $d_{kg_2} = 4.5$ mm, $d_{kg_3} = 8$ mm, $d_{kp} = 10$ mm, length of plate = 5.5 cm, width of plate = 3 cm. The cutoff amplification factor is 11.2. Express the answer in amperes per volt$^{3/2}$.

2. Calculate the perveance of a type 6AG5 pentode using the characteristic curves supplied by your instructor. The screen-grid amplification factor is 40. Check it at three or four different points on the curves, including one or two at very low plate voltages. Compare the answers.

3. Calculate the screen, plate, and cathode currents flowing in a parallel-plane pentode having the following dimensions: $d_{kg_1} = 100$ mils, $d_{kg_2} = 200$ mils, $d_{kg_3} = 350$ mils, $d_{kp} = 400$ mils, area of electrodes = 2 in.^{2}, diameter of all grid wires = 2 mils, spacing of screen-grid wires = 10 mils. The cutoff amplification factor is 20, and the electrode voltages are as follows: $e_{c_1} = -8$, $e_{c_2} = 250$, $e_{c_3} = 0$, $e_b = 325$ volts.

4. Calculate the perveance of a type 6AK6 pentode using the plate characteristics supplied by your instructor. Use a plate voltage of 200 volts and a grid voltage of -6 volts. Assume $\mu_{SG} = 10$. What is the equation for the *space* current in this tube as a function of the grid and screen potentials?

5. Using the plate characteristics of a type 6SH7 pentode supplied by your instructor, plot a curve of space current vs. plate voltage for $e_c = 0$. (The available curves must show screen as well as plate currents.)

6. A certain pentode has a cutoff mu of 8. What control-grid voltages are required to make the plate current approach zero for screen-grid voltages of 50, 150, and 250 volts?

7. From the plate characteristics for a type 6SJ7 pentode supplied by your instructor, graphically compute μ, r_p, and g_m at grid and plate voltages of 0 and 160 volts, respectively.

8. From the plate characteristics for a type 6F6 pentode supplied by your instructor, graphically compute μ, r_p, and g_m at grid and plate voltages of -10 and 250 volts, respectively.

9. From the plate characteristic curves for a type 6SK7 pentode, plot transfer curves for plate voltages of 20, 100, and 240 volts.

10. Calculate the transconductance of a type 6SK7 pentode by drawing tangents to the transfer curve obtained in Prob. 9 for $e_b = 240$ volts. Plot a curve of transconductance vs. negative control-grid voltage.

11. Repeat Prob. 9 for a type 6SJ7 pentode.

12. Repeat Prob. 10 for a type 6SJ7 pentode.

13. From the plate characteristic curves for a type 6F6 pentode supplied by your instructor, plot constant-current curves for $i_b = 10$, 20, and 40 ma.

14. Explain why the amplification factor of a tetrode is approximately equal to the screen-grid amplification factor multiplied by the triode amplification factor of the three outer electrodes.

15. A type 6SH7 sharp-cutoff pentode has a transconductance of 4,000 μmhos and a plate resistance of 0.35 megohm at plate and screen voltages of 100 and a control-grid voltage of -1 volt. The corresponding plate and screen currents are 5.3 and 2.1 ma, respectively. If the plate voltage is raised to 120 volts and the grid voltage is reduced to -0.5 volt, what is the new plate current? What is the new screen current? (Assume that the tube factors and the screen voltage remain constant. Also assume a constant current ratio between plate and screen.)

16. A type 6AU6 pentode has the following specifications at

$$e_b = 250,\ e_{c_2} = 150,\ e_{c_3} = 0, \text{ and } e_{c_1} = -1 \text{ volt:}$$

$$g_m = 5{,}200\ \mu\text{mhos}$$
$$r_p = 1 \text{ megohm}$$
$$i_b = 10.8 \text{ ma}$$
$$i_{c_2} = 4.3 \text{ ma}$$

If the plate current is to go down 0.5 ma when the grid voltage is changed to -1.2 volts, to what value must the plate voltage be readjusted? (Assume the tube coefficients stay constant.)

17. A certain glass-type pentode was being used as an audio power amplifier. The primary winding of a transformer was connected in series with the plate of the tube to the high-voltage plate power supply, and a small paper capacitor was connected from plate to cathode of the tube. The paper capacitor became faulty and shorted the plate of the tube to the cathode. In a very short time, the amplifier ceased to function, and it was noticed that the screen grid in the tube was red hot. What had happened?

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CHAPTER 5

BEAM-POWER TETRODES

It was discovered in the mid-thirties that suppressor-grid action could be achieved in a screen-grid tube even without a suppressor grid, provided the electrodes were constructed and arranged inside the tube in a special manner. Such a tetrode is variously called a beam-power tetrode, beam-power tube, beam tetrode, or simply beam tube. Such tubes have replaced pentodes to a large extent in applications involving the handling of any amount of power. The ordinary pentode is still unexcelled in such applications as voltage amplifiers at radio frequencies, but the beam-power tube is generally considered preferable in such services as small audio power amplifiers or power amplifiers in high-frequency radio transmitter circuits.

5.1. Physical Characteristics of Beam-power Tetrodes. Figure 5.1 illustrates the type of construction ordinarily employed in beam-power tetrodes. The cathode in this particular tube is of the indirectly heated type and is flat on both of the emitting sides. In transmitting-type beam-power tubes thoriated-tungsten filamentary cathodes are generally used. The control and screen grids are elliptical helices wound with the same pitch. In addition, the grid and screen wires are aligned, *i.e.*, the screen wires lie in the shadow of the control-grid wires.

The control grid, screen and plate are curved so that electrons approach perpendicularly all parts of the electrodes. The screen-plate distance is usually made somewhat larger than in ordinary screen-grid tetrodes or pentodes. Special electrodes known as beam-forming plates are located on opposite sides of the tube perpendicular to the flat sides of the cathode. In tubes with heater-type cathodes the beam-forming plates are usually connected internally to the cathode, whereas in tubes with filamentary cathodes the beam-forming plates are brought out to a base pin for an external connection. Figure 5.1 shows the symbols for beam-power tubes.

Some beam-power tubes are designed for service at frequencies as high as several hundred megacycles, whereas other tubes are designed principally for audio power amplification. They are built in sizes ranging from the miniature receiving type to medium-sized transmitter tubes. Figures 5.2 to 5.5 illustrate the diverse shapes and sizes in which beam-power tubes are built. They are similar in external appearance to pentodes.

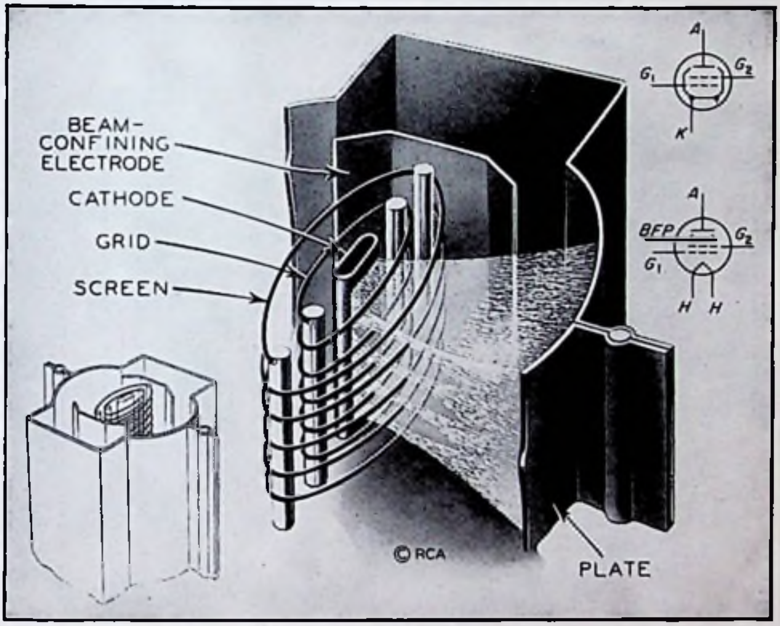

FIG. 5.1. A cutaway sketch of a beam-power tetrode showing the arrangement of the electrodes. (*Courtesy RCA.*)

5.2. Electrical Characteristics of Beam-power Tubes. Essentially the same circuit as that shown in Fig. 4.9 for obtaining the electrical characteristics of screen-grid tetrodes can be used for beam-power tubes. The beam-forming plates in filamentary-cathode tubes in which the plates are not internally connected should be operated at cathode potential. If the filaments are heated by alternating current, the beam-forming plates should preferably be connected to the center tap of either the secondary winding of the filament transformer or a low resistance shunted across the filament leads.

Plate Characteristics of Beam Tubes. The plate characteristics of beam-power tubes are similar to those of pentodes. There are several important differences, however, which make beam-power tubes superior in many applications. First, screen currents in beam tubes are generally much lower than in comparable pentodes. Whereas ratios of plate to screen current of 5 or 6 to 1 are typical of power pentodes, ratios as high as 15 or 20 to 1 are not uncommon

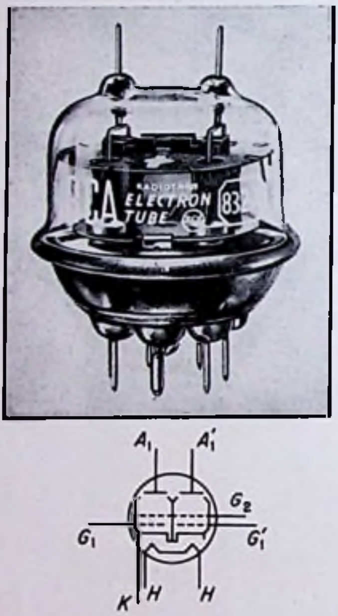

FIG. 5.2. A twin-beam power tube designed for push-pull amplifier or oscillator service at high frequencies. (*Courtesy RCA.*)

FIG. 5.3. A miniature receiving-type beam-power tube having a high-voltage heater for use in a-c/d-c radio receivers. (*Courtesy RCA.*)

for beam-power tubes. The latter types are consequently more efficient and as a rule have higher transconductances.

There are several other important advantages of beam-power tubes over pentodes, arising chiefly from the sharp shoulders on the plate-current–plate-voltage curves. The plate current rises rapidly as the plate voltage is increased from zero and levels off sharply at a substantially constant value. In linear power-amplifier service, beam tubes are capable of yielding high output powers at high efficiencies, since the *range* over which the plate voltage can be allowed to vary is very great, as a rule much greater than in the case of pentodes.

Figure 5.6 illustrates the principal differences between the characteristics of beam-power tubes and pentodes. Whereas the plate current of the pentode does not level off until the plate voltage exceeds 50 to 75 per cent of the screen-grid voltage, the plate current of the beam-power tube saturates for plate voltages as low

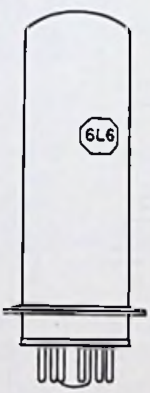

FIG. 5.4. A receiving-type beam-power tube having a metal envelope.

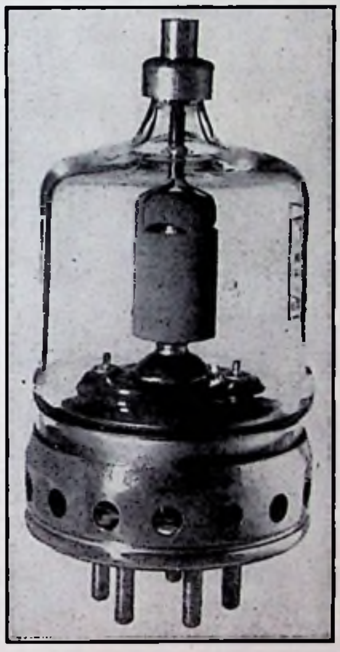

FIG. 5.5. A medium-power transmitting beam-power tube. (*Courtesy Eitel-McCullough.*)

as 20 to 30 per cent of the screen-grid voltage. The screen current of the beam-power tube drops more rapidly as the plate voltage is increased from zero.

The complete plate characteristics of an actual beam-power tube are shown in Fig. 5.7. The knees of the plate-current curves for positive control-grid voltages have unusual shapes. There may even be slight discontinuities at the knees of the curves. As the plate voltage is slowly changed in the neighborhood of the knees, the plate current may abruptly jump from one value to another. These effects are pronounced only for high current densities, such as occur at positive control-grid voltages. In the case of some beam-power tubes, the kinks at the knees of the plate-current curves do not occur for the electrode voltages commonly used. The plate current simply rises rapidly with plate voltage and saturates sharply.

Secondary-emission effects in well-designed beam-power tubes are hardly noticeable, except perhaps at very low current densities. In Fig. 5.7, the characteristic dips in plate current associated with

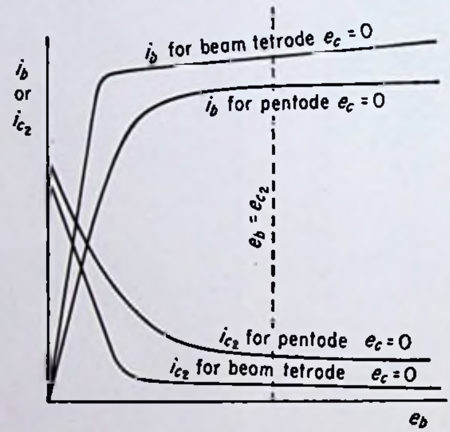

FIG. 5.6. Plate and screen currents plotted as functions of plate voltage for a pentode and a beam-power tube, showing the advantages of the latter.

screen-grid tetrodes for plate voltages lower than the screen voltage are apparent for plate currents lower than about 40 ma. The dips are not very pronounced, however, and are not objectionable because the tube is seldom operated in this region. Ordinarily, when the instantaneous plate current is low, the instantaneous plate voltage is much higher than the screen voltage.

Transfer Curves and Tube Coefficients for Beam Tetrodes. The transfer characteristics of beam-power tubes are very similar to those of ordinary tetrodes and pentodes. The curves in Fig. 4.13 are typical of beam-power tubes as well as ordinary screen-grid tubes.

The tube coefficients of beam-power tetrodes are compared with those of triodes and pentodes in Fig. 4.24. Compared to pentodes, beam-power tubes usually have a higher transconductance and a lower plate resistance. The higher transconductance is an advantage, as is the lower plate resistance in many applications.

5.3. Theories Used to Explain the Electrical Characteristics of Beam-power Tubes. The beam-power tetrode is similar in many respects to the ordinary screen-grid tetrode. The screen grid shields the plate electrostatically from the control grid and cathode. The plate-to-grid capacitance can be made low enough to permit

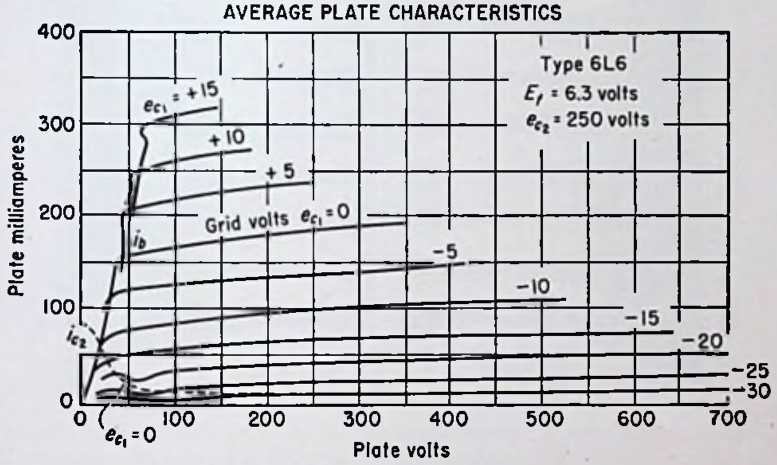

FIG. 5.7. Plate characteristics of a beam-power tube at negative and low positive control-grid voltages.

the tube to be used in radio-frequency circuits without neutralization, provided sufficient external shielding is used. (Neutralization is a process whereby the effect of the grid-to-plate capacitance is nullified, thus preventing instability and oscillation.) The low plate-to-cathode capacitance gives the tube a very high amplification factor, comparable to a pentode. The plate resistance, on the other hand, is generally lower than that of a pentode because there are only two grids instead of three shielding the plate from the cathode.

Alignment of Grid Wires. The low screen current in beam-power tubes results from the placement of the screen wires directly behind the control-grid wires. Furthermore, when the control grid is negative, the electrons are given a focusing action. By making the grid-screen spacing the same as the "focal length" of the "electron lens," a further reduction in screen current is obtained. Figure 5.8 illustrates the electron paths in a typical beam-power tube. The use of aligned grid and screen wires makes the current intercepted by the screen considerably lower than the value calculated on the basis of the projected area of the screen wires.

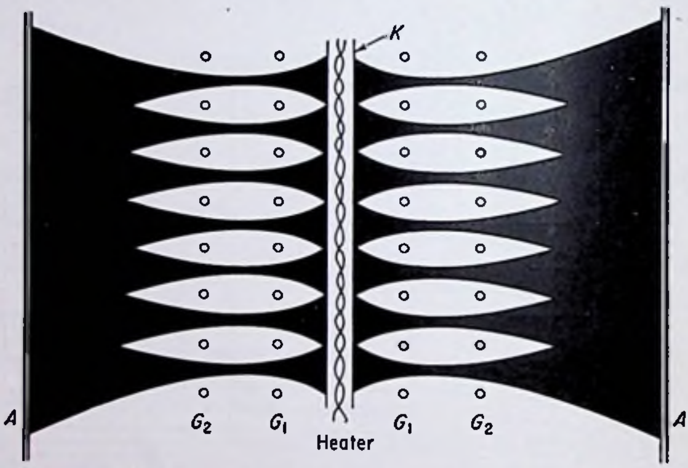

FIG. 5.8. Side view of a beam-power tetrode showing the focusing action of the control grid and the electron "beams" formed by the aligned control and screen grids.

The aligned control and screen grids also form the electrons into sheets or beams, hence the name "beam" tube. This beaming action causes less deflection of the electrons passing through the grids than occurs for pentodes. Also, since there are only two grids instead of three, the total deflection is less for beam-power tubes. Two important advantages accrue from the lower electron deflections. The shoulders of the plate-current–plate-voltage curves tend to be sharper, and fewer electrons return to the screen because of excessive deflection, thus helping to maintain a low screen current.

Action of the Beam-forming Plates. The elimination of secondary-emission effects can be explained on a qualitative basis by considering first the action of the beam-forming plates. Because they are at cathode potential, they prevent the beams from spreading out as they leave the screen grid. Figure 5.9 is a top view of a tube *without* the beam-forming plates, and Fig. 5.10 shows the effect of adding the plates. The function of the beam-forming plates is twofold. First, by concentrating the electron beams in a narrower path, the space charge is increased in the screen-anode region. This high space charge is responsible for the elimination of secondary-emission effects, as will be seen shortly. Second, any secondary electrons from the plate that try to reach the screen grid can do so only by traveling *through* the beams. They are prevented from reaching the screen *outside* of the beams by the

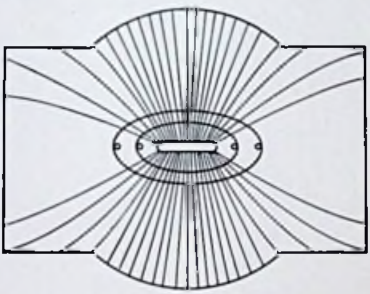

Fig. 5.9. Electron paths in a tube without the beam-forming plates.

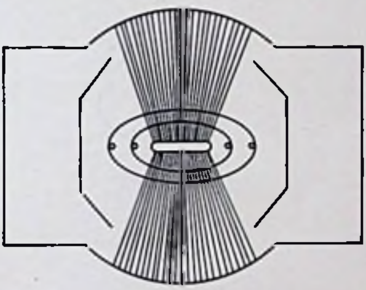

Fig. 5.10. Electron paths in a properly constructed beam-power tube.

beam-forming plates, which are bent so that their edges almost touch the beams.

Potential Model of a Beam Tetrode. The reason for the beaming action of the beam-forming plates can be made clear by studying the potential distribution in an idealized tube. In all the potential models considered so far, a section has been taken through the tube at right angles to the grid wires. In the beam-power tube, however, a section must be taken *parallel* to the grid wires in order to show the effects of the beam-forming plates.

Figure 5.11 shows a potential model of a beam-power tube taken in a plane midway between two sets of grid wires. The tube is considered to be a parallel-plane tube with plane beam-forming plates for the sake of simplicity. The complete model is symmetrical, and only one side of the potential surface is shown so that the nature of the surface can be seen more clearly.

The beam-forming plates "channel" the electrons from the cathode to the plate. Electrons which approach the beam-forming plates are repelled. The natural tendency of the beams to spread owing to the mutual repulsion of the electrons in the space charge is therefore prevented.

Space-charge Effects in the Screen-anode Region. Figure 5.11 represents the true conditions inside a beam tube only for high

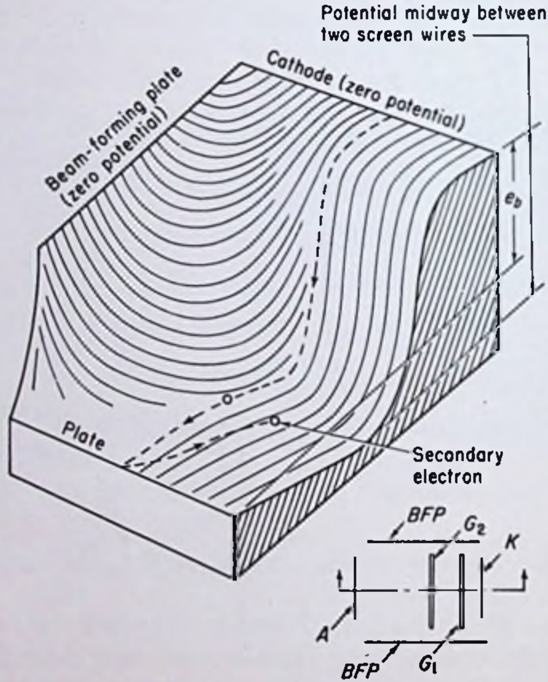

FIG. 5.11. An idealized beam-power tetrode and the corresponding potential distribution midway between the grid wires for $e_b < e_{c2}$ and space charge neglected.

negative grid voltages, corresponding to low plate currents. Under such conditions, secondary electrons are freely exchanged between screen and plate, as shown by the model in Fig. 5.11. The plate characteristic should therefore exhibit secondary-emission effects at low plate currents, as evidenced by the curves in Fig. 5.7.

For moderate and high plate currents, a modification of the space potential occurs in the screen-anode region owing to the presence of the space charge. Figure 5.12 shows the condition that may exist at moderate currents. A potential "hump" occurs between the screen grid and plate. The location of the hump depends on the relative voltages on the screen and plate. For equal voltages, the hump is theoretically midway between the two electrodes. If the hump is more negative by at least 20 volts than either the plate or screen, very few secondaries will be exchanged. This *potential minimum*, as it is called, is responsible for the absence of dips in the plate-current curves in Fig. 5.7 for moderate

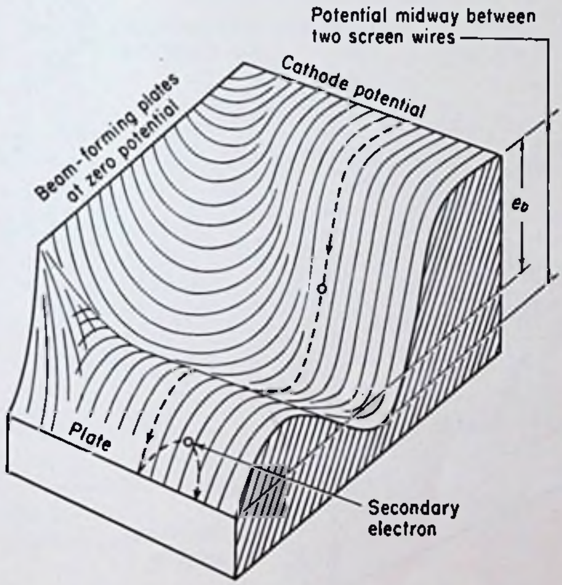

FIG. 5.12. A potential model of a beam-power tetrode for $e_b < e_{c_2}$ and a moderate plate current.

plate currents. Notice the "secondary marble" in Fig. 5.12 being returned to the plate.

There are several factors contributing to the creation of the potential minimum. It is found that a nearly parallel flow of electrons from the cathode to the plate is necessary. This condition is approximately fulfilled in an actual tube by the combination of aligned control and screen grids and the use of beam-forming plates. Another condition that is necessary is a large screen-to-plate spacing. A large spacing means a *greater number* of electrons in the screen-plate region. A greater number of electrons intercepts a greater number of flux lines from both plate and screen and thus lowers the flux density and field intensity between the two electrodes.

Another factor is the lower velocity of the electrons in the presence of the potential minimum caused by all the other factors. The electrons become packed more closely together at the potential minimum, a situation which might be compared to automobiles becoming packed more closely together on a steep hillside as a

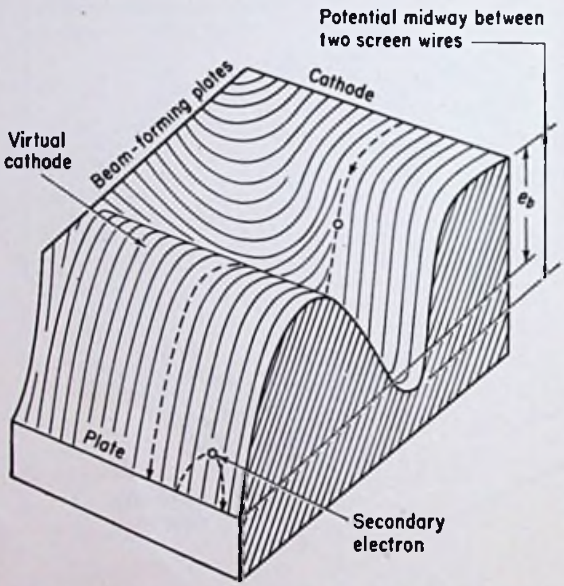

FIG. 5.13. A potential model of a beam-power tetrode for $e_b < e_{c_2}$ and a high plate current, causing a virtual cathode.

result of their reduced speeds. The increased electron density near the potential minimum lowers the potential still further in that region.

As the current density is increased past a certain point, the above effects become cumulative. The potential minimum lowers the electron velocities; this lowers the potential minimum; this lowers the electron velocities, etc. The potential minimum decreases until it reaches zero potential, thus creating a virtual cathode. Figure 5.13 illustrates the potential distribution for this condition. Not all the electrons which reach the virtual cathode pass on through and reach the plate. Some of them have insufficient energy to "get over the hump" and are returned to the screen. The virtual cathode acts as a velocity filter, passing only the electrons with the greatest energy directed toward the plate. This is the same situation existing near the cathode of any vacuum tube which is being operated under conditions of voltage saturation. Only the highest energy electrons emitted from the cathode penetrate the virtual cathode, the rest being returned into the cathode surface.

Potential Distribution in the Screen-anode Region. The potential distribution in the region between the screen grid and plate depends

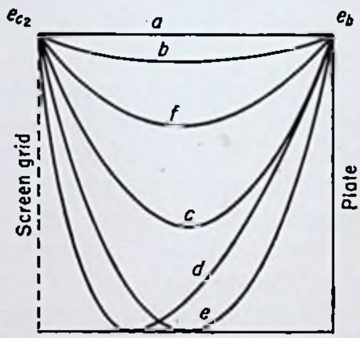

Fig. 5.14. Potential distribution in a beam-power tetrode for equal plate and screen voltages for various control-grid voltages.

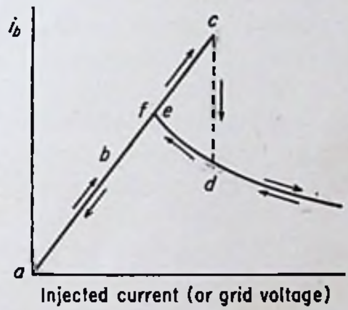

Fig. 5.15. Plate current in a beam-power tetrode as a function of the current injected from the screen (or the grid voltage).

upon the screen and plate potentials and *also* upon the manner in which the potentials were established. Likewise the plate current depends on the screen and plate potentials, but, for certain voltage ranges, upon the manner in which the potentials were established as well. This can be illustrated by observing the changes which occur in the potential distribution and plate current as the grid voltage is decreased from a high negative value. Figure 5.14 shows the successive changes in the potential distribution, and Fig. 5.15 shows the corresponding changes in plate current. The screen and plate potentials are assumed equal, but similar changes occur for unequal potentials. In Fig. 5.15 the plate current is plotted as a function of the current injected into the screen-anode region from the screen. Similar curves are obtained if the plate current is plotted vs. the grid voltage, because for fixed screen and plate potentials, the injected current is proportional to the grid voltage (measured in a positive direction).

Point *a* corresponds to a cutoff grid voltage giving zero plate current. The space charge in the screen-anode region is zero, and therefore the potential distribution from screen to plate is a straight horizontal line. As the grid voltage is made less negative, the injected current increases, the plate current increases by the same amount (since the two are equal in this region), and the potential becomes depressed by the presence of the space charge, as shown at *b*. As the grid voltage is made still less negative, point *c* is reached, which is a limiting condition. If an attempt is made to increase the plate current beyond the value obtaining at point *c*, the potential curve drops all the way to zero because of the cumulative effect of the decreasing electron velocities and corresponding decreasing potential curve. When the potential curve drops to zero, a virtual cathode is formed, and not all the injected electrons have enough energy to reach the plate. Therefore, the plate current drops to the value corresponding to point *d*, and the screen current increases. To the left of the virtual cathode, electrons are going both ways. Therefore the space charge to the left of the virtual cathode is very high, which shifts the virtual cathode closer to the screen, as shown at *d*. The change from the potential distribution at *c* to that at *d* occurs very quickly as the injected current is increased past the value corresponding to point *c*.

As the injected current is increased still further, the virtual cathode moves closer to the screen because of the increased space charge to the left of the virtual cathode. This *decreases* the plate current, just as the plate current in a diode is decreased as the cathode is moved farther from the plate.

If the injected current is now gradually reduced to zero, the potential-distribution and plate-current curves do not retrace their original paths. The plate current increases as the injected current is decreased until point *e* is reached. Notice that this value of plate current is not so high as the maximum value obtained for *increasing* injected current. At point *e*, virtually all the electrons are penetrating the virtual cathode and reaching the anode. Therefore, as the injected current is decreased still further, the plate current does not jump to a higher value as the potential curve jumps from the e condition to that at f. As the injected current is decreased from f to a, the plate current decreases correspondingly, and the potential curve flattens out to a straight horizontal line as the space charge goes to zero.

Reference to Fig. 5.7 shows that the above variations of plate current occur for low plate voltages. For a plate voltage of 50 volts, the plate current increases at first as the grid voltage is made less negative. The plate current is about 245 ma for a positive grid voltage of 10 volts. Notice, however, that the plate current is less than 200 ma for a positive grid voltage of 15 volts. Therefore, for 10 volts a potential minimum exists, but for 15 volts a

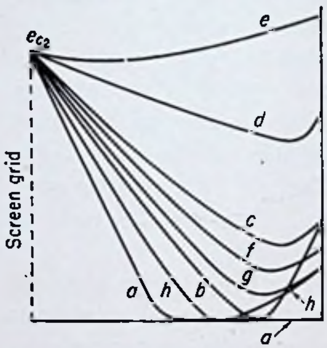

FIG. 5.16. Potential distributions in a beam-power tetrode for fixed screen and grid potentials and various plate voltages.

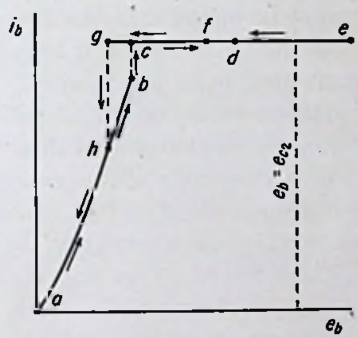

FIG. 5.17. Plate current vs. plate voltage in an idealized beam-power tetrode.

virtual cathode exists. All the plate-current curves overlap at low plate voltages. *This is not true of the plate-current curves of pentodes.*

Consider now the potential distributions for fixed screen and grid potentials and various plate voltages. Figure 5.16 shows successive potential curves for a high value of injected current, such as exists for positive grid voltages, as the plate voltage is increased from zero. Figure 5.17 shows the corresponding variations in plate current as a function of the plate voltage.

For zero plate volts, the plate current is zero. A virtual cathode exists near the plate, as shown by curve a in Fig. 5.16. The potential is zero between the virtual cathode and the plate. As the plate voltage is increased, the virtual cathode moves closer to the anode and the plate current increases correspondingly. Point b is the limiting condition for which a virtual cathode can exist. As the plate voltage is increased beyond the value corresponding to point b, the potential curve abruptly changes from b to c. The dotted line in Fig. 5.17 from b to c indicates a transient current condition. The jump in current is caused by the sudden elimination of the virtual cathode.

As the plate voltage is increased past the value corresponding to point c, the plate current does not increase in the idealized beam-power tube because the plate is completely shielded from the cathode and cannot influence the space current. All the injected current is being transmitted to the plate, and the plate current cannot be higher than the injected current.

As the plate voltage is lowered, the plate current remains constant until point g is reached. This point represents the limiting condition before a virtual cathode is established. As the plate voltage is lowered still further, the potential curve suddenly drops to zero, creating a virtual cathode once again. This causes a sudden drop in plate current because some of the injected current is returned to the screen from the virtual cathode.

There are two very important facts to be gained from a study of Figs. 5.16 and 5.17. First, notice that a potential *minimum* exists near the anode for all the points lying on the constant-plate-current line for plate voltages less than the screen voltage. This potential minimum is responsible for the absence of secondary-emission dips in the plate-current curves. Most of the secondary electrons from the plate are unable to "climb over" the potential barrier presented by the potential minimum. The curves in Fig. 5.16 correspond to *high* current densities. For low current densities, the potential minimum may not be negative enough to repel all the secondary electrons from the plate, and hence small dips may appear at low values of plate current.

The second fact to be gained from a study of the two figures is the rapid increase in plate current with plate voltage below the knee of the curve. Even if the virtual cathode were to remain stationary, the plate current would increase with the three-halves power of plate voltage. (This is Child's law applied to a beam-power tube with the virtual cathode near the anode acting as a cathode of a space-charge-limited diode and the plate acting as the plate.) However, the virtual cathode moves closer to the anode as the plate voltage is increased. Therefore, the plate current increases faster than the three-halves power of plate voltage. This accounts in a large measure for the sharp shoulders exhibited by the curves of plate current vs. plate voltage for beam-power tetrodes.

Figure 5.17 is for an idealized beam-power tube. Figure 5.7 shows the corresponding curves for an actual tube. The greatest deviation from the theoretical occurs near and above the knees of the curves. Instead of an abrupt change of current at the knees, the curve goes through a small S for high current densities. At low current densities, the kinks do not appear. Above the knees, the plate current rises slowly with increase of plate voltage owing to the imperfect shielding afforded by the screen.

PROBLEMS

1. Calculate the perveance of a parallel-plane beam tetrode having the following dimensions: $d_{kg_1} = 2.5$ mm, $d_{kg_2} = 6$ mm, $d_{kp} = 15$ mm, length of plate = 6 cm, width of plate = 4 cm. The cutoff amplification factor is 15. Express the answer in amperes per volt.$^{3/2}$ (Neglect the field distortion caused by the beam-forming plates.)

2. Calculate the perveance of a type 6L6 beam tube using the characteristic curves supplied by your instructor. The screen-grid amplification factor is 8. Check it at three or four different points on the curves, including one or two at very low plate voltages. Compare the answers.

3. Using the plate characteristics of a type 6V6 beam tetrode supplied by your instructor, plot a curve of space current vs. plate voltage for $e_c = 0$. (The curves must show screen as well as plate currents.)

4. From the plate characteristics for a type 807 beam-power transmitting tube supplied by your instructor, graphically compute μ, r_p, and g_m at grid and plate voltages of 0 and 350 volts, respectively.

5. A type 6L6 beam tetrode has a transconductance of 6,000 μmhos and a plate resistance of 22,500 ohms for a control-grid voltage of -14 volts and screen and plate voltages of 250 volts each. The corresponding plate and screen currents are 72 ma and 5 ma, respectively. If the plate voltage is raised to 350 volts and the control-grid voltage is changed to -18 volts, what are the new plate and screen currents? (Assume that the tube factors and the screen voltage remain constant. Also assume a constant current division between screen and plate.)

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CHAPTER 6

CATHODE-RAY TUBES

A TUBE which has proved valuable in many branches of science and engineering is the cathode-ray tube. It is the heart of the cathode-ray oscillograph, or *oscilloscope*, an instrument invaluable in the study of time-varying voltages and currents. The cathode-ray tube forms an indispensable part of every radar installation. In a special form known as the *kinescope* it is used in television receivers to give a visual reproduction of the scene being televised at the transmitting end. Television camera tubes also employ many of the same basic techniques utilized in the cathode-ray tube. The electron microscope is an outgrowth of the principles first formulated and utilized in the cathode-ray tube. Some of these same principles are also used in the construction of certain very-high-frequency tubes.

6.1. Physical Characteristics of Cathode-ray Tubes. There are many different forms in which cathode-ray tubes are constructed. All, however, have an *electron gun*, a *deflection system*, and a *fluorescent screen*, as shown in Fig. 6.1. The electron gun includes a thermionic cathode, a control electrode which controls the number of electrons being "shot" from the gun, an accelerating electrode which gives the electrons a high velocity, and a focusing system which directs the stream of electrons toward the fluorescent screen. The focusing system may be electrostatic, electromagnetic, or a combination of both. The deflection system allows control of the exact spot on the screen at which the beam of electrons impinges. This is achieved by deflecting the beam somewhere between the electron gun and the fluorescent screen. Either electrostatic, electromagnetic, or a combined system of deflection may be employed. The fluorescent screen converts part of the kinetic energy of the electrons in the beam into visible light energy. The spot at which the electron beam hits the screen is thus visible from the front of the tube.

Figure 6.2 illustrates a tube employing both electrostatic focusing and electrostatic deflection. The cathode is of the indirectly heated type and consists of a nickel cylinder, the *end* of which is coated with the emitting material, and a conventional heater inside. A slightly larger cylinder is usually placed around the nickel

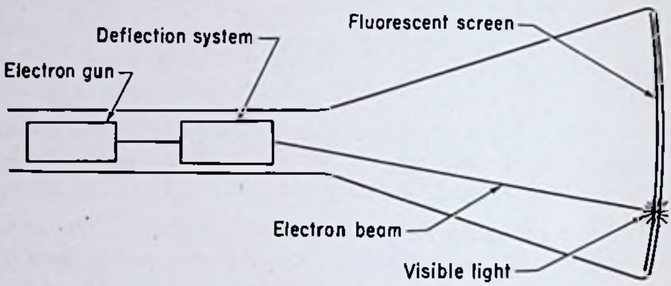

FIG. 6.1. The three basic components of cathode-ray tubes.

cathode to serve as a heat shield and to provide a rough focusing action on the emitted electrons. The shield is thermally insulated from the nickel cylinder near the emitting end but is at the same electrical potential as the cathode. The shield projects slightly beyond the end of the cathode to aid in the focusing action just mentioned.

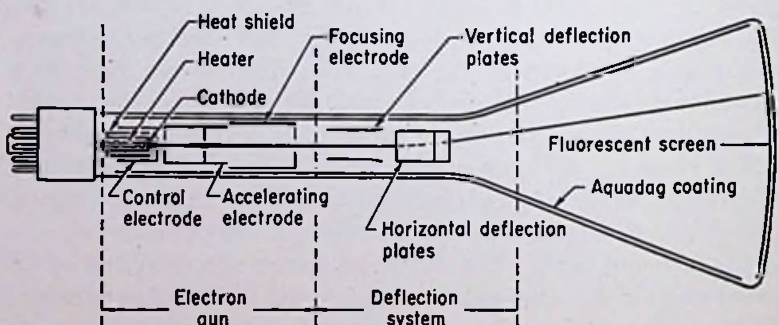

FIG. 6.2. A cathode-ray tube employing electrostatic focusing and electrostatic deflection.

The control electrode, sometimes called the grid, is a cylinder surrounding the heat shield with a single round hole in its end. The potential of the control electrode is usually within a few volts of the potential of the cathode. Variation of the grid potential allows control of the intensity or brightness of the luminous spot on the fluorescent screen.

The accelerating electrode, sometimes called the first anode, is a cylinder placed just beyond the control electrode. The end nearest the cathode is always closed except for a small hole at the center. In addition, one or more limiting apertures are sometimes placed inside the accelerating anode.

The focusing electrode, sometimes called the second anode, is a cylinder usually somewhat larger than the first anode and located beyond the first anode. The first and second anodes constitute an electron "lens" system. The names "accelerating electrode" and "focusing electrode" are misnomers because both electrodes accelerate the electrons and both electrodes are essential for proper focusing action. As a matter of fact, the beam is generally focused by varying the voltage on the first anode, even though the second anode is called the focusing electrode. The second anode usually contains a limiting aperture at the output end and may contain others throughout its length.

The deflection system shown in Fig. 6.2 consists of two pairs of "deflecting plates," as they are called. The *average* potential of both pairs of plates is made equal to the second-anode potential. A potential *difference* between the two plates in either set deflects the electron beam passing through. The two pairs of plates are at right angles, one set being located farther down the neck of the tube than the other. Under the usual conditions of operation, the tube is oriented so that one pair of plates produces a vertical or up-and-down displacement of the beam, whereas the other pair produces a horizontal beam deflection. The former plates are called the vertical deflecting plates and the latter the horizontal deflecting plates.

The plates are seldom parallel throughout their entire length but are generally flared out toward the screen. This prevents interception of the electron beam by the plates for large deflections.

The fluorescent screen consists of a thin layer of crystals of one of a group of materials known as phosphors. The factors governing the choice of phosphor for any particular tube are the desired "persistence" characteristics, the color of the emitted light, the secondary-emission characteristics, the luminous efficiency, and the resistance to screen burning or fatigue. The term "persistence" refers to the light emitted from the phosphor *after* the electron bombardment of the screen has stopped. This afterglow is called *phosphorescence*, and it should be carefully distinguished from fluorescence, which refers to the light emitted *during* electron bombardment. Screens are sometimes classified as long-persistence, medium-persistence, and short-persistence, according to the length of time they phosphoresce.

The fluorescent screen, besides converting part of the beam energy into light energy, plays an additional role in the operation of the tube. Since the phosphor and the glass walls of the tube are good insulators, some means other than solid conduction must be provided for the electrons to return to the cathode. This return path is by means of secondary electrons emitted from the

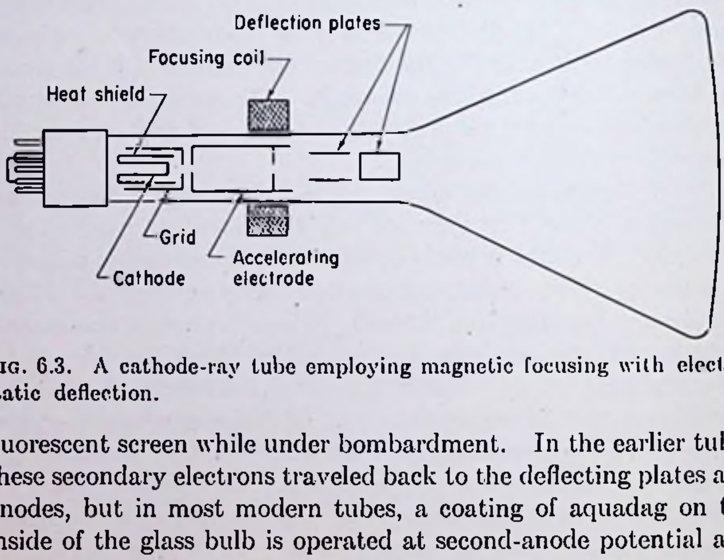

FIG. 6.3. A cathode-ray tube employing magnetic focusing with electrostatic deflection.

fluorescent screen while under bombardment. In the earlier tubes these secondary electrons traveled back to the deflecting plates and anodes, but in most modern tubes, a coating of aquadag on the inside of the glass bulb is operated at second-anode potential and serves to attract the secondary electrons. The aquadag coating usually extends from the base of the tube almost to the fluorescent screen. It also serves as an effective electrostatic shield for the tube by preventing stray electric fields from influencing the electron beam.

Magnetic focusing of the beam of electrons on the fluorescent screen can be achieved by placing a solenoid around the neck of the tube near the end of the accelerating electrode. Only one anode is required in this case, its sole purpose being to accelerate the electrons to a high velocity. Figure 6.3 shows the physical arrangement of parts usually employed for magnetic focusing. An iron path for the flux is sometimes provided to help in shaping the field.

It is also possible to obtain a combined electric and magnetic focusing action. Figure 6.4 shows one possible arrangement. Two anodes are used, just as in an electrostatically focused tube, but a magnetic focusing coil is also placed around the neck as in a magnetically focused tube.

The arrangement of electrodes used in the electron gun of the tube shown in Fig. 6.2 suffers from a fairly serious defect. It is found that the focus and intensity controls are not independent. Variation of the grid potential not only affects the intensity of the spot on the screen but also the focus. Likewise variation of

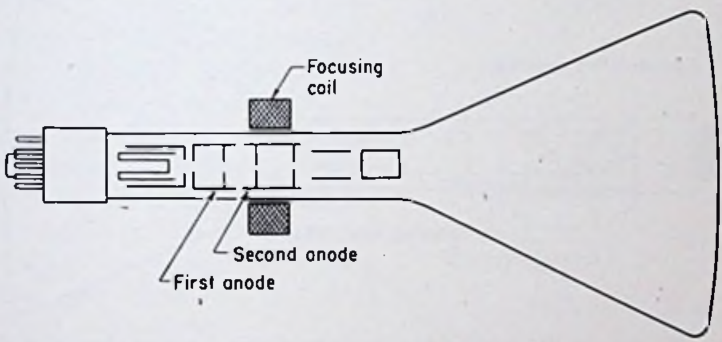

FIG. 6.4. A cathode-ray tube with combined electric and magnetic focusing.

the first-anode potential affects not only the focus but also the spot intensity. This is troublesome to the operator of the tube, since a simultaneous adjustment of both controls is necessary whenever a variation of either intensity or focus is desired. Even more serious is the defocusing effect in tubes in which a varying potential is applied to the control grid, as in television picture tubes.

This defect is not so serious in magnetically focused tubes, since the grid potential has little effect on the focus and the intensity is independent of the current in the magnetic focusing coil. By the use of special gun designs, it is also possible to correct the defect in a tube using pure electrostatic focusing. Figure 6.5 illustrates one arrangement which accomplishes this objective. The accelerating electrode is divided into two parts with the focusing electrode inserted in the middle. The part nearest the cathode serves to shield the control electrode from the focusing electrode, thus preventing any interaction between the two. The second part of the accelerating electrode, along with the focusing electrode, serves in a normal manner to accelerate the electrons and focus them on the screen.

It is possible to deflect the beam magnetically rather than electrostatically. This is achieved by using two pairs of coils, as shown in Fig. 6.6. One pair produces horizontal deflection, the other vertical deflection of the beam. The assembly of coils is referred to as the yoke, and it is designed so that it can easily be slipped over the neck of the tube from the base. Sometimes the coils are placed in slots in an iron frame, as in the stator of a-c machines.

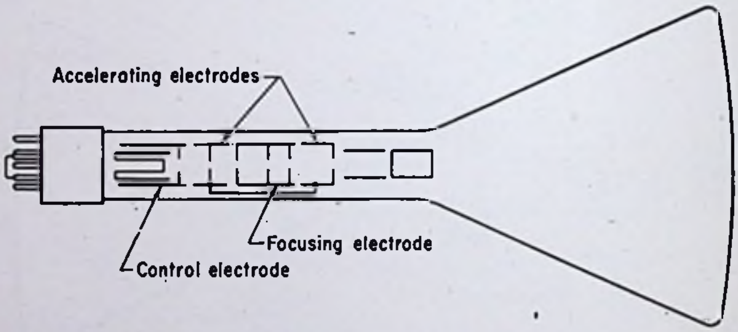

FIG. 6.5. A cathode-ray tube having electrostatic focusing electrodes designed to prevent interaction between focus and intensity.

An advantage of magnetic deflection is the shorter tube construction which it makes possible. This is an advantage in television picture tubes, and it is possible because of the greater deflection *angles* which can be achieved using magnetic deflection. As we shall later see, magnetic deflection has the additional advantage of less loss in deflection sensitivity as the beam velocity is increased.

An important disadvantage of magnetic deflection is the greater circuit complexity required. The instantaneous beam deflection is proportional to the instantaneous coil current. However, because of the inductance of the coil, the instantaneous coil current is *not* proportional to the instantaneous coil voltage. This limits the application of magnetic deflection to those cases wherein a simple linear deflection is desired, as in television tubes.

For oscillographic use, horizontal deflection of the beam magnetically is possible because of the desired linear time base. Vertical deflection must be accomplished electrostatically, however, in order to obtain a true reproduction of the impressed waveform.

Another disadvantage of magnetic deflection is the frequency limitation imposed by its use. The flux density causing the deflection is proportional to the coil *current*. As the frequency is increased, the impedance of the coils increases, necessitating a larger coil voltage and power to give the same deflection.

The brightness of the luminous spot on the screen is directly proportional to the beam velocity. As we shall see later, however, greater beam velocities necessitate larger deflection voltages, in the case of electrostatic deflection, or larger coil currents, in the case of magnetic deflection, to produce the same spot deflection on the screen. Hence a compromise must be made in any tube between high spot intensity and high deflection sensitivity. It will be shown in Sec. 6.4 that the deflection is inversely proportional to the first power of the beam voltage in the case of electrostatic deflection, but inversely proportional to the square root of the beam voltage in the case of magnetic deflection. Hence magnetic deflection is advantageous in tubes requiring very high beam intensity, such as television projection tubes.

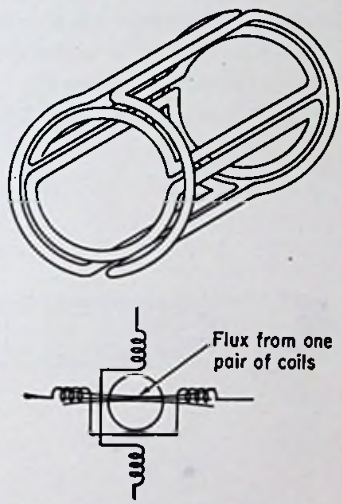

FIG. 6.6. Magnetic deflecting coils for magnetic deflection of the electron beam in cathode-ray tubes.

By employing what is known as postdeflection acceleration, some improvement can be obtained in tubes having electrostatic deflection. The principle consists in deflecting the beam while it is at a moderate velocity and accelerating it to higher velocities *after* it has been deflected. The deflection sensitivity is high because the beam is deflected at a moderate velocity, and the spot intensity is high because the beam velocity is high as it hits the screen.

The structure of a postdeflection-acceleration tube is shown in

Fig. 6.7 and is seen to be conventional except for the addition of an "intensifier" electrode adjacent to the fluorescent screen. The intensifier electrode is usually a conducting coating operated at about twice the potential of the second anode relative to the cathode. Such an arrangement gives the tube a deflection sensitivity several times as great as an ordinary tube having the same final beam velocity. A still greater improvement could be obtained were it not for the fact that the intensifier electrode exercises a convergent influence on the beam, as shown in Fig. 6.7.

6.2. Electrical Characteristics of Cathode-ray Tubes. A circuit suitable for investigating the electrical characteristics of a cathode-ray tube is shown in Fig. 6.8. A tube having both electrostatic

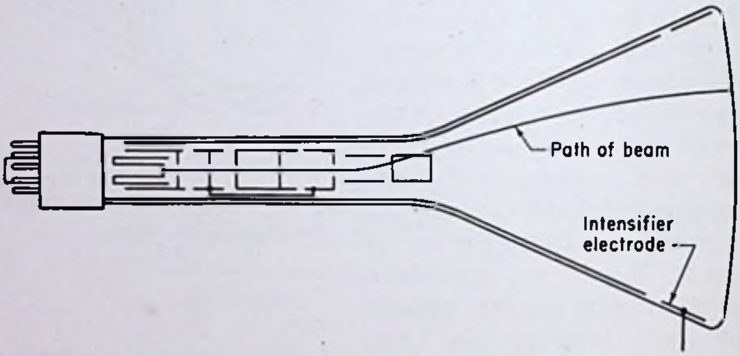

FIG. 6.7. A postdeflection-acceleration tube, showing the nonlinear beam path due to the intensifier electrode.

focusing and electrostatic deflection is assumed. The heater connections have been omitted for the sake of simplicity. The two pairs of deflecting plates are connected to two center-tapped resistors R_1 and R_2. The center taps of the two resistors are grounded, thus making the *average* voltage on each pair of plates zero with respect to ground.

It should be noticed that the cathode is *not* grounded in this circuit but is placed at a high negative potential relative to ground. The electrode which is grounded is the second anode. Therefore the average potential of each pair of deflecting plates is the same as that of the second anode. This is essential for proper deflection of the electron beam.

It is a common practice in cathode-ray-tube circuits to ground the second anode. By making such a connection, the deflecting plates, aquadag coating, and fluorescent screen are all near ground potential. This minimizes the possibility of electrocution of the operator and is advantageous in other ways as well.

Electrostatic Focusing. Assume that the circuit shown in Fig. 6.8 has been set up in the laboratory. With the vertical and horizontal deflecting-plate voltages set at zero, consider the influence of the first- and second-anode voltages. For any particular first-anode voltage (relative to the cathode), such as 100 volts, it

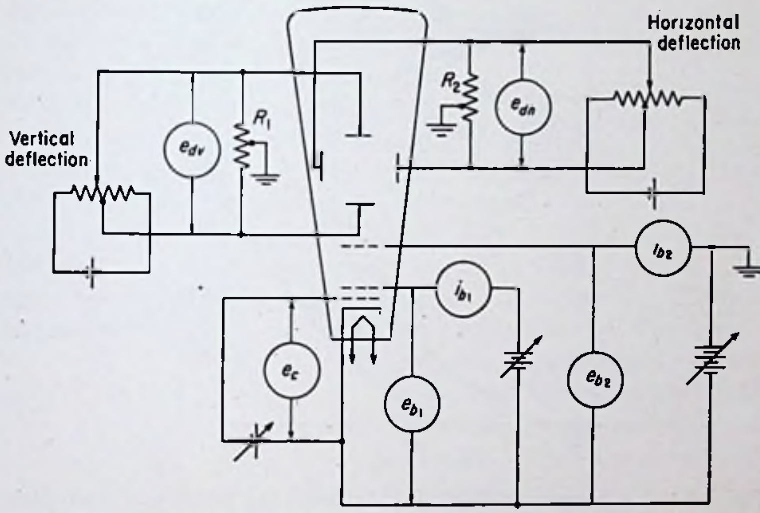

Fig. 6.8. A circuit diagram suitable for investigating the electrical characteristics of cathode-ray tubes employing electrostatic focusing and electrostatic deflection.

should be possible to obtain a fine focus on the screen for some particular value of second-anode voltage, such as 400 volts. If the first-anode voltage were increased to 200, it would be found necessary to increase the second-anode voltage to 800 in order to bring the beam back into focus. In other words, the *ratio* of the second-anode voltage to the first-anode voltage necessary to obtain a focus is a constant for any particular tube. Typical ratios of second-anode to first-anode voltage for commercial cathode-ray tubes lie in the neighborhood of 2 to 8.

The anode currents i_{b_1} and i_{b_2} are functions of the anode voltages

e_{b_1} and e_{b_2} and the control-electrode voltage e_c. We are largely concerned with a variation of these currents as a function of the control-electrode voltage for fixed anode voltages. Figure 6.9 shows the type of variation encountered in practice for two fixed values of second-anode voltage. This tube employs the type of construction illustrated in Fig. 6.5, which explains the low first-anode currents. The first-anode voltage is held constant in each case at the correct value for good focus. It should be noticed that the anode currents are in the neighborhood of 1 ma or less.

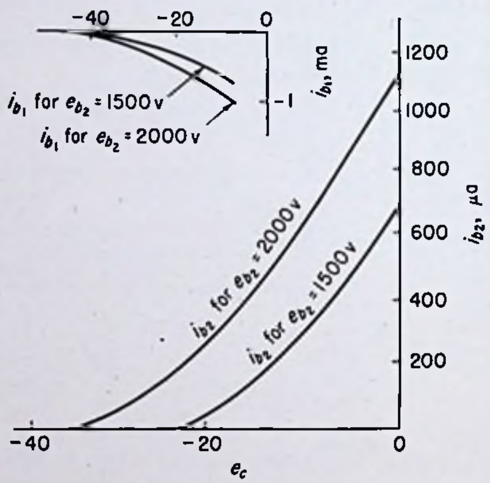

FIG. 6.9. Anode currents of a cathode-ray tube as a function of the control-electrode voltage.

The control electrode is ordinarily operated at a negative potential relative to the cathode, since it draws a current when operated at a positive potential.

More important than the variation in the anode currents is the change in the intensity of the spot on the screen with a variation of the control-electrode voltage. The beam current, or the electron current *emerging* from the second anode, is also a function of the control-electrode voltage. As the potential of the control electrode is made more negative, the beam current is reduced and the intensity of the spot on the screen is correspondingly reduced. Figure 6.10 illustrates the type of variation encountered in practice.

Electrostatic Deflection. Next consider the action of the deflecting plates. If the vertical and horizontal deflecting voltages e_{dv} and e_{dh} are set at zero, the electrons emerging from the second anode continue moving in a straight line to the screen. If the movable arm on the potentiometer in the horizontal deflecting circuit is set so that a difference of potential exists between the horizontal deflecting plates, the beam is deflected horizontally either to the right or left, depending on the polarity of the impressed voltage. Similarly, if the movable arm on the potentiometer in the vertical deflecting circuit is set so that a difference of potential exists between the vertical deflecting plates, the beam is deflected vertically either up or down, depending on the polarity of the impressed voltage. The beam is always deflected toward the positive plate. By using the proper combination of e_{dh} and e_{dv}, the spot of light can be caused to appear at any point on the face of the screen.

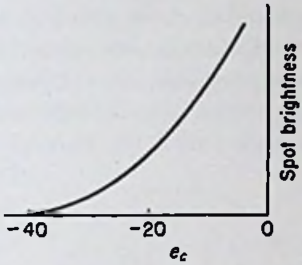

FIG. 6.10. Intensity of the luminous spot on the cathode-ray-tube screen as a function of the control-electrode voltage.

Figure 6.11 shows that the deflection is directly proportional to the deflecting voltage and inversely proportional to the second-anode voltage.

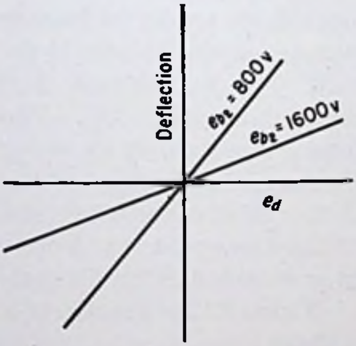

FIG. 6.11. Deflection of the spot on the face of a cathode-ray-tube screen as a function of the deflecting voltage. Either horizontal or vertical deflection is assumed.

A word of caution should be inserted concerning the spot of light on the screen. If the intensity of the spot is high and the beam is well focused, considerable heat is developed in the fluorescent material where the beam hits the screen. If the beam is allowed to remain too long on any one spot, the screen material may be burned, causing a discoloration and loss of sensitivity at that point. If either of the deflecting voltages e_{dh} and e_{dv} varies with time, the beam is not stationary, and there is little danger of screen burning. In the event the deflecting voltages must be made constant with time for any reason, either the intensity of the beam should be reduced or the spot should be defocused sufficiently to prevent screen burning.

Under ordinary conditions of operation, the spot of light is caused to move about on the face of the screen in accordance with the instantaneous values of the deflecting voltages. In most cases, the spot retraces the same path many times per second. If the repetition rate is sufficiently high, the persistence of the screen, coupled with the natural retentivity of the human eye, gives an illusion of a continuous *trace*, as the pattern is sometimes called. For a repetition rate less than about 30 cps with medium-persistence screens, noticeable flicker of the pattern occurs.

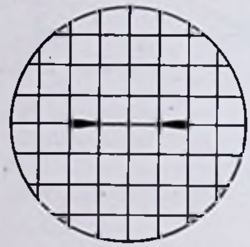

FIG. 6.12. The pattern on a cathode-ray-tube screen caused by impressing a sinusoidal voltage on the horizontal deflecting plates, illustrating the effect of spot speed on intensity and focus.

The speed of the spot moving across the face of the screen influences the characteristics of the trace in two important ways. First, as the speed is increased, the *intensity* of the trace decreases. Second, as the speed is increased, the focus appears to improve. For example, suppose a sinusoidal voltage were to be substituted for the battery and potentiometer in the horizontal deflection circuit. The trace would then be a straight horizontal line. The brightness of the line would vary from a minimum at its center to a maximum at both ends. For a sinusoidal deflecting voltage, the beam would be moving fastest at the center of the screen and slowest near the ends. The width of the line would vary from a minimum at its center to a maximum at both ends, thus illustrating the effect of beam speed on focus. Figure 6.12 is a sketch of a trace due to a sinusoidal deflecting voltage.

Magnetic Focusing. The basic circuit for a magnetically focused cathode-ray tube is given in Fig. 6.13. The circuit also differs from the one shown in Fig. 6.8 in that electromagnetic deflection is shown instead of electrostatic deflection.

The spot is focused in Fig. 6.13 by adjustment of the current in the focusing coil or by sliding the coil up and down the neck of the tube. Actually, magnetic focusing *can* produce results on a par with electrostatic focusing, with the advantage of practically no interaction between the focus and intensity controls. However, the design of a satisfactory focusing coil is rather complicated, and in practice electrostatic focusing is usually more convenient.

Electromagnetic Deflection. In the circuit of Fig. 6.13, the vertical deflecting coils produce a magnetic field in the tube which is *horizontal* and perpendicular to the electron beam. The beam is deflected either up or down, depending on the direction of the cur-

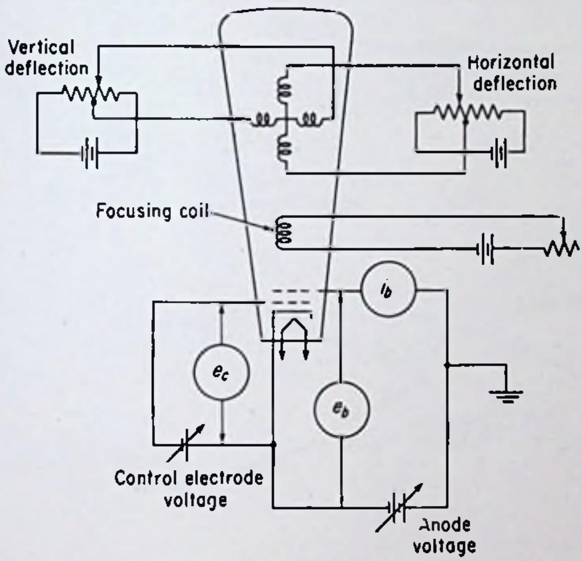

FIG. 6.13. A circuit diagram suitable for investigating the electrical characteristics of a cathode-ray tube employing magnetic focusing and electromagnetic deflection.

rent in the coils. Similarly, the horizontal deflecting coils produce a magnetic field which is *vertical* and perpendicular to the electron beam. The direction of deflection can be determined by the application of any one of several rules. A typical rule states that, if the thumb points in the direction of motion of the moving charge and the forefinger points in the direction of the magnetic field, the middle finger will point in the direction in which the moving charge is urged, provided the three fingers are mutually perpendicular, and provided the charges are moving perpendicular to the magnetic field. The right hand is used for a positive charge in motion, and the left hand is used for a negative charge in motion. Figure 6.14 shows how the rule may be applied to a cathode-ray tube employing electromagnetic deflection.

The deflection of the spot on the screen is proportional to the current in the deflecting coils provided the deflection is not too great. Some nonlinearity may occur for large deflections, as

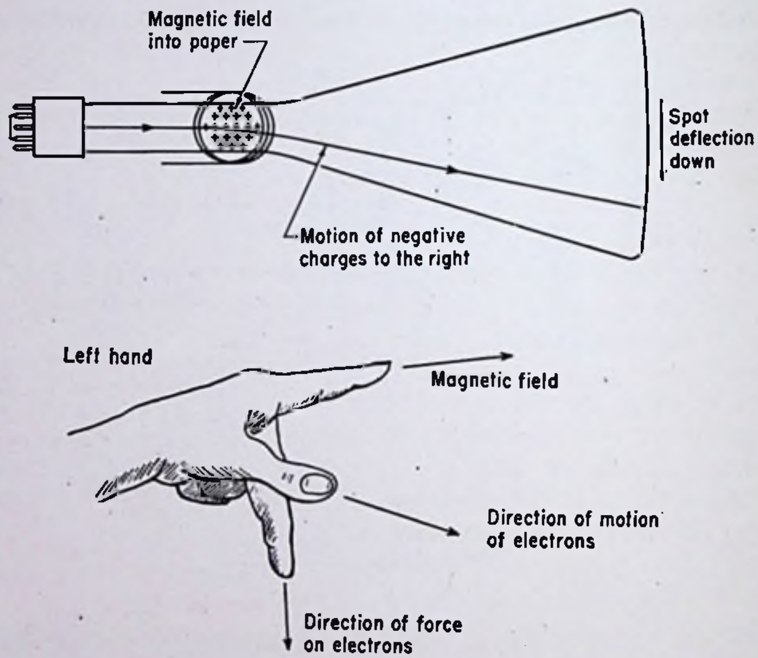

FIG. 6.14. The left-hand rule for magnetic deflection of electrons. (The right hand is used for positive charges.) Remember the fingers thus: Thumb is velocity (hitchhiking). Forefinger is Field (or Flux). Middle finger is the direction in which the charge tends to Move.

shown by the curves in Fig. 6.15. However, by proper design the deflection can be made almost a linear function of the coil current over the entire screen. The curves also show that the deflection varies inversely with the accelerating-anode potential, although the deflection is less influenced by accelerating voltage in this case than it was in the case of electrostatic deflection.

6.3. Theories Used to Explain the Electrical Characteristics of Cathode-ray Tubes. *Electron Guns.* A basic component of every cathode-ray tube is an electron gun, so named because it shoots electrons out in a thin stream, like bullets from a machine gun. A better analogy than a machine gun, however, is a camera. Figure 6.16 shows a point light source A, two limiting apertures, a lens B, and a screen C, upon which an image of the light source can be focused at point D. In a camera the screen is a photographic film, and point A is any point on the image to be photographed.

Figure 6.17 gives the basic elements of an electron gun and illustrates the focusing action obtained by means of the "electron lens," by analogy with the camera lens in Fig. 6.16. A point source of electrons (in the ideal case) is obtained a short distance in front of the cathode at point A. (Proper shaping of the cathode heat shield and the control electrode aids in producing a focusing effect at point A.) Electrons then are accelerated by the positive potentials applied to the first and second anodes and travel from point A through the holes in the limiting apertures on to the screen, where part of their energy is converted into visible light. Some of the electrons are, of course, intercepted by the baffles and never reach the screen.

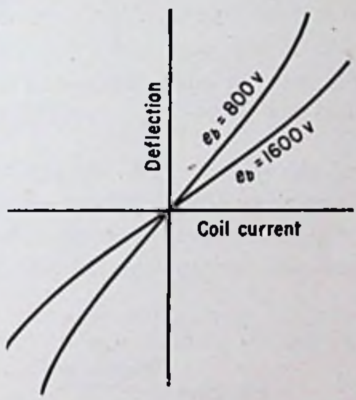

Fig. 6.15. A plot of deflection vs. coil current in a cathode-ray tube employing electromagnetic deflection.

The potentials on the anodes perform a dual function. First, the anodes are given high positive potentials relative to the cathode so that the electrons will attain a considerable velocity before reaching the fluorescent screen. Secondly, the proper combination of potentials on the anodes serves to produce an electric field inside the anodes which exercises a convergent or focusing effect on the beam of electrons passing through.

Theory of Electrostatic Electron Lenses. In contrast to the light lens, which has definite boundaries and is relatively thin, the electron lens has no distinct boundaries, and the focusing action is obtained throughout a considerable distance inside the cylindrical anodes.

The baffles in the anodes are actually not essential to the focusing action. They serve merely to intercept electrons which are far "off the beam," thus giving a sharper edge to the spot of light

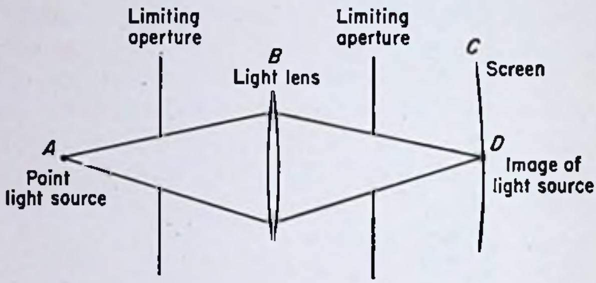

FIG. 6.16. A simple lens system illustrating focusing of a point source of light on a screen.

on the screen. The essentials of an electron lens consist simply of two cylinders, laid concentrically end to end. The diameters of the cylinders, although influencing the focal length of the lens, are not particularly critical. Conventional practice is to use a

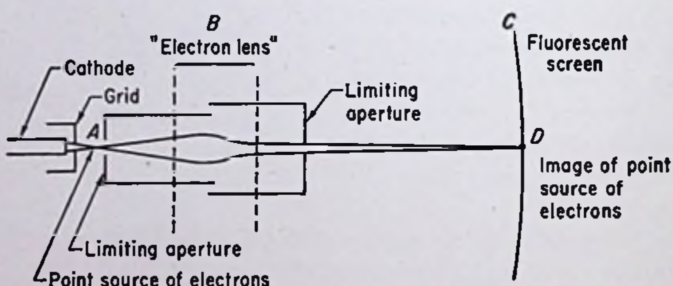

FIG. 6.17. A simple electron lens system illustrating focusing of a point source of electrons on a fluorescent screen.

second anode which is slightly larger in diameter than the first anode.

More important than the ratio of diameters is the ratio of voltages impressed upon the two cylinders. In order to provide a convergent beam emerging from the second anode, the potential difference between the second anode and cathode *must be larger* than the potential difference between the first anode and cathode.

This means that the electrons travel *faster* through the second anode than through the first anode. This fact should be kept constantly in mind as the discussion proceeds.

Consider now the potential distribution inside the two cylinders. Figure 6.18 is a sketch of the electrostatic field. An arrowhead at any point on a flux line indicates the direction in which a positive charge is urged if placed at that point. Negative charges are urged in a direction *opposite* to that of the arrowheads.

An electron moving to the right at point M in Fig. 6.18 is urged toward the axis of the cylinders. Thus the path of the electron from M to N is inward toward the axis. However, from N to O the electron is urged *away* from the axis. The electron lens thus exercises first a convergent influence on the electrons and then a

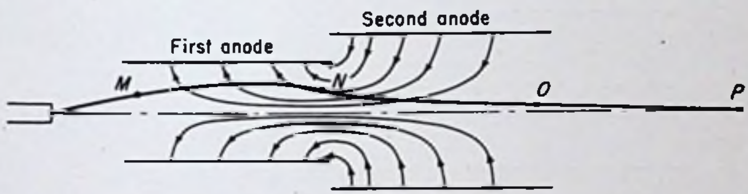

FIG. 6.18. The electrostatic field in an electron lens, showing the convergent action in the first anode and the divergent action in the second anode.

divergent influence. *However, when it is considered that the electrons are traveling much faster while inside the second anode than while inside the first anode, it can be seen that the convergent action is predominant and the electrons leaving the second anode cross the axis at some point P.* If the initial beam angle is small enough, all the electrons in the beam cross the axis at the same point P, regardless of their initial direction from point A in Fig. 6.17.

The focusing operation consists simply in moving the point P back and forth along the axis until it coincides with the inside surface of the fluorescent screen. In the camera setup of Fig. 6.16 the focusing operation consists in moving the lens back and forth until point D coincides with the surface of the film.

Theory of Magnetic Electron Lenses. So far in this text we have not considered the effect of a magnetic field on the motion of electrons. Qualitatively, the influence of a magnetic field can be summarized as follows:

1. A magnetic field cannot change the kinetic energy of a moving charge.

2. A magnetic field produces no force on a stationary charge, *i.e.*, stationary with respect to the field.

3. A magnetic field produces no force on a charge moving *parallel* to the field.

4. When a charge moving in a magnetic field has a component of velocity perpendicular to the field, a force is exerted on the charge at right angles to the magnetic field and to the direction of motion of the charge.

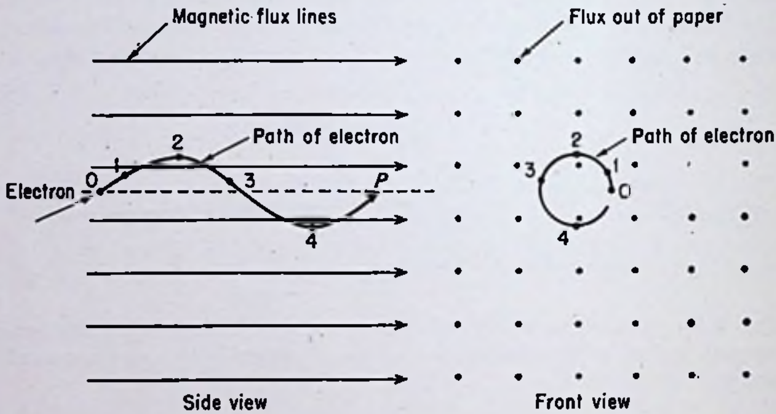

FIG. 6.19. Motion of an electron moving almost parallel to a uniform magnetic field.

5. The force on a charge moving in a magnetic field is proportional to the component of velocity perpendicular to the field, the magnitude of the charge, and the strength of the magnetic field.

Consider an electron moving almost parallel to a uniform magnetic field, as illustrated in Fig. 6.19. The motion of the electron is initially forward and up at point 0. Application of the left-hand rule for negative charges shows that the component of velocity perpendicular to the field urges the electron to the left (in the front view). The motion appears in the front view to be circular. In fact, if the component of velocity parallel to the field were zero, the motion *would* be circular. The actual path traced by the electron in Fig. 6.19 is a helix. In other words, the electron crosses the axis at point P after having completed one revolution.

In some electronic devices it is possible to employ a uniform magnetic field, as in Fig. 6.19, for focusing a stream of electrons. However, in cathode-ray tubes this is not practicable, and a slightly different arrangement must be used. If an axial magnetic

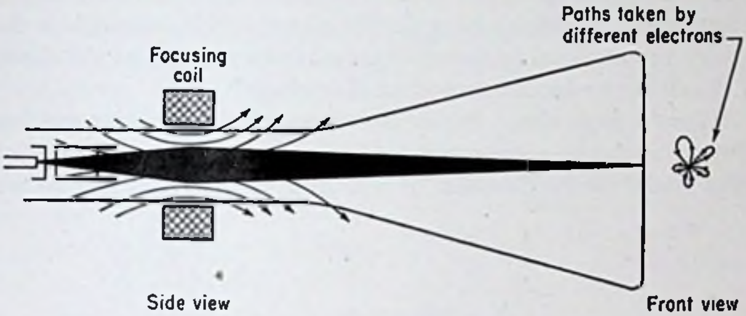

Fig. 6.20. Magnetic focusing of an electron beam by means of a short solenoid.

field is established throughout only a portion of the length of travel of the electrons, it is found that they are still bent sufficiently to cause them to recross the axis some distance down the tube, as in Fig. 6.20.

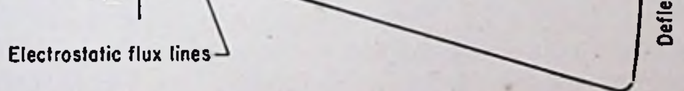

Fig. 6.21. Electrostatic deflection of an electron beam.

Electrostatic Deflection. In a tube employing electrostatic deflection, the electron beam, after emerging from the second anode, passes through the deflecting plates. Each pair of deflecting plates constitutes a simple capacitor. When a potential difference is impressed between the two plates, an electric field is set up across the intervening space, as in Fig. 6.21. The electrons are urged toward the positive plate while under the influence of the field, but travel in a straight line upon emergence from the field until they hit the fluorescent screen.

The amount of deflection of the spot on the screen is proportional to the length of the plates, the distance from the plates to the screen, and the voltage between the plates. The deflection is inversely proportional to the separation of the plates and the speed of the electrons (or the second-anode voltage).

Magnetic Deflection. It has been shown that an electron moving at right angles to a magnetic field has exerted upon it a force at right angles to the direction of motion of the electron and to the

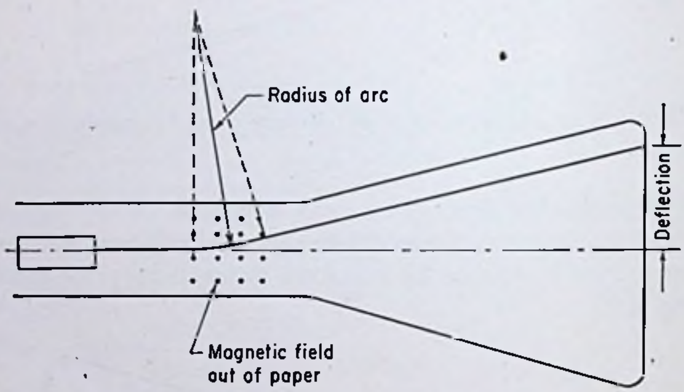

FIG. 6.22. Magnetic deflection of an electron beam.

magnetic field. In cathode-ray tubes employing magnetic deflection a magnetic field is set up perpendicular to the axis of the tube. Electrons passing through are bent in the arc of a circle, as shown in Fig. 6.22. Upon emerging from the magnetic field, they continue in a straight line to the screen. The amount of deflection is proportional to the flux density in the field (and hence to the current in the deflecting coils), the distance from the coils to the screen, the effective length of the field, and inversely proportional to the speed of the electrons (and hence to the second-anode voltage).

There is a serious drawback to magnetic deflection that has not been mentioned yet. In any vacuum tube there are bound to be a few negative ions produced by residual molecules acquiring additional electrons. In a cathode-ray tube a few negative ions are produced in the electron gun and are shot out with the electrons. Owing to their large mass, however, they are deflected only slightly by the magnetic field produced by the deflecting coils. The center of the fluorescent screen is thus under continual bombardment by these negative ions. A discoloration and loss of sensitivity is eventually produced at this spot, resulting in what is termed a "negative-ion blemish." When electrostatic deflection is used, the negative ions are deflected the same amount as the electrons, and no negative-ion blemish occurs.

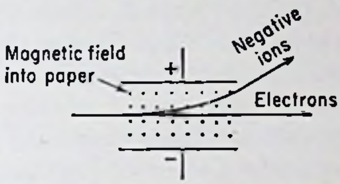

Fig. 6.23. A negative-ion trap used to prevent formation of a negative-ion blemish on the screen of a cathode-ray tube using magnetic deflection.

The difficulty can be overcome by using a so-called "ion trap," one of the simplest types of which is shown in Fig. 6.23. The beam, upon emerging from the second anode, passes through a

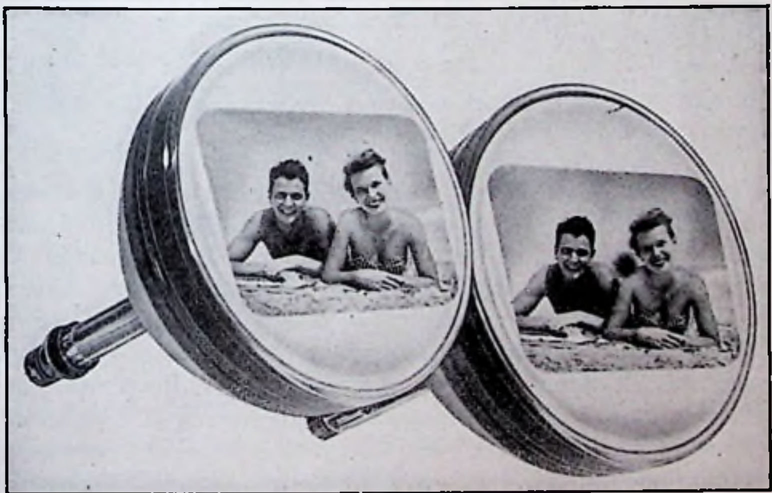

Fig. 6.24. Photographs showing the elimination of the negative-ion blemish by means of an ion trap. (*Courtesy Sylvania Electric Products, Inc.*)

pair of plates across which a constant difference of potential is maintained. A transverse magnetic field is also set up by appropriate coils mounted outside the tube The strength of the fields is adjusted so that the force on an electron due to the electrostatic field is equal in magnitude and opposite in direction to the force due to the magnetic field. Hence the electrons pass through the trap undeflected. The negative ions, however, are deflected appreciably, since the force due to the electrostatic field is much greater than the force due to the magnetic field. The negative ions are collected by a suitable electrode at second-anode potential. Figure 6.24 shows a television picture being displayed by two cathode-ray tubes employing magnetic deflection, one with and one without a negative-ion trap. Both tubes are assumed to have been in operation a considerable number of hours.

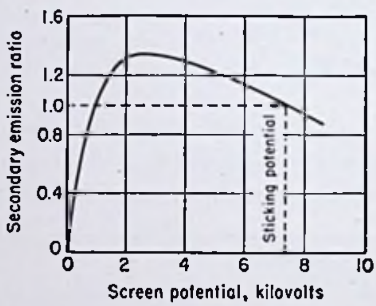

FIG. 6.25. Ratio of secondary to primary electrons as a function of screen potential for a typical cathode-ray-tube screen.

Importance of Secondary Emission. As the electrons in the beam hit the fluorescent screen, part of their energy is converted into light, part into heat, and part of it is imparted to electrons in the screen material, resulting in secondary emission from the screen. As shown in Fig. 6.25, the ratio of secondary to primary electrons depends on the velocity of the primary electrons as they hit the screen, which depends in turn on the potential of the screen relative to the cathode. The potential of the screen is determined somewhat by the secondary-emission ratio. In order to reach an equilibrium condition, the sum of the electrons entering the screen must exactly balance the sum of the electrons leaving the screen. If the secondary-emission ratio is greater than unity, the screen takes up a potential slightly more positive than the second anode and aquadag coating, and some of the emitted secondary electrons are attracted back into the screen. An equilibrium can be reached only as long as the secondary-emission ratio is equal to or greater than unity. The speed of the primary electrons ordinarily must exceed about 200 volts before this condition is obtained. At extremely high velocities, the screen must be negative relative to the second anode in order to slow down the arriving electrons sufficiently to make the secondary-emission ratio unity. The potential above which the screen cannot be raised is termed the "sticking potential." The sticking potential in Fig. 6.25 is about 7,300 volts.

Postdeflection Acceleration. Figure 6.7 shows a postdeflection-acceleration tube and the nonlinear path taken by the beam in reaching the screen. The reason for the curvature is the "lens" action exhibited by the intensifier electrode in conjunction with the aquadag coating. The intensifier electrode is at a higher potential than the aquadag coating, and thus an electric field is set up which exercises a convergent influence on the electron beam. This reduces the deflection sensitivity somewhat, but still represents a considerable improvement over ordinary tubes.

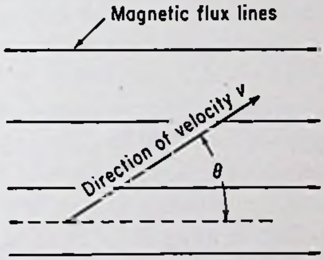

FIG. 6.26. A charged particle moving at an angle θ through a uniform magnetic field.

6.4. Mathematical Analysis of Cathode-ray Tubes. *Behavior of Charged Particles in Magnetic Fields.* In Fig. 6.26 consider a particle having a charge Q moving with a velocity v in a uniform magnetic field having a flux density B. The angle θ is measured between the direction of motion of the particle and the magnetic flux lines. The expression for the force on the particle is

$$f = BQv \sin \theta \tag{1}$$

The fundamental units in Eq. (1) are dynes for f, gauss for B, abcoulombs for Q, and centimeters per second for v. These units are fundamental in the cgs absolute magnetic system of units. An abcoulomb is 10 coulombs, or 3×10^{10} statcoulombs. A clear distinction should be drawn between the cgs electro*static* system of units and the cgs *ab*solute magnetic system of units. Both systems use the centimeter, the gram, and the second as the fundamental units of length, mass, and time, but almost all other units are different. The electrostatic system is based on Coulomb's law of attraction or repulsion between two point charges, whereas the absolute magnetic system is based on Coulomb's law of attraction or repulsion between two point magnets, or unit poles. The defining equations in both systems have no constants of proportionality, but, unfortunately, the more common units of electrical measurement in the two systems are not the same. Most of the units in the cgs electro*static* system have the prefix *stat-*, for example, statcoulomb, statvolt, etc. Most of the units in the cgs absolute magnetic system of units have the prefix *ab-*, for example, abcoulomb, abvolt, etc. Table V in the Appendix gives the conversion constants from one system to another.

The advantage of the mks practical system becomes apparent when we deal with electrostatic and electromagnetic quantities simultaneously. For example, in Eq. (1), the units in the mks system are newtons, webers per square meter, coulombs, and meters per second. One weber is 10^8 cgs maxwells. The common units of electrical measurement, such as coulombs, amperes, volts, etc., are fundamental in all equations when using the mks system. No conversion factors have to be applied when dealing with electrostatic and electromagnetic quantities simultaneously.

When using Eq. (1), it must be remembered that the force f is perpendicular to the magnetic flux lines and to the direction of travel of the particle. The sense of the force can be determined by applying the right-hand rule for positive charges and the left-hand rule for negative charges.

It will be recognized that $v \sin \theta$ in Eq. (1) is merely the *component* of v perpendicular to the field. If the electron motion is all perpendicular to the field, θ is 90 deg, $\sin \theta$ is unity, and

$$f = BQv \tag{2}$$

Equations (1) and (2) are similar to the equations for the force on a wire carrying a current in a magnetic field. In fact, the equations can be looked upon as saying the same thing from slightly different viewpoints. For a wire having a length l carrying a current I in a magnetic field having a flux density B, the force f is

$$f = BIl \sin \theta \tag{3}$$

where θ is the angle between the wire and the field. If Eq. (1) is applied to a straight wire carrying a charge Q a distance l in a time interval Δt, then the force given by the equation is the total average force acting on the length l of the wire. Equation (1) can then be written

$$f = BQ\frac{l}{\Delta t}\sin\theta \tag{4}$$

But $Q/\Delta t$ is by definition the average current over the interval of time Δt. Therefore Eq. (4) reduces to Eq. (3).

Example:

An electron is moving due north with a speed of 10^5 cm/sec through a magnetic field having a flux density of 1,000 gauss. The flux lines are oriented due north but point down at an angle of 30 deg to the horizontal. Find the magnitude of the force on the electron.

Solution in cgs units:

$$\begin{aligned} f &= BQv\sin\theta \\ &= (1{,}000)\ (1.6\times 10^{-20})\ (10^5)\sin 30° \\ &= 8\times 10^{-13}\text{ dyne} \quad \textit{Ans.} \end{aligned}$$

(The quantity 1.6×10^{-20} is the charge of an electron in *ab-coulombs.*)

Solution in mks units:

$$\begin{aligned} 10^5\text{ cm/sec} &= 10^3\text{ m/sec} \\ 1{,}000\text{ gauss} &= 1{,}000\text{ lines/cm}^2\times 10^{-8}\text{ weber/line}\times 10^4\text{ cm}^2/\text{m}^2 \\ &= 0.1\text{ weber/m}^2 \\ f &= BQv\sin\theta \\ &= (0.1)\ (1.6\times 10^{-19})\ (10^3)\sin 30° \\ &= 8\times 10^{-18}\text{ newton} \quad \textit{Ans.} \end{aligned}$$

The two solutions are the same, since 1 newton = 10^5 dynes.

Since the force on a moving charge in a magnetic field is at all times perpendicular to the direction of motion, a magnetic field cannot change the kinetic energy of the particle. The velocity of the particle remains constant in a magnetic field (provided there is no electrostatic field present also). If the particle is moving perpendicular to a uniform magnetic field, the path of the particle is a circle. The inward force holding the particle in a circular path is that due to the magnetic field. The outward centrifugal force, which must be equal in magnitude and opposite in direction to the inward force, is

$$f = \frac{mv^2}{r} \tag{5}$$

where m is the mass of the particle, v is its velocity, and r is the radius of the circular path along which it is traveling. Equating Eqs. (2) and (5) gives

$$BQv = \frac{mv^2}{r} \tag{6}$$

Solving for r yields

$$r = \frac{mv}{BQ} \tag{7}$$

Example:

An electron is moving perpendicular to a uniform magnetic field having a flux density of 50 gauss with a velocity of 6×10^6 cm/sec. Find the radius of the circular path taken by the electron.

Solution in cgs units:

$$\begin{aligned} r &= \frac{mv}{BQ} \\ &= \frac{(9.1 \times 10^{-28})(6 \times 10^6)}{(50)(1.6 \times 10^{-20})} \\ &= 6.82 \times 10^{-3} \text{ cm} \quad \textit{Ans.} \end{aligned}$$

Solution in mks units:

$$v = 6 \times 10^6 \text{ cm/sec} \times 10^{-2} \text{ m/cm} = 6 \times 10^4 \text{ m/sec}$$
$$B = 50 \text{ gauss} \times 10^{-4} \text{ weber/m}^2\text{/gauss} = 5 \times 10^{-3} \text{ weber/m}^2$$

$$\frac{m}{Q} = \frac{1}{1.76 \times 10^{11}} \text{ kg/coulomb}$$

$$\begin{aligned} r &= \frac{mv}{BQ} \\ &= \frac{6 \times 10^4}{(5 \times 10^{-3})(1.76 \times 10^{11})} \\ &= 6.82 \times 10^{-5} \text{ m} \quad \textit{Ans.} \end{aligned}$$

It should be noticed that if two particles have the same charge and move through the same magnetic field with the same velocity, the particle having the larger mass will travel in a larger circle.

It is informative to consider the length of time required for a charged particle moving perpendicular to a uniform magnetic field to complete one revolution. The time t required for a particle moving with a velocity v to travel a distance s is

$$t = \frac{s}{v} \tag{8}$$

Let s be the circumference of the circle in which the particle is moving. Then t becomes the period, T.

$$T = \frac{2\pi r}{v} \tag{9}$$

Solving for v in Eq. (7) and substituting into Eq. (9) gives

$$T = \frac{2\pi m}{BQ} \tag{10}$$

It should be noticed that the period is independent of the velocity of the particle and the radius of its path. Thus two particles having the same charge and mass and moving through the same magnetic field will rotate the same number of revolutions per second irrespective of their relative velocities. The one having the higher velocity simply moves in a larger circle.

If a charged particle has a component of velocity parallel to a magnetic field, the parallel component is uninfluenced by the field. If the magnetic field is uniform, the particle travels in a helical path, which is a circular motion due to the perpendicular component of velocity combined with a translational motion due to the parallel component of velocity.

The focal length of a magnetic lens due to a uniform magnetic field can now be determined. The focal length is simply the pitch of the helix. The electron travels a distance equal to the helix pitch in a time interval equal to the period of its circular motion. Stated in mathematical terms,

$$T = \frac{l}{v \cos \theta} \tag{11}$$

where $v \cos \theta$ is the component of velocity parallel to the field and l is the pitch of the helix. Equating Eqs. (10) and (11) gives

$$\frac{2\pi m}{BQ} = \frac{l}{v \cos \theta} \tag{12}$$

Solving for l,

$$l = \frac{2\pi mv}{BQ} \cos \theta \tag{13}$$

If θ is very small, $\cos \theta \simeq 1$, and Eq. (13) reduces to

$$l = \frac{2\pi mv}{BQ} \tag{14}$$

Example:

Calculate the strength of a uniform magnetic field required to focus a stream of electrons at a distance of 10 cm from their point source if they enter the field with a velocity of 5×10^9 cm/sec.

Solution in mks units:

From Eq. (14),

$$\begin{aligned} B &= \frac{2\pi mv}{lQ} \\ &= \frac{(2\pi)(5 \times 10^9 \times 10^{-2})}{(10 \times 10^{-2})(1.76 \times 10^{11})} \\ &= 1.785 \times 10^{-2} \text{ weber/m}^2 \\ &= 178.5 \text{ gauss} \quad \textit{Ans.} \end{aligned}$$

A magnetic lens consisting of a short solenoid is much more difficult to analyze mathematically than the uniform-magnetic-field lens. However, it should be evident that the flux density required of the short solenoid is appreciably higher than that given by Eq. (14).

Electrostatic Beam Deflection. Consider two parallel plates having a length l and separated a distance d, as in Fig. 6.27. Let the origin be located as shown, and assume an electron is traveling to the right from the origin with an initial velocity in the x direction of v_{0x} and an initial velocity in the y direction of v_{0y} equal to zero.

If a potential difference is established between the two plates, an electric field will be set up. Assuming no fringing of flux, the field

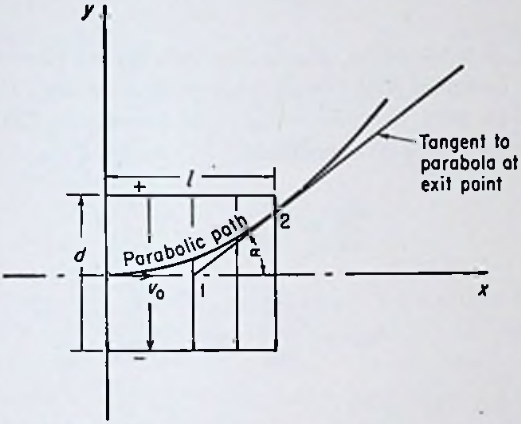

FIG. 6.27. A beam of electrons being shot into a uniform electrostatic field.

intensity $\mathcal{E}$ is given by the equation

$$\mathcal{E} = \frac{V_d}{d} \tag{15}$$

where V_d is the potential difference between the two plates. A force f_y is exerted on the electron in the y direction equal to

$$f_y = Q\mathcal{E} = Q\frac{V_d}{d} \tag{16}$$

thus causing an acceleration in the y direction, a_y, equal to

$$a_y = \frac{f_y}{m} = \frac{QV_d}{md} \tag{17}$$

Equation (17) can be written in terms of the velocity in the y direction v_y.

$$a_y = \frac{dv_y}{dt} = \frac{QV_d}{md} \tag{18}$$

or

$$dv_y = \frac{QV_d}{md}\,dt \tag{19}$$

Integration of Eq. (19) yields

$$v_y = \frac{QV_d}{md}\,t + K_1 \tag{20}$$

The constant of integration, K_1, is the velocity at time equal to zero. If it is assumed that the electron passes through the origin at time equal to zero, then $K_1 = v_{0y} = 0$. Equation (20) can be written in terms of the y coordinate.

$$\frac{dy}{dt} = \frac{QV_d}{md}\,t \tag{21}$$

or

$$dy = \frac{QV_d}{md}\,t\,dt \tag{22}$$

Integration of Eq. (22) gives

$$y = \frac{QV_d}{md}\frac{t^2}{2} + K_2 \tag{23}$$

The constant K_2 is the y position at $t = 0$, which is zero. Therefore Eq. (23) becomes

$$y = \frac{QV_d}{md}\frac{t^2}{2} \tag{24}$$

The electric field thus imparts to the electron a motion in the y direction. *At the same time, the motion in the x direction remains unchanged.* Thus the total velocity and energy of the electron increase with time. The velocity in the x direction, v_x, at any time is the same as the initial velocity in the x direction v_{0x}. Therefore the x position as a function of time is simply

$$x = v_{0x}t \tag{25}$$

Equations (24) and (25) describe completely the motion of the electron as a function of time. These are two parametric equations which may be solved simultaneously to eliminate the variable t. Solving for t in Eq. (25) and squaring gives

$$t^2 = \frac{x^2}{v_{0x}^2} \tag{26}$$

Solving for t^2 in Eq. (24) and equating to Eq. (26) gives

$$\frac{2myd}{QV_d} = \frac{x^2}{v_{0x}^2} \tag{27}$$

Solving for y gives

$$y = \left(\frac{QV_d}{2mdv_{0x}^2}\right) x^2 \tag{28}$$

which is the equation of a parabola. At point 2, x is equal to l, and Eq. (28) becomes

$$y_2 = \frac{QV_d\, l^2}{2mdv_{0x}^2} \tag{29}$$

In a cathode-ray tube employing electrostatic deflection the electron travels in a straight line after leaving the deflecting plates until it hits the fluorescent screen. In order to calculate the deflection on the screen, we must know the angle at which the beam leaves the deflecting plates and the apparent point from which the beam originates. In other words we must know α and x_1 in Fig. 6.27.

The equation for the tangent to a curve at any point x is found by taking the derivative of y with respect to x. Thus

$$\begin{aligned}\frac{dy}{dx} &= \frac{d}{dx}\left(\frac{QV_d x^2}{2mdv_{0x}^2}\right)\\ &= \frac{QV_d\, x}{mdv_{0x}^2}\end{aligned} \tag{30}$$

We are concerned with the slope of the curve at point 2 in Fig. 6.27, where the electron leaves the field. Equation (30) at this point becomes

$$\left(\frac{dy}{dx}\right)_2 = \frac{QV_d\, l}{mdv_{0x}^2} \tag{31}$$

The slope at point 2 is also equal to the tangent of the angle α. Hence

$$\tan \alpha = \frac{QV_d\, l}{mdv_{0x}^2} \tag{32}$$

From Fig. 6.27 it can be seen that

$$\tan \alpha = \frac{y_2}{l - x_1} \tag{33}$$

Substituting tan α from Eq. (32) and y_2 from Eq. (29) into Eq. (33) yields

$$\frac{QV_d l}{mdv_{0x}^2} = \frac{QV_d l^2}{2mdv_{0x}^2(l - x_1)} \tag{34}$$

Judicious cancellation leaves

$$1 = \frac{l}{2(l - x_1)} \tag{35}$$

Solving Eq. (35) for x_1 yields

$$x_1 = \frac{l}{2} \tag{36}$$

Thus the beam appears to originate at the midway point between the deflecting plates.

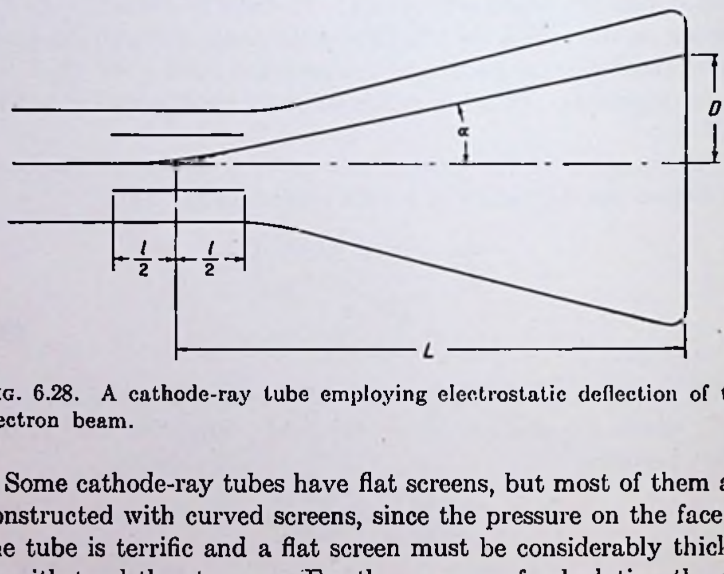

FIG. 6.28. A cathode-ray tube employing electrostatic deflection of the electron beam.

Some cathode-ray tubes have flat screens, but most of them are constructed with curved screens, since the pressure on the face of the tube is terrific and a flat screen must be considerably thicker to withstand the stresses. For the purpose of calculating the deflection, we may assume a flat screen with little error being introduced irrespective of the actual shape.

Referring to Fig. 6.28, it can be seen that the deflection D of the spot on the screen is related to the distance L from the center of the deflecting plates to the screen by the tangent of the angle α.

$$\tan \alpha = \frac{D}{L} \tag{37}$$

Equating Eqs. (37) and (32),

$$\frac{D}{L} = \frac{QV_d l}{mdv_{0x}^2} \tag{38}$$

$$D = \frac{QV_d lL}{mdv_{0x}^2} \tag{39}$$

The velocity v_{0x} is related to the second-anode voltage V_a by the equation

$$v_{0x} = \sqrt{2V_a \frac{Q}{m}} \tag{40}$$

Substituting Eq. (40) into Eq. (39) and simplifying gives

$$D = \frac{lLV_d}{2dV_a} \tag{41}$$

Any convenient units for l, L, and d can be used as long as they are the same, and D will be given in the same units. The *deflection sensitivity* is by definition the deflection per unit of deflecting voltage. If D.S. is used to denote deflection sensitivity,

$$\text{D.S.} = \frac{lL}{2dV_a} \tag{42}$$

The deflection sensitivity is usually expressed in millimeters per volt. The *deflection factor* is by definition the deflecting voltage per unit of deflection and is commonly expressed in volts per inch. If D.F. is used to denote deflection factor,

$$\text{D.F.} = \frac{2dV_a}{lL} \tag{43}$$

The horizontal and vertical deflection sensitivities of a cathode-ray tube are usually not the same because the value of L is different for the two sets of plates. For example, a certain tube has a sensitivity of 0.404 mm/volt for one pair of plates and 0.446 mm/volt for the other. The latter pair is obviously farther from the screen than the former.

It should be noticed in Eq. (42) that the sensitivity is inversely proportional to the first power of the second-anode or final accelerating voltage V_a. For example, the values given in the preceding paragraph correspond to an accelerating voltage of 1,500 volts. For 2,000 volts, the values are 0.303 and 0.334 mm/volt, or just three-fourths of the original values. Physically, the reason for the lower sensitivity at the higher voltage is to be found in the shorter transit time between the plates at the higher voltage, thus allowing the deflecting force to act for a shorter time interval and produce less deflection.

Example:

A certain cathode-ray tube has parallel deflecting plates 2 cm in length and separated a distance of 0.5 cm. The distance from the center of the horizontal plates to the screen is 40 cm, and the distance from the center of the vertical plates to the screen is 42.5 cm. Calculate the vertical and horizontal deflection sensitivities in millimeters per volt for an accelerating voltage of 1,500 volts.

Solution:

$$\begin{aligned}\text{Horizontal D.S.} &= \frac{lL}{2dV_a}\\ &= \frac{(2)(40)}{(2)(0.5)(1{,}500)}\\ &= 5.33 \times 10^{-2}\ \text{cm/volt}\\ &= 0.533\ \text{mm/volt} \quad \textit{Ans.}\\ \text{Vertical D.S.} &= 0.533\left(\frac{42.5}{40}\right)\\ &= 0.566\ \text{mm/volt} \quad \textit{Ans.}\end{aligned}$$

Magnetic Beam Deflection. In order to derive an equation for the amount of deflection due to a magnetic field, some simplifying assumptions should be made. Referring to Fig. 6.29, let us assume that the magnetic field is uniform throughout a circular region as shown. If the angle θ is small, then to an approximation we can write

$$\frac{D}{L} \simeq \frac{l}{r} \tag{44}$$

where l is the diameter of the field, r is the radius of the circular path, D is the deflection, and L is the distance from the center of the circle to the screen Substituting the value of r from Eq. (7), we obtain for the deflection

$$D = \frac{lLBQ}{mv_0} \tag{45}$$

where v_0 is the velocity due to the final accelerating voltage V_a. Substituting $\sqrt{2V_a(Q/m)}$ for v_0 into Eq. (45) and simplifying, we obtain

$$D = \sqrt{\frac{Q}{m}} \frac{lLB}{\sqrt{2V_a}} \tag{46}$$

The deflection sensitivity is by definition the deflection per unit of flux density, or

$$\text{D.S.} = \sqrt{\frac{Q}{m}} \frac{lL}{\sqrt{2V_a}} \tag{47}$$

It should be noticed in Eq. (47) that the deflection sensitivity is inversely proportional to the square root of the accelerating voltage, whereas the deflection sensitivity in the electrostatic case

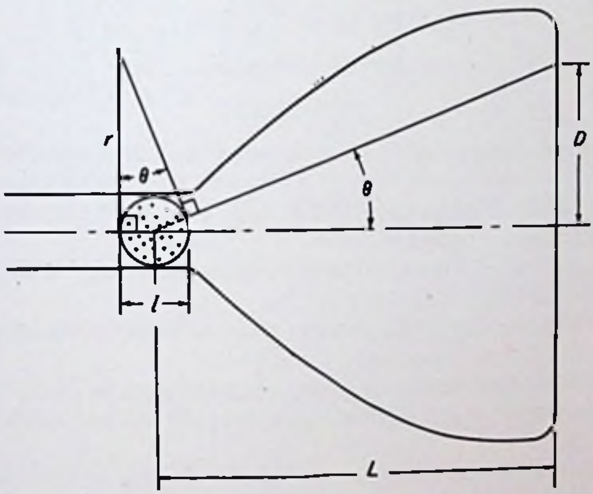

FIG. 6.29. Magnetic deflection of an electron beam.

is inversely proportional to the first power of the accelerating voltage, as shown by Eq. (42). Thus magnetic deflection is advantageous in tubes having extremely high accelerating voltages.

Example:

Find the flux density required to produce a deflection of 5 cm on a screen 35 cm from the center of a circular magnetic field having a radius of 3 cm. The accelerating voltage is 3,000 volts. Repeat for an accelerating voltage of 4,000 volts.

Solution using the cgs system:

$$D = \sqrt{\frac{Q}{m}} \frac{lLB}{\sqrt{2V_a}}$$

Solving for B,

$$\begin{aligned} B &= \frac{\sqrt{2V_a}\,D}{lL} \sqrt{\frac{m}{Q}} \\ &= \frac{\sqrt{(2)(3{,}000)}(5)}{(3)(35)} \sqrt{\frac{9.1 \times 10^{-28}}{1.6 \times 10^{-20}}} \\ &= 8.8 \times 10^{-4} \text{ gauss} \quad \textit{Ans.} \end{aligned}$$

For $V_a = 4{,}000$ volts,

$$\begin{aligned} B &= 8.8 \times 10^{-4} \sqrt{4000/3000} \\ &= 10.2 \times 10^{-4} \text{ gauss} \quad \textit{Ans.} \end{aligned}$$

PROBLEMS

1. Find the force acting on an electron moving with a velocity of 3.5×10^8 cm/sec perpendicularly through a magnetic field having a flux density of 3,000 gauss. Work the problem in both the cgs electromagnetic and the mks practical systems of units.

2. Work Prob. 1 if the electron is traveling at an angle of 60 deg with respect to the field.

3. Find the radius of the circular path followed by the electron in Prob. 1.

4. Find the revolutions per second of the electron in Prob. 1.

5. Find the radius and pitch of the helical path followed by the electron in Prob. 2.

6. Find the revolutions per second of the electron in Prob. 2.

7. Find the strength of a uniform magnetic field required to focus a stream of electrons at a distance of 6.5 in. from their point source if they enter the field with a velocity of 10^9 cm/sec. (Assume the electrons all enter almost parallel to the field.)

8. A certain cathode-ray tube has parallel deflecting plates 2.5 cm long and separated a distance of 0.65 cm. The distance from the center of the vertical plates to the screen is 51 cm, and the distance from the center of the horizontal plates to the screen is 54 cm. Calculate the vertical and horizontal deflection sensitivities in millimeters per volt for accelerating voltages of 1,250 and 1,600 volts.

9. Calculate the deflection factors of the tube in Prob. 8 for the given accelerating voltages. Express the answers in volts per inch.

10. How large can the screen be made in the tube of Prob. 8 before the beam becomes intercepted by the deflecting plates? (Assume the tube is to be so constructed that the beam can be directed to any point on the screen.)

11. If the tube of Prob. 8 has a 10-in. screen, how wide should the vertical deflecting plates be so that the beam always stays between the plates?

12. Find the flux density required to produce a deflection of 3 cm on a screen 30 cm from the center of a circular magnetic field having a diameter of 5 cm. The accelerating voltage is 2,500 volts.

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CHAPTER 7

GLOW-DISCHARGE TUBES

ALL OF the electron tubes discussed so far depend for their successful operation on the maintenance of an extremely high vacuum inside the envelope of the tube. Such tubes can properly be classified as "high-vacuum tubes." Another class of electron tubes depend for their successful operation on the maintenance of a certain amount of gas within the tube envelope. The pressures used in these gas tubes, as they are called, are usually low compared to atmospheric, but are ordinarily many times the pressures used in high-vacuum tubes. Although constructed along the same general lines, no difficulty should ever be encountered in distinguishing between the two types of tubes while they are in operation. Whereas the only visible effect inside a high vacuum tube is the light given off by the thermionic cathode, every gas tube, from the smallest to the largest, emits light in the space *between* the electrodes. The glow tube, as may be implied by the name, is no exception, and it will be discussed first because of its relative simplicity.

7.1. Physical Characteristics of Glow Tubes. A glow-discharge tube, or simply a glow tube, as it is sometimes called, consists essentially of two metallic electrodes enclosed within a chamber containing a certain gas or mixture of gases at a certain pressure. The particular configuration of electrodes and the pressure and kind of gas used depend somewhat on the use to be made of the tube.

A glow tube is unique among electron tubes in that usually either electrode can be the cathode. In other words, both electrodes are usually capable of providing a supply of electrons. There are exceptions to this rule, however; in some glow tubes one electrode is designed specifically to be used as the cathode under ordinary operating conditions, as will presently be shown.

Figure 7.1 shows one manner in which a glow tube could be constructed. A is the glass envelope; B is the gas inserted into the tube; and C and D are the two electrodes, the leads to which are brought out through the sides of the envelope.

The electrodes of a glow tube are usually constructed of nickel. Frequently one or both of the electrodes are coated with a special material having a low work function to provide operation at a lower voltage. The gas used must not react chemically with the electrodes. Ordinarily one of the inert gases is used, such as argon, neon, or helium.

Figure 7.2 shows an assortment of small neon glow lamps used principally for the production of light. They range in power from $\frac{1}{25}$ to 3 watts and are used for night lights, signal lights, Christmas tree lights, and voltage indicators. A number of different electrode configurations are noticeable in this group.

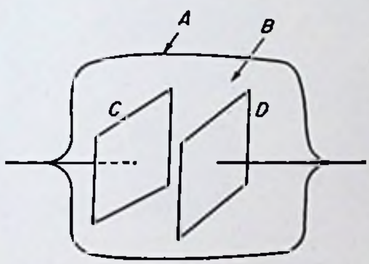


Fig. 7.1. A basic form of glow tube.

Figure 7.3 is a sketch and photograph of a glow tube designed specifically to be used as a voltage regulator. The tube is placed in the circuit so that the large cylinder is the cathode and the small axial wire is the anode. The short stub wire projecting from the cathode toward the anode allows the tube to "fire" or "break down" at a lower voltage than it could otherwise.

Actually, practically any glow tube can be used as a voltage regulator. However, tubes specifically designed for such service will give better results. Their characteristics are more stable over long periods of time, and the characteristics of a number of tubes of the same type are more uniform. In addition, the starter probe shown in Fig. 7.3 permits operation from a lower supply voltage. And last but not least, the voltage-regulator tubes give better voltage regulation, in general, than ordinary glow tubes.

If it is desired to use one of the glow lamps pictured in Fig. 7.2

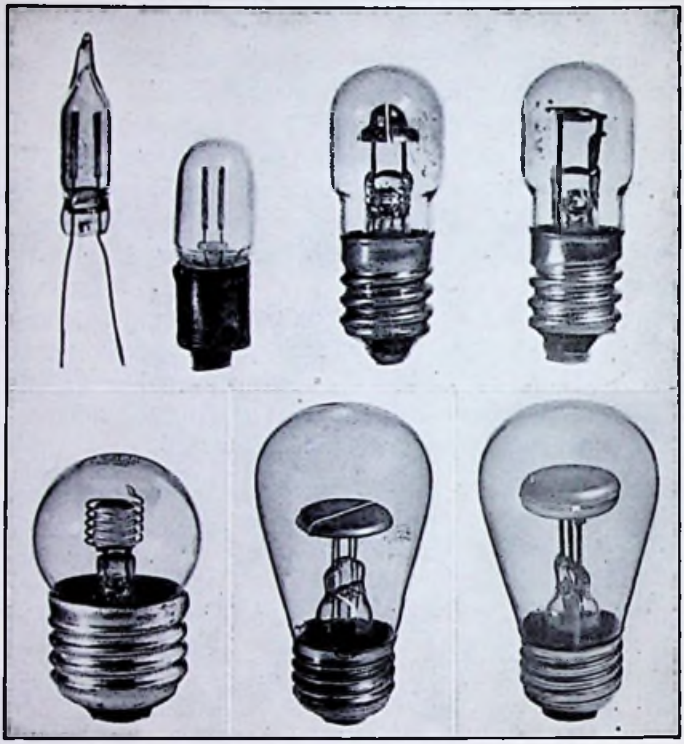


FIG. 7.2. A group of neon glow lamps. (*Courtesy General Electric Company.*)

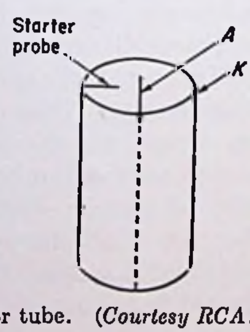


FIG. 7.3. A voltage-regulator tube. (*Courtesy RCA.*)

as a voltage regulator, inspection should be made to determine if a resistance has been added in series with the tube by the manufacturer. Ordinarily, a small resistor is placed in the base of the lamp in order to limit the current through the tube to the correct value. If such a resistor is found, it should be removed before the tube is used as a voltage regulator.

Another type of glow tube having a special application is shown in Fig. 7.4, the so-called T-R (transmit-receive) tube, used in radar systems in conjunction with wave guides and resonant cavities to switch a common antenna from a microwave transmitter to a microwave receiver. When the transmitter is turned on, the transmit-receive tubes in the system "fire" and, in effect, short the receiver terminals to prevent overloading the receiver. When the transmitter is off, the tubes stop functioning, and the antenna signal goes to the receiver.

Fig. 7.4. A T-R (transmit-receive) tube used in radar systems.

Another type of glow tube is designed specifically to be used as a modulated source of light. Such tubes are used for recording sound on film and for facsimile transmission. Figure 7.5 is a sketch of

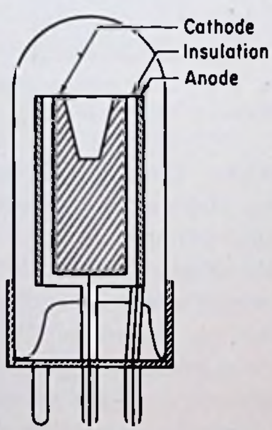


Fig. 7.5. Cross section of a glow tube used to produce a modulated light.

Fig. 7.6. Cold-cathode glow tube used as a variable light source. (*Courtesy Sylvania Electric Products, Inc.*)

such a tube, and Fig. 7.6 is a photograph showing the circular opening for the light exit. The cathode has a cone-shaped hole in which the light is produced, the amount of light being proportional to the current through the tube.

All the tubes discussed so far in this chapter are two-electrode tubes and are thus analogous to high-vacuum diodes, which were considered in Chap. 2. There are a few specially designed glow-discharge tubes which can be classified as triodes, in that they have three electrodes instead of two. One of these, the so-called grid glow tube, is shown in Fig. 7.7. The cathode is a large

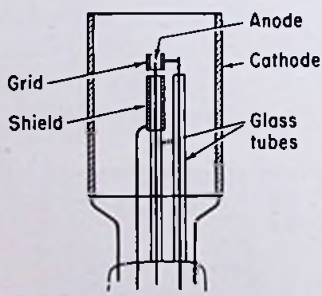


FIG. 7.7. Cross section of a grid glow tube.

FIG. 7.8. A starter-anode gas triode. (*Courtesy RCA.*)

cylinder surrounding the other electrodes. The anode is in the form of an axial wire, immediately above which is placed a control electrode, or "grid," in the form of a small cylinder or wire. The anode is provided with a metallic shield which is ordinarily connected to the cathode through a resistance of several megohms.

Another form of "cold-cathode triode" is shown in Fig. 7.8. This type of tube is sometimes called a starter-anode gas triode, and tubes of this nature find wide application in the telephone industry for relay purposes. In the particular tube shown the cathode is a large cylindrical surface. The anode is a short wire to the left of and parallel to the cathode, and the grid, or "starter anode," is a U-shaped piece of wire supported very close to the cathode surface. A slightly different arrangement of electrodes is sometimes used in which the cathode and starter anode are split halves of a circular disk.

An important distinction should be noted between the construction of high-vacuum thermionic triodes and cold-cathode gas triodes. The leads to the various electrodes in high-vacuum triodes are usually insulated only by the intervening vacuum. However, if this type of construction were employed in gas triodes, the tube would not function properly. Not only would current flow between the electrodes themselves, but in many cases, current would flow between the leads to the electrodes as well. This would

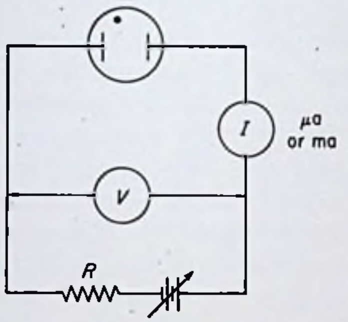


FIG. 7.9. A circuit diagram for investigating the electrical properties of glow tubes.

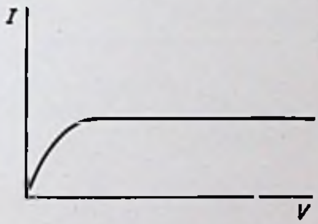


FIG. 7.10. Volt-ampere curve of a glow tube for low voltages.

probably upset the normal functioning of the tube and can be avoided by enclosing the leads in glass tubing, as in Figs. 7.7 and 7.8, or by otherwise suitably insulating those portions of the electrodes which are not supposed to take part in the discharge, as in Fig. 7.5.

7.2. Electrical Characteristics of Glow Tubes. A circuit suitable for investigating the electrical characteristics of two-element glow-discharge tubes is shown in Fig. 7.9. The black dot in the tube symbol denotes the presence of gas, as pointed out in Chap. 1 in connection with gas phototubes. The current instrument in the circuit should be capable of reading extremely minute currents but should be able to withstand several milliamperes without burning out. This is not readily achieved in a physical instrument, so that the extremely minute currents are seldom read in an ordinary laboratory.

The series resistance R is absolutely essential in the circuit to prevent damage to the equipment. It should be large enough so that if the full supply voltage were impressed across it, the resultant current would be only a little larger than the full-load current of the glow tube.

As the voltage V is gradually raised from zero, the current I behaves as shown in Fig. 7.10. The current is essentially zero with zero voltage and rises to an almost constant value for voltages above a few volts. The magnitude of the saturation current is extremely small, on the order of a microampere or less. In an actual physical setup, extreme precautions must be taken to prevent leakage current around the glow tube and through the insulation in the circuit. The tube current is so small that it is almost correct to say that the gas inside the tube is a perfect insulator. However, as small as this current may be, it plays a vital role in the initiation of the glow discharge itself, as we shall presently see.

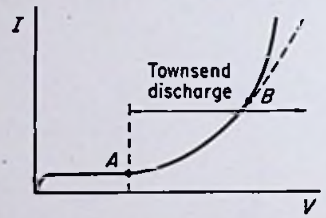


FIG. 7.11. A continuation of Fig. 7.10, showing the Townsend discharge.

Townsend Discharge. As the voltage is increased still further, there is eventually obtained an increase of current above the saturation value, as shown in Fig. 7.11. The action taking place in this region is termed the Townsend discharge. It should be noted that Fig. 7.11 is identical with the curves in Fig. 1.12, which are current-voltage curves for a gas-type phototube. The current in the phototube is due to photoelectric emission from the cathode, whereas the current in a glow tube is due primarily to ionization of the gas molecules by some form of radiation such as X rays or cosmic rays, although photoelectric emission from the cathode may play a part in some cases.

Breakdown. The actions in a glow tube which have been discussed up to this point are not self-sustaining, *i.e.*, the current is maintained because of the external source of ionization. If the tube could be completely shielded from all outside sources of radiation (a feat which actually would be well-nigh impossible), it would be found that the current through the tube would be zero. However, as the voltage is increased still further in the Townsend discharge region, a point is eventually reached where the current becomes self-sustaining; *i.e.*, the current cannot be reduced to zero by shielding the tube against outside sources of ionization. Referring to Fig. 7.12, as the voltage is increased past point 2, a sudden transition occurs to point 3, corresponding to a higher current and a lower voltage. This sudden transition is known as *breakdown*, and the voltage corresponding to point 2 is called the *breakdown voltage*. Actually, as will be pointed out in Sec. 7.3,

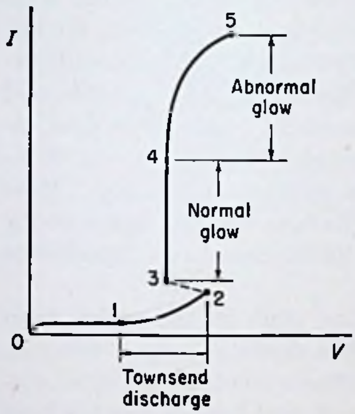


FIG. 7.12. A complete current-voltage curve for a glow tube, showing the regions of normal and abnormal glow.

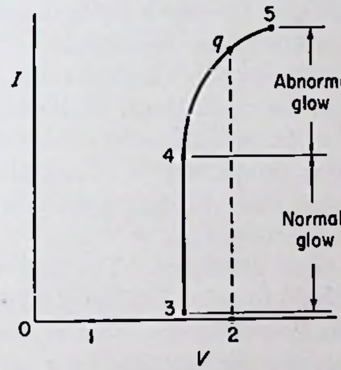


FIG. 7.13. The same curve shown in Fig. 7.12 but with a linear current scale.

there are certain conditions under which breakdown as described will not occur. A properly designed glow tube will, of course, break down.

The lower portion of the curve in Fig. 7.12 has been exaggerated in order to show the entire characteristics over a wide range of current and voltage values. If a linear scale for current is used, the curve from point 0 to point 2 lies for all practical purposes on the horizontal axis, and the curve appears as in Fig. 7.13.

The current flowing in the circuit of Fig. 7.9 after breakdown is determined almost entirely by the magnitude of the series resistance R. The tube itself has no current-limiting mechanism as does a high-vacuum diode. As R is made smaller and smaller, the current after breakdown becomes larger and larger, so that the actual operating point after breakdown may be anywhere along the curve 3-4-5 in Fig. 7.13 up to point q, corresponding to zero series resistance. If R is low enough, the current after breakdown may be so high that a dynamic arc may be formed at the cathode resulting in possible destruction of the tube. The series resistance is needed not only to protect the tube (and the other circuit elements as well) from damage due to excessive currents, but it may be necessary in order to obtain any permanent glow discharge at all.

The higher the series resistance, the lower the current after breakdown. However, if the resistance is made too high, the circuit goes through a series of cyclical variations of voltage and current known as "oscillations." This is not always undesirable, and circuits employing glow tubes are frequently used to produce relaxation oscillations, as they are called. (In order to have relaxation oscillations, a capacitor must shunt the glow tube. If no extra capacitance is added, the oscillations can still occur owing to the stray wiring capacitance and the interelectrode capacitance of the tube.)

Glow Discharge. The action taking place in the region from point 3 to point 5 in Fig. 7.12 is called a glow discharge. Whereas the Townsend discharge is nearly always invisible, the glow discharge is characterized by a soft fuzzy glow of light emanating from various portions of the tube. The color of the light depends principally on the kind of gas or gases contained in the tube. It also depends to a certain extent upon the pressure of the gas. If an alternating voltage is impressed across the tube, the color depends somewhat on the frequency of the applied voltage. Neon glow tubes produce an orange light at audio frequencies and a lavender light at radio frequencies.

Normal Glow. It can be seen from Fig. 7.12 that the voltage drop across the tube is relatively constant from point 3 to point 4. As an attempt is made to increase the voltage in this region, the current increases instead, and the increased voltage is absorbed across the series resistance R. The action taking place from point 3 to point 4 is called the *normal glow*, and it will be found that the size of the visible glow near the cathode surface increases from a minimum at point 3 to a maximum at point 4. At point 4 the entire cathode is covered with the glow, and any further increase of voltage and current past point 4 simply makes the glow brighter without much change in its size.

Abnormal Glow. From point 4 to point 5 the voltage drop across the tube increases as the current through the tube is increased. This is the region of *abnormal glow.* Ordinarily, glow tubes are operated only in the normal-glow region, one of the main reasons being the greater likelihood of damage to the tube, particularly to the cathode, in the abnormal-glow region. In many tubes the cathode is coated with a layer of barium and strontium oxide to reduce the work function of the surface, and such surfaces are very

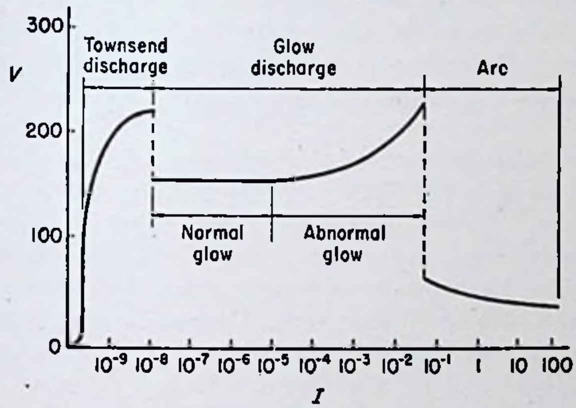


FIG. 7.14. Typical volt-ampere curve for a gaseous discharge tube, showing the various transition stages.

susceptible to damage at the higher voltages occurring in the abnormal-glow region.

Arc. Perhaps an even more important reason for avoiding the abnormal-glow region is the possibility of a sudden transition from the abnormal glow to a dynamic arc, the consequences of which have already been pointed out. Figure 7.14 shows the entire voltage-current curve for a typical gaseous discharge tube. The current scale is logarithmic, and current has been used as the independent variable instead of voltage. This is more in keeping with the characteristics of the tube, since a given voltage cannot ordinarily be established arbitrarily across the tube as for a high-vacuum tube. The voltage drop adjusts itself so that the tube can pass the *current* demanded by the rest of the circuit.

The transition point from an abnormal glow to an arc is not readily predictable, and hence the safest policy to follow in preventing an arc in a glow tube is to prevent an abnormal glow. However, if the cathode is not allowed to become excessively hot, high currents in the abnormal-glow region are permissible. Thus it is usually safe to permit high current pulses of short duration to pass through a glow tube, as when discharging a capacitor.

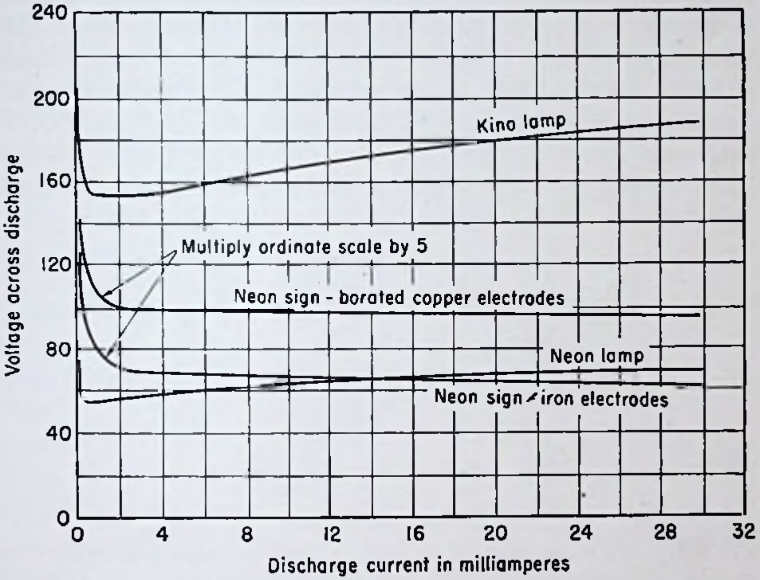
Extinction. As an attempt is made to lower the voltage across a glow tube that has fired, the current decreases instead and the voltage remains almost constant. The size of the glow at the cathode surface decreases as the current drops. At some value of current, called the *extinction current*, the glow discharge suddenly stops, and the operation shifts to the Townsend discharge region once again. The extinction current may be somewhat lower than the initial current flowing through the tube when breakdown occurs.

The current-voltage curves of several commercial glow-discharge tubes are given in Fig. 7.15.

Circuit and Characteristics of Grid Glow Tubes. A circuit suitable for obtaining the characteristics of a grid glow tube is shown in Fig. 7.16. The anode shield is connected to the cathode through a resistance of 5 to 10 megohms. Current-limiting resistors R_c and R_b are placed in series with the grid and plate leads, respectively. Notice that the grid supply voltage is polarized to make the grid *positive*, instead of negative, relative to the cathode.

First assume the grid voltage e_c is set at zero. As the plate voltage e_b is gradually raised from zero, the plate current i_b is essentially zero. If e_b were to be raised to a high enough value, a self-sustaining condition known as *ignition* would occur, but the tube would not break down as explained previously. Ordinarily, the plate voltage in an actual circuit would be less than the ignition potential, so that it is virtually correct to say that no current flows between the grid and anode under the assumed conditions. Breakdown between anode and cathode does not occur, because nearly all the electrostatic flux lines from the anode terminate on the grid.

Next assume e_c is gradually raised from zero with e_b set at zero. When e_c reaches the grid-to-cathode breakdown voltage, a glow discharge occurs between these two electrodes. Now, as the anode voltage e_b is gradually increased, it will be found that, at some particular value of e_b, a glow discharge will occur between cathode and anode. The value of anode voltage required to transfer the discharge from the grid to the anode is always greater than the grid voltage, the exact value depending primarily on the magnitude of the grid current. Figure 7.17 is a plot of the difference between anode and grid voltages necessary for transfer plotted against grid



Neon signs—8mm I.D.; 35 cm long; Neon pressure = 5mm of Hg.
Kino lamp—Al electrodes 40 × 45 mm; Neon gas
Neon lamp—2-watt, 110 volt; series resistance in base removed; Electrodes covered with Al & Mg.

FIG. 7.15. Volt-ampere curves of several glow-discharge tubes. (*Reproduced by permission from Electrical Engineering Staff MIT, "Applied Electronics," John Wiley & Sons, Inc., New York,* 1943.)

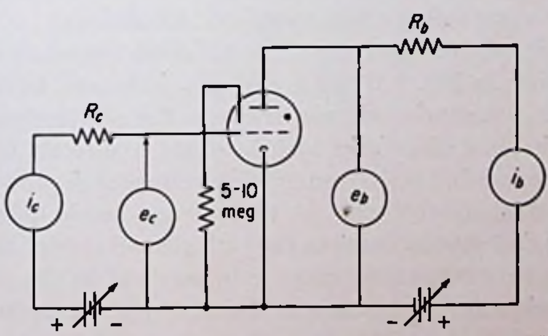


FIG. 7.16. Basic circuit for obtaining the characteristics of a grid glow tube.

current. The higher the grid current before transfer, the lower the required anode voltage.

Assume that the anode voltage has been increased to a value sufficient to cause a cathode-to-anode breakdown. It will be found that, once this has occurred, the grid voltage e_c has practically no effect upon the magnitude of the plate current i_b. The plate current cannot be reduced to zero by making the grid highly negative, as in a high-vacuum triode. The only way the plate current can be stopped is by reducing the plate voltage until the extinction current for the plate-to-cathode discharge is reached. Then the plate-to-cathode glow stops, and the only glow then pos-

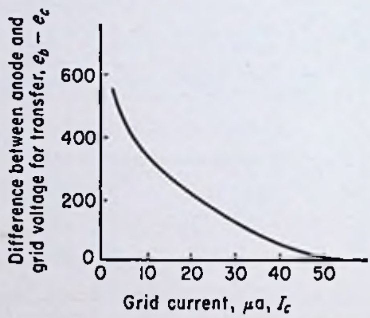


FIG. 7.17. Curve showing the increase of anode voltage above grid voltage required to produce breakdown between cathode and anode, as a function of grid current.

sible is a cathode-to-grid glow, which still remains if the grid is sufficiently positive.

If the grid circuit is opened so that the grid is left free, it generally assumes a potential only slightly more positive than the cathode, thus preventing a grid-to-cathode breakdown.

Circuit and Characteristics of Starter-anode Glow Tubes. The circuit shown in Fig. 7.16 for a grid glow tube can be used just as well for a starter-anode gas triode. The starter anode is connected in place of the grid, and the shield connection is omitted.

It is found that a moderately high voltage is required to initiate a glow discharge between the cathode and anode unless a breakdown is first started between the cathode and starter anode. The breakdown voltage from cathode to anode is on the order of 250 volts, whereas the breakdown voltage from cathode to starter anode is only about 90 volts. Once a glow has been started from cathode to starter anode, the required breakdown voltage from cathode to anode decreases with an increase of starter-anode current just as the breakdown voltage for a grid glow tube decreases with an increase of grid current, as shown in Fig. 7.17.

Figure 7.18 shows the entire breakdown characteristics of a typical starter-anode gas triode. The curve shows all the various possibilities of breakdown between the three electrodes for both polarities. The reason for giving both polarities is that the tube is frequently operated on alternating voltage. The cathode-to-starter-anode section of the curve is the only section ordinarily used.

7.3. Theories Used to Explain the Electrical Characteristics of Glow-discharge Tubes. *Ionization by Radiation.* In Sec. 7.2 it was mentioned that a minute current flows between the two electrodes in a glow tube before breakdown, owing to ionization of the gas by X rays or cosmic rays. Such ionization can also be caused by radiation from radioactive materials in the walls or electrodes of the tube in minute quantities or even by ultraviolet radiation. In addition, a small amount of photoelectric emission may occur owing to radiation falling on the surface of the cathode. Since this extremely small current, sometimes called the *dark current*, because of the absence of appreciable visible radiation, is absolutely essential to the formation of a glow discharge, the student should obtain a clear understanding of the processes governing its behavior. A review of Sec. 1.3 might be desirable at this point before proceeding further.

In Sec. 1.3 it was pointed out that according to the quantum theory, light travels in discrete packets of energy called photons, the energy of a photon being directly proportional to the frequency of the light. Figure 7.19 is a table of the spectrum of radiation, and it shows that cosmic rays have the greatest energy, then gamma rays (which come from radioactive materials), with X rays next, and ultraviolet rays last in the amount of energy contained in each photon.

When a photon collides with a particle, there is a *possibility* of the photon transferring its energy to the particle. This process has already been discussed in connection with photoelectric emission from a metallic surface. The action is somewhat similar in a gas. The photon may impart its energy to an electron in a gas atom, causing either excitation or ionization of the atom. Since a

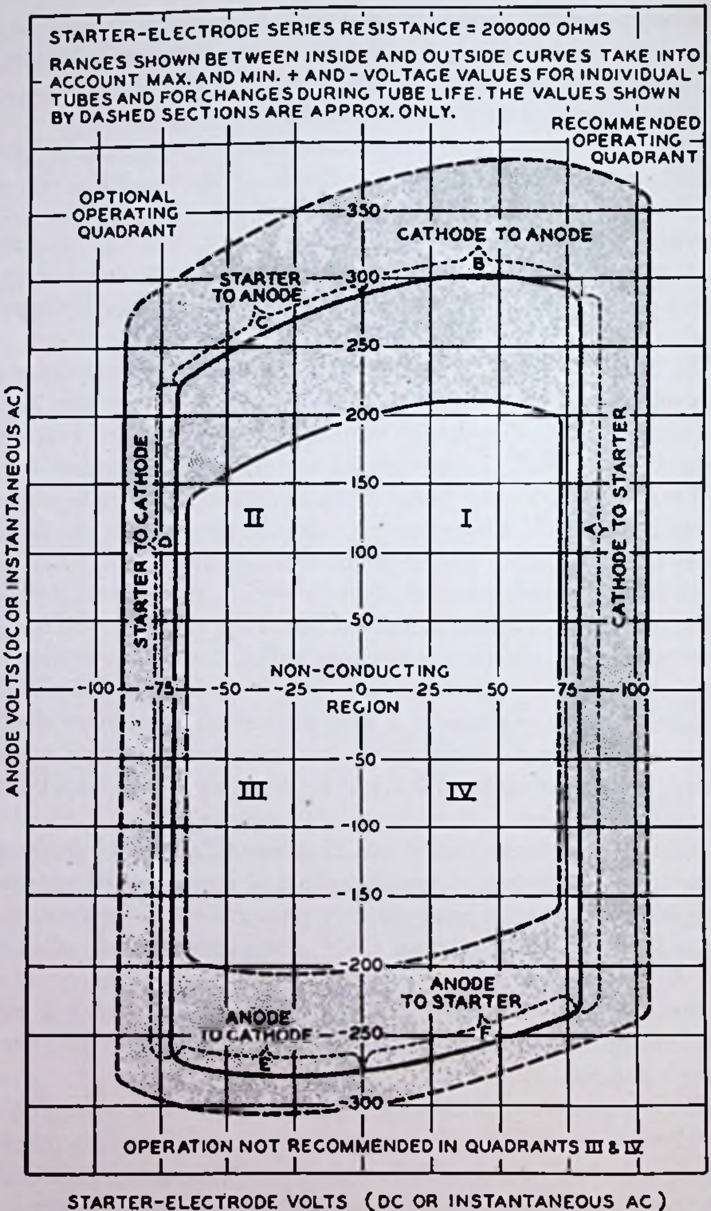


FIG. 7.18. Breakdown characteristics of a typical starter-anode cold-cathode gas triode. (*Courtesy RCA.*)

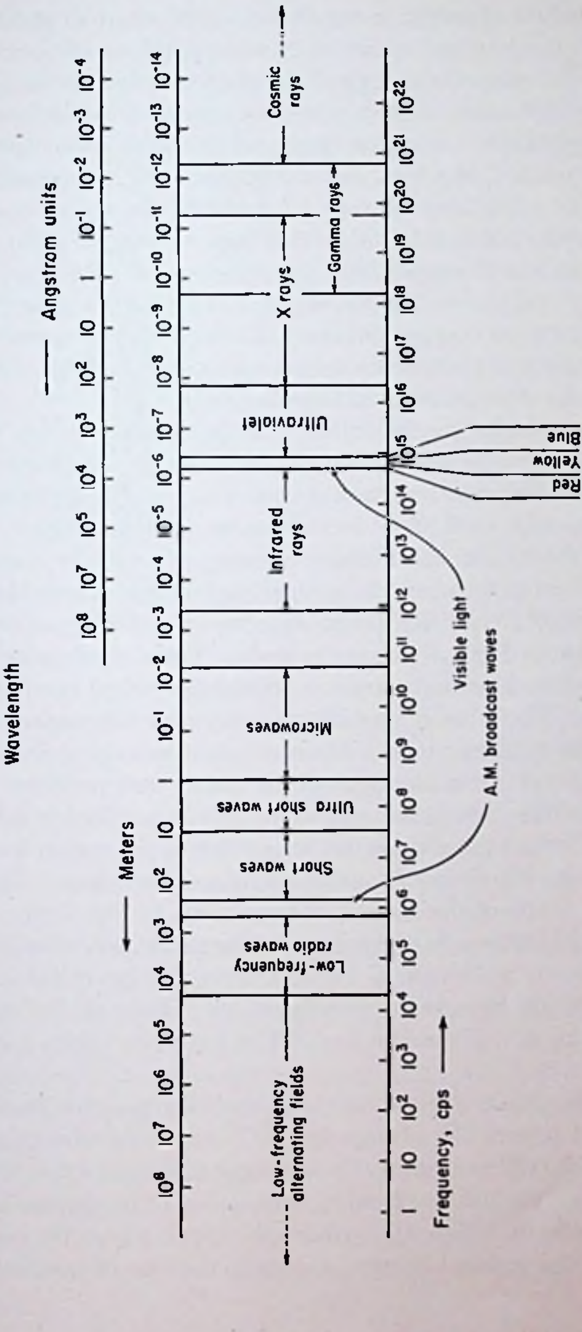


FIG. 7.19. Spectrum of radiant energy arranged in ascending order of frequency or descending order of wavelength.

definite amount of energy is required to excite an atom and since a photon cannot lose just a part of its energy, the excitation energy must exactly equal the energy of the photon before excitation can occur. Before ionization can occur, the energy of the photon must equal or exceed the ionization energy of the atom *unless* the atom is already excited, in which case a multiple type of ionization can occur. The atom may already be excited from collision with a previous photon or an electron set free from some other atom. The photon then has to supply only the *difference* between the ionization energy and the excitation energy of the atom to cause ionization. Any excess energy contained in the photon over and above the value required to cause ionization appears in the form of kinetic energy in the electron released from the atom.

In any gas, including the ordinary atmosphere, ionization by the process just described is continually in progress. In the absence of an electric field, the resultant electrons and positive ions wander about aimlessly until they recombine to form a neutral atom. Upon recombination, the ionization energy is generally converted into heat. In glow tubes, the applied electric field causes the electrons to travel toward the positive electrode and the positive ions to travel toward the negative electrode. For a weak field, some of the positive ions and electrons recombine before reaching the electrodes. These recombinations may occur on the surface of the walls of the tube envelope. As the applied voltage is increased, however, fewer recombinations occur before the particles reach their respective electrodes, and eventually a saturation point is reached when all the charges are swept out of the region between the electrodes before any recombinations can take place. This explains the shape of the current-voltage curve in Fig. 7.10.

The initial increase in current above the saturation value in Fig. 7.11 is due to ionization of the gas molecules by collision with electrons which have been accelerated sufficiently by the applied electric field, as explained in Sec. 1.3 in connection with gas-type phototubes.

Ionization Due to Positive-ion Collision. The positive ions being accelerated toward the cathode in the Townsend discharge region may acquire sufficient energy to ionize gas molecules upon impact. Positive ions are not so effective as electrons in producing ionization by collision. Near the cathode, however, where the positive ions have the greatest energy, a certain number of positive ions (and electrons) will be created by these collisions. The new positive ions travel on to the cathode with the original ones; there they combine with electrons to form neutral atoms. The electrons set free near the cathode by the positive-ion collisions travel toward the anode, and owing to the large potential drop through which they can move, *there is a very definite possibility that these new electrons may acquire ionizing energy themselves before reaching the anode.* This is a very significant fact, for it introduces the possibility of the discharge becoming self-sustaining, or independent of any external source of ionization.

Secondary Emission Due to Positive-ion Collision. The positive ions bombarding the cathode in the Townsend discharge region may impart enough energy to electrons in the surface of the metal to enable them to overcome the potential-energy barrier and break away from the surface. Thus secondary emission due to positive-ion bombardment of the cathode releases electrons at the cathode surface. The emitted electrons travel toward the anode and, along with electrons set free by positive-ion collision, as explained in the preceding paragraph, *may acquire sufficient energy in transit to cause ionization of the gas molecules by collision.* Thus there are two ways in which a Townsend discharge (which is not self-sustaining) may suddenly shift to a new type of self-sustaining discharge: ionization by collision of positive ions with gas molecules near the cathode, and secondary emission from the cathode due to positive-ion bombardment.

Ignition and Breakdown. As the voltage applied to a glow-discharge tube is gradually raised in the Townsend discharge region, the current continues to increase for several reasons:

1. Increased ionization due to electron collision.
2. Increased ionization due to positive-ion collision near the cathode.
3. Increased secondary emission due to positive-ion bombardment.
4. Increased photoelectric emission from the cathode because of photons emitted from excited molecules returning to the normal state.

Eventually a point is reached at which the discharge becomes self-sustaining. This condition is termed *ignition,* and the corresponding tube voltage is the *ignition potential.* Ordinarily, ignition is immediately followed by breakdown and a glow discharge between the electrodes. However, under certain conditions, ignition may *not* be followed by breakdown, and increase of voltage above the ignition potential merely increases the current without causing a glow discharge. This will be explained presently.

The student should obtain a clear understanding of the distinction between a self-maintaining and non-self-maintaining discharge. In the non-self-maintaining discharge, the number of electrons produced at or near the cathode by the *products* of the discharge (positive ions and photons) is insufficient to create the number of positive ions and additional electrons necessary to reproduce the existent conditions at the cathode. In other words, if the outside source of ionization were to be completely shut off, the first effects would be a decrease in the number of positive ions and electrons in the interelectrode space. Fewer electrons would be accelerated toward the anode to produce positive ions and additional electrons. Fewer positive ions would be accelerated toward the cathode to produce electrons and additional positive ions by collision and secondary electrons by cathode bombardment. Thus the discharge would quickly die out, and the current would drop to *zero*.

In the self-sustaining type of discharge, on the other hand, outside sources of ionization have only minor effects on the discharge. In particular, *the discharge is not dependent for its existence on the outside sources of ionization.* The current flow can be explained on the basis of the behavior of the particles in the discharge, uninfluenced by outside radiation. Assuming no external influences, the following condition must be fulfilled in the self-sustaining discharge: assuming the walls of the tube to be perfect insulators, the number of electrons entering the anode over any interval of time must equal the sum of the secondary electrons leaving the cathode, the electrons leaving the cathode in combination with positive ions to form neutral molecules, and the electrons leaving the cathode as a result of photoelectric emission. The largest number of electrons leaves the cathode in most tubes as a result of secondary emission caused by positive-ion bombardment. Thus conditions must be favorable at the cathode for secondary emission. Coating the surface with a material having a low work function aids in the production of secondary electrons.

Whereas space charge is negligible in the Townsend discharge owing to the extremely low order of current magnitude, the presence of appreciable numbers of positive and negative charges in the interelectrode space in a glow discharge plays a major role in the determination of the tube's behavior. The number of electrons set free in the interelectrode space over any interval of time is *greater* than the number of positive ions created over the same time interval. This follows because every time a positive ion is created, an electron is also set free, whereas electrons are ejected from the cathode by both photoelectric and secondary emission with no corresponding production of positive ions.

Hence it might be thought at first that negative space charge would predominate in a glow-discharge tube. However, such an assumption would be entirely erroneous. For, although more electrons than positive ions are set free between the electrodes over any interval of time, at any particular *instant* of time *there are larger numbers of positive ions than electrons in the interelectrode space.* The reason for this paradox is to be found in the difference in the masses of an electron and a positive ion. Even the lightest positive ion, that of hydrogen, has approximately 1,840 times the mass of an electron, and the mass of an ion of one of the inert gases generally used in glow tubes is even greater. As shown in Sec. 1.4 the velocity acquired by a particle in falling through a given potential difference is inversely proportional to the square root of the mass of the particle. Taking hydrogen as an example, this means that an electron acquires a velocity about $\sqrt{1,840} = 43$ times the velocity reached by a hydrogen ion in falling through the same potential difference.

As a consequence of the much greater velocities of the electrons as compared to the positive ions, the electrons are swept out of the interelectrode space much faster than the ions. As a result, positive space charge is much more important in glow-discharge tubes than negative space charge.

Potential Distribution in a Glow Discharge. The potential-distribution curve for a tube having parallel-plane electrodes and zero space charge is a straight line, as shown in Sec. 1.3. Negative space charge was shown to *depress* the potential curve, causing it to be concave upward. Positive space charge has just the opposite effect, tending to *raise* the potential curve and make it concave downward. The potential-distribution curve for a typical parallel-plane glow tube as determined experimentally is shown in Fig. 7.20.

A small drop in potential usually occurs at the anode, called the "anode potential drop." Adjacent to this region is a region of comparatively low field strength, terminating in a potential minimum. The potential minimum is adjacent to a potential maximum, from which point the potential nose-dives to zero at the cathode. The drop in potential from the potential maximum to the cathode is commonly called the "cathode potential drop," or the "cathode fall of potential."

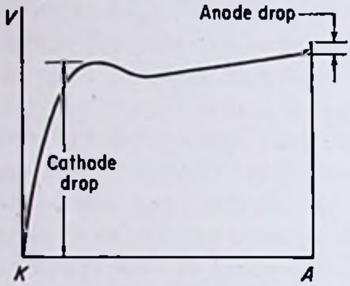


FIG. 7.20. Potential distribution inside a glow tube having parallel-plane electrodes.

Figure 7.21 shows the distribution of light being emitted from the various regions in the discharge. Starting at the cathode, there exist, in turn, regions known as the Aston dark space (also known as the Crookes dark space), the cathode glow, the cathode dark space, the negative glow, the Faraday dark space, the positive column, the anode glow, and the anode dark space. The potential maximum in Fig. 7.20 occurs in the region known as the negative

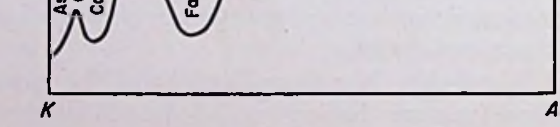


FIG. 7.21. Light distribution in a glow-discharge tube having parallel-plane electrodes.

glow; the potential minimum occurs in the Faraday dark space. The region of comparatively low field strength occurs in the positive column, with the anode drop occurring in the anode dark space. The distribution of light is significant because it indicates the relative number of atoms being excited in the different regions. The light is emitted from excited atoms returning to the normal state and releasing the excitation energy as photons.

In the positive column, electrons are moving at a comparatively low velocity toward the anode while positive ions are moving much more slowly toward the cathode. There are practically equal numbers of positive ions and electrons in the positive column. At the surface of the anode there is a slight deficiency of positive ions, owing to repulsion from the positive charges on the anode, thus yielding a slight excess of negative charges in this region. This accounts for the anode potential drop.

A large number of positive ions exist in the negative glow and the cathode dark space. There are several reasons for this. First of all, positive ions are migrating from the positive column toward the cathode. However, they are slowed down considerably by the potential maximum occurring in the negative glow. This tends to increase the positive-ion density in this region. A second reason is the large number of positive ions being *created* in the region by collision with electrons moving very rapidly away from the cathode. These electrons come from three sources: (1) secondary emission from the cathode due to positive-ion bombardment, (2) photoelectric emission from the cathode, and (3) electrons released from atoms by ionizing collisions with either positive ions or electrons. The last-mentioned source of electrons is also a source of additional positive ions. And finally, the large mass of the positive ion as compared to the electron increases the number of ions present at any particular *instant* of time over the number of electrons. This preponderance of positive ions over electrons near the cathode explains the potential maximum occurring in the negative glow.

The potential minimum occurring in the Faraday dark space is due primarily to the large number of electrons present in this region at any particular instant of time. Electrons traveling from the cathode acquire energy in falling through the cathode potential drop. However, many of them lose at least a part of their energy in the negative-glow region upon collision with positive ions. Even those collisions which result in no net transfer of energy, so-called elastic collisions, change the *direction* of travel of the electrons and tend to increase the electron concentration in the Faraday dark space just beyond the negative glow. Many of the collisions in the negative glow are inelastic, however, thus slowing down the electrons appreciably. The inelastic collisions result in a transfer of energy to the atoms, causing either excitation or ionization. The high intensity of light in the negative glow testifies to the large number of atoms being excited in this region. The ionization process releases additional electrons, which tend to increase the electron concentration in the Faraday dark space. A final reason for the high negative space charge in this region is the negative field strength, which tends to slow down electrons arriving from the negative glow.

It should be obvious to the student that the potential distribution in a glow discharge depends on the relative distribution of positive and negative charges, and the distribution of charges depends in turn on the potential distribution. It would probably be possible to set up an infinite variety of combinations of potential distributions and charge distributions that would fulfill the necessary conditions. Hence we must find a more satisfactory answer to the question of why the potential curve in a glow discharge assumes the form shown in Fig. 7.20.

Paschen's Law. A key to the reason for the potential distribution found in a glow discharge is the manner in which the ignition potential varies with the pressure of the gas and the spacing between the electrodes. If the spacing between two parallel-plane electrodes in a glow tube is held constant while the pressure is varied, the ignition potential varies as shown in Fig. 7.22. There is a certain pressure which gives the lowest ignition potential for any particular spacing of electrodes. The reason for the high ignition potential at low pressures is the small number of collisions between gas molecules and electrons in transit from cathode to anode. The lower the pressure, the fewer the number of gas molecules present between the electrodes, and the fewer the number of collisions per electron. The reason for the high ignition potential at high pressures is the short distance an electron moves, on the average, before colliding with a molecule. A certain amount of energy is required to ionize an atom, and the shorter the distance an electron has moved, the lower the energy of the electron upon collision.

If the electrode spacing is varied while the pressure is held constant, the ignition potential varies as shown in Fig. 7.23. The high ignition potential at low spacings is the result of the small number of collisions made by the electrons in transit from cathode to anode.

At large spacings, the field strength is so low that the energy obtained by the average electron between collisions is less than the ionizing energy. Hence the ignition potential is high for large electrode spacings. At some optimum spacing, a minimum voltage is required to cause ignition.

If the spacing between electrodes were to be doubled, the field strength would be halved. Hence, in order to keep the ignition potential from increasing, the gas pressure would have to be halved so that the average distance between collisions would be doubled,

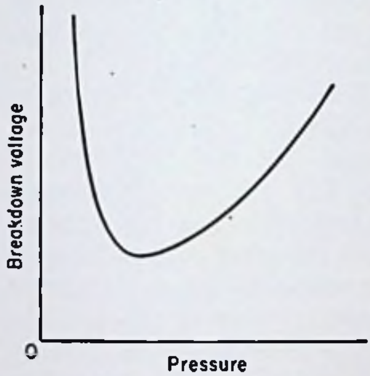


FIG. 7.22. Relation between breakdown voltage and pressure in a glow tube having parallel-plane electrodes separated a constant distance.

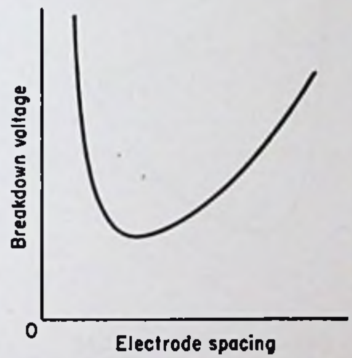


FIG. 7.23. Relation between breakdown voltage and electrode spacing in a glow tube having parallel-plane electrodes immersed in a gas at constant pressure.

permitting the electrons to obtain the same energy between collisions. If the spacing were halved, the pressure would have to be doubled to keep the ignition potential from increasing. This is because for half the spacing, fewer collisions would be made per initial electron, requiring a doubling of the pressure to keep the number of ionizing collisions the same.

In other words, *as long as the pressure and spacing are both varied simultaneously in such a manner as to keep their product constant, the ignition potential is not changed.* This relation is known as Paschen's law, and every glow tube must be designed accordingly. A tube with large electrode spacing may have the same ignition potential as one with close electrode spacing *provided* the pressures are in an inverse ratio with the spacings. Figure 7.24 shows the dependence of ignition potential upon the product of pressure and electrode spacing. A minimum ignition potential occurs at some particular product, as shown.

Distinction between Ignition and Breakdown. Ignition has been defined as the process by which a discharge becomes self-sustaining. Breakdown is ignition followed by a *cumulative* increase in current and drop in voltage resulting in a glow discharge and the type of potential distribution illustrated in Fig. 7.20. Ignition is a stable discharge which is self-limiting, whereas breakdown results in a discharge which must be limited by the resistance of the circuit in series with the tube.

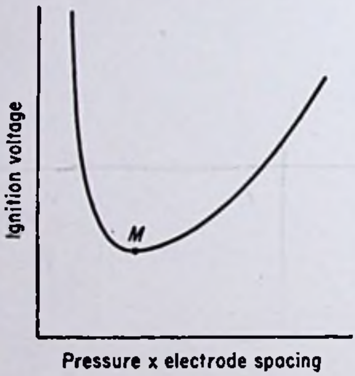


FIG. 7.24. Relation between ignition potential and the product of pressure and electrode spacing.

Breakdown always follows ignition *provided* the type of potential distribution shown in Fig. 7.20 can occur. It should be noticed in Fig. 7.20 that almost the entire potential drop is concentrated across a narrow space in front of the cathode. Actually this narrow region is the only region absolutely *essential* to a glow discharge. This can be proved experimentally by moving the anode toward the cathode while the glow discharge is in progress. The different regions remain fixed relative to the cathode and disappear one at a time into the anode. When the anode reaches the potential maximum and approaches the cathode still more closely, the potential across the tube quickly rises until it equals the supply voltage and the tube goes out.

The potential maximum is a virtual anode, in that the region between the potential maximum and the anode is a good conductor. In other words, the tube behaves almost as if the anode actually were located at the potential maximum. Breakdown can be looked upon as the process of transferring the anode from its actual location up to a position very close to the cathode. Just before breakdown, the voltage across the tube is very high and space charge is negligible, as shown by curve 1 in Fig. 7.25. As the potential is raised just a little higher, ignition is reached, and a cumulative build-up of current begins as explained previously. During the build-up of current, positive space charge predominates because of the relatively greater mass of the ions as compared to the electrons. Thus, as breakdown proceeds, the current in the circuit builds up, causing a higher IR drop in the external resistance and a lower drop across the tube, as shown by curves 2, 3, 4, and 5. The reason the lower tube drop is permissible is that the anode is,

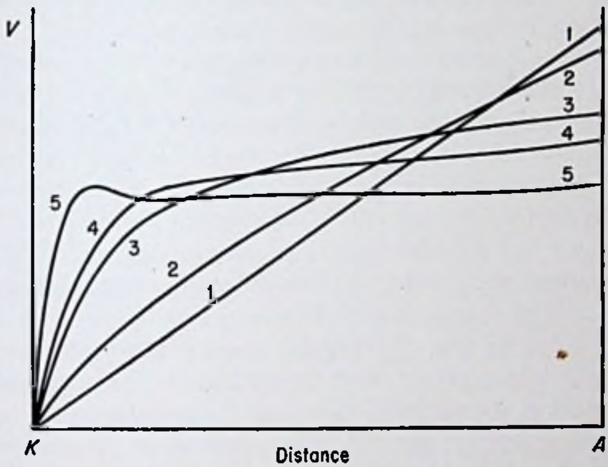


FIG. 7.25. Potential-distribution changes in a glow tube during breakdown.

for all practical purposes, moving closer to the cathode, and Fig. 7.23 (or Fig. 7.24) shows that the ignition potential decreases as the spacing between electrodes is decreased. The current continues to build up; the tube voltage continues to fall; and the anode continues to move closer to the cathode *until* the spacing corresponding to point M in Fig. 7.24 is reached. An equilibrium is then reached, because if the virtual anode were to move any closer to the cathode, the current would have to be greater to cause the larger positive space charge required for the movement. A larger current would cause a higher IR drop in the external resistance, however, thus lowering the tube voltage still further. Figure 7.24 shows, however, that in order for the spacing to be less than M, the tube voltage would have be higher, and as a consequence, the actual spacing between the cathode and the potential maximum is that corresponding to point M in Fig. 7.24 (or Fig. 7.23).

Thus, in order for breakdown to follow ignition, the pressure inside the tube and the electrode spacing must be such that a point to the right of point M in Fig. 7.24 exists prior to breakdown. For a point to the left of M, a cumulative increase in current cannot occur, for such an increase would give a high positive space charge in the tube, moving the virtual anode closer to the cathode. Such a closer spacing would conflict with the decreasing voltage across the tube due to the higher IR drop in the external resistance, since by Fig. 7.24 a closer spacing than that corresponding to point M requires an increase in tube voltage, not a decrease.

Distinction between Normal and Abnormal Glow. Since the magnitude of the current flowing in a glow discharge is determined almost entirely by the supply voltage and the external series resistance, the tube must have some way to produce the required potential-distribution curve, as shown in Fig. 7.20, irrespective of the magnitude of the current. The shape of the potential curve is determined by the distribution of charges, so that the charge density must have certain values at various distances from the cathode. The charge density, however, is determined by the current density, so that the current density must assume certain values at various points from the cathode. The total current is the product of the current density and the cross-sectional area over which the current is flowing. Therefore, since the current is determined by the external circuit, and the current density is determined by the required potential-distribution curve, the cross-sectional area over which current is flowing is a dependent function of these two quantities *and is not necessarily equal to the cross-sectional area of the electrodes.* The current density must be independent of the magnitude of the current if the potential curve is to remain constant irrespective of current. *Therefore, as the current increases, the current density remains constant and the cross-sectional area over which current flows increases instead.*

Over the normal-glow region of the current-voltage curve given in Fig. 7.12, the process just described applies. However, as soon as the glow covers the entire surface of the cathode, the cross-sectional area over which current flows can no longer increase. The increased cathode emission required to give larger values of current cannot be obtained by exploiting larger and larger areas of the cathode. The increased emission can be obtained only by giving the positive ions additional energy as they bombard the cathode so that more secondary electrons are splashed out of the metal. This also permits the positive ions to produce more ionization by collision near the cathode. The increased energy requires a larger cathode fall of potential, so that the tube drop must increase with an increase in current in the abnormal-glow region. The amount of ionization in the negative glow is also increased because of the higher electron energies attained in falling through the greater potential difference.

Breakdown and Deionization Times. The processes of breakdown and extinction do not occur instantaneously. The time required for a tube to break down upon the sudden application of a voltage greater than the breakdown voltage depends on several factors. It varies inversely with the applied voltage, as shown in Fig. 7.26. The breakdown time and the breakdown voltage both depend on the previous history of the tube. They are reduced by the presence of appreciable ionization in the tube, which may be the result of a prior discharge.

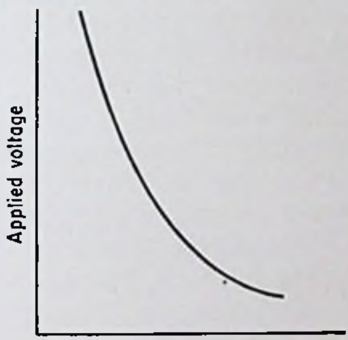


FIG. 7.26. Breakdown time of a typical glow tube as a function of applied voltage.

The time required for extinction likewise depends on several factors. Deionization, which means the process by which positive ions and electrons recombine to form neutral molecules, occurs largely at the walls and electrodes of the tube. The large mass of the positive ions generally hampers deionization because of their necessarily sluggish movements. The use of a gas having a low atomic weight permits relatively rapid deionization because of the greater velocities of the lighter ions.

Theory of the Grid Glow Tube. The grid glow tube is an excellent example of the practical application of Paschen's law. The pressure in the tube and the spacing between the grid and anode are such as to yield a point to the left of point M in Fig. 7.24. Thus breakdown is prevented between these two electrodes, although ignition may occur at high potentials. The spacing between grid and cathode, however, is such as to yield a point just to the *right* of point M. Thus a low grid-to-cathode voltage can cause breakdown. The resulting ionization allows a discharge to take place between cathode and anode provided the anode is sufficiently more positive than the grid. Before a cathode-to-grid breakdown, all the electrostatic flux lines from the plate terminate on the grid, thus preventing a plate-to-cathode breakdown. After a cathode-to-grid breakdown, however, some of the flux lines from the anode terminate on electrons which became attracted to the grid but missed that electrode and traveled on into the grid-anode region. Thus ionization can be set up in the grid-anode region by collision if the anode is positive enough to accelerate the electrons sufficiently. Once the breakdown has transferred from the grid to the anode, the grid is powerless to regain control. If it is made positive, a cloud of electrons forms around the grid and neutralizes the positive field. If it is made negative, a cloud of positive ions forms around the grid and neutralizes the negative field. The only means of stopping the discharge is by reduction of the anode voltage below the extinction value long enough to allow deionization.

Theory of the Starter-anode Gas Triode. The gas tube illustrated in Fig. 7.8 also utilizes Paschen's law, but not in the same way as the grid glow tube. The pressure used in the tube and the spacing between the cathode and anode yield a point considerably to the right of point M in Fig. 7.24. Thus a rather high voltage is necessary to cause breakdown from cathode to anode. The closer spacing between the starter anode and cathode, however, yields a point just to the right of point M. Consequently, a rather low voltage can cause a breakdown from starter anode to cathode. Once a discharge has been initiated between starter anode and cathode, the resulting ionization lowers the breakdown voltage from anode to cathode by an amount determined by the magnitude of the starter-anode current. The starter anode is unable to stop a cathode-to-anode discharge once it has started, the only function of the starter anode being to initiate the discharge. This is accomplished by impressing between the cathode and anode a voltage lower than the breakdown voltage in the absence of any ionization, but high enough to cause breakdown once a discharge occurs between the starter anode and cathode.

7.4. Mathematical Analysis of Glow Tubes. *Ionization and Excitation Potentials.* The theories of excitation and ionization were covered in Sec. 1.3. For any particular atom, a certain amount of energy is required to make an electron in a given orbit jump to a larger orbit. The energy, when expressed in electron volts, is known as the *excitation potential.* The *first* excitation potential is the minimum amount of energy necessary to excite a normal neutral atom.

The energy required to remove an electron entirely from an atom is called the ionization potential, when expressed in electron volts. The more complex atoms have numerous ionization potentials corresponding to the removal of different numbers of electrons. The *first* ionization potential is the energy in electron volts required to remove the first electron from a normal neutral atom. The *second* ionization potential is the energy required to remove the second electron from the atom, etc. The first ionization potential is the *minimum* energy required for ionization.

TABLE II

FIRST EXCITATION ENERGY AND MINIMUM IONIZING ENERGY FOR THE MONATOMIC GASES AND MERCURY*

Gas	Excitation energy, electron volts	Ionization energy, electron volts
Helium (He)	19.73	24.48
Neon (Ne)	16.60	21.47
Argon (A)	11.57	15.69
Krypton (Kr)	9.9	13.3
Xenon (Xe)	8.3	11.5
Mercury (Hg)	4.66	10.39

* This table was compiled from data taken with permission from Table I of A. W. Hull, Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases, *Trans. AIEE*, Vol. 53, p. 1436, 1934.

Table II gives the first excitation and first ionization potentials of several gases commonly used in glow tubes or other forms of gas tubes.

Referring to Fig. 7.11, the potential at which the Townsend discharge begins is approximately the first ionization potential of the gas used. The breakdown voltage for a glow tube is always many times the first ionization potential. This is because the positive ions need considerably more energy than the minimum ionizing energy in order to produce sufficient secondary emission from the cathode and ionization by collision near the cathode surface to sustain a glow discharge. If some other means of producing the required number of electrons were at work, the voltage drop across the tube would not have to be so large. For example, in Chap. 8 it will be shown that, if the cathode is hot enough to emit thermionically all the electrons needed to carry the current demanded by the circuit, the voltage drop across the tube is only about the first ionization potential of the gas used.

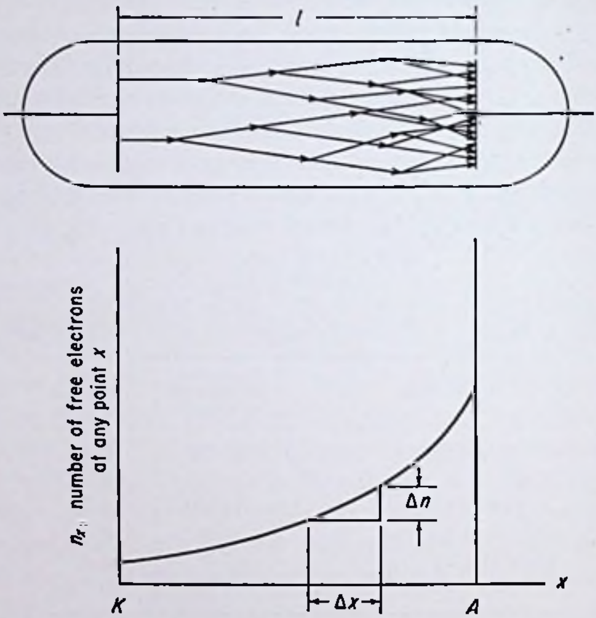


FIG. 7.27. The number of free electrons plotted against distance, showing the great increase from cathode to anode.

Equation for Townsend Discharge. Ordinarily the amount of current flowing in a glow tube throughout the Townsend discharge region is very small. Over the range from A to B in Fig. 7.11 the current is usually so small that the effect of space charge is negligible. In a tube having parallel-plane electrodes this means that the field strength is uniform. Hence an electron is accelerated the same amount after each collision irrespective of its position between the electrodes. This, in turn, means that the same number of ionizing collisions occur per centimeter of advance of the electron regardless of its position between the electrodes. The number of ionizing collisions produced per electron per centimeter of advance toward the anode is by definition the *ionization coefficient*, or more specifically the *first Townsend coefficient*. Each ionizing collision releases an additional electron, so the number of new electrons released per centimeter is equal to the number of ionizing collisions.

Figure 7.27 shows the manner in which the number of ionizing collisions varies with the distance from the cathode, and consequently the manner in which the number of free electrons varies with distance from the cathode. Let α represent the ionization coefficient and n_x the number of free electrons at any distance x from the cathode. From the definition of α we can write

$$\alpha = \frac{\Delta n_x}{n_x \, \Delta x} \tag{1}$$

where Δn_x is the increase in the number of free electrons over a distance Δx, as shown in Fig. 7.27.

As the distance Δx is made smaller and smaller, the quantity Δn_x becomes smaller and smaller, so that in the limit, as Δx approaches zero, the ratio $\Delta n_x/\Delta x$ approaches the derivative of n_x with respect to x. Thus we can write

$$\alpha = \frac{1}{n_x} \frac{dn_x}{dx} \tag{2}$$

Multiplying both sides of Eq. (2) by dx gives

$$\frac{dn_x}{n_x} = \alpha \, dx \tag{3}$$

Neglecting space charge and assuming parallel-plane electrodes, α is independent of x. Therefore integration of Eq. (3) gives

$$\ln n_x = \alpha x + K$$

where K is the constant of integration for both sides of the equation. At $x = 0$, $n_x = n_0$, the initial number of electrons produced at or near the cathode.

$$\ln n_0 = 0 + K$$

Therefore

$$\ln n_x = \alpha x + \ln n_0 \tag{4}$$

At $x = l$, the anode-cathode spacing, $n_x = n$, the total number of electrons reaching the anode. Therefore

$$\ln n = \alpha l + \ln n_0 \tag{5}$$

$$\ln \frac{n}{n_0} = \alpha l$$

or

$$n = n_0 \epsilon^{\alpha l} \tag{6}$$

Equation (6) states that the number of electrons reaching the anode is greater than the number of electrons leaving the cathode by a factor of $\epsilon^{\alpha l}$. Therefore the current flowing in the Townsend discharge region is greater than the saturation current flowing below point A in Fig. 7.11 by a factor of $\epsilon^{\alpha l}$.

$$I = I_0 \epsilon^{\alpha l} \tag{7}$$

It should be borne in mind that, although the number of electrons reaching the anode is greater than the number of *free* electrons being produced at the cathode, the total number of electrons leaving the cathode must equal the number entering the anode. For each electron produced by an ionizing collision a positive ion is also set free. The positive ions migrate relatively slowly to the cathode, where they combine with electrons to form neutral gas molecules. Thus the number of *free* electrons leaving the cathode plus the number of electrons leaving the cathode with positive ions to form neutral molecules equals the number of electrons entering the anode.

The ionization coefficient α in Eq. (7) is a function of the field strength between the cathode and anode. The higher the anode voltage, the higher the ionization coefficient. Therefore the current in the Townsend discharge increases with an increase in anode voltage, as shown by Fig. 7.11.

Example:

Calculate the gas amplification in a photoelectric tube having parallel-plane electrodes spaced 1.5 cm. The ionization coefficient may be taken as 1.3 for the particular voltage being used.

Solution:

$$\begin{aligned} \text{Gas amplification} &= \epsilon^{\alpha l} \\ &= \epsilon^{(1.3)\ (1.5)} \\ &= 7 \quad \textit{Ans.} \end{aligned}$$

Strictly speaking, Eq. (7) applies only to tubes wherein the initial electrons are produced at the cathode surface, as by photoelectric emission in a phototube. In a glow tube, the initial electrons may result partially from photoemission from the cathode, but in many cases ionization within the volume of gas between the electrodes, due to X rays, cosmic rays, and the like, accounts for the greatest number of initial free electrons. Hence Eq. (7) is not applicable to all types of tubes operating in the Townsend discharge region.

Cumulative Ionization. Equation (7) explains the initial increase of current above the saturation value in Fig. 7.11. Experiments show that Eq. (7) applies over the region from A to B in Fig. 7.11. However, considerable departure from the values predicted by Eq. (7) occurs at higher values of voltage and current. This is due to the production of electrons near the cathode either by secondary emission due to positive-ion bombardment or ionization due to positive-ion collision. In an actual tube, both phenomena may occur simultaneously, as already explained. Assuming the new electrons are produced entirely by ionization due to positive-ion collision, an equation can be derived for the current flowing between two parallel-plane electrodes. If space charge is assumed negligible,

$$I = I_0 \frac{(\alpha - \beta)\epsilon^{(\alpha-\beta)l}}{\alpha - \beta\epsilon^{(\alpha-\beta)l}} \tag{8}$$

where β is the number of ionizing collisions produced per positive ion per centimeter of advance toward the cathode and the other quantities are as defined for Eq. (7). The factor β is known as the *second Townsend coefficient.*

If it is assumed that all the new electrons are produced by secondary emission as a result of positive-ion bombardment of the cathode, the equation for the current in a parallel-plane-electrode tube is

$$I = I_0 \frac{\epsilon^{\alpha l}}{1 - \gamma\epsilon^{\alpha l}} \tag{9}$$

where γ is the number of secondary electrons produced by each bombarding positive ion and the other quantities are as defined previously.

It should be noted that, whereas Eq. (7) will always yield a finite result, there is a possibility of an infinitely large answer resulting from the application of either Eq. (8) or Eq. (9). In Eq. (8), as the electric field is increased, both α and β are increased. Ordinarily α is larger than β. However, the exponential factor causes the second term in the denominator to increase at a faster rate than the first term. As the second term approaches the first term in magnitude, the denominator approaches zero and the current theoretically becomes infinitely large. Actually, space charge, which was neglected in the derivation, prevents the current from increasing without limit (aided by the external series resistance, of course).

TABLE III*

CONSTANTS FOR DETERMINING NORMAL CURRENT DENSITY FOR DIFFERENT GASES AND ELECTRODE MATERIALS

Constant	Gas	Electrode material						
		Al	Zn	Cu	Fe	Ag	Au	Pt
a	H_2	0.140	0.120	0.125	0.140	0.125	0.150	0.125
	N_2	0.225	0.240	0.350	0.325	0.260	0.225	0.290
	Ne	0.008	0.006	0.024	0.026	0.021	0.019	0.011
b	H_2	2.05	1.94	1.86	1.89	1.86	1.80	1.90
	N_2	2.02	1.91	1.75	1.77	1.75	1.87	1.85
	Ne	1.50	1.83	1.06	1.38	1.00	1.14	1.30

* This table was compiled from data taken from W. Wien and F. Harms, "Handbuch der Experimentalphysik," Part III, Vol. 13, p. 373, Akademische Verlags gesellschaft m.b.h., Leipzig, 1929.

As an approximation, however, it can be said that the criterion for breakdown is for the denominator in Eq. (8) to become zero, or

$$\alpha = \beta\epsilon^{(\alpha-\beta)l} \tag{10}$$

In Eq. (9), as the electric field is increased, the second term in the denominator approaches unity and the current theoretically approaches an infinitely large value. The criterion for breakdown in this case is given by the equality

$$\gamma\epsilon^{\alpha l} = 1 \tag{11}$$

Normal Current Density. An empirical relation between the current density J and the gas pressure p in the normal-glow region is

$$J = ap^b \tag{12}$$

where a and b are constants depending on the gas and electrode material used. Table III gives values of a and b for several gas-electrode combinations. If p is given in millimeters of mercury, the units for J are milliamperes per square centimeter.

Example:

A neon glow tube with iron electrodes must carry a current of 20 ma. How large should the electrodes be to prevent operation in the abnormal-glow region if a gas pressure of 30 mm Hg is to be used?

TABLE IV*

CATHODE POTENTIAL DROP FOR VARIOUS COMBINATIONS OF CATHODE MATERIALS AND GASES

Electrode	O_2	H_2	N_2	He	Ne	A	Hg vapor
Na	...	185	178	80	75		
Au	...	247	233				
Mg	310	153	188	125	94	119	
Hg	...	270	226	142.5	...	...	340
Al	...	171	179	141	120	100	
W	...	...	...	...	125		
Fe	343	198	215	161	...	131	389
Ni	...	211	197	...	...	131	
Pt	364	276	216	160	152	131	340

* This table was compiled from data taken with permission from J. Slepian, "Conduction of Electricity in Gases," Westinghouse Electric and Manufacturing Company, Pittsburgh, 1933.

Solution:

From Table III, $a = 0.026$, $b = 1.38$.

$$J = ap^b$$

$$= (0.026)\ (30)^{1.38}$$

$$= 2.84 \text{ ma/cm}^2$$

$$A = \frac{I}{J}$$

$$= \frac{20}{2.84}$$

$$= 7.04 \text{ cm}^2 \quad \textit{Ans.}$$

Cathode Fall of Potential. As previously explained, most of the voltage drop across a glow tube is taken up in a region near the cathode known as the cathode dark space. This cathode drop, as it is called, is relatively constant in the normal-glow region. It depends on the gas as well as the electrode material used. Table IV gives typical values for the cathode potential drop for various combinations of pure metal cathodes and gases.

PROBLEMS

1. A certain gas phototube is to have a gas amplification of 5 at a plate voltage which yields a first Townsend coefficient of 1.5. Assuming parallel-plane electrodes, calculate the spacing required between the electrodes.

2. A glow tube having parallel-plane electrodes separated 0.5 cm breaks down at 150 volts. If the positive-ion secondary-emission ratio is 0.009, calculate the first Townsend coefficient at the breakdown voltage. Neglect ionization due to positive-ion collision.

3. A certain glow tube has parallel-plane electrodes separated 0.2 cm. Assume the Townsend coefficients are related to the field strength $\mathcal{E}$ by the following equations:

$$\alpha = 2 \times 10^{-6}\mathcal{E}^2$$
$$\beta = 10^{-8}\mathcal{E}^2$$

where α and β are expressed in collisions per centimeter per electron or ion and $\mathcal{E}$ in volts per centimeter. Neglecting secondary emission due to positive ions, calculate the theoretical breakdown voltage.

4. A neon glow tube has 1- by 2-cm parallel-plane aluminum electrodes spaced 0.25 cm apart. Find the total power dissipated by the tube in the normal-glow region for a pressure of 10 mm Hg. Assume that one-half of the cathode surface is covered with glow.

5. A voltage-regulator tube using neon gas has 2.5- by 2-cm silver-plated electrodes. If a pressure of 35 mm Hg is used and operation must be limited to the normal-glow region, calculate the maximum current rating.

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CHAPTER 8

THERMIONIC GAS DIODES

In the early days of electronics, many electron tubes were "gassy," unintentionally, owing to poor vacuum equipment. Thus much experience with gaseous electron tubes was acquired from the beginning. It might be expected that the development of gas tubes would have progressed as rapidly as the corresponding development of high-vacuum tubes. Such, however, was not the case. Difficulties of one kind or another, principally in connection with tube life, prevented the widespread commercial use of thermionic gas tubes until the late twenties.

Gaseous electron tubes, instead of competing with high-vacuum tubes, have for the most part widened the fields of application of electronics. The thermionic gas diode is unsurpassed as a high-voltage, medium-current rectifier and as such has found wide application in rectifier-type power supplies for radio transmitters and other types of electronic equipment.

8.1. Physical Characteristics of Thermionic Gas Diodes. *Tungar Tubes.* There are actually two different types of thermionic gas diodes. One type, known as the *tungar* tube, is illustrated in Fig. 8.1. The construction, it will be noted, is radically different in many respects from that commonly employed in high-vacuum diodes. The anode does not surround or enclose the cathode, and the anode-cathode spacing is rather large. In high-vacuum diodes such large spacings would, by Child's law, keep the current at a very low value. Tungar tubes are able to carry several amperes of current in actual operation, however, so it is evident that Child's law as derived for vacuum diodes does not apply in this case.

The cathode is a heavy, coiled filament designed to conserve heat and increase the emission efficiency. The required emission current is obtained by operating the filament at a very high temperature. This also contributes to a high emission efficiency, as explained in Sec. 2.3. The filament is generally of the thoriated-tungsten type, and the active material is prevented from evaporating by employing a relatively high gas pressure. Either argon gas or mercury vapor is introduced into the bulb at a pressure of several millimeters of mercury, at which pressure the rate of evaporation of the thorium is low enough to provide satisfactory tube life.

The peak inverse voltage rating of a tungar tube is quite low. This is because at the relatively high gas pressure employed the glow-breakdown voltage is low. As a result, tungar tubes are not suitable for the rectification of voltages over about 100 volts. They have found extensive application in storage-battery charging and similar services where a high current at a low voltage is required.

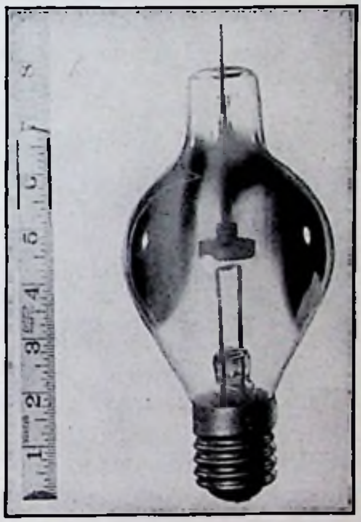

FIG. 8.1. A tungar rectifier tube. *(Courtesy General Electric Company.)*

Low-pressure Thermionic Gas Diodes. The other type of thermionic gas diode differs principally from the tungar in the magnitude of the gas pressure employed. Whereas the tungar tube operates at a comparatively high gas pressure, in the other type either mercury vapor or an inert gas such as argon is maintained at a pressure of only a few microns. In the mercury-vapor type, which has found the widest application, a few drops of liquid mercury is introduced into the bulb during manufacture, and the correct gas pressure is maintained in operation by keeping the tube at the proper operating temperature.

Cathodes in Low-pressure Gas Diodes. Owing to the low pressure used in all gas diodes (except the tungar), high cathode temperatures are not permissible. Excessive evaporation of the active cathode material would shorten the life of the tube. Hence some other means of securing high emission efficiency is necessary. In practice, high efficiency is accomplished by taking advantage, in the design of the cathode structure, of certain characteristics of the mechanism of current flow in the tube. Briefly, it may be stated that the surface of the cathode need not be exposed *directly* to the anode in a gas diode in order to secure usable emission. This permits the use of a cathode structure in a gas diode that would be utterly impossible in a high-vacuum tube. In the latter type of tube, electrostatic flux lines from the anode must reach every portion of the cathode surface if the full surface is to be active in supplying electrons for current flow. In gas diodes, however, heat shields may be employed to reduce heat losses, and the emitting surface may be arranged in such a manner that heat radiated from one portion is intercepted by another portion instead of being radiated from the tube.

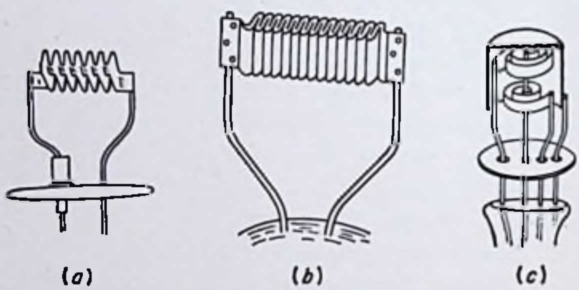

FIG. 8.2. Heat-conserving filamentary cathodes for thermionic gas diodes.

Both filamentary and indirectly heated cathodes are employed in thermionic gas diodes. In the filamentary type, the filament can be crimped, folded, spiraled, or wound helically. Figure 8.2(*a*) to (*c*) illustrates several possible arrangements.

Indirectly heated cathodes have the advantage of permitting a higher heater voltage to be used. In filamentary cathodes, the drop of potential along the filament causes the anode-to-cathode voltage to vary along its length. A low heater voltage must be used to prevent the anode-to-cathode drop measured from the negative end of the filament from exceeding a value of about 22 volts, because it is found that positive-ion bombardment of the cathode strips the thorium or oxide coating from the surface for voltages in excess of this value. Also, the possibility of an arc forming between the ends of the filament necessitates the use of a low filament voltage. In practice, mercury-vapor gas diodes using filamentary cathodes are designed for a filament voltage of 5 volts. No such restrictions on heater voltage are imposed upon tubes with indirectly heated cathodes, and an effective voltage of 115 volts can be used.

Figure 8.3(*a*) and (*b*) shows two possible arrangements for indirectly heated cathodes in gas diodes. In (*a*) the inside surface of the smallest of the three outer cylinders and the outside surface of the inner cylinder are both coated with barium and strontium oxides. This gives a larger emitting surface and yields a higher emission efficiency. The two outermost cylinders are highly polished to reflect heat. In (*b*) the radial vanes are coated with emitting material and further increase the emitting surface without increasing the required heating power.

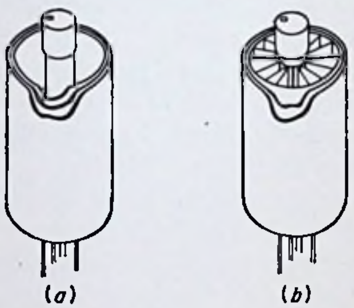

FIG. 8.3. Heat-conserving indirectly heated cathodes for thermionic gas tubes.

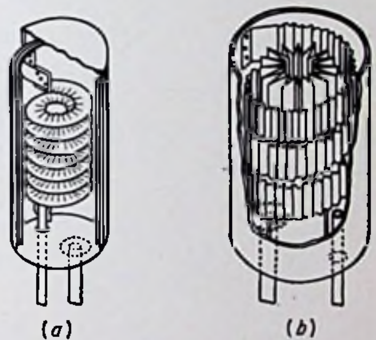

FIG. 8.4. Heat-conserving cathodes combining direct and indirect heating.

Figure 8.4(*a*) and (*b*) shows structures combining direct and indirect heating. In both figures the heating element and the inner surface of the inner cylinder are both coated with emitting oxides. Very high emission efficiencies are possible from such structures. For example, a type FG-53 tube has a heater rating of 80 amp at 5 volts and an emission-current rating of 600 amp. A type 891 high-vacuum tube has a two-section heater rated at 60 amp and 11 volts per section with a maximum plate current rating of only 2 amp. Thus the gas tube delivers 300 times the plate current with less than one-third the heating power!

The only major drawback to the use of the highly efficient heat-conserving type of cathode is the increased heating time thereby required. As the cathode is made more efficient, the necessary heating power is reduced and the time required to reach operating temperature is increased. Heating times as long as 30 min are required in the larger sized mercury-vapor tubes. A very important word of precaution is necessary regarding the cathode heating time: *plate voltage should not be applied to a thermionic gas tube until the cathode has reached full operating temperature.* The manufacturer generally supplies information about the required heating time for the different tubes. *Failure to observe the above precaution may result in destruction of the cathode.*

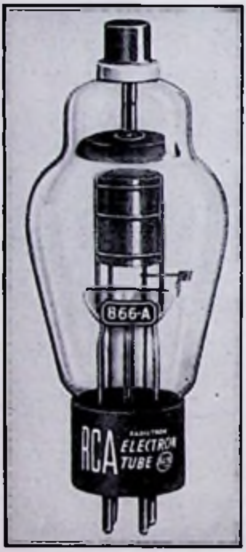

FIG. 8.5. A typical low-power mercury-vapor diode. (*Courtesy RCA.*)

Miscellaneous Features of Hot-cathode Gas Diodes. The smaller mercury-vapor tubes are built with glass envelopes and in general appearance are similar to ordinary high-vacuum tubes, as shown in Fig. 8.5. The particular tube shown has a peak inverse voltage rating of 10,000 volts and can deliver a peak plate current of 1 amp with a voltage drop of only about 10 volts.

The larger sized hot-cathode gas diodes are frequently constructed with metal envelopes to give greater ruggedness, as shown in Fig. 8.6. This tube has a peak inverse voltage rating of 1,500 volts and can deliver a peak plate current of 75 amp with a voltage drop of about 9 volts.

Figure 8.7 shows a xenon gas diode with a tantalum anode. The peak inverse voltage rating is 920 volts, and the tube can deliver a maximum current of 12.8 amp with a 9-volt drop. This tube uses a somewhat higher gas pressure than mercury-vapor diodes but has the advantage of being less critical as to temperature.

8.2. Electrical Characteristics of Thermionic Gas Diodes. Figure 8.8 is a circuit diagram suitable for investigating the electrical properties of thermionic gas diodes. The cathode heating circuit, being conventional, has been omitted. It should be remembered that sufficient time must be allowed for the cathode to reach operating temperature before applying plate voltage. In the case of mercury-vapor tubes, this is doubly important, because the gas pressure is dependent on the bulb temperature, and insufficient heating time may cause the pressure to be too low for proper operation. *Destruction of the cathode may result from too low a gas pressure as well as from too low a cathode emission.*

The resistance R is absolutely essential in the circuit to prevent possible destruction of the tube. *The current through a thermionic gas diode must be limited by the external circuit.* There is no auto-

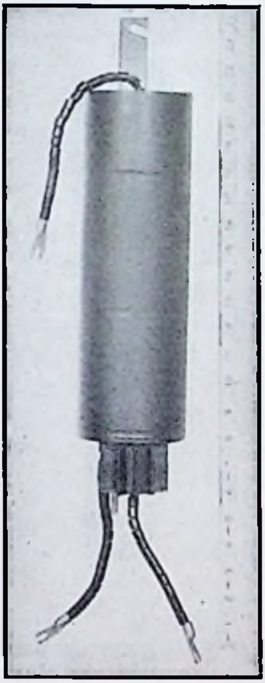

FIG. 8.6. A type FG-166 hot-cathode gas diode with a metal envelope. (*Courtesy General Electric Company.*)

FIG. 8.7. A type EL6B gas rectifier tube. (*Courtesy Electrons, Inc.*)

matic current-limiting mechanism in a gas diode as there is in a high-vacuum diode as a result of space charge. The resistance should be large enough to limit the plate current to a value less than the emission current from the cathode at all times. *The plate current should never be allowed to exceed the normal emission current from the cathode. Failure to observe this precaution may result in loss of cathode emission, shortened tube life, or even destruction of the tube.*

As the supply voltage is slowly increased from zero, the current is small and approximately follows the three-halves-power law, as shown in Fig. 8.9. When a voltage usually in the neighborhood of the first ionization potential of the gas is reached, the tube "breaks down" or "fires," the current jumps to a value determined by the external resistance in series with the tube, and a visible glow appears between the electrodes. Over the solid portion of the curve the tube drop is relatively constant with changes in tube current and may even decrease slightly with increasing current.

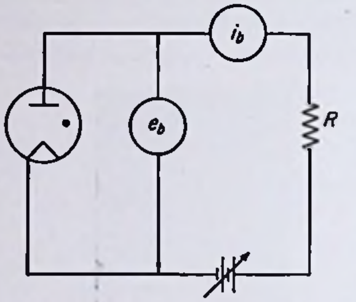

FIG. 8.8. A circuit suitable for obtaining the electrical characteristics of thermionic gas diodes.

If an attempt is made to increase the current beyond the emission current of the cathode, the tube drop increases and, if allowed to exceed a critical value dependent on the gas used, may damage the cathode. The dotted curves in Fig. 8.9 show the type

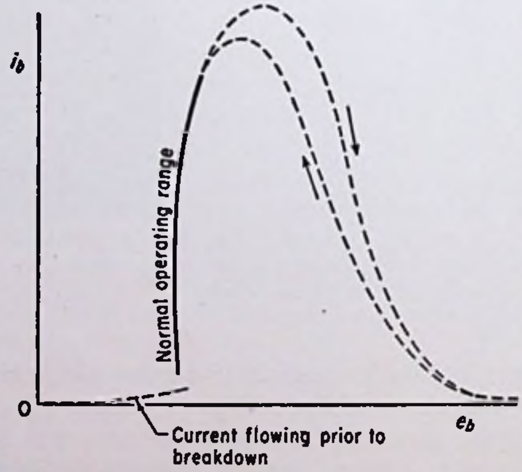

FIG. 8.9. Volt-ampere relationship for a thermionic gas diode having a thoriated-tungsten cathode.

of variation encountered when using thoriated-tungsten cathodes. Beyond a certain tube drop the plate current *decreases* for any further increase in voltage. Provided the cathode is not destroyed, the current rises again when the plate voltage is reduced, although the decreasing curve may fall somewhat below the increasing curve, as shown. In the case of oxide-coated cathodes, the emitting material may be entirely removed by permitting excessive tube drops, thus permanently ruining the tube.

The action taking place in a thermionic gas diode is sometimes called an arc, but there is little physical resemblance between the arc in a hot-cathode mercury-vapor tube and the arc observed, for example, at switch blades when an inductive circuit is opened. The arc in a thermionic gas tube more nearly resembles a glow discharge than an ordinary atmospheric arc. The distinction is not one of appearance, however, but of tube drop. The voltage across a glow discharge is ordinarily many times the ionizing potential of the gas, whereas an arc is necessarily a discharge occurring at a potential difference in the neighborhood of the ionization potential. A more precise definition would specify that the emission of electrons from the cathode in an arc discharge must be by means other than secondary emission, thus excluding glow discharges. Thermionic emission is the principal means in hot-cathode mercury-vapor diodes. In the last two chapters of this book other possible means of emission in arcs will be discussed.

Another distinction between a glow discharge and the arc in a thermionic gas diode should be noted. The glow in a glow discharge covers a percentage of the cathode determined by the tube current, whereas the glow in a hot-cathode gas tube covers the entire cathode irrespective of the tube current.

8.3. Theories Used to Explain the Characteristics of Thermionic Gas Diodes. *Neutralization of Space Charge.* In order to understand the operation of thermionic gas diodes, it will be helpful first to consider the effect of the insertion of a small amount of gas into an ordinary high-vacuum diode. As the gas pressure is increased, the mean free path is reduced, and more electrons collide with gas molecules before hitting the plate. Such collisions occur, of course, even in the best vacuum obtainable, but the number of collisions is extremely small in good high-vacuum tubes.

In Fig. 8.10 the volt-ampere curves of two tungsten-filament tubes are plotted. They are identical in every respect except that a very high vacuum has been drawn in one and a small amount of gas has been admitted in the other. The high-vacuum curve is conventional in every way, following the three-halves-power law below the knee and saturating at a relatively constant current above the knee. The tube containing the small amount of gas draws *less* current for low plate voltages, but *more* current for plate voltages above a certain amount.

The peculiar behavior exhibited by the slightly gassy tube is due to a number of effects. For plate voltages appreciably below the ionizing potential of the gas, the principal effect of the gas molecules is to impede the motion of the electrons. More electrons collide with gas molecules before reaching the anode, and even though the collisions are for the most part elastic, they cause a redirection of the energies of the electrons and increase their transit

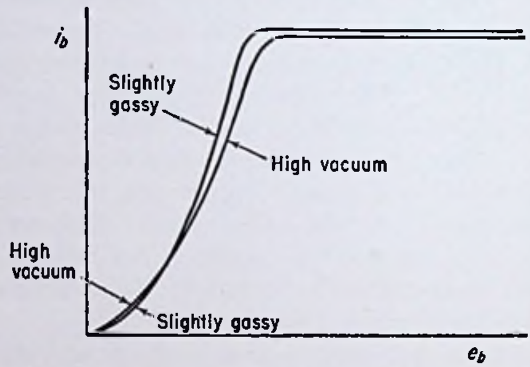

FIG. 8.10. Volt-ampere curves for a thermionic diode with and without a small amount of gas.

time. The increased transit time of the electrons causes the negative space charge to have a greater effect on the potential distribution in the tube and thus causes a slight reduction in space current.

Some of the collisions between electrons and gas molecules are inelastic, resulting in either excitation or ionization of the molecules. Heretofore in this text it has been assumed that an excited atom very quickly returns to the normal state and releases the excitation energy as a photon of light. However, in the atoms of some elements there are certain energy levels that an electron can occupy for a relatively long time. The reason is obscure, except that an electron is apparently forbidden to jump from certain larger to certain smaller orbits. An atom excited to one of these "forbidden" levels is called a *metastable* atom, and mercury vapor has several such metastable states.

The importance of the metastable atoms lies in the much greater probability, due to their longer life, of their becoming ionized before returning to the normal state. The energy required to ionize an excited atom is, of course, much less than the energy required to ionize a normal one. For example, consider a hypothetical atom which requires 5 e-v for excitation and 8 e-v for ionization. If two electrons happened to hit such an atom in very rapid succession in just the correct manner, the atom could be ionized, even though the first electron had only 5 e-v energy and the second only 3 e-v energy, the difference between 8 and 5. However, owing to the extremely short life of an ordinary excited atom, the probability of such a two-step type of ionization is very small. In the case of gases having metastable states, however, ionization is possible when the maximum electron energies are as low as the excitation energy for the lowest metastable state.

Referring once again to Fig. 8.10, as the voltage is increased past a certain point, appreciable ionization begins. The exact voltage depends on whether or not the gas has metastable states. The current is increased by ionization for two reasons. The electrons set free by the ionization process are quickly drawn to the anode, and the positive ions are drawn with considerably less speed to the cathode. This increased flow of charge adds to the current, which accounts for the greater current flow above the knee in the case of the gassy tube.

Below the knee of the curve the ionization of the gas exerts a far more powerful influence on the magnitude of the current, however, as can be seen from Fig. 8.10. Below the knee the current is space-charge-limited, meaning that the potential-distribution curve is depressed sufficiently to set up a slightly negative potential gradient at the cathode surface. As was pointed out in Sec. 7.3, the effect of positive space charge is opposite to the effect of negative space charge, tending to make the potential curve concave downward instead of concave upward. Thus, whereas negative space charge tends to *reduce* the current, positive space charge tends to *increase* the current.

It might be thought at first that the positive ions produced by the ionization process would have no effect on the potential distribution in the tube, since an electron is released simultaneously with the production of a positive ion. But when the large difference in mass between electrons and positive ions is considered, the influence of the positive ions becomes quite obvious. The electrons set free by the ionization process are drawn to the anode very rapidly. The positive ions, on the other hand, move relatively slowly toward the cathode and stay in the interelectrode space much longer.

As an example, consider mercury vapor, the molecules of which have an atomic weight of 200.61 and therefore a mass 200.61 × 1,840 times that of an electron. The ratio of speeds of these two particles is the inverse of the square root of the mass ratio (see Sec. 1.4). Thus an electron acquires a velocity about 607 times that of a mercury ion in falling through the same potential difference. One mercury ion has the same effect on the potential distribution as several hundred electrons.

The positive ions tend to neutralize the negative space charge and raise the potential-distribution curve. The space-charge-limited current is therefore increased by the ionization process. Although no practical commercial tube is built having the pressure of gas illustrated by the "slightly gassy" curve in Fig. 8.10, the processes just described illustrate in a simplified fashion some of the actions taking place in actual thermionic gas tubes.

Breakdown. If the gas pressure is sufficiently great, the ionization process becomes cumulative and the tube "breaks down," or "fires," giving the type of curve shown in Fig. 8.9 instead of the one shown in Fig. 8.10. Breakdown in a thermionic gas diode is an entirely different process from breakdown in a glow-discharge tube. Whereas space charge and the space potential distribution have no appreciable effect in a glow tube prior to breakdown, the overcoming of negative space charge and the corresponding change in the potential-distribution curve constitute the major phenomena in the breakdown of a thermionic gas tube.

As the voltage is increased from zero in a thermionic gas diode, a point is reached at which ionization begins. As the voltage is raised still further, the amount of ionization is increased, which increases the space current, which in turn increases the ionization, etc. This is a cumulative process, and eventually a voltage is reached at which the current jumps suddenly until the increase in the IR drop across the external series resistance lowers the tube voltage to a value just sufficient to draw the required current through the tube.

It is commonly assumed that when a gas tube breaks down, the positive space charge neutralizes *completely* the negative space charge in the interelectrode space and eliminates entirely the negative potential gradient existing at the cathode surface. The corresponding potential-distribution curve is assumed to be as shown in Fig. 8.11. A small potential drop (or rise) usually occurs near the anode; this is called the "anode drop." Most of the space between the electrodes is occupied by a region of low positive potential gradient known as the *plasma*. Separating the plasma from the cathode is a region of comparatively high positive field strength known as the *cathode sheath*. This theory is correct except for the shape of the potential curve near the cathode. The

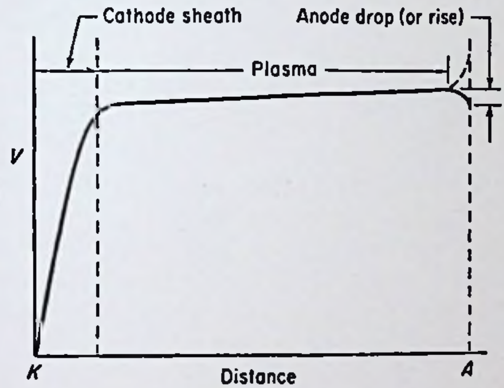

FIG. 8.11. Potential distribution in a thermionic gas diode, assuming complete neutralization of negative space charge.

curve shown in Fig. 8.11 exists only when the tube current is equal to or greater than the emission current of the cathode, a condition ordinarily avoided in practice because of the likelihood of damage to the cathode surface.

Under ordinary operating conditions with a plate current less than the emission current of the cathode, the potential gradient at the cathode surface must be negative, as in a high-vacuum diode. A consideration of the following facts will make this point clear:

1. For every electron leaving the cathode and entering the plasma there must be *at least* one electron entering the anode. Electrons cannot travel in appreciable numbers from the plasma to the cathode owing to the high positive voltage gradient existing in the cathode sheath. The only charges moving in appreciable numbers from the plasma to the cathode are the positive ions

created by collisions between gas molecules and electrons. Upon reaching the cathode, the positive ions combine with electrons to form neutral molecules. But for each positive ion created by a collision between an electron and a molecule, an additional electron is also set free. Therefore the creation of positive ions does not in itself change the *difference* in the number of positive and negative charges in the interelectrode space. In order for an equilibrium to be established and a negative space charge prevented from building up ad infinitum in the interelectrode space, every electron leaving the cathode must be balanced by one electron entering the anode *plus* any additional electrons, created by ionization due to the original electron, that do not recombine with positive ions before reaching the anode.

2. Not every electron emitted from the thermionic cathode enters the plasma when the plate current is less than the cathode emission current. This follows directly from statement 1, since, as was pointed out, the electrons in the plasma cannot return to the cathode, their only outlet being the anode. But, as was also pointed out, the number entering the anode is greater than the number leaving the cathode. Therefore the number permanently leaving the cathode is less than the number emitted from the cathode.

3. The facts established in the foregoing statements necessitate the existence of a negative voltage gradient at the cathode surface. This is the same situation which exists in a thermionic high-vacuum diode and obviously calls for a virtual cathode to act as a "velocity" filter, permitting only the highest energy electrons to travel on to the plasma.

The preceding arguments require a potential-distribution curve of the form shown in Fig. 8.12. In addition to the cathode sheath, sometimes called a *positive-ion sheath*, there must exist adjacent to the cathode surface an *electron sheath*, or a region where negative space charge prevails.

Such an electron sheath is not only absolutely essential, but it is quite logical. The number of electrons in this region greatly exceeds the number of positive ions. This is because the number of electrons making ionizing collisions is quite small compared to the total number of electrons traversing the interelectrode space. Furthermore the positive ions reach their maximum velocity in this region and hence exert the least influence here. Electrons emerging from the cathode, on the other hand, are moving relatively slowly, even for the case illustrated in Fig. 8.11. For the case illustrated in Fig. 8.12, the electron velocities are still lower, thus further increasing their influence.

The thickness of the electron sheath is quite small. This fact has probably been one reason why writers have tended to ignore the double-sheath theory. The physical similarity between a glow discharge and a thermionic arc discharge has probably been another contributing factor. The conditions in a glow discharge are quite different, however. The number of positive ions near the cathode in a glow tube greatly exceeds the number of electrons,

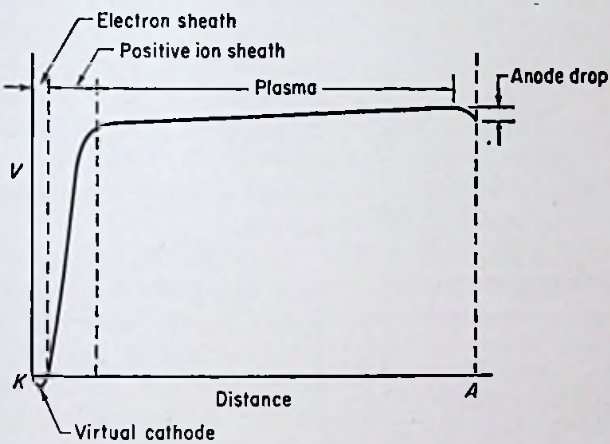

FIG. 8.12. Potential distribution in a thermionic gas diode, assuming incomplete neutralization of negative space charge.

since the electrons are largely the result of secondary emission due to positive-ion bombardment of the cathode, and the secondary-emission ratio is always considerably less than unity for positive ions.

The high-current–low-voltage characteristics of the thermionic gas diode can be explained on the basis of the behavior of the plasma, which contains almost equal numbers of positive and negative charges. The voltage gradient in the plasma is very low and relatively constant, thus giving it about the same characteristics as a metallic conductor. For all practical purposes, then, the anode is located at the boundary between the cathode sheath and the plasma. In Sec. 2.4 it was shown that under conditions of space-charge-limited current, the current varies inversely with the cathode-anode spacing for a constant plate voltage. The small effective cathode-anode spacing in Fig. 8.12 accounts, in part at least, for the high current flowing at the low potential difference.

Figure 8.13 compares the potential-distribution curves for a high-vacuum diode and a thermionic gas diode carrying about the same current. The voltage drop across the high-vacuum diode is several times that across the gas tube. In practice, vacuum diodes are seldom constructed with cathode-anode spacings as large as those commonly employed in gas tubes. Even with close electrode spacings, however, vacuum diodes are not capable of carrying as much current as gas diodes with the same voltage drop, and the voltage drop of gas diodes is almost constant with changes in current instead of being proportional to the current.

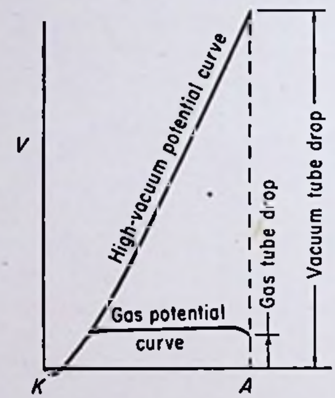

FIG. 8.13. Comparison of the potential distributions in a high-vacuum and a gas diode carrying the same current.

The small thickness of the electron and positive-ion sheaths accounts for the emission obtained from cavities in the cathodes of thermionic gas diodes. As long as the cavities are wider than about twice the thickness of the cathode sheaths, the plasma extends into the cavities and for all practical purposes carries the anode along with it.

As an attempt is made to increase the voltage drop across a thermionic gas diode, either by increasing the supply voltage or by decreasing the external series resistance, the electrons are momentarily swept more quickly out of the plasma. This leaves behind a surplus of positive ions and causes the plasma to expand and the cathode sheath to contract. The decreased effective cathode-to-anode spacing raises the potential minimum and increases the current until a new equilibrium is established at a higher current level, the tube drop remaining practically constant.

As an attempt is made to decrease the voltage drop across the tube, either by decreasing the supply voltage or increasing the external series resistance, the opposite actions take place. The plasma contracts, the cathode sheath expands, the potential minimum drops, and the current drops until a new equilibrium is established at a lower value of current, the tube drop remaining practically constant.

Cathode Considerations. The cathode is continuously bombarded by positive ions in a hot-cathode gas tube. These positive ions have little effect on the cathode, however, unless their energy exceeds a critical value. When a voltage known as the *disintegration voltage* is reached, the ions have sufficient energy to strip the layer of thorium or the oxide coating from the cathode surface, thus reducing or destroying the emitting properties of the cathode. The disintegration voltage is about 22 volts for mercury vapor, 25 volts for argon, and 27 volts for neon.

Thoriated-tungsten cathodes may not be permanently damaged by voltages in excess of the disintegration voltage, as shown in Fig. 8.9. The dotted curves in Fig. 8.9 represent equilibrium conditions such that thorium is being removed by positive-ion bombardment as fast as it is being replaced by more thorium diffusing out from the interior of the cathode. For very high plate voltages, the emission is practically that from the pure-tungsten cathode. The tube drop rises for currents in excess of the emission current so that secondary emission from the cathode may tend to keep the emission high.

Peak Inverse Voltage. The peak inverse voltage rating is one of the most important ratings given to a hot-cathode gas diode by the manufacturer. The pressures and electrode spacings used in gas tubes are always such as to place the point of operation to the left of point M in Fig. 7.24. This means that an *increase* in gas pressure lowers the voltage necessary to cause ignition in a tube when the anode is negative. Tungar tubes, operating at pressures of a few millimeters of mercury, have as a consequence low peak inverse voltage ratings, generally in the neighborhood of 50 to 100 volts. Hot-cathode gas diodes using the noble gases are generally operated at somewhat lower pressures. A lower limit on pressure is necessary because of a "cleanup" action of the gas over a long period of time. The electrodes and walls of the tube tend to "soak up" the gas molecules and reduce the gas pressure. If the pressure is initially low, it may eventually become so low that insufficient ionization is produced to neutralize effectively the negative space charge, causing a rise in the tube drop and, if the

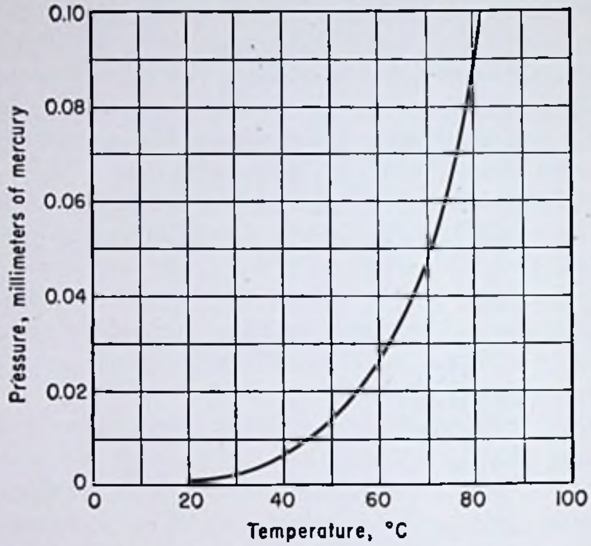

FIG. 8.14. Relationship between the pressure of the mercury vapor in a thermionic gas tube and the condensed-mercury temperature.

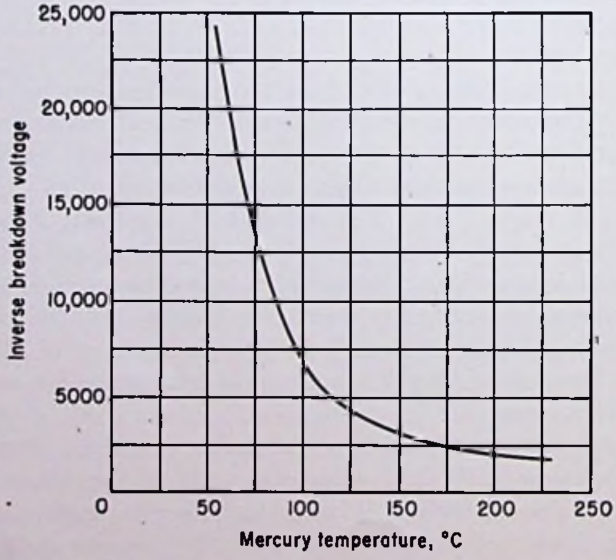

FIG. 8.15. Relationship between inverse breakdown voltage and condensed-mercury temperature in a typical gas diode.

disintegration voltage is exceeded, damage to the cathode. A moderately high gas pressure gives a factor of safety and allows for a certain amount of cleanup over the lifetime of the tube.

Mercury-vapor hot-cathode gas diodes are operated at even lower pressures, usually in the neighborhood of a few hundredths of a millimeter of mercury. Thus the peak inverse voltage rating can be made rather high, up to several thousand volts.

Effect of Temperature in Mercury-vapor Tubes. The pressure inside a mercury-vapor gas diode is dependent upon the temperature of the coolest portion of the bulb, since the mercury condenses in this region. Figure 8.14 shows that the pressure increases with an increase in the condensed-mercury temperature.

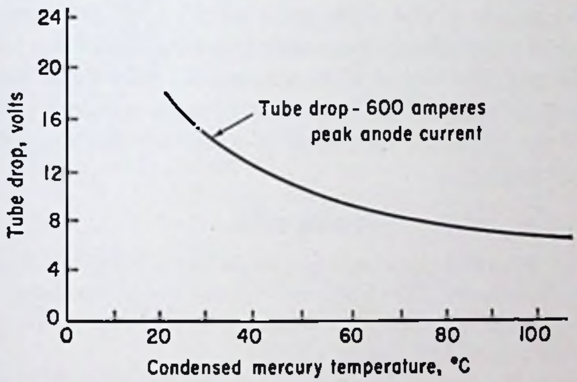

FIG. 8.16. Tube drop as a function of condensed-mercury temperature in a hot-cathode mercury-vapor diode.

The inverse breakdown voltage decreases as the pressure, and therefore as the condensed-mercury temperature, is increased. Figure 8.15 shows the relationship in a typical case. Sufficient ventilation must always be provided to prevent the bulb temperature from rising to excessive values. For approximate estimating purposes, a 15 to 30° difference in temperature may be expected between the condensed mercury and ambient. The manufacturer generally specifies the inverse peak voltage for a condensed-mercury temperature of 75°C.

A minimum temperature limit for mercury-vapor tubes is also necessary to prevent excessive tube drops and resultant cathode destruction. Figure 8.16 shows the relationship between tube drop and condensed-mercury temperature. At the lower temperatures the pressure is so low that ineffective space-charge neutralization causes the tube drop to rise. A minimum temperature of about 20 to 25°C is ordinarily recommended by the manufacturer for mercury-vapor gas tubes. In cold climates, special precautions may be necessary in outdoor or other installations where ambient temperatures are likely to be so low as to cause condensed-mercury temperatures below 20°C.

Deionization. When the voltage applied to a thermionic gas diode is suddenly reduced to zero, the current does not drop to zero instantaneously. Owing to the large mass of the positive ions, an appreciable time elapses before all the ions within the tube recombine with electrons to form neutral molecules. Recombination occurs largely at the walls and electrodes of the tube, so that application of a negative voltage may hasten deionization by speeding up the positive ions. If an alternating voltage is impressed across a hot-cathode gas diode, an upper frequency limit is imposed because of the increased likelihood of flashback in the presence of appreciable ionization.

PROBLEMS

1. A type FG-166 hot-cathode gas diode has a 2.5-volt 100-amp filamentary-type cathode. The maximum *average* anode current is 20 amp. Compute the emission efficiency in milliamperes per watt. How does this compare with typical high-vacuum tubes?

2. Compute the instantaneous tube loss and efficiency in a circuit in which a hot-cathode diode is operated in series with a 50-ohm resistor and an alternating supply voltage when the supply voltage has an instantaneous value of 320 volts. Assume a tube drop of 12 volts. How much current flows in the circuit?

3. The tube of Prob. 1 conducts current in rectangular pulses. If the maximum *instantaneous* anode current of 75 amp is drawn during the conduction periods, how long should the pulses last for a repetition frequency of 10 cps in order to draw 20 amp *average* current?

4. A sinusoidal alternating voltage is supplied to the gas diode of Fig. 8.15 in series with a suitable load resistance. For a room temperature of 40°C, what is the maximum rms voltage that may be applied before an inverse breakdown occurs? (Assume a 25°C temperature difference between ambient and condensed mercury.)

5. Plate voltage was accidentally applied prematurely to a certain thermionic gas diode having a thoriated-tungsten filament. The emission dropped sharply. The tube was believed ruined and was taken out of service. However, a second test a short time later showed the emission to be normal. (Sufficient heating time was allowed in the second instance.) Describe what had happened.

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CHAPTER 9

THYRATRONS

When the problems involved in constructing commercially practical thermionic gas diodes were solved, the next step involved the application of grid control, already a proved success in high-vacuum tubes. It was clear from the beginning, however, that such "gas triodes" would have characteristics quite different from high-vacuum triodes. This, in turn, has led to somewhat different applications for the grid-controlled gas tubes. Whereas high-vacuum tubes have been used *principally* in connection with communications equipment and the control of small amounts of power, grid-controlled gas tubes have found application *principally* in connection with the rectification and control of large amounts of power. The applications of grid-controlled *thermionic* gas tubes, called *thyratrons*, are quite numerous, and, just to mention a few, include speed control of motors, lighting control, welding control, and voltage-regulated rectification of alternating current.

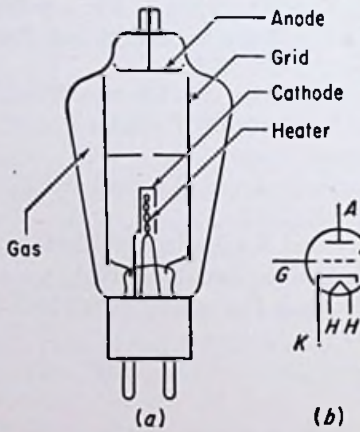

FIG. 9.1(*a*). Sketch of a thyratron gas triode. (*b*). Symbol for a thyratron.

9.1. Physical Characteristics of Thyratrons. Figure 9.1(*a*) is a cross-sectional sketch of a thyratron showing the cathode, anode, and control electrode, or "grid," following the nomenclature used in vacuum tubes. The cathode is constructed along the same lines employed in thermionic gas diodes (see Sec. 8.1). The grid is a large cylinder with one or more perforated baffles placed near the center. The anode is a small disk located near the top of the bulb. The symbol for a thyratron is the same as for a high-vacuum triode with the exception of the addition of a dot to denote the presence of gas, as shown in Fig. 9.1(*b*).

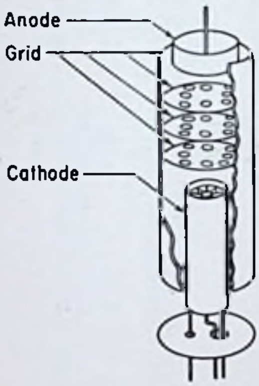

FIG. 9.2. Electrode structure of a positive-grid thyratron.

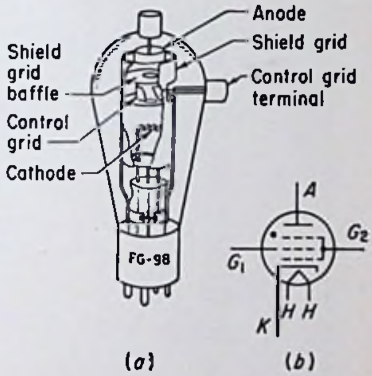

FIG. 9.3(*a*). Electrode structure of a shield-grid thyratron. (*b*). Symbol for a shield-grid thyratron.

The gas most commonly used in thyratrons is mercury vapor. A few drops of mercury is inserted into the tube prior to sealing, and the correct gas pressure is maintained by operating the tube within certain temperature limits, as in mercury-vapor diodes. Other gases sometimes used include argon, xenon, and hydrogen.

Indirectly heated cathodes are usually employed, except in the smallest thyratrons. A unipotential cathode gives the tube a more uniform and stable firing characteristic. Heat-conserving features are incorporated into the cathode structures, as for thermionic gas diodes, in order that high emission efficiencies may be obtained.

The type of grid structure shown in Fig. 9.1(*a*) results in what is generally known as a *negative-grid* thyratron, for reasons which will be given in Sec. 9.2. A *positive-grid* thyratron is obtained by employing the type of grid construction illustrated in Fig. 9.2. Several baffles separate the cathode and anode, and numerous small holes are used instead of a single large one.

A special type of thyratron known as a *screen-grid*, or *shield-grid*, thyratron has been developed to overcome some of the limitations of ordinary thyratrons. Figure 9.3(*a*) illustrates the type of con-

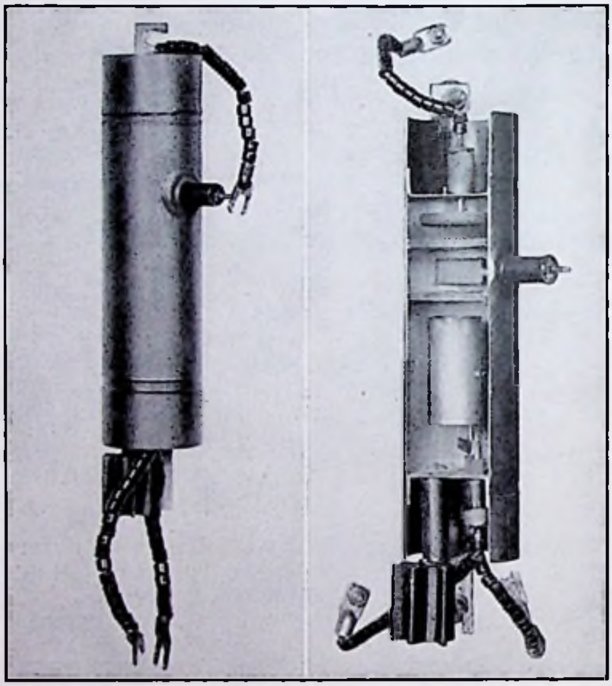

FIG. 9.4. Construction of a type FG-172 shield-grid thyratron. (*Courtesy General Electric Company.*)

struction generally used. The shield grid is a large cylinder with two baffles placed between the cathode and anode. The control grid is a cylinder with a diameter slightly larger than and located between the two holes in the baffles. Connection to the control grid is made through a hole in the side of the shield grid. Figure 9.3(*b*) shows the symbol used for shield-grid thyratrons.

The smallest sized thyratrons are usually constructed with glass envelopes, but in the large sizes a metal envelope is sometimes used, which gives greater ruggedness and, incidentally, helps overcome any tendency toward nonacceptance in industrial applications due to the apparent fragility of glass tubes. Figure 9.4 shows the construction of a type FG-172 shield-grid thyratron having a metal envelope. The electrode configuration, it will be noted, is very similar to that shown in Fig. 9.3(a).

FIG. 9.5. A miniature-type GL-5663 thyratron. (*Courtesy General Electric Company.*)

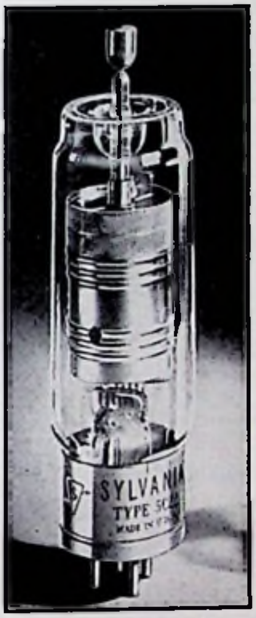

FIG. 9.6. A hydrogen-filled thyratron having a short deionization time. (*Courtesy Sylvania Electric Products, Inc.*)

Figure 9.5 shows a miniature-type GL-5663 thyratron requiring only 10 sec heating time and suitable for the control of small amounts of power.

Figure 9.6 shows a hydrogen thyratron developed for use in radar circuits in the Second World War. The deionization time is much shorter than that of conventional tubes, and operation at frequencies up to several thousand cycles per second is possible.

9.2. Electrical Characteristics of Thyratrons. *Firing Characteristics.* Figure 9.7 is a circuit diagram suitable for investigating the electrical characteristics of negative-grid thyratrons. The resistors R_1 and R_2 in series with the grid and plate, respectively, are absolutely essential to prevent possible damage to the tube. They should be large enough to limit the grid and plate currents to the maximum allowable average values as given by the manufacturer. As in a thermionic gas diode, the tube itself has no automatic current-limiting mechanism, and the electrode currents must be limited by the circuit resistances.

Assume the plate supply voltage is set at zero and the grid supply voltage at some high negative value. Next assume the plate voltage is raised to some moderately high value. Provided the grid is sufficiently negative, it will be found that the plate current is essentially zero. Assume now that the grid voltage is slowly made

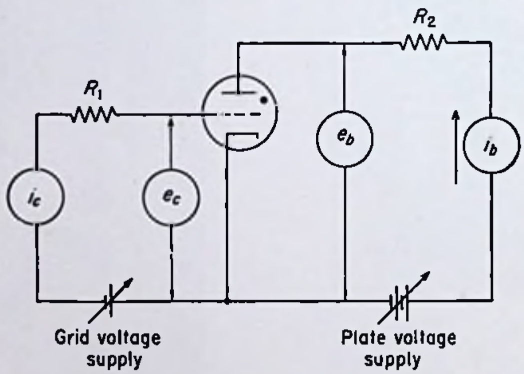

FIG. 9.7. Circuit diagram for obtaining the electrical characteristics of a negative-grid thyratron.

less negative. At some critical value of grid voltage the plate current suddenly jumps to a high value, and a visible glow appears between the electrodes. The exact value to which the plate current jumps depends on the value of R_2, being higher as R_2 is reduced. When the plate current abruptly rises, the tube is said to "break down" or "fire."

Once the tube has fired, it will be found that the grid has absolutely no control over the magnitude of the plate current. The current cannot be stopped or even reduced by making the grid highly negative. After breakdown, the tube is for all practical purposes the same as a thermionic gas diode, and the volt-ampere curves given in the previous chapter hold equally well for thyratrons.

The grid voltage at which the tube fires is called the *critical* *grid voltage*, and it depends upon the plate voltage and the pressure of the gas inside the tube. If the pressure is constant, it depends only upon the plate voltage. Thus for thyratrons using an inert gas or some other gas such as hydrogen, the critical grid voltage is completely determined by specifying the plate voltage. But for mercury-vapor thyratrons, the gas pressure varies with the condensed-mercury temperature, and hence the exact critical grid voltage depends on the temperature of the coolest part of the bulb as well as the plate voltage.

Assuming a constant gas pressure, the relation between critical grid voltage and plate voltage can be determined by setting the plate voltage at various values and at each value allowing the tube to fire by slowly reducing the negative grid voltage. A plot of the plate voltage vs. the grid voltage *just prior to firing* is called a *grid-control characteristic*. Figure 9.8 is typical for negative-grid thyratrons.

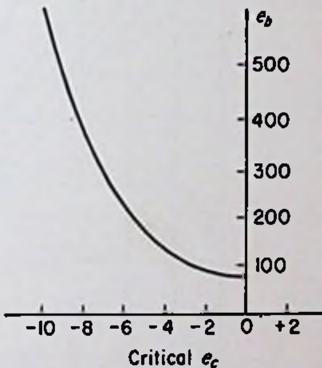

FIG. 9.8. Grid-cont ol characteristic for a negative-grid thyratron.

It should be recognized that, in order to determine whether or not a tube has fired, it is not sufficient merely to specify the grid voltage. Any point to the *right* of the curve in Fig. 9.8 definitely indicates a breakdown has occurred, but a point to the *left* of the curve does not necessarily indicate that a breakdown has *not* occurred. Once the grid voltage has excursioned to the right of the curve, the tube will continue to conduct regardless of the value of the grid voltage.

After a tube has fired, the only way the plate current can be stopped is by reduction of the plate-to-cathode voltage to a value less than the ionizing potential of the gas, for a length of time sufficient to permit deionization of the gas inside the tube. The plate-to-cathode voltage can be reduced either by increasing the circuit resistance or decreasing the plate supply voltage.

Effect of Condensed-mercury Temperature in Mercury-vapor Tubes. For mercury-vapor tubes a series of grid-control curves can be plotted for different condensed-mercury temperatures. Figure 9.9 shows the characteristics for a type FG-57 thyratron. This tube has a structure similar to that shown in Fig. 9.1. As shown, the critical grid voltage increases with an increase in condensed-mercury temperature. Or for a constant grid voltage, the breakdown plate voltage decreases with an increase in temperature.

Grid-control Characteristics of Positive-grid Thyratrons. The circuit shown in Fig. 9.7 can be used for positive-grid thyratrons provided the polarity of the grid supply voltage is reversed. Figure 9.10 shows the characteristics of a type FG-33 positive-grid thyratron, the structure of which is shown in Fig. 9.2. This is a

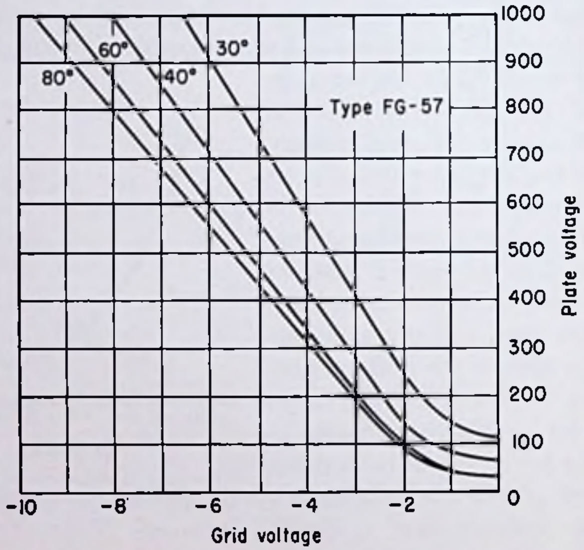

FIG. 9.9. Grid-control characteristics of a type FG-57 negative-grid thyratron.

mercury-vapor tube, and hence several curves for different condensed-mercury temperatures are given. As shown, the critical grid voltage is almost independent of the anode voltage.

Thyratron Grid Current Prior to Breakdown. Assume that the thyratron in Fig. 9.7 has not been permitted to fire by maintaining a high negative voltage on the control grid. It will be found that the grid current, though small, is not zero, as might be expected. A few electrons reach the grid because of their high emission velocities. A few positive ions are created by collision, owing to the initial velocities of the electrons emitted from the cathode, and these positive ions are drawn to the grid. Also any positive ions created in the tube by cosmic rays, X rays, and the like will be attracted to the grid. The positive ions bombarding the grid may produce a small amount of secondary emission, particularly if any active material from the cathode has been deposited on the grid. A small amount of thermionic emission from the grid is also possible if it has been contaminated with emitting material.

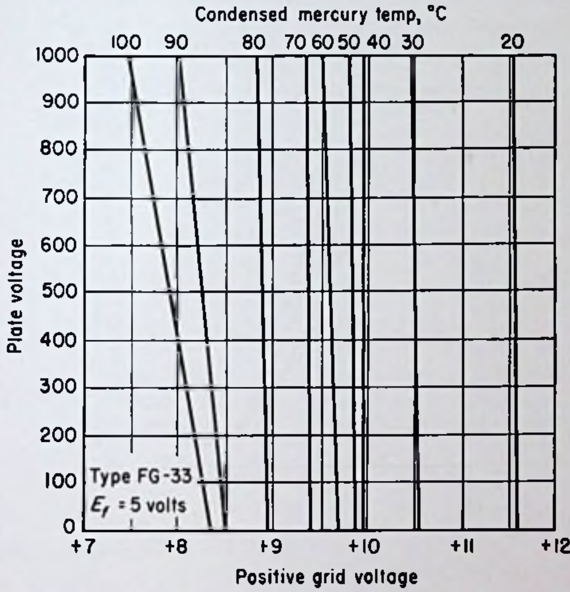

FIG. 9.10. Grid-control characteristics of the type FG-33 positive-grid thyratron.

In addition to the above causes of grid current, there exist two other causes of a somewhat different nature. When the grid voltage is altered, a charging or discharging current flows in the grid circuit, owing to the electrostatic capacitance between the grid and the other electrodes in the tube. And finally there is always a small contribution to the grid current due to leakage current flowing in and on the surface of the insulation between the grid and the other electrodes.

Owing to the many variables influencing the magnitude of the grid current, a reliable set of curves can hardly be drawn for any particular tube. Thus the grid-control characteristics given in

Figs. 9.9 and 9.10 should be interpreted merely as representative or average curves, and individual tubes might be expected to depart considerably from the average.

The grid current flowing prior to firing sets a limit on the maximum grid-circuit resistance that can be used if reliable firing is to be secured. The grid current may be either positive or negative, thus tending to make the grid either more or less negative. Figure 9.11 is a plot of the grid current of a negative-grid mercury-vapor thyratron immediately prior to firing. The grid voltage corresponding to any particular point can be obtained by consulting the grid-control characteristic curves.

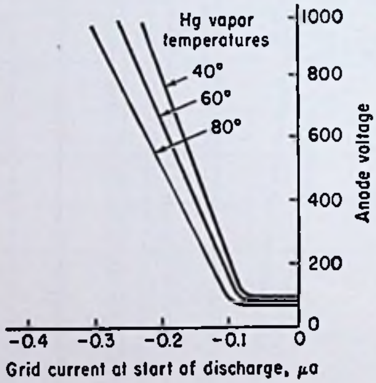

FIG. 9.11. Grid current of a negative-grid mercury-vapor thyratron immediately before breakdown.

Figure 9.12 is a plot of grid current vs. grid voltage for a type FG-17 thyratron before firing. The arrows indicate breakdown points.

Characteristics of Shield-grid Thyratrons. The grid-current limitations of ordinary thyratrons can be largely overcome through the use of a shield-grid thyratron, the constructional features of which were given in Sec. 9.1. A marked reduction in control-grid current prior to breakdown is possible using this tube. This permits the use of grid circuits having very high resistance, such as phototube circuits.

A circuit suitable for obtaining the characteristics of shield-grid thyratrons is given in Fig. 9.13. Either positive or negative potentials can be applied to the two grids by means of the center-tapped potentiometers as shown. The tube can be made to have either positive-grid or negative-grid characteristics by proper adjustment of the shield-grid voltage. For positive shield-grid voltages, the tube has negative-grid characteristics, whereas for negative shield-grid voltages, the tube has characteristics similar to those of positive-grid thyratrons.

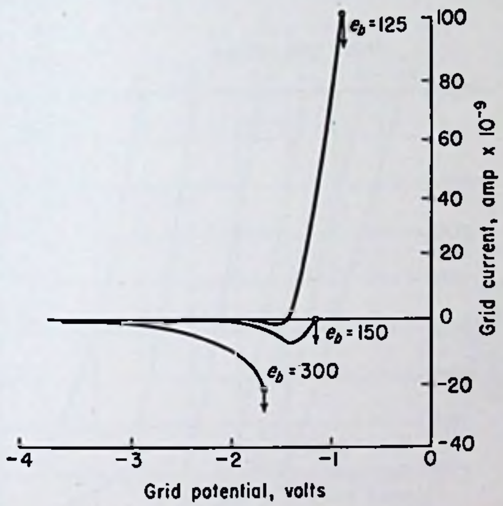

FIG. 9.12. Grid current of a type FG-17 thyratron as a function of grid voltage before breakdown.

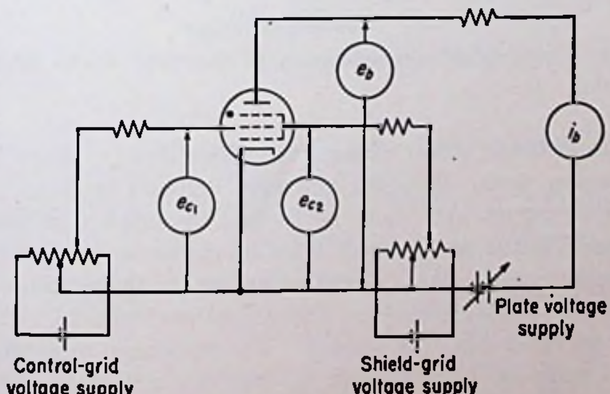

FIG. 9.13. Circuit diagram for determining the electrical characteristics of shield-grid thyratrons.

Figure 9.14 shows the grid-control characteristics of a type FG-95 shield-grid thyratron for one value of condensed-mercury temperature. It should be noted that the characteristics are about as sensitive to changes in shield-grid voltage as to changes in control-grid voltage. This is in contrast to a high-vacuum screen-grid tube, wherein the control grid is usually many times as effective as the screen grid in controlling the plate current.

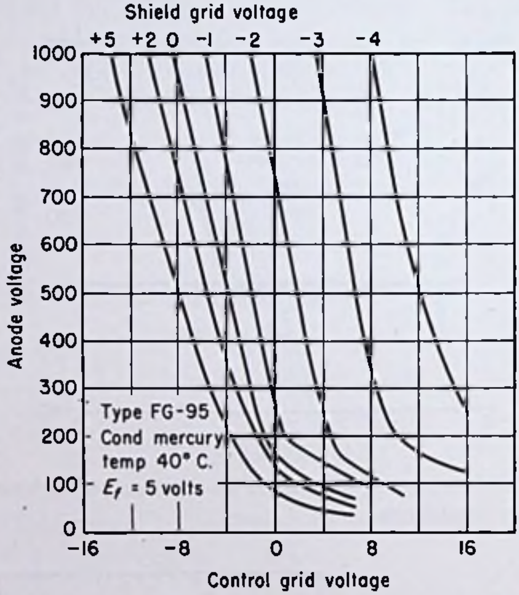

FIG. 9.14. Grid-control characteristics of the type FG-95 shield-grid thyratron.

Thyratron Grid Current Subsequent to Breakdown. When breakdown occurs, both the plate and grid currents tend to rise to destructive values and must be limited by external resistances. The "load" in the plate circuit must be chosen so that the maximum instantaneous plate current as well as the maximum average plate current is not exceeded. Thyratrons are identical with thermionic gas diodes in this respect. The resistance in series with the grid must be large enough to limit the grid current to the maximum allowable value. The resistance must not be so large, however, that reliable firing cannot be secured, as mentioned previously. Values of resistance which meet these requirements generally fall in the range of ¼ to 2 megohms.

Grid current subsequent to breakdown is a function of grid voltage and plate current. In the case of high-vacuum grid-controlled tubes, grid current flows only for positive grid voltages. However, in the case of thyratrons, grid current also flows for negative grid voltages, owing to the action of the positive ions. Figure 9.15 is a grid-current characteristic for a negative-grid thyratron. Several curves are shown for various fixed values of plate current. Figure 9.16 is a similar characteristic for a positive-grid thyratron. Current that flows *toward* the grid in the

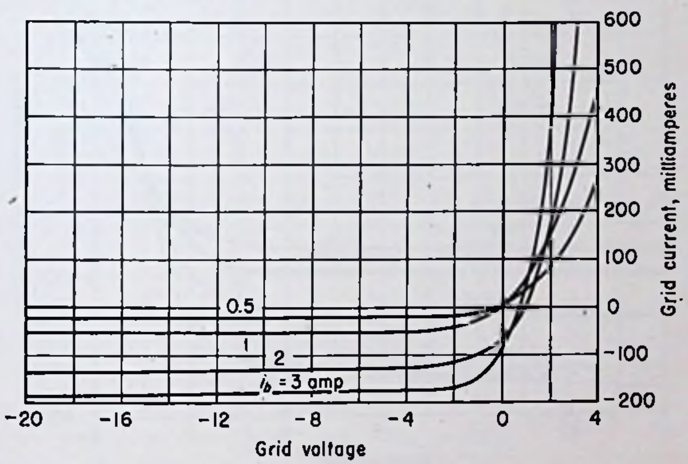

Fig. 9.15. Grid current in a negative-grid mercury-vapor thyratron after breakdown.

external circuit is taken to be positive. Conventional current flow *away* from the grid is considered negative.

9.3. Theories Used to Explain the Electrical Characteristics of Thyratrons. *Potential Distribution in a Negative-grid Thyratron Prior to Breakdown.* The potential distribution in a thyratron before breakdown plays such an important role in the breakdown process that it will be instructive to consider it in great detail. Prior to breakdown, the currents flowing in the tube are so small that the effects of space charge on the potential distribution are negligible. A potential model similar to those described previously for high-vacuum tubes can be obtained by passing a plane through the axis of the tube, as shown in Fig. 9.17. The electrodes are then raised or lowered relative to the cathode so that their height above or below the cathode represents their potentials relative to that electrode. The intervening surfaces take up heights corresponding to the space potentials in the actual tube. The resulting potential model is shown in Fig. 9.18.

Breakdown in a Negative-grid Thyratron. A side view of a section of the potential model of Fig. 9.18 is shown in Fig. 9.19. For the particular combination of electrode voltages used, a repelling field is presented to electrons emitted from the cathode. For high

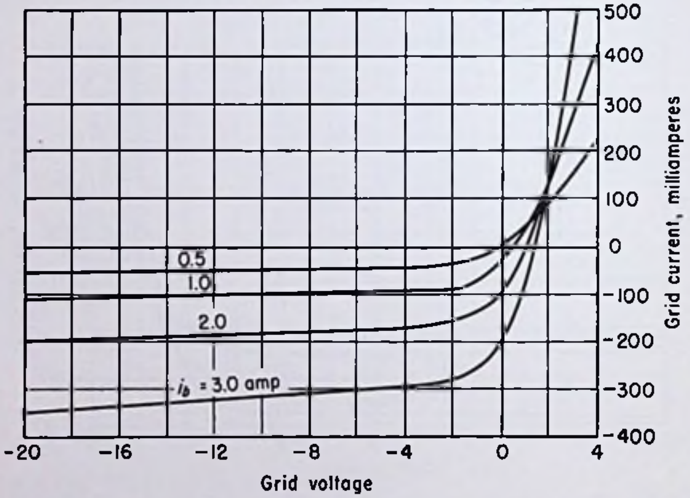

FIG. 9.16. Grid current in a positive-grid mercury-vapor thyratron after breakdown.

negative grid voltages, none of the emitted electrons are able to "climb over" the potential hump near the cathode, and therefore the plate current is essentially zero. As the grid is made less negative, the potential hump drops, permitting the highest energy electrons to pass through the hole in the baffle and enter the grid-anode region. Here they are accelerated toward the anode by the strong potential gradient. For plate voltages higher than the ionizing potential of the gas, some of these electrons make ionizing collisions before reaching the anode. The positive ions are accelerated toward the grid. Owing to their large mass, they remain in the interelectrode space a considerable length of time. As a consequence these positive ions may have an appreciable effect on the space potential distribution.

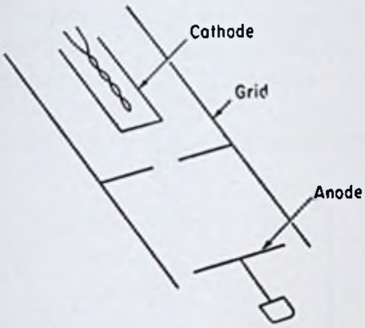

FIG. 9.17. A cross section of a negative-grid thyratron.

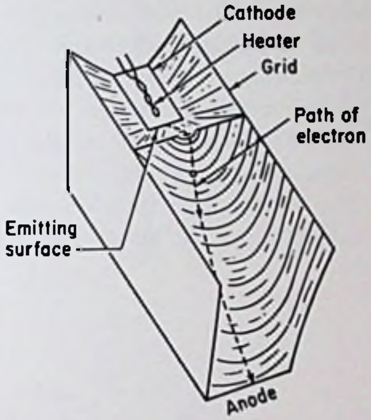

FIG. 9.18. Potential model of a negative-grid thyratron just before breakdown.

The electrons which reach the anode set up a small plate current, and the positive ions which reach the grid combine with electrons to form neutral gas molecules and cause a negative grid current. In Fig. 9.12 the initial current rise (in the negative direction) with decrease of negative grid voltage is due to these positive ions reaching the grid.

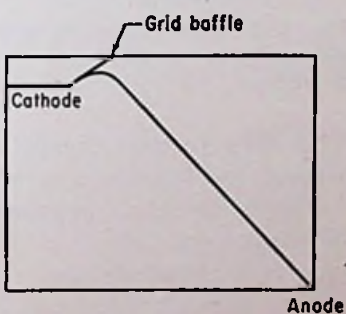

FIG. 9.19. A section of the potential model of Fig. 9.18.

The electrode currents produce IR drops in the series resistors and modify the electrode voltages correspondingly. The plate voltage is reduced slightly, and the grid voltage is either increased or decreased, depending on whether the current is positive or negative. At first the grid current is predominantly due to the positive ions, and a negative current flows, tending to reduce the negative grid voltage. But as the plate current is increased by making the grid less negative, the number of electrons able to reach the grid increases relative to the number of positive ions, and the grid current may become positive, as shown by the curve for $e_b = 125$ volts in Fig. 9.12. For higher plate voltages the tube may break down before the grid current becomes positive, however.

In order to understand the phenomenon of breakdown in a thyratron, consideration must be given to the manner in which the plate current varies with the grid voltage prior to breakdown. It should be evident that, as the grid is made less negative, more electrons are able to enter the grid-anode region to produce ionization. The increased ionization tends to increase the current because of the action of the positive ions on the space potential distribution.

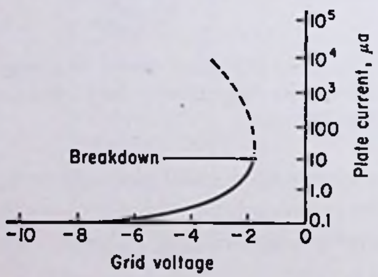

FIG. 9.20. Plate current vs. grid voltage in a thyratron prior to breakdown.

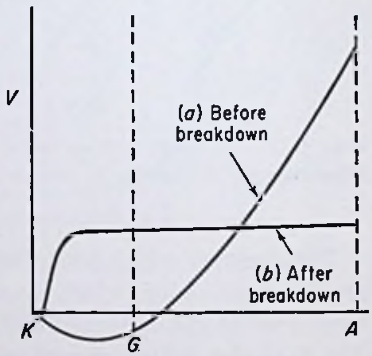

FIG. 9.21. Potential distribution (a) before and (b) after breakdown in a negative-grid thyratron.

This effect becomes cumulative at some particular value of grid voltage, and breakdown occurs.

Figure 9.20 shows the dependence of plate current before breakdown upon grid voltage. For high negative grid voltages the plate current is essentially zero. As the grid voltage is reduced, the current rises, slowly at first, and then more rapidly as ionization becomes appreciable. At some critical value of grid voltage, the slope of the i_b-e_c curve becomes infinite and breakdown occurs. The plate current rises until limited by the external series resistance. The positive ions in the interelectrode space tend to neutralize the negative space charge of the emitted electrons, and the potential distribution quickly shifts from that shown as curve (a) in Fig. 9.21 to curve (*b*), which is similar to the curves given in the previous chapter for thermionic gas diodes.

Essentially the same actions occur if the tube is fired by increasing the plate voltage while the grid voltage is held constant. For low plate voltages the potential "hump" near the cathode is so large that no electrons can "climb over" and enter the grid-anode region through the hole in the grid baffle. As the plate voltage is increased, however, the potential minimum is raised, which permits the highest energy electrons to enter the grid-anode region and, after acceleration, create ionization by collision. At some critical

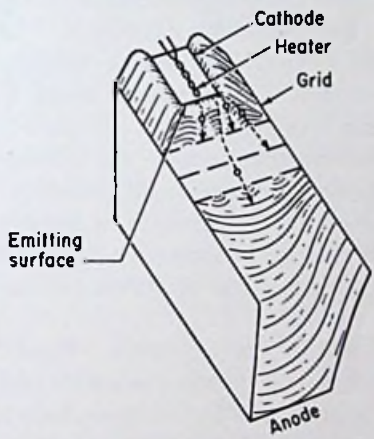

FIG. 9.22. Potential model of a positive-grid thyratron just before breakdown.

anode voltage, the plate current increases cumulatively, and the tube fires.

Breakdown in a Positive-grid Thyratron. A sketch of a potential model of a positive-grid thyratron is given in Fig. 9.22. From a study of this figure the following facts can be deduced:

1. The plate voltage has practically no influence on the potential distribution near the cathode.

2. The regions between the grid baffles are regions of practically zero field strength.

3. Very few electrons pass through all three baffles and reach the grid-anode accelerating region. Most of the emitted electrons hit one of the grid baffles.

Since the plate voltage has almost no effect on the potential distribution near the cathode, it is to be expected that the critical grid voltage should be practically independent of the anode voltage. This is clearly indicated by the curves in Fig. 9.10.

As the grid is made more positive (prior to breakdown), the number of electrons penetrating the potential minimum increases. Of perhaps greater importance is the fact that the electrons are accelerated to higher velocities. When the grid voltage reaches the ionizing potential of the gas, the electrons produce ionization by collision. For gases having metastable states, ionization by collision may begin for voltages less than the ionization potential. The initial velocities of the emitted electrons also permit ionization at voltages lower than the ionizing potential. As in a thermionic gas diode, at some critical accelerating voltage, the current increases, which increases the ionization, which increases the current, etc., resulting in a cumulative current build-up. When a grid-to-cathode breakdown occurs, the discharge immediately transfers to the anode if it is sufficiently positive.

It should be noted that, whereas in a negative-grid thyratron breakdown occurs because of ionization in the grid-anode region, in a positive-grid tube breakdown occurs because of ionization in the cathode-grid region.

Breakdown in a Shield-grid Thyratron. Breakdown in a shield-grid thyratron is similar to that in a negative-grid tube in that the main purpose of the grids is to *prevent* breakdown and not to initiate it. Both grids in a shield-grid tube influence the potential distribution near the cathode. For positive shield-grid voltages the control grid must be made negative to prevent electrons from entering the grid-anode accelerating region. For positive control-grid voltages the shield grid must be made negative to prevent electrons from passing through the holes in the baffles.

Thyratron Grid Action after Breakdown. When a thyratron fires, the potential distribution inside the tube becomes essentially the same as for a thermionic gas diode. Almost the entire region between the cathode and anode is taken up by a region of low field strength known as the plasma, containing almost equal numbers of electrons and positive ions.

The grid structure in the thyratron is immersed in the plasma and as a result has almost an unlimited reservoir of charges upon which to draw for a current. The resistance in series with the grid must be large enough to limit the grid current to the maximum allowable values. If the grid is positive, electrons are attracted, and a positive (in the *conventional* sense) grid current flows. If the grid is negative, positive ions are attracted, and a negative grid current flows. The curves in Figs. 9.15 and 9.16 do not pass exactly through the origin, so that the foregoing statements are only approximate. For slightly negative grid voltages, *some* electrons reach the grid and subtract from the negative current. As the grid is made less negative and finally positive, the electron current increases and the positive ion current decreases, the latter becoming negligible for high positive grid voltages. Notice that a saturation current is reached for negative grid voltages, indicating a condition wherein positive ions are being attracted to the grid as fast as they can be replaced from the plasma. A saturation current is theoretically possible for positive grid voltages, but owing to the much greater velocities of the electrons as compared to the positive ions, saturation occurs at grid voltages seldom reached in practice.

The reason for the inability of the grid to control the magnitude of the plate current after breakdown should be evident. The grid is in effect shielded from the cathode by the plasma, which, as pointed out in Sec. 8.3, acts much the same as a good conductor. For positive grid voltages, the flux lines from the grid are intercepted by electrons near the grid, and for negative grid voltages, flux lines reaching the grid originate from positive ions near the grid. In neither case does the electrostatic field near the grid have any effect on the field near the cathode, and as shown in Sec. 8.3, the voltage gradient near the cathode determines the magnitude of the plate current.

Advantages of Shield-grid Thyratrons. The particular constructional features employed in shield-grid thyratrons result in a number of advantages over ordinary tubes. One of these advantages is the fact that the tube can be made to have either positive-grid or negative-grid characteristics, depending on the polarity of the shield-grid voltage.

Another advantage which has already been mentioned is the lower grid current prior to breakdown, enabling the use of a much higher grid-circuit resistance. Thus shield-grid thyratrons can be used in many circuits in which it would be impossible to use conventional tubes because of the instability in the firing characteristics that would result.

In conventional thyratrons, the control grid is exposed directly to the heated cathode, and, throughout the life of the tube, active material is gradually evaporated from the cathode surface and condensed on the grid. If the grid ever became heated, thermionic emission from the grid might occur, resulting in loss of grid control. In the shield-grid thyratron the shield-grid baffle effectively intercepts most of the material that otherwise might find its way to the grid surface. (Actually the large area of the control grid in ordinary thyratrons tends to keep down thermionic emission by radiating a large amount of heat and thus keeping the grid temperature low.) The control grid in shield-grid thyratrons is shielded from the heat of the cathode as well as from the discharge stream itself so that thermionic emission from the grid can be kept at low enough values.

The current flowing to the control grid following breakdown in shield-grid thyratrons is considerably lower than in conventional tubes. This is because the control-grid current flowing after the tube has fired is roughly proportional to the area of the control grid exposed to the plasma. A glance at Figs. 9.2 and 9.3 shows the area of the control grid in shield-grid tubes to be much less than in ordinary tubes.

A final advantage of the shield-grid thyratron is the much lower capacitance between the control grid and the other electrodes. When the control voltage is altered rapidly, a charging or discharging current flows in the grid circuit, requiring a source of voltage capable of supplying a certain amount of power. The low interelectrode capacitance of the shield-grid tube permits control to be effected by an exceedingly small amount of power.

Incidentally, the reason for enclosing the cathode and anode so completely by the shield grid (or the control grid in ordinary thyratrons) is to shield the electrodes from stray fields and charges on the glass walls of the tube. Such fields would affect the potential distribution near the cathode and cause erratic firing.

Ionization and Deionization Times. The time required for breakdown in a thyratron after the application of a grid voltage above the critical value is very short. The *ionization time* decreases as the grid overvoltage is increased. The breakdown time is also inversely proportional to anode voltage and gas pressure. Figure 9.23(*a*) and (*b*) gives the exact relationships for a negative-grid thyratron. The condensed-mercury temperature is constant in Fig. 9.23(*a*), the ionization time being plotted as a function of the grid overvoltage for several fixed anode voltages. In (*b*) the anode voltage is constant, and curves of ionization time vs. grid overvoltage for several fixed temperatures are given. Ionization times as short as 0.3 μsec are possible for large grid overvoltages.

Unfortunately, deionization is a much slower process than ionization. Whereas ionization involves principally the acceleration of electrons to produce ions by collision, deionization involves the movement of relatively heavy and slow positive ions. Recombination of positive ions and electrons occurs largely at the walls and electrodes of the tube. Therefore the deionization time can

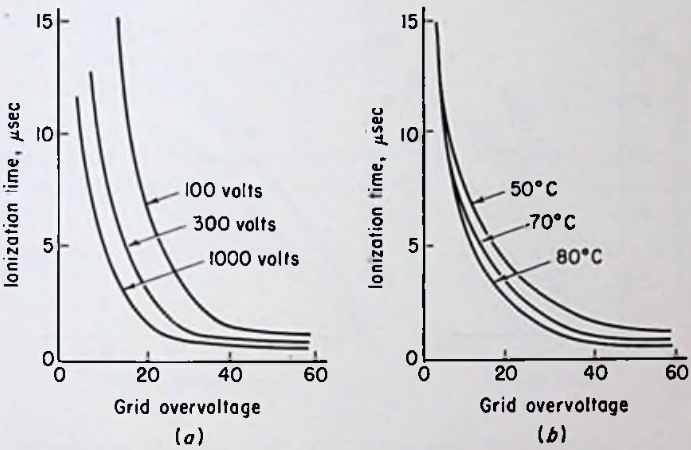

FIG. 9.23(*a*). Ionization time vs. grid overvoltage for various plate voltages. Condensed-mercury temperature = 70°C. (*b*). Ionization time vs. grid overvoltage for various temperatures. Anode voltage = 300 volts.

be reduced by providing ample surface area for recombination. Close electrode spacing is helpful, as is close spacing between the electrodes and the glass walls of the tube (if a glass envelope is used). Whereas ordinary tube construction yields a deionization time in the neighborhood of 1,000 μsec, special design features as mentioned above can reduce the deionization time to 100 μsec or less.

The use of a gas having a low atomic weight is beneficial in reducing the deionization time. Hydrogen has been employed for this purpose, as well as some of the lighter inert gases.

The deionization time can be reduced by applying a high negative voltage to the control grid (or the shield grid in a shield-grid tube). This speeds up the positive ions and permits a more rapid rate of recombination at the surfaces of the grid.

When an alternating voltage is impressed on the anode of a thyratron, the frequency must not be so high that the grid is unable to regain control after each cycle. Assuming the anode is negative for one-half a period, the deionization time must be less than one-half a period to enable the grid to regain control while the anode is negative and the tube is not conducting.

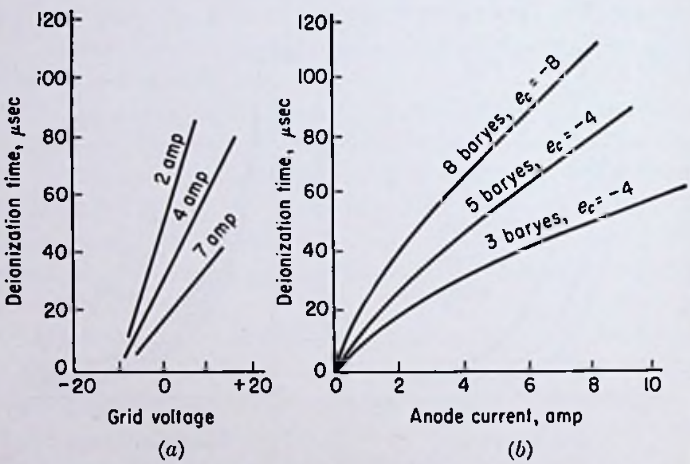

FIG. 9.24. Deionization time of a typical thyratron: (*a*) condensing temperature = 30°C, (*b*) effect of anode current for different condensing temperatures.

The deionization time depends on the plate current and gas pressure as well as the electrode separation and grid voltage. Figure 9.24(*a*) and (*b*) shows the experimental results on a typical tube. In (*a*) the deionization time is plotted as a function of grid voltage for three values of plate current. In (*b*) the deionization time is plotted as a function of the anode current for three conditions of gas pressure and grid voltage.

9.4. Mathematical Analysis of Thyratrons. *Grid-control Ratio of Negative-grid Thyratrons.* A factor which is useful in certain calculations involving the use of negative-grid thyratrons is the *grid-control ratio.* By definition, this is simply the ratio of the anode voltage to the grid voltage just prior to breakdown. Clearly this factor is not a constant, but for many calculations it may be assumed so. The grid-control ratio is analogous to the amplification factor of an ordinary high-vacuum triode. However, the analogy does not carry too far, because the grid-control ratio is simply the ratio of anode to grid voltage, whereas the amplification factor is the *rate of change* of anode voltage with respect to grid voltage for constant plate current. Nevertheless at zero anode current the two coefficients are quite similar.

If the grid-control ratio is denoted by the symbol μ, we have

$$\mu = -\frac{e_b}{e_c} \tag{1}$$

[Compare Eq. (1) with Eq. (11), Chap. 3.]

Example:

A certain negative-grid thyratron has a control ratio of 80. Compute the critical grid voltage for an anode voltage of 320 volts.

Solution:

$$\begin{aligned} e_c &= -\frac{e_b}{\mu} \\ &= -\frac{320}{80} \\ &= -4 \text{ volts} \quad \textit{Ans.} \end{aligned}$$

Deionization Time. For typical grid-anode structures Hull has shown that the deionization time of a grid-controlled gaseous discharge tube is given by the approximate empirical equation

$$t = \frac{0.0012pI^{0.7}}{e_g^{3/2}x} \qquad \text{sec} \tag{2}$$

where p is the gas pressure in dynes per square centimeter, I is the anode current to be extinguished, x is the distance between anode and grid in centimeters, and e_g is the negative grid potential relative to the surrounding space.

Example:

The gas pressure in a certain thyratron having a grid-anode spacing of 2 cm is 5 baryes (dynes per square centimeters). Find the deionization time for a grid potential of −3 volts and an anode current of 4 amp. (Assume the plasma near the grid to be at a potential of +10 volts.)

Solution:

$$t = \frac{0.0012pI^{0.7}}{e_g^{3/2}x}$$

$$= \frac{(0.0012)(5)(4)^{0.7}}{(3+10)^{3/2}(2)}$$

$$= 1.69 \times 10^{-4} \text{ sec}$$

$$= 169\ \mu\text{sec} \quad \textit{Ans.}$$

Positive-ion-sheath Thickness. After a thyratron fires, the grid loses control and cannot stop conduction. A negative control grid repels electrons and attracts positive ions from the plasma. The positive-ion current to the grid is space-charge-limited, just as the electron current in a high-vacuum tube is limited by space charge. In fact, the space-charge equations derived in Chap. 2 can be used directly provided due account is taken of the greater mass of the positive ion as compared to an electron. Assuming the parallel-plane equation to be applicable in this case, we have for the positive-ion current density going to the grid,

$$J_+ = \frac{2.34 \times 10^{-6}}{\sqrt{1{,}840M}} \frac{e_g^{3/2}}{s^2} \qquad \text{amp/cm}^2 \tag{3}$$

where M is the atomic weight of the positive ions, e_g is the potential difference between the grid and the surrounding space [as in Eq. (2)], and s is the thickness in centimeters of the so-called "positive-ion sheath" which forms around the grid.

In high-vacuum tubes under conditions of voltage saturation, the cathode-anode spacing [corresponding to s in Eq. (3)] remains fixed, and the current varies with the three-halves power of the applied voltage. In the plasma of a gaseous discharge, however, the positive-ion current reaching a negative grid is almost independent of the grid voltage; instead the thickness s of the positive-ion sheath varies to maintain the equality in Eq. (3). The positive-ion grid current is determined almost entirely by the anode current: the greater the anode current, the greater the *number* of positive ions (and electrons) in the plasma, and the greater the *random positive-ion current* reaching the grid. In order for the grid to receive this current, it must be only a few volts negative relative to the cathode. Figures 9.15 and 9.16 both illustrate quite clearly the above facts. For large negative grid voltages the grid current is almost constant.

The *thickness* of the positive-ion sheath can be found simply by solving Eq. (3) for s.

$$s = \sqrt{\frac{2.34 \times 10^{-6}}{\sqrt{1{,}840M}} \frac{e_g^{3/2}}{J_+}} \qquad \text{cm} \tag{4}$$

The value of J_+ is commonly of the order of 1 ma/cm^2.

Example:

Compute the thickness of the positive-ion sheath around a control grid which is -15 volts relative to the surrounding space. The tube uses mercury vapor, and a value of 1 ma/cm^2 may be assumed for J_+.

Solution:

$$M = 200.6 \text{ for Hg}$$

Therefore

$$s = \sqrt{\frac{2.34 \times 10^{-6}}{\sqrt{1{,}840M}} \frac{e_g^{3/2}}{J_+}}$$

$$= \sqrt{\frac{(2.34 \times 10^{-6})(15)^{3/2}}{\sqrt{(1{,}840)(200.6)}(1)}}$$

$$= 0.0472 \text{ cm} \qquad \textit{Ans.}$$

If the openings in the grid structure were made small enough, it would be possible to make the positive-ion sheaths from the opposite sides of an opening overlap. This would stop conduction to the anode, and thus the tube would have complete grid control. However, the extremely low value found in the above example shows the difficulty involved in such an undertaking. Also it should be noted from Eq. (4) that s is inversely proportional to the grid current and hence to the anode current. Thus a value of grid voltage which might stop conduction for low or moderate currents would probably be insufficient for heavy currents. The large grid voltages and powers required to stop conduction by this method are too great for practicability.

PROBLEMS

1. Calculate the approximate grid-control ratio of a type FG-57 thyratron, using the grid-control characteristics of Fig. 9.9.

2. If a certain thyratron has a grid-control ratio of 70, at what anode voltages will the tube fire for grid voltages of -2, -5, and -10 volts?

3. The rated deionization time for a type FG-67 thyratron is 100 μsec. If a sinusoidal alternating voltage is applied to the anode, what is the highest frequency that can be used if the grid is to regain control after every positive half cycle?

4. A 1,000-ohm resistor is connected in series with the grid of a negative-grid thyratron. A fixed bias of -6 volts is used to prevent breakdown until the anode voltage reaches 650 volts. Before breakdown, a *negative* grid current of 5 μa is measured. After breakdown, a positive grid current of 2 ma is measured. What were the actual grid-to-cathode voltages preceding and following breakdown?

5. The type EL-C16J xenon-filled thyratron has a filament rated at 2.5 volts and 31 amp. The rated d-c current is 16 amp. Compute the emission efficiency of the cathode.

6. The tube of Prob. 5 has a peak inverse voltage rating of 1,250 volts. If a sinusoidal alternating supply voltage is used in the plate circuit, what is the maximum rms voltage that may safely be used?

7. Compute the instantaneous efficiency of the tube of Prob. 5 when delivering an instantaneous current of 20 amp to a load resistance of 15 ohms. Assume a tube drop of 10 volts and include the filament power in the calculations.

8. A 60-cycle sinusoidal supply voltage of 800 volts rms is connected to the anode circuit of a negative-grid thyratron having a grid-control ratio of 150. A fixed negative grid bias of -5 volts is connected to the control grid. During what percentage of the total cycle of anode voltage will the tube fire? (Assume the tube conducts until the anode voltage drops to zero.)

9. Calculate the deionization time in a thyratron operating at a vapor pressure of 3 dynes/cm^2. The anode current is 6.5 amp; the grid is 18 volts negative relative to the plasma; and the grid-anode spacing is 1 cm.

10. The openings in the grid structure of a certain mercury-vapor thyratron are 0.2 cm from edge to edge. The area of the grid is 100 cm^2, and the grid current is 20 ma. What negative grid voltage and power would be required to stop conduction to the anode?

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CHAPTER 10

MERCURY-POOL ARC RECTIFIERS

ALL OF the gas tubes discussed thus far have been either (1) glow-discharge tubes, wherein electron emission from the cathode is obtained principally by positive-ion bombardment causing secondary emission, or (2) thermionic gas tubes, wherein electrons are emitted from the cathode principally by thermionic emission due to the externally supplied cathode heating energy. We now come to a consideration of a class of gas tubes wherein electron emission from the cathode is obtained without the use of a thermionic filament or cathode, and one in which secondary emission plays a very minor role. Such tubes employ a pool of liquid mercury for a cathode, and electron emission occurs from one or more small bright spots, called *cathode spots*, on the surface of the liquid. These *mercury-arc rectifiers*, as they are called, are inherently high-current, high-efficiency tubes and have found extensive application in the rectification of alternating current in the electrochemical, mining, and transportation industries.

10.1. Physical Characteristics of Mercury-pool Arc Rectifiers. Essentially a mercury-arc rectifier consists of a liquid-mercury-pool cathode and one or more anodes located in a sealed chamber, either permanently evacuated or connected to a suitable vacuum system. Practically, the minimum number of anodes that can be used is two, for reasons to be discussed subsequently.

An early form of arc rectifier is shown in Fig. 10.1. This type is now considered practically obsolete, but the internal mechanism is simpler than in some of the later models. In the particular model shown, there are two anodes, A_1 and A_2, located in the two side arms projecting from the main body of the glass bulb. In addition, there are sometimes provided additional anodes, A_1' and A_2', called *excitation anodes*, the purpose of which will be explained in a later section. In addition to the cathode K there is provided a *starter* cathode K', which can be joined to the main cathode by tilting the bulb. When the bulb is uprighted, the pools part, and the circuit is arranged so that an arc forms between the two pools. The dome at the top provides a large surface area exposed to the free circulation of air for cooling purposes. During operation, mercury is evaporated rapidly from the hot cathode spot, condenses in the dome, and runs down the sides back into the cathode pool. In this manner the cathode is prevented from depletion. The bulb is evacuated to a pressure of 1 mm Hg or less.

Glass-bulb arc rectifiers have been built with as many as six main anodes in the same envelope. A polyphase source of supply voltage is used with tubes having more than two anodes. The two-anode type requires only a single-phase source and is generally used in what is known as a *full-wave-rectifier* circuit. The three-anode type requires a three-phase power source. When a tube with more than three anodes is used, a bank of transformers is arranged to supply the proper number of phases from a three-phase source, since this is the type of power generally available. In this manner as many as 36 anodes can be fed from a three-phase supply.

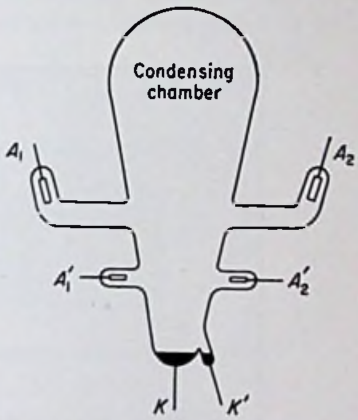

FIG. 10.1. Full-wave glass-bulb mercury-pool arc rectifier.

In the larger sizes the glass-bulb type becomes fragile, difficult to manufacture, and hard to cool. Its chief advantage appears to be the fact that it can be permanently evacuated and sealed off. By sacrificing this advantage, tubes can be constructed to handle much larger powers. The *steel-tank* rectifier, although it cannot be permanently sealed off except in the smallest sizes, can be built to handle powers on the order of several thousand kilowatts. This contrasts with a maximum of about 500 kw for the glass bulb type.

Figure 10.2 shows the external appearance and Fig. 10.3 the internal construction of a typical steel-tank mercury-arc rectifier. The steel body of the rectifier is generally insulated from both the cathode and the anode in order to prevent any current flow to or from the tank. Steel is used because it is not affected by the mercury. The tanks are of rolled-steel construction, and the tank diameter varies from about 3.5 ft in the smallest sizes to about 9.5 ft in the largest sizes. The inside surface of the tank is sand-blasted and cleaned very carefully during construction.

A vacuum-pump connection is shown at the top of Fig. 10.3. The auxiliary pumping equipment is usually built on the top or

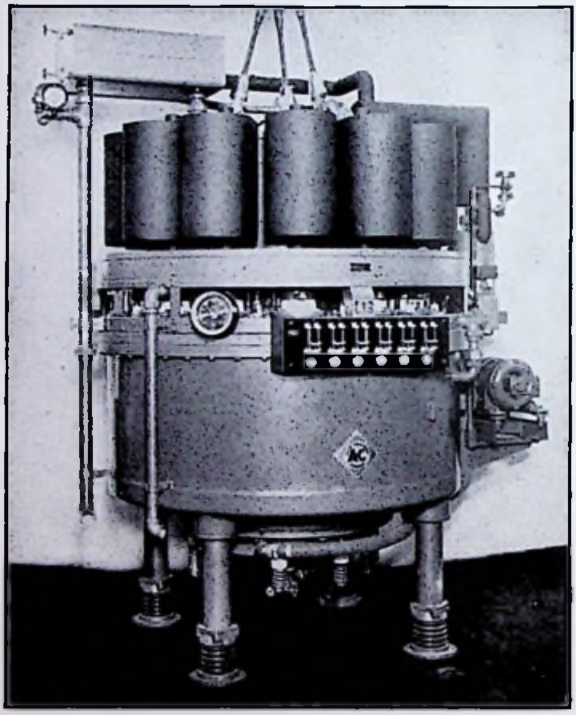

FIG. 10.2. Typical steel-tank mercury-pool arc rectifier. Over-all height is 9 ft, and capacity is 2,750 kw at 600 volts. (*Courtesy Allis-Chalmers Mfg. Company.*)

side of the tank, as shown in Fig. 10.2, and serves to maintain a low pressure while the rectifier is in operation. A vacuum gauge controls the operation of the pumping equipment, automatically starting the pump when the pressure rises above a certain level. In the smallest sizes, tank rectifiers have been constructed with seals sufficiently tight to permit permanent evacuation and sealing, but this is not considered feasible in the larger sizes because of

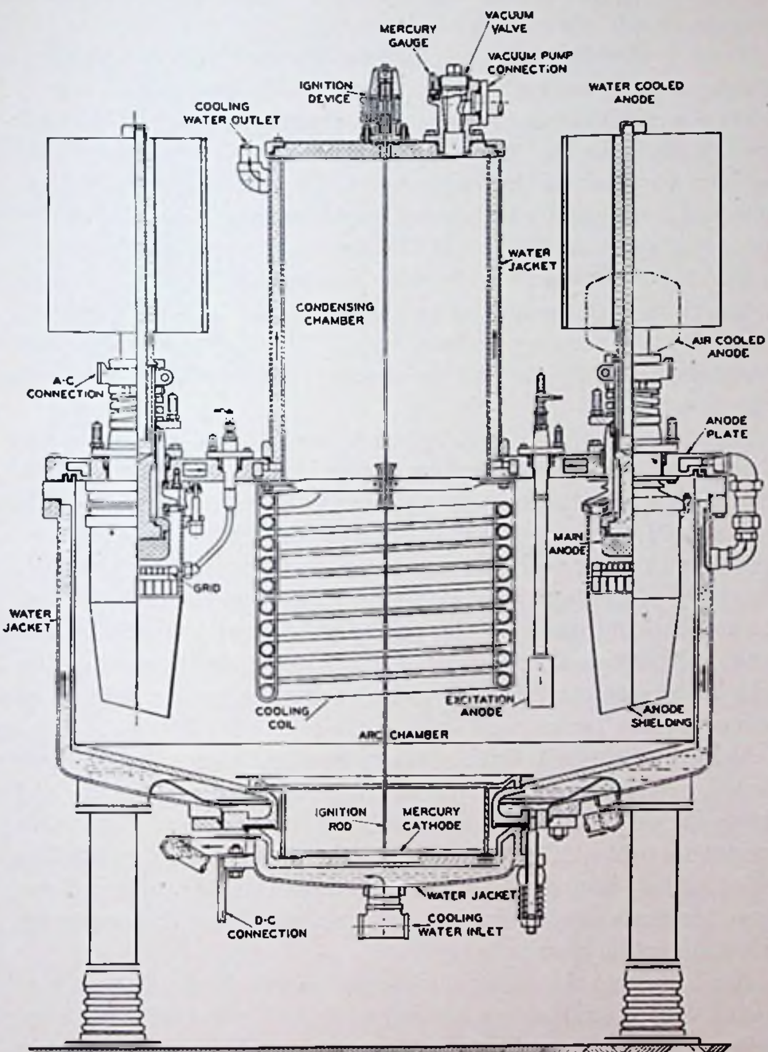

FIG. 10.3. Cross section of typical mercury-arc multianode steel-tank rectifier. The main anode is either air-cooled or water-cooled as shown. (*Courtesy Allis-Chalmers Mfg. Company.*)

the greater number of seals and the larger surface area from which gases can be driven at high temperatures.

Water is circulated through jackets surrounding the tank, and in some designs cooling coils are placed inside the tank at appropriate places. Cooling fins are sometimes provided on the external anode leads, as in Fig. 10.3. Or, alternatively, water-cooled radiators can be used on the anode leads. It will be shown in Sec. 10.3 that it is desirable to prevent condensation of mercury on the anode surfaces. At light loads, the anodes may not be hot enough to prevent condensation. In some designs heaters are provided in the vicinity of the anodes to keep them above the condensing temperature of mercury at light loads. The anodes are generally constructed of graphite and are designed for current densities of 5 to 10 amp/cm^2.

The cathodes are water-cooled to prevent excessive evaporation of mercury. Sufficient mercury is provided (2 to 10 lb per 100-amp rating) so that momentary overloads will not exhaust the cathode. The mercury that is evaporated from the cathode condenses on the tank walls and runs down the sides back into the pool. The body of the tank must be so insulated from the cathode that the mercury returning to the pool cannot short the pool to the tank. Otherwise a cathode spot might form on the side of the tank and cause excessive gas to be evolved or even a hole to be burned in the tank.

As in the glass-bulb type, auxiliary anodes are provided in steel-tank arc rectifiers in addition to the main anodes. Figure 10.3 shows the arrangement of main and auxiliary anodes. The main anodes are protected from the mercury spray by shields and baffles which may be insulated both from the anodes and the tank. These serve the same purpose in the steel-tank rectifier as the projecting side arms in the glass-bulb type.

In addition to the anode shields, each anode is usually provided with a control grid, either integral with the anode baffle or placed between the baffle and anode. These serve the same purpose as the control grids in thyratrons.

Steel-tank arc rectifiers cannot conveniently be started by tilting, as in the glass-bulb type. Instead, the arc is generally started by inserting the end of a *starting* anode, or *ignition* anode, momentarily into the mercury and then quickly withdrawing it. The starting-anode circuit is arranged so that an arc forms between the tip of the starting anode and the mercury surface at the instant contact is lost. The starting anode is operated externally by means of a spring-loaded solenoid.

10.2. Electrical Characteristics of Mercury-arc Rectifiers. *Starting Circuit.* Mercury-pool arc rectifiers are unique among electron tubes in that the discharge cannot be initiated simply by applying normal voltage between cathode and anode. Some kind of auxiliary starting device must be provided to initiate the arc, after which the discharge will transfer to one of the anodes if it is sufficiently positive. Two types of starting devices have just been discussed. A third method will be discussed in Chap. 11 in connection with the *ignitron* type of arc tube.

In order to form an arc in either the glass-bulb type or the steel-tank type when contact is broken between the cathode and the

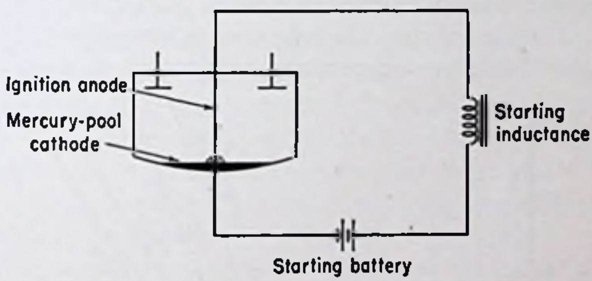

FIG. 10.4. Auxiliary starting circuit for a mercury-pool arc rectifier.

auxiliary starting electrode, a current must be sent through the circuit, as shown in Fig. 10.4. When the contact is broken, the inductance provides a spark, which quickly changes to an arc. The initial arc current to the starting anode is relatively small.

Volt-ampere Characteristics of the Arc. Mercury-pool arc rectifiers are always operated from an alternating voltage source. However, in order to determine the electrical characteristics of the arc, it is of more benefit to consider a circuit such as that shown in Fig. 10.5. Once the arc is established by some kind of auxiliary starting device, the discharge transfers immediately to the most positive anode, provided the anode voltage is slightly higher than the arc drop just before the transfer.

When the discharge has transferred to the anode, the volt-ampere relationship of the tube can be determined by varying the supply voltage in steps and recording the corresponding tube drops and the ammeter readings. For low currents, the voltage drop may *decrease* with an increase in current, but for high currents the

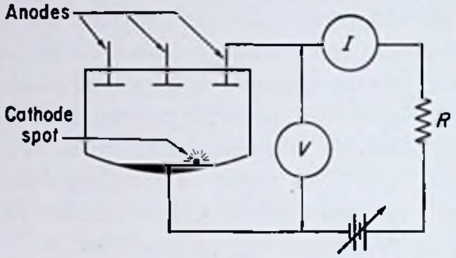

FIG. 10.5. Circuit for obtaining the volt-ampere characteristics of a mercury-pool arc.

drop increases with an increase in current, particularly for shielded anodes. For low currents the tube drop is almost independent of the condensed-mercury temperature, but for high currents the drop

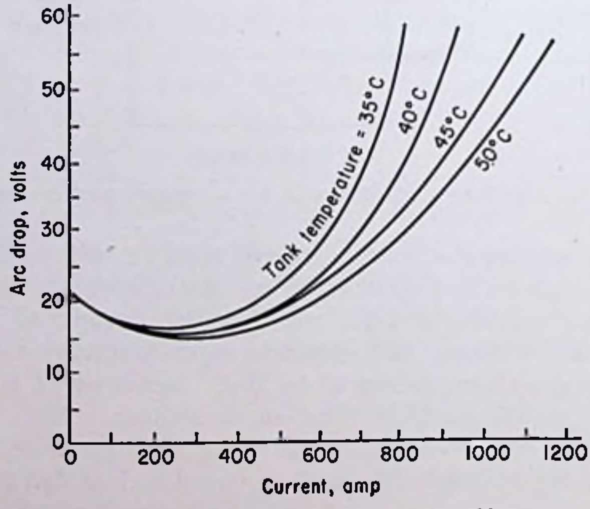

FIG. 10.6. Arc drop vs. current for mercury-pool rectifiers at several tank temperatures.

is inversely proportional to the tank temperature. Figure 10.6 shows curves typical of mercury-pool arc rectifiers having shielded anodes. For arc drops in excess of about 50 volts, it has been found that *arcbacks*, or *backfires*, become frequent. Hence the current must be limited *at all times* to a value giving a tube drop of 50 volts or less. Since the *peak* current may be several times the average value, the maximum *average* current must be considerably less than the value corresponding to 50 volts drop.

As mentioned previously, the arc discharge concentrates at one or more small spots on the cathode called cathode spots. For small or moderate currents there is usually only one cathode spot, but for heavy currents there may be several spots, each carrying about the same current. These spots dance rapidly over the surface of the liquid unless constrained by a special electrode known as a spot fixer. This is a piece of molybdenum or tungsten arranged on the surface of the mercury so that it becomes amalgamated and causes the cathode spots to run up and down the length of the metal.

The use of a spot fixer is beneficial in that the *extinction* current is considerably reduced. Whereas the arc usually extinguishes for currents less than about 3 amp without a spot fixer, currents as low as 50 ma can be stabilized through their use. The disadvantages of the spot fixer are twofold. First, the random motion of the cathode spot tends to produce a stirring action of the pool, resulting in a more uniform temperature and lower rate of evaporation of mercury. Second, the metal from the spot fixer gradually evaporates and contaminates the walls of the tube.

In order to prevent extinction of the arc at light loads or periods of no load and thus eliminate the necessity for mechanically restarting the arc each time the load is reapplied, a small fixed load is generally maintained on the *excitation anodes*, which may be fed from a separate small transformer bank. It is also possible to apply a direct voltage to an excitation anode and thus eliminate the necessity for more than one auxiliary "keep-alive" electrode. The starter anode in small steel-tank rectifiers is sometimes operated in this manner.

Backfires. Arcbacks, or *backfires*, as they are sometimes called, are much more destructive in multianode arc rectifiers than in other types of gas rectifier tubes. Conduction in the reverse direction is objectionable, of course, in any rectifier, but in the case of multianode rectifiers there is not only the possibility of conduction from cathode to anode when the anode is negative, but there is also the possibility of a breakdown from one anode to another. This constitutes a virtual short circuit on the transformer bank, and the resultant high current flow may seriously damage or destroy the transformers unless high-speed circuit breakers are employed. Backfires are random in occurrence, and it is virtually impossible to design a multianode rectifier which is completely free from them. The use of anode baffles and shields tends to reduce their occurrence by preventing mercury spray from hitting the anodes. Rapid deionization near the anodes is also beneficial in reducing arcbacks. Anode shields and baffles, as well as control grids, decrease the deionization time by providing large surface areas at which recombination can take place. The incidence of arcbacks can be reduced by maintaining the tank temperature (and consequent tank pressure) within certain limits. In particular, excessive temperatures increase the probability of arcback by making the glow breakdown voltage low. The anodes should be kept hot enough, on the other hand, to prevent the condensation of mercury on the anode surfaces, which may be a contributory factor in the formation of a "cathode spot" on an anode. Excessive tube drops increase the likelihood of backfires, so that operation within the prescribed current and temperature limits is advisable from this standpoint. The presence of impurities on the anode surfaces increases the probability of backfires. The anodes are thoroughly cleaned and degassed during manufacture, but absorption and subsequent reemission of gas may occur from the anodes. Small "bursts" of gas may facilitate the formation of a cathode spot on a negative anode.

Grid Control. The action of the control grid in a multianode mercury-arc rectifier is similar to that in a negative-grid thyratron. The grid is able to control the starting but not the stopping of the anode conduction period. A negative control grid in a multianode rectifier also "shields" the anode from the plasma and thus may inhibit arcbacks. Positive ions straying from the main body of the discharge are intercepted by the grid and prevented from hitting the anode.

10.3. Theories Used to Explain the Electrical Characteristics of Mercury-pool Arc Rectifiers. *Electron Emission from a Cathode Spot.* The arc on the mercury surface is maintained by a liberal supply of electrons emitted from the pool. Originally it was believed that thermionic emission was the principal factor in the production of electrons, with perhaps secondary emission due to positive-ion bombardment playing a secondary role. Upon determination of the rate of evaporation of mercury from the surface, however, the temperature of the cathode spot was found to be no greater than 300 or 400°C, at which the amount of thermionic emission is quite small. It is generally accepted now that a phenomenon known as *high-field emission,* or simply field emission, is responsible for the tremendous emission-current densities observed from mercury-pool arcs. Current densities of the order of 5,000 amp/cm^2 are common in the cathode spots of mercury-arc rectifiers.

In visualizing the process of field emission, it is helpful to consider the wave nature of electrons rather than the particle concept.

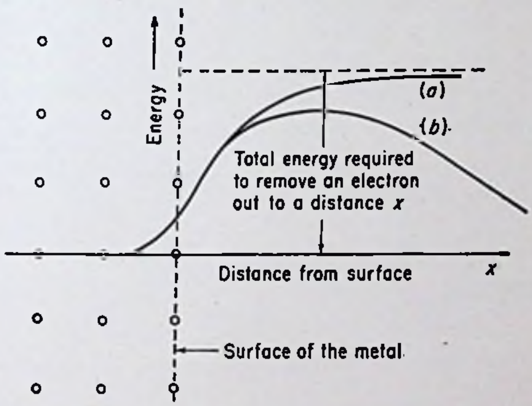

FIG. 10.7. Potential energy barrier at the surface of a metal (*a*) with no external electric field, (*b*) with an external field.

If a beam of electrons is regarded as a wave phenomenon, it is easy to conceive of refraction and reflection of the beam at a boundary between two regions of different potentials. In a metal, the free electrons are continually in motion, and an extremely large number of electrons constantly approach the metal boundaries. However, if no external electrostatic field is present, the "thickness" of the potential-energy barrier is infinite, as shown by curve (*a*), Fig. 10.7. Hence no electrons having energies less than the value indicated by the dotted line are emitted. However, if a strong electric field is applied to the surface of the metal, the thickness of the potential-energy barrier becomes finite, and of all the electrons which approach the surface with an energy less than the value required to surmount the barrier, some will penetrate the barrier and the rest will be reflected.

A similar situation exists when a beam of light strikes a glass surface. Some of the light is transmitted through the glass, and the rest is reflected.

It should be noticed that according to this "wave-mechanics" theory, as it is called, electrons are not required to have the full energy needed to "climb over" the potential-energy barrier in order to escape, as required by the classical particle theory. The energy required to escape by the wave theory is relatively small. An analogy could be made to a lake with a dam at one end. Agitation of the water might splash a small amount *over* the dam, but most of the water molecules would have too little energy to surmount the

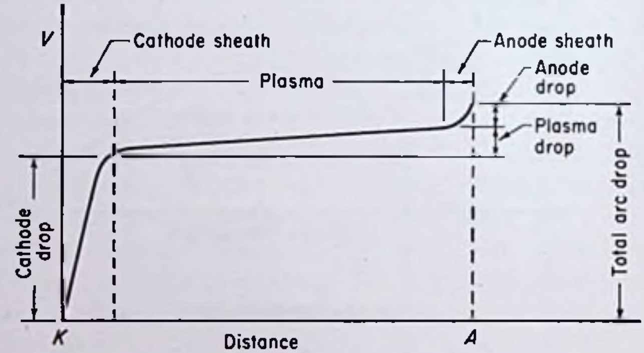

FIG. 10.8. Potential distribution in a typical mercury-pool arc discharge.

barrier imposed by the dam. However, if the dam were to break and the top half crumble away, all the water above that level would gush forth in tremendous volume. Similarly, in a metal it is not essential that electrons have enough energy to surmount the potential-energy barrier in order to escape. Simply by lowering the barrier through the application of a strong electric field, electrons "gush forth" in tremendous volume.

Potential Distribution in an Arc Discharge. Figure 10.8 shows the potential distribution in a typical arc discharge. The region adjacent to the cathode is known as the *cathode sheath,* and the voltage drop across this region is called the *cathode drop.* The cathode drop is ordinarily in the neighborhood of 10 volts, and the thickness of the cathode sheath is so small that a very strong voltage gradient is set up at the surface of the cathode. This high field strength is responsible for the field emission of electrons from the cathode.

Electrons are accelerated in the cathode sheath and acquire ionizing energy at a very short distance from the cathode. At low current densities, the cathode drop is relatively high, and most of the ionization is of the single-impact type. However, at the higher load currents, the cathode drop is too low to give the electrons enough energy to cause ionization in a single step. Hence multiple-impact ionization due to the existence of metastable states is believed to play a very important role in the operation of mercury-arc discharges.

Positive ions are accelerated through the cathode sheath toward the cathode. Owing to their large mass and consequent low velocity, they exert a powerful influence on the potential distribution in this region. The electron current away from the cathode exceeds the positive-ion current moving toward the cathode. Even so, however, positive space charge predominates, and the negative electron space charge is very effectively neutralized.

Most of the space between the cathode and anode is occupied by a region of comparatively low field strength known as the *plasma*, similar to the plasma in thermionic gas tubes (see Sec. 8.3). In this region electrons and positive ions are present in about equal numbers, the electrons drifting slowly toward the anode and the positive ions moving even more slowly toward the cathode. Ionization and excitation are in progress throughout the plasma, although the visible glow is not nearly so intense as that from the cathode spot, which in many ways resembles an ordinary atmospheric arc.

Adjacent to the anode there may exist a region known as the *anode sheath*. At low currents the *anode drop* existing in this region is very low, because electrons are reaching the anode at a rate sufficient to meet the demands of the external circuit. However, at high currents the anode drop increases so that electrons will be drawn more quickly to the anode in order to supply the external current demands. Positive ions are repelled from the anode, and as a consequence the anode sheath is a region composed almost entirely of electrons.

Referring to Fig. 10.6, the initial decrease of arc drop as the current is increased from zero is due to the greater amount of multiple-impact ionization which can take place at somewhat lower accelerating energies. The anode drop is practically zero in this range of currents, the variation in arc drop with current being due almost entirely to changes in the cathode drop. The increased arc drop at high currents is due to the greater anode drop required to draw a sufficient number of electrons from the plasma to meet the current demands of the external circuit. The higher the tank temperature, the higher the vapor pressure and the greater the number of both electrons and positive ions in the plasma. Hence the lower the required anode drop for any particular load current.

10.4. Mathematical Analysis of Mercury-pool Arc Rectifiers. *Field Emission.* An equation based on the wave-mechanics theory has been derived by Fowler and Nordheim which gives the emission from pure metal surfaces as a function of the applied electric field. The current density J in amperes per square centimeter is given by the expression

$$J = \frac{Q_e}{2\pi h} \frac{\mu^{1/2}}{(\mu + \phi)\phi^{1/2}} \mathcal{E} \, \epsilon^{-4K\phi^{3/2}/3\mathcal{E}} \tag{1}$$

where $\mathcal{E}$ = field strength, statvolts/cm

$$\mu = \left(\frac{3n}{\pi}\right)^{2/3} \frac{h^2}{8m}$$

$$K = \frac{2\pi}{h}\sqrt{2m}$$

Q_e = charge on an electron
h = Planck's constant
m = mass of an electron
n = number of free electrons/cm^3
ϕ = work function of the surface

Equation (1) can be simplified by combining the various quantities which are constant in any particular case, yielding

$$J = A_f \mathcal{E} \, \epsilon^{-b_f/\mathcal{E}} \tag{2}$$

where A_f and b_f are approximately constant coefficients dependent upon the properties of the metal.

The striking similarity between Eq. (2) and the thermionic-emission equation [Eq. (4) of Chap. 2] should be noted. An empirical equation similar to (2) was used before Eq. (1) was derived.

Deionization Time. The length of time required for the region near an anode to become deionized is an important consideration, since about 50 per cent of backfires are found to occur during this time. Reduction in the deionization time lessens the likelihood of arcback. Since most of the recombination of positive ions and electrons occurs at the walls and electrodes of the tube, the time required for the positive ions to diffuse to the walls of the enclosing structure determines the deionization time. In most mercury-arc rectifiers the walls of the enclosing structure are cylindrical. The time T required for the ion density to decrease to $1/\epsilon$ of its initial value by diffusion to the walls of a cylinder of diameter d in centimeters is

$$T = \frac{d^2 p}{27{,}000} \quad \text{sec} \tag{3}$$

where p is the mercury vapor pressure in millimeters of mercury. Clearly a reduction in either the pressure or the cylinder diameter causes a reduction in the deionization time.

Example:

What length of time is required for the ion concentration to decrease to $1/\epsilon$ of its initial value in a steel-tank rectifier in which anode shields having a diameter of 8 in. are used? Assume a gas pressure of 0.05 mm Hg.

Solution:

$$\begin{aligned} T &= \frac{d^2 p}{27{,}000} \\ &= \frac{(8 \times 2.54)^2(0.05)}{27{,}000} \\ &= 765\ \mu\text{sec} \quad \textit{Ans.} \end{aligned}$$

PROBLEMS

1. Compute the instantaneous efficiency of a steel-tank rectifier in which one anode is supplying a current of 100 amp from an instantaneous source voltage of 550 volts. Assume an arc drop of 20 volts. If the load is a pure resistance, what is its magnitude?

2. The cathode voltage drop in a certain mercury-arc rectifier is 10 volts. If the positive-ion sheath is 0.05 cm thick, what is the approximate field strength at the emitting surface of the cathode?

3. If a current density of 3,000 amp/cm^2 is produced from a mercury pool with an applied field of 10^6 volts/cm and 5,000 amp/cm^2 for a field of

1.2×10^6 volts/cm, calculate the coefficients of the field-emission equation.

4. A certain steel-tank rectifier is carrying a current of 150 amp. If a current density of 4,000 amp/cm² is assumed, what would be the area of each of two cathode spots carrying equal currents?

5. The vapor pressure in the anode shield of a certain arc rectifier is to be 0.1 mm Hg. If the ionization is to decrease to $1/\epsilon$ of its initial value in 500 μsec, what should the shield diameter be?

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CHAPTER 11

IGNITRONS

THE MULTIANODE steel-tank rectifier has a number of important disadvantages. The presence of appreciable ionization *at all times* while the rectifier is in operation increases the probability of arcbacks. Any damage to an anode or grid makes the entire unit inoperative and necessitates the shutdown of the complete unit until the necessary repairs have been made. Many circuits cannot be used with multianode rectifiers because of the common cathode. All these disadvantages could be overcome if single-anode tubes could be used. Such a tube is the ignitron (*ig·ni'tron*). In multianode rectifiers the anodes alternately carry the load current so that the arc is never extinguished. In the ignitron, however, the single anode carries current for only a portion of an a-c cycle, and the arc extinguishes after each period of conduction. In order to avoid the necessity for starting the arc mechanically each time a conduction period is desired, the ignitron is equipped with a simple, reliable, *electrical* starting mechanism.

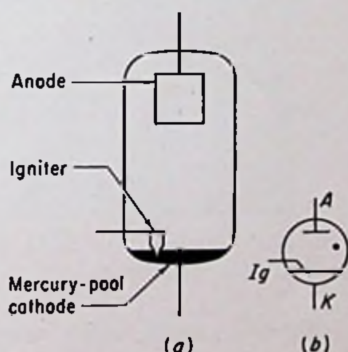

FIG. 11.1(*a*). Basic elements of an ignitron. (*b*). Symbol for an ignitron.

Ignitrons are unexcelled for resistance-welding control, in which capacity they serve in the nature of switches. They are also used extensively in the rectification of large amounts of a-c power, having displaced multianode steel-tank rectifiers somewhat in this capacity in recent years.

11.1. Physical Characteristics of Ignitrons. Basically, an ignitron consists of three electrodes, as shown in Fig. 11.1. The cathode is of the mercury-pool type, and the anode is generally a block of graphite. In addition, there is provided a special electrode called an *igniter*, the tip of which projects into the mercury pool. In the smallest sizes the envelope is constructed of glass, and air cooling is used. In the larger sizes metal envelopes are employed, and water jackets surrounding the tube are used for cooling.

The igniter is made of a high-resistance material such as silicon or boron carbide. Such semiconductors are heat-resistant and are not wet by the mercury. The shape of the igniter is carefully designed so that reliable ignition can be obtained with a minimum igniter current and voltage.

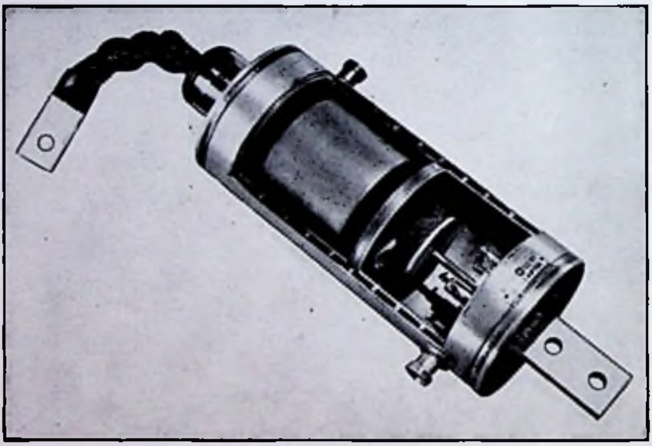

FIG. 11.2. Internal view of a medium-sized ignitron tube. (*Courtesy General Electric Company.*)

Figure 11.2 shows the internal construction of a medium-sized ignitron having a permanently sealed-off metal envelope designed for water cooling. Figure 11.3 shows the construction of a large-capacity ignitron in which the vacuum is maintained by means of an externally connected vacuum pump. In the largest sizes this is generally considered preferable to permanent evacuation. A mercury splash baffle and anode shield are frequently provided in the larger sizes to aid in the prevention of arcbacks. Figure 11.4 shows a typical rectifier installation using ignitrons.

As in the multianode steel-tank rectifier, the heavy-duty ignitron is sometimes provided with cooling coils for the mercury pool as

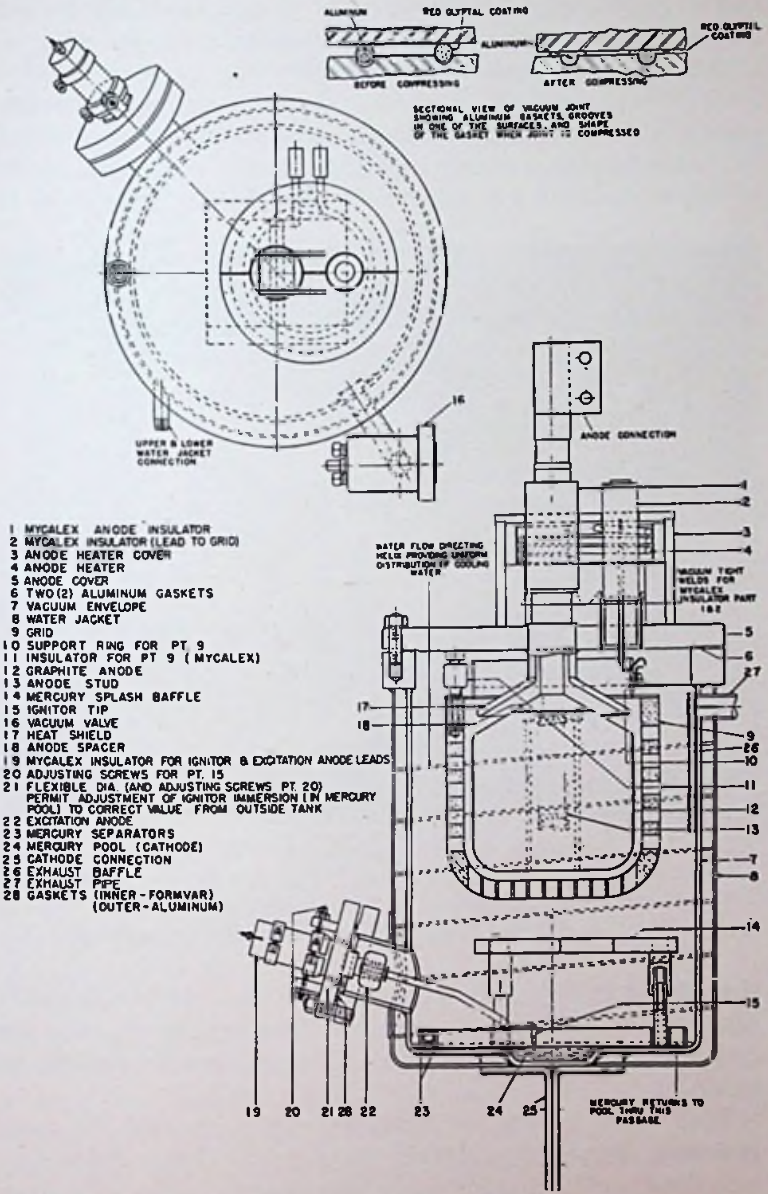

FIG. 11.3. Vertical section of a large heavy-duty ignitron. (*Courtesy General Electric Company.*)

well as water jackets surrounding the walls. Anode heaters are also sometimes provided as in the multianode tank rectifiers.

11.2. Electrical Characteristics of Ignitrons. *Igniter Characteristics.* Many novel and interesting circuits have been developed especially for ignitrons. Although they are generally operated from an a-c supply, their electrical characteristics can more readily be determined with a simple circuit using direct current, such as

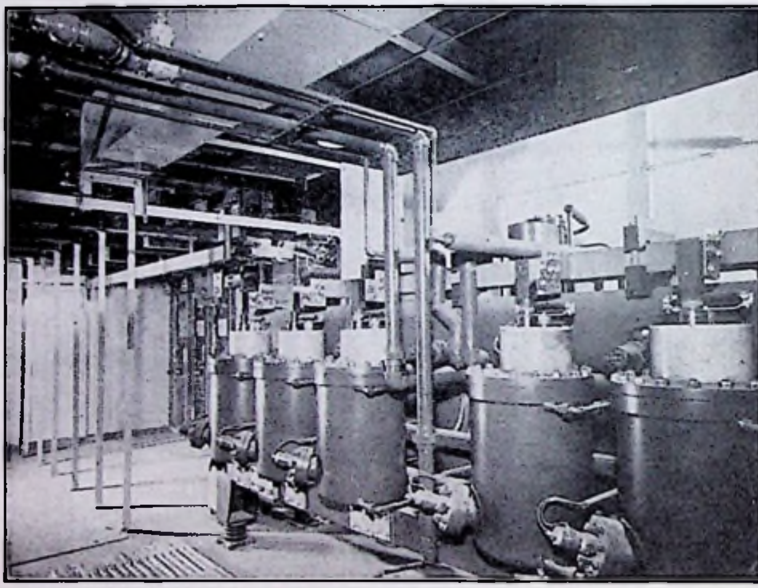

FIG. 11.4. Twelve-tank ignitron rectifier with d-c switchgear in background and negative bus duct overhead. Part of 1,500-kw, 250-volt, mercury-arc-rectifier unit substation in central shops of Gary Steel Works of the Carnegie-Illinois Steel Corp. (*Courtesy General Electric Company.*)

that shown in Fig. 11.5. The anode is connected to the plate supply voltage through a current-limiting resistor R_b, and the igniter is connected to the anode through a current-limiting resistor R_i.

With switch S open, the igniter current is zero, and the anode current is likewise zero. When the switch is closed, igniter current flows, and if the magnitude of this current is sufficiently great, an arc is formed on the surface of the mercury pool at the igniter tip. This arc constitutes a cathode spot, and the anode current immediately jumps to a high value as the anode voltage falls to a value in the neighborhood of the ionization potential.

The igniter current required to start conduction is generally of the order of several amperes, and if this current were permitted to flow continuously following firing, the tube would be uneconomical in operation. However, the igniter circuits are always arranged so that the igniter current flows only in a short pulse. This makes the average current and average power loss over a period of time relatively low in spite of the high peak values. Referring to Fig. 11.5, as soon as the tube "fires," the anode voltage falls to a relatively low value, which causes the igniter voltage (and current) similarly to fall.

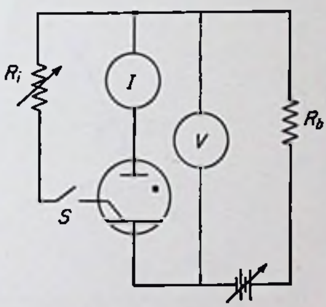

FIG. 11.5. Circuit for investigating the electrical characteristics of ignitrons.

The igniter voltage and current required to start conduction depend to a great extent on the design of the igniter probe. The material must have a relatively high resistivity in order for the igniter to function properly. On the other hand, a high igniter resistivity calls for a relatively high igniter voltage, and a compromise is usually effected at around 10^3 ohms/cm³. The probe must be long enough so that the tip always projects into the pool at least ¼ in. The length above the pool must be at least ½ in. to prevent a short circuit across the igniter due to splashed mercury. The length should be kept short, however, so that the required igniter voltage will not be excessively high. Again a compromise must be effected.

The starting current varies directly with the igniter diameter, as shown in Fig. 11.6, so that a small diameter appears to be desirable. However, as the diameter is reduced, the igniter resistance is increased, necessitating a higher voltage, so that once again a compromise must be reached. The required starting current is much reduced through the use of an igniter material which is not wet by mercury, such as the semiconducting materials.

A short time elapses after the application of igniter voltage before a cathode spot is formed. The time interval varies inversely with the applied voltage, as shown in Fig. 11.7. This curve is merely an average of the values, and considerable variation in ignition time may actually be experienced in practice.

Anode Characteristics. Once a cathode spot has been initiated, the anode current is independent of the igniter voltage or current and depends only upon the applied voltage and the resistance in series with the tube. The anode characteristics are in every way identical with the ones given in the previous chapter for any one anode of a multianode mercury-pool arc rectifier.

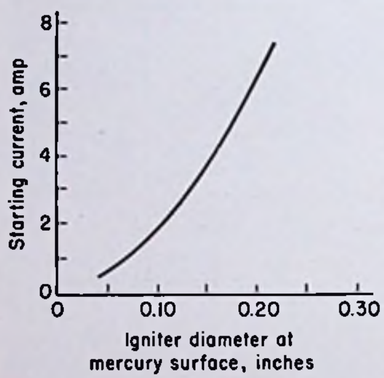

FIG. 11.6. Relation between the igniter current required to start conduction and the diameter of the igniter probe.

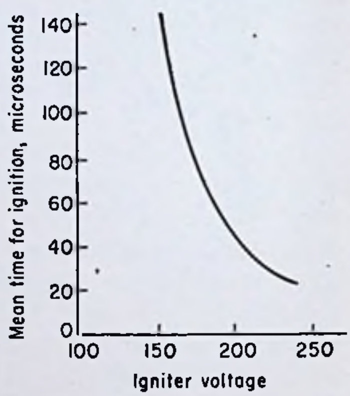

FIG. 11.7. Relation between the igniter voltage and the average time required for ignition.

It must be recognized, of course, that a backfire from anode to anode cannot occur in rectifiers employing ignitrons, since each anode is enclosed in a separate container and is not exposed to a continuously ionized plasma. An arcback, or flashback, from anode to cathode may occur, but this type of reverse conduction does not place such a severe strain on the equipment and is therefore not so serious as an anode-to-anode backfire.

11.3. Theories Used to Explain the Electrical Characteristics of Ignitrons. *Theories of Igniter Action.* There are several theories concerning the processes occurring during ignition. The surface of the igniter is not smooth but rather contains many sharp projections. Since mercury does not wet the igniter material, contact is made with the mercury at the ends of these sharp points. A very high voltage gradient may be developed along these projections so that high-field emission may produce the first few electrons that start the breakdown process. There is also the possibility that a spark occurs between the rod and the mercury as a result of the high field strength between the liquid and a sharp projection not actually in contact with the mercury. Such a spark would quickly develop into an arc, and the cathode spot would be formed.

Another possibility is thermionic emission from points of contact between the rod and mercury. The relatively high contact resistance may cause a high I^2R loss and consequent high temperature to be developed at one or more localized spots. Only a very few electrons would be required to cause a complete arc breakdown. Also the high temperature would increase the vapor pressure in that region and improve the conditions necessary for the formation of a positive-ion space charge.

At the points of contact between the igniter rod and the mercury, the heat developed may vaporize the liquid so rapidly that contact is momentarily broken. At the instant of losing contact a small arc may form between the projection and the liquid, followed by a complete cathode-to-anode arc breakdown.

It is quite possible that several, if not all, of the above phenomena play a part in the ignition process. The somewhat random firing characteristics may be due to the variation in the relative importance of the different phenomena from one firing period to the next.

Arc Breakdown. As soon as a few electrons are emitted from the mercury by any of the several processes discussed above, they are attracted to the positive metal igniter mounting. Ionization by collision ensues with the resulting positive ions being attracted to the mercury pool. Secondary emission from the cathode due to positive-ion bombardment may then hasten the breakdown process. The positive anode attracts the electrons, and the resulting ionization decreases the voltage gradient throughout the tube except at the cathode, where the field is increased. This process continues until a complete cathode spot is formed.

Arcbacks in Ignitrons. It was originally believed that single-anode mercury-pool arc tubes would be completely free from backfires, since one of the chief causes of backfires in multianode rectifiers is the presence of a continuously ionized plasma near the anodes. Complete deionization in a multianode rectifier is, of course, impossible, whereas rapid deionization is extremely desirable in an ignitron. However, arcbacks occasionally occur in ignitrons, and frequently after a considerable period of time has elapsed following the previous conduction cycle. Thus the presence of appreciable ionization cannot be the only principal cause of arcbacks.

The formation of a cathode spot on an anode was discussed in the previous chapter in connection with multianode arc rectifiers, and the same conditions apply in an ignitron. The incidence of arcbacks in ignitrons can be reduced by adequate cooling of the walls and maintenance of the anode within the desired temperature limits. Anode shields and mercury splash baffles likewise are beneficial in preventing backfires.

Although not an arcback in the strictest sense, a phenomenon peculiar to ignitrons may result in damage to the tube. The metal walls of the tube are not insulated from the cathode as in multianode steel-tank rectifiers. Hence the cathode spot may reach the walls and cause considerable sputtering of metal or even a hole to be burned in the wall. To prevent this, the conduction period should be limited to a relatively low value, or else a spot fixer should be used. This difficulty is not experienced, of course, with glass-enclosed tubes.

PROBLEMS

1. The igniter in a certain ignitron requires a starting current of 15 amp at 150 volts. Ignition is effected in an average time of 100 μsec. If the igniter current is zero following breakdown, find the average energy in joules required for ignition.

2. The ignitron of Prob. 1 is fired 60 times per second. Find the average igniter power and compare with the instantaneous power.

3. The ignitron of Prob. 1 has an arc drop of 15 volts when carrying a current of 20 amp. For this condition compute the total average power loss in the tube, including the losses in the igniter. Find the voltage and power in the anode load resistance for a supply voltage of 150 volts. Compute the efficiency if power in the anode resistor is taken as power output.

4. The type WL-679 ignitron has the following ratings:

Peak inverse voltage	2,100 volts
Peak anode current	600 amp
Maximum average anode current	75 amp

If a sinusoidal 60-cycle supply source is used, find the maximum allowable rms value of the supply voltage. If the average current carried per cycle of supply voltage is 300 amp, how many cycles out of each 60 per second can the tube be permitted to conduct without exceeding the maximum average anode current rating?

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APPENDIX

TABLE V

RELATIONSHIP BETWEEN UNITS IN THE CGS AND MKS SYSTEMS (COMMONLY ENCOUNTERED IN ELECTRONICS)

	Mks practical unit	Cgs electrostatic unit (esu)	Cgs magnetic unit (emu)
Distance, s	1 meter	10^2 centimeters	10^2 centimeters
Mass, M	1 kilogram	10^3 grams	10^3 grams
Time, T	1 second	1 second	1 second
Force, F	1 newton	10^5 dynes	10^5 dynes
Energy, W	1 joule	10^7 ergs	10^7 ergs
Power, P	1 watt	10^7 ergs/second	10^7 ergs/second
Voltage, V or E	1 volt	$\frac{1}{3} \times 10^{-2}$ statvolt	10^8 abvolts
Current, I	1 ampere	3×10^9 statamperes	10^{-1} abampere
Charge, Q	1 coulomb	3×10^9 statcoulombs	10^{-1} abcoulomb
Resistance, R	1 ohm	$\frac{1}{9} \times 10^{-11}$ statohm	10^9 abohms
Magnetic flux, Φ	1 weber	....	10^8 maxwells
Magnetic flux density, B	1 weber/meter^2	....	10^4 gauss
Magnetomotive force, mmf	1 ampere-turn	....	$4\pi/10$ gilberts
Inductance, L	1 henry	$\frac{1}{9} \times 10^{-11}$ stathenry	10^9 abhenrys
Capacitance, C	1 farad	9×10^{11} statfarads	10^{-9} abfarad

TABLE VI

PHYSICAL CONSTANTS FREQUENTLY ENCOUNTERED IN ELECTRONICS (MKS UNITS)

Name and Symbol	Value
Charge of electron, Q_e	1.6×10^{-19} coulomb
Mass of electron, m_e	9.11×10^{-31} kg
Ratio of charge to mass of electron, Q_e/m_e	1.76×10^{11} coulombs/kg
Velocity of light in free space, c	3×10^8 m/sec
Planck's constant, h	6.624×10^{-34} joule-sec
Boltzmann constant, k	1.38×10^{-23} joule/°K
Ratio of mass of proton to mass of electron	1,840
Atomic weight of neon	20.2
Atomic weight of argon	39.9
Atomic weight of xenon	131.3
Atomic weight of mercury	200.6

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