# BASIC VACUUM TUBES

## and their uses

*by*

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*and*

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# PREFACE

Vacuum tubes are still the key element in the ever-growing field of electronics. In addition to their familiar place in the fields of telecommunications, radio and television broadcasting, no limits are as yet apparent to the applications of vacuum tubes for industrial processing and control, scientific instruments, and specialized military applications. Without a doubt, the vacuum tube is among the two or three most important inventions of our century in its revolutionary effects on practically all phases of our daily life. It plays a strategic role in man's perennial struggle to control his environment and modify it to his own objectives.

A great many books have been written about vacuum tubes, but few of these address themselves to the general lay reader and the elementary technical student and technician. The present book is *elementary* and is accessible to anyone who is interested in the fascinating tale it unfolds. Although presented with a minimum of simple mathematics, the book gives an accurate, scientific explanation of the theory and operation of the *basic types* of vacuum tubes. We have purposely limited the scope of this book to these few basic types, along with some key applications, in order to lay a solid foundation for the understanding of elementary electron behavior, on which the reader may build his knowledge of the more advanced and specialized types of vacuum tubes.

Portions of this book are based on an earlier volume—"Inside the Vacuum Tube"—and the acknowledgments contained therein apply to the present book, also. The authors wish to express their gratitude to the John F. Rider organization for their assistance in the preparation of the manuscript and the illustrations. Special thanks go to the managing editor, Mr. Milton S. Snitzer, for his many suggestions and his help in editing the manuscript for the book.

*New York, N.Y.*
*March, 1955* *H.J.*

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## Chapter 1

# INTRODUCING THE VACUUM TUBE

*. . . Aladdin had no sooner rubbed the lamp, then in an instant a genie of gigantic size appeared before him, and said in a voice like thunder, "What would'st thou have? I am ready to obey thee as thy slave" . . .*

This is a tale about one of the greatest technical marvels in the world—the vacuum tube. This incredible device fulfills the promise of Aladdin's magic lamp and in addition performs feats of control and power never dreamt of in the "Arabian Nights". It has transformed all our lives and social behavior and has brought us unheard of comforts. The vacuum tube operates with invisible negative particles of electricity called electrons—so small that they have never been seen under the most powerful microscope—and utilizes less electricity than most flashlights. Yet it controls the most powerful motors and machines in the world and is capable of transporting the sound of a voice and the appearance of a face to the four corners of the earth in a fraction of a second. When used in electronic brains, the vacuum tube performs in seconds mathematical calculations of such complexity that it would take expert mathematicians years to duplicate them, and these electronic brains are so clever, that they have begun to run many factories completely automatically.

The vacuum tube counts peas or atoms, finds flaws in metals, inspects the edges of razor blades, regulates the levels of liquids, guides aircraft to the landing field through fog and night, paints maps of shore lines in utter darkness, determines thickness of layers to a millionth of an inch, measures weight, color, light intensity, odors, and the tiniest time intervals. It does so many more amazing things that we could fill up this book listing a fraction of its applications—and it is not an exaggeration to say that the lion's share of our technical advances in the last 30 years depend on it. If you can understand the basic working of a vacuum tube and its few essential functions, you will have no difficulty understanding the most ingenious devices and inventions of this electronic age.

### Historical Origins

How did it all come about? Was the invention of this boon to mankind the result of a concerted effort by a single-minded individual working late into the night, or a group of devoted scientists? Did someone spend a billion dollars to force its discovery, as was done in the case of the atom bomb? To be quite candid, it was neither as logical nor quite as romantic as all that. As with many other great inventions, such as the beginnings of electricity itself, men with great curiosity who experimented with everything stumbled upon this discovery—generally while looking for something else—and only dimly realizing its significance. Simple vacuum tubes began to be used long before anyone really understood "the Electron Theory of Matter" upon which its operation is based. Later the theoreticians went to work and supplied the scientific base for further progress. Finally, organized research in private industries and universities began to take over the promising child and developed it to its present state of impressive perfection.

*Edison Effect.* While it is difficult to find an exact beginning to our story—which is so intimately linked with the development of electricity—the so-called "Edison effect" may be taken as the forerunner of the modern vacuum tube. In 1883, while a young man of 36 years, Edison experimented with carbon filament incandescent bulbs and was annoyed by the constant burning out of the filaments near the positive end. To determine the

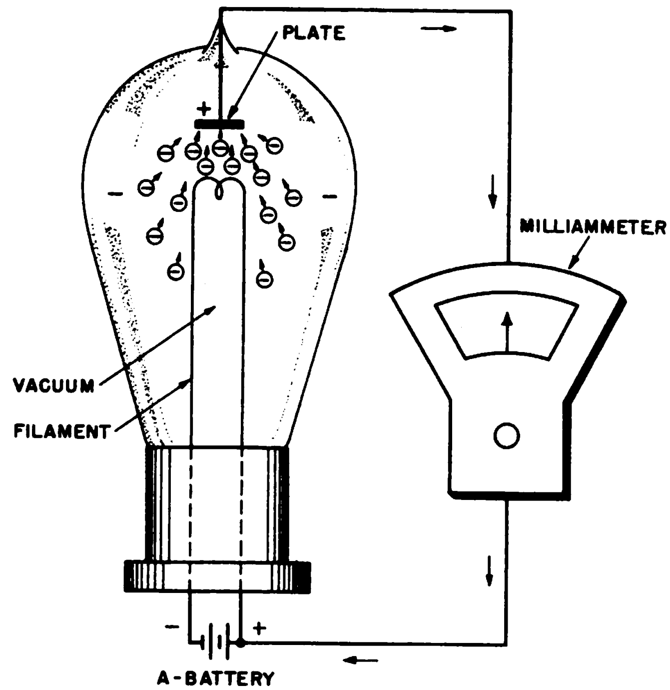



**Fig. 1-1. Circuit of two-electrode bulb, where the Edison Effect was first observed.**

cause of these filament failures, he sealed a small metal plate inside the glass bulb of the lamp, near the filament but not touching it, as is shown in Fig. 1-1. He connected a battery and a milliammeter between the filament and the plate. When the plate was connected to the positive terminal of the battery, Edison noted that the milliammeter indicated a current flow between the filament and the plate through the intervening vacuum. When the plate was connected to the negative terminal of the battery, however, the meter indicated no current flow. Edison neither had the time nor the inclination to answer the two fundamental questions arising out of his discovery:

(1) How did the high vacuum within the lamp conduct an electric current? and

(2) Why did the current flow only when the wire was connected to the positive terminal of the battery?

It remained for the British scientist Sir J.J. Thomson in 1889 to explain the *Edison effect* in terms of emission of tiny negative particles of electricity (which he termed *electrons*) from the heated filament of the bulb. These negatively charged particles were attracted to the plate when it was connected to the positive terminal of the battery, resulting in an electron current flow from the fil-

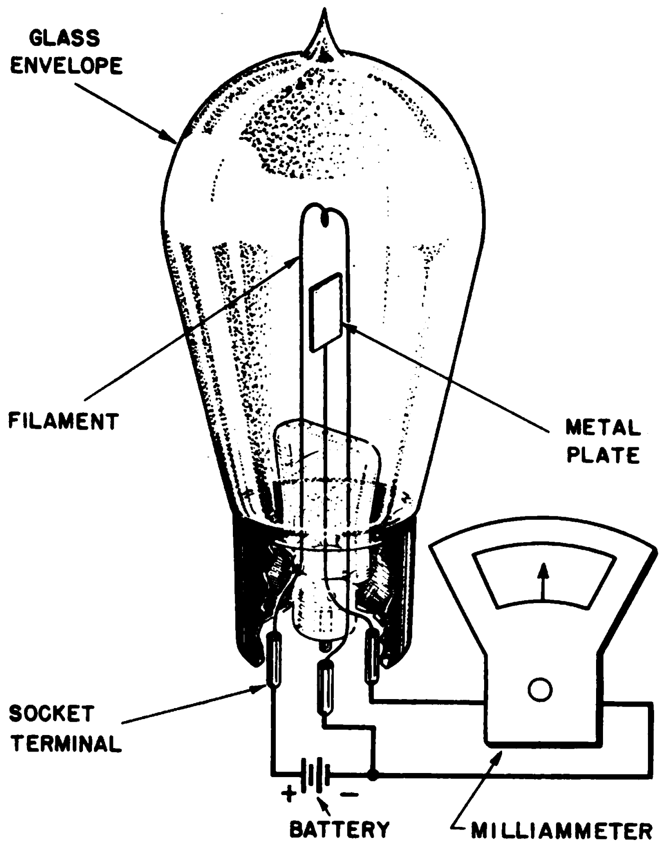



**Fig. 1-2. Fleming's Valve. With plate connected to negative voltage, no current flows through tube.**

ament through the intervening vacuum to the plate. When the plate was connected to the negative end of the battery, the negatively charged electrons were repelled and no current flow resulted. The emission of negative particles of electricity—electrons—from a heated filament is one of the fundamental physical facts on which the operation of all hot-filament vacuum tubes is based, and it will be discussed in detail in Chapter 2.

*The Fleming Valve.* The Edison effect was put to work in 1896 by Professor A.J. Fleming in a simple evacuated glass bulb, known as the *Fleming Valve*. Into the glass envelope he placed a filament (also called a *cathode*) to emit the negative particles of of electricity, or electrons, and a metal plate (also called an *anode*) to collect these particles (Fig. 1-2). Since the tube contains only two basic elements it is known today as a "diode" ("di" means "two").

As Edison had discovered, a current of electricity flowed through the tube, when its filament (or cathode) was heated and its plate was connected to a positive voltage. Fleming discovered that when the plate is made alternately positive and negative by placing an a-c voltage on it, current will flow through the tube only during the positive half-cycles. One positive current pulse will result during each complete a-c cycle. This action of converting ac into pulsating dc is called *rectification* of an alternating current. Fleming knew from Marconi's work that radio signals could be detected and made audible by passing them through such a rectifier, and he used the diode tube for this purpose. However, detection of radio signals by this method was so insensitive that Fleming's valve found only limited use and the future of vacuum tubes in general was rather precarious at that point in their development. With the discovery of the amplifying vacuum tube by Lee De Forest, the problem of insensitivity became unimportant and diodes came back into popularity. Today they are used extensively for rectification and detection purposes, and we shall consider them more closely in Chapter 3.

*Lee De Forest's Audion* The next great step forward in the story of the vacuum tube was the invention of the triode ("tri" means "three") by Lee De Forest in 1906, named the "audion"

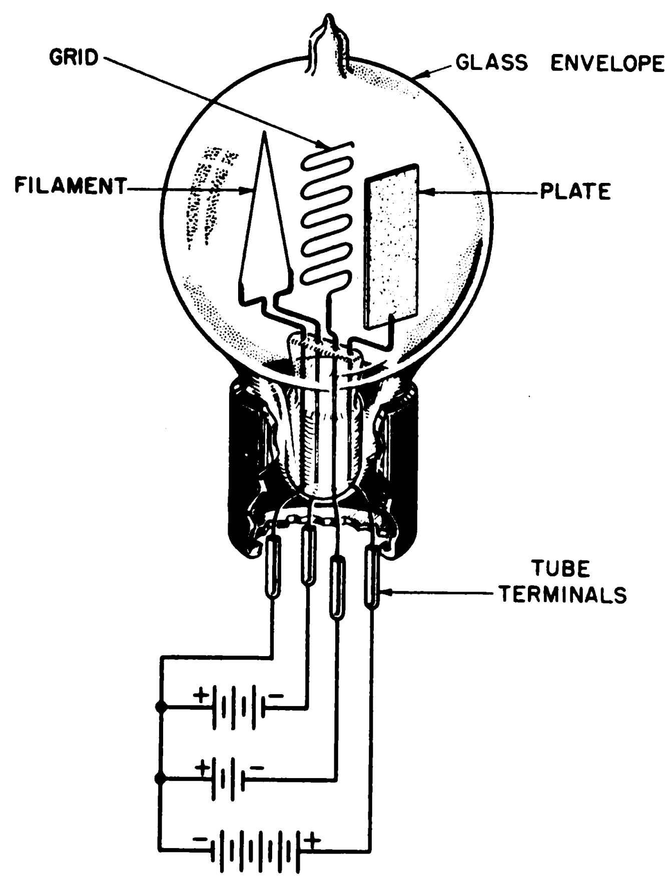



**Fig. 1-3. De Forest's three-element "audion" tube, or triode.**

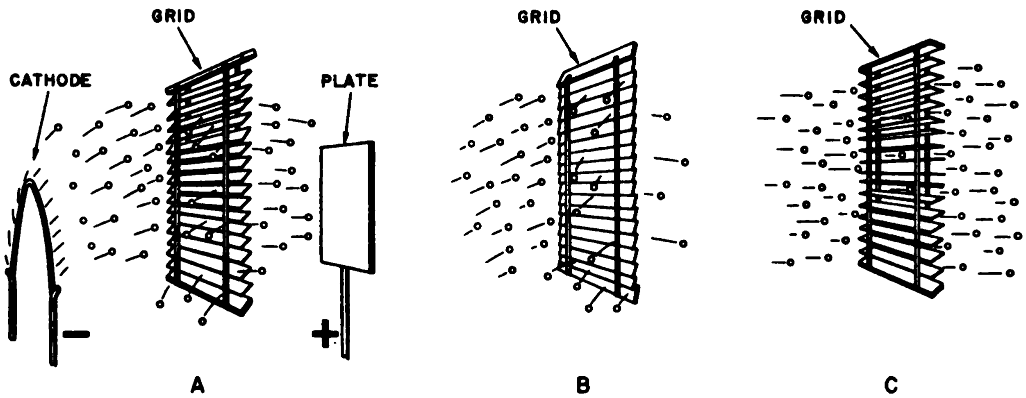



Fig. 1-4. (A) A grid inserted between filament and plate acts like a Venetian blind. (B) The more negative the voltage on the grid, the fewer electrons can pass through the closed blind. (C) The more positive the voltage on the grid, the more electrons can pass through the open blind.

by him. By placing a third element or *grid,* consisting of a few turns of fine wire, between the filament and plate of a diode (Fig. 1-3), De Forest found that he was able to control the flow of electrons within the tube.

The wire grid in the triode tube acts somewhat like a Venetian blind or valve (Fig. 1-4). By placing a voltage on the grid, the flow of electrons from cathode (emitter) to plate (collector) can be controlled very sensitively. The more negative the voltage on the grid, the more electrons will be repelled from the grid, and the fewer will pass through the "blind" on their way to the plate. On the other hand, the more positive the voltage on the grid, the more electrons will be attracted to pass through the open "blind" or grid to the plate of the tube. A very tiny change in the voltage on the grid of the tube produces a big change in the current of electrons flowing towards the plate. This is the heart of the valve or *amplifying action,* which makes the vacuum tube so useful in practically all modern electronic devices, such as radio and television. Thus a tiny amount of radio energy, caught in your antenna and applied to the grid of a triode is capable of controlling much larger currents, which eventually operate your radio loudspeaker. Triodes can perform all the basic functions for which vacuum tubes are used, though sometimes a little less efficiently than the more complex tube structures developed later on. We shall encounter triodes again in Chapter 4, where we shall devote the major part of our story to them.

*Multielectrode Tubes.* In later chapters we shall discuss other tubes, having more than three elements, such as the screen-grid tube or *tetrode,* which has four elements ("tetra" means "four"), the beam-power tube, and the *pentode* (with five elements). The tube classification depends on the number of elements, also called electrodes, contained within the evacuated glass envelope: one with two elements is called a *diode,* with three elements a *triode,* with four elements a *tetrode,* with five elements a *pentode,* and so forth. All vacuum tubes must have at least an emitter of electrons, or *cathode,* usually heated to incandescence, and a collector of electrons, called a *plate* or *anode.* The other electrodes are generally grids for controlling the flow of current within the tube. The basic amplifying action of multielectrode tubes does not differ materially from that of triodes and they need not be discussed further at this point.

*Photoelectric Tubes.* Although we shall not be able to discuss it in detail, it is of interest to note that there are vacuum tubes in which the emission of electrons does not depend on a heated filament or cathode. In the photoelectric tube, also often called the *phototube* or *electric eye,* electrons are emitted from a specially prepared metal surface by shining light upon it. This "light" may be visible or it may be invisible ultraviolet or infrared radiation ("black light"). The brighter the light shined upon the light-sensitive surface, the more electrons are liberated, and attracted toward the positively charged plate. Thus changes in the level of illumination are converted into the corresponding electron current changes.

This photoelectric property has proved exceedingly useful in a host of applications. It is used, for example, to count objects moving past a light source on a conveyor belt. As the object casts its shadow on the phototube by interrupting the light beam, the current through the tube is cut off, which results in advancing a mechanical register by one unit. The phototube is further used to convert the variations of black and white on the sound track of a movie film into the corresponding electric currents which, in turn, operate a loudspeaker to reproduce the original sound. Finally, the photoelectric principle is utilized in a television camera to transform instantaneously an entire visual scene into the corresponding "electric image" for transmission by means of radio waves.

*Cathode-Ray Tubes.* Electrons can be made to perform some strange feats. After having been emitted from a hot cathode, they can be bundled into a pencil-sharp beam by means of a series of electrodes, called an *electron gun,* which acts the same as an optical lens does on a light beam. Such a beam of electrons may be deflected from its normally straight course by means of the attraction of a positively charged plate in its vicinity, or by the repulsion of a negatively charged plate. The beam of electrons may also be swung around by means of a magnet held near it. The magnet attracts the beam much like iron filings. These principles are used in an amazing device, called the *cathode-ray tube*[1].

In the cathode-ray tube, a sharply focused electron beam is shot out of the electron gun, consisting of an electron-emitting cathode and an "electron lens". The beam strikes a glass screen coated with fluorescent material, which produces light wherever it is struck. On its way to the screen, the beam can be deflected either by the influence of two charged "deflecting plates" through which it passes, or by means of the magnetic field generated by an electromagnet placed around the neck of the tube. By impressing an electrical signal on the two deflecting plates, or controlling the field of the magnet with it, the electron beam can be made to trace out an accurate visible graph of the electrical signal on the screen of the cathode-ray tube. This is extremely useful in many electric measurements and for the display of electric waveforms. Cathode-ray tubes are also used in radar sets to visually indicate on their screen some distant "target" or paint a complete radar map of a far-off location. Perhaps their most important application is in the television picture tube, where the beam is swung back and forth many thousands of times a second in order to trace a bright pattern on the screen. By impressing the "electric image" transmitted from the television camera onto the electron gun of the cathode-ray tube, to vary the intensity of the beam, it traces on the screen the image of the picture seen by the television camera.

[1] See TECHNICIAN'S GUIDE TO TV PICTURE TUBES by Ira Remer, published by John F. Rider Publisher, Inc.

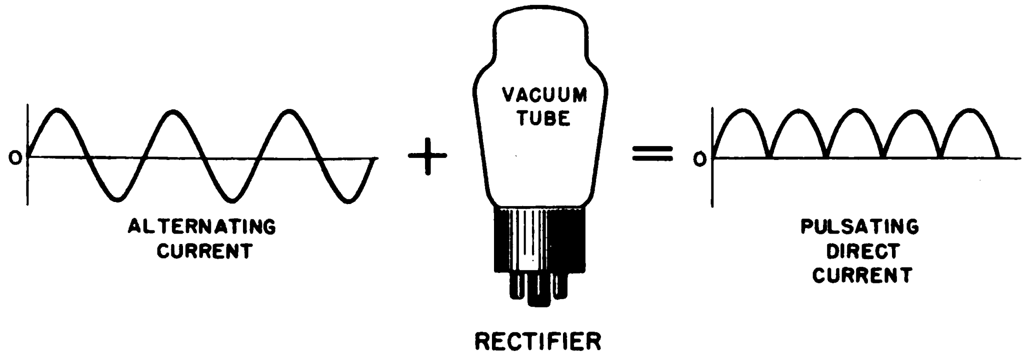



Fig. 1-5. Function of diode tube as rectifier of alternating current.

## Basic Tube Functions

Although the applications of vacuum tubes are myriad in number, the fundamental functions on which these applications depend are few. We shall discuss these functions in great detail in later chapters, and need only briefly list them here for reference.

*Rectification.* Vacuum tubes are capable of converting alternating currents into direct currents. This action, called *rectification* is an inherent property of all tubes, since as we have seen current can only flow in one direction from the cathode to the plate. If an a-c voltage is applied to such a rectifier tube, as in Fig. 1-5, a pulsating d-c voltage results in the output of the tube. Additional devices, called *filters,* are used to smooth out these pulsations to a constant voltage dc. Rectification is very important, since most electronic devices operate best on direct current, while

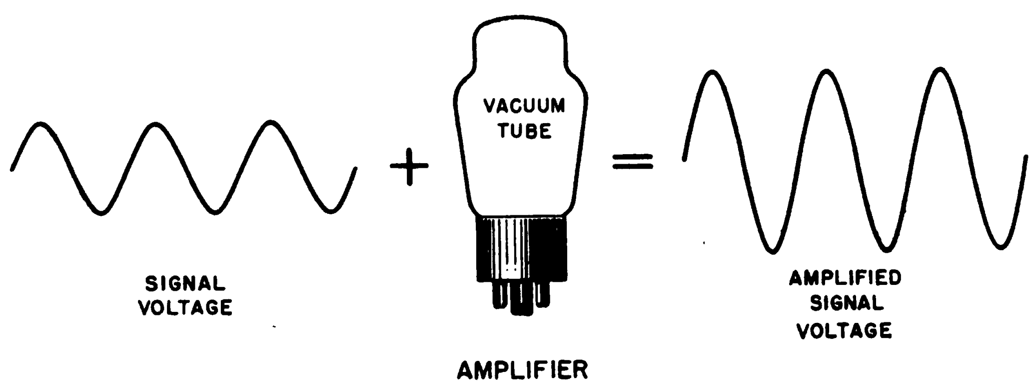



Fig. 1-6. Function of triode tube as an amplifier.

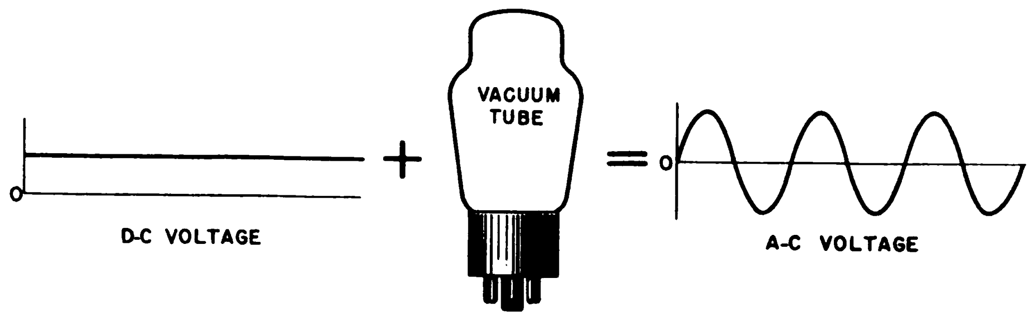



Fig. 1-7. Function of tube as a generator of alternating current.

the required power is generally generated and transmitted in alternating form.

*Amplification.* Undoubtedly the most outstanding function of vacuum tubes is their ability to amplify voltage or power to almost any desired level. The tube does not actually increase in power, but rather it controls relatively large amounts of power from a local source by means of a tiny signal voltage from another source, impressed upon its grid (Fig. 1-6.) The action is that of a Venetian blind (see Fig. 1-4) or a *valve,* the term the British use to designate vacuum tubes. The amplifying ability of vacuum tubes is the basis of all long-distance telephony, public-address systems, radio and television reception and countless other applications.

*Oscillation.* The vacuum tube can act as a generator of a-c voltages, when fed from a d-c source. Thus it converts direct-current energy into alternating current and voltage (Fig. 1-7). This remarkable property is also based upon the amplifying ability of the tube. The generation of alternating currents from dc, called *oscillation,* is obtained by feeding back part of the output of an amplifier tube to its input, thus making the device self-excited and self-sustaining. Oscillator tubes can be built that generate oscillations from as low as 1 cycle per second to frequencies as high as 60,000,000,000 or more cycles per second. The high-frequency oscillator tube is the basis of all radio transmitters.

*Frequency Conversion.* Vacuum tubes are capable of shifting the frequency of an alternating-current wave. By "mixing" waves of two different frequencies in a vacuum tube, a wave equal to the difference between the two frequencies can be obtained in the output of the "mixer" tube. This function of a vacuum tube is closely related to rectification.

*Modulation.* In addition to all these feats, vacuum tubes permit the superimposition of waves of one frequency upon the backs of waves of a higher frequency. Thus in radio transmission, the speech or *audio* frequencies coming out from the microphone are far too low to be transmitted directly over the air. Thus the intelligence contained in these frequencies must be saddled upon the backs of higher frequencies which can be radiated by a radio transmitter. This superimposition is known as *modulation.* In one form of modulation known as *amplitude modulation,* the amplitudes (maximum peaks) of the high-frequency waves are varied

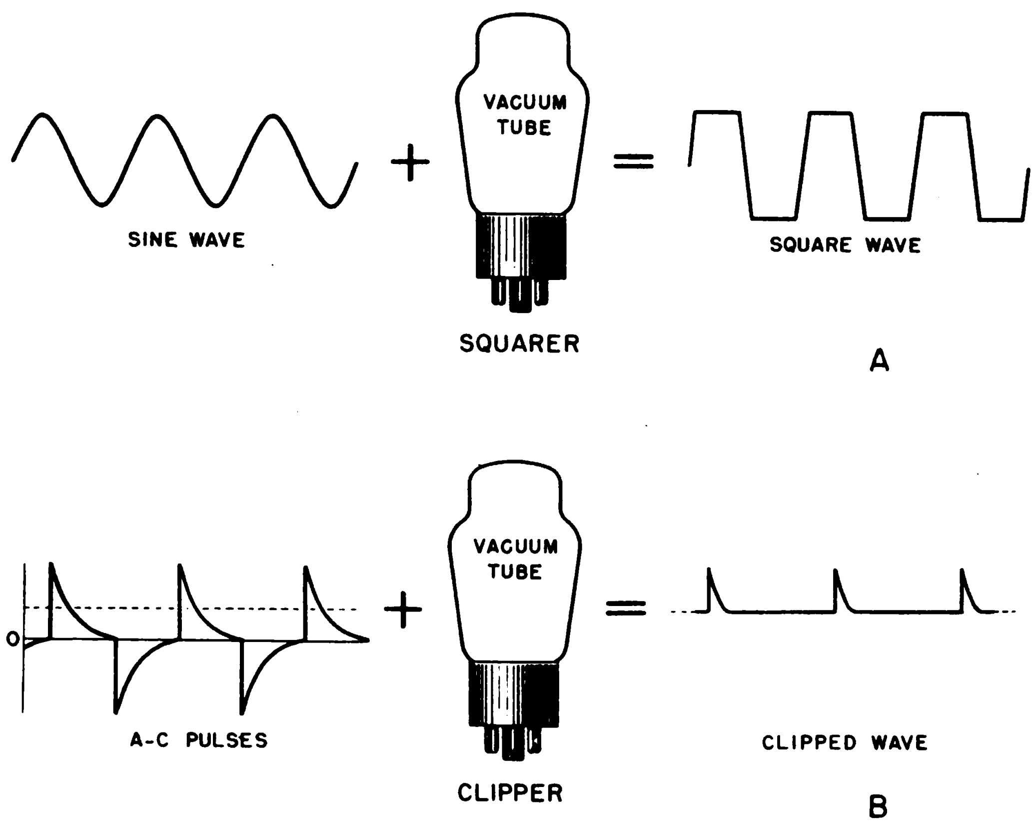



Fig. 1-8 Function of tube for shaping alternating-current waves. (A) Tube shapes a sine-wave input to a square-wave ouput. (B) Tube clips off the negative half-cycles and part of the positive half-cycles of the input wave; only portions of the positive peaks of the input signal are present in the output.

in accordance with the low audio frequencies of the intelligence to be transmitted. In another form of modulation, called *frequency modulation,* the frequency of the high-frequency waves is changed in accordance with the audio-frequency intelligence.

*Detection.* The inverse function of modulation is known as *demodulation* or *detection.* In this process, the intelligence contained in a modulated wave is extracted by rectifying the high-frequency wave in a vacuum tube rectifier, similar to those discussed previously. It is found that the average values of the rectified pulsations follow the original audio-frequency amplitude variations of the intelligence imposed at the transmitter. We shall discuss the process in greater detail in Chapter 3.

*Other Functions.* Another important function of vacuum tubes is their ability to modify the waveforms of the currents and voltages applied to their input. In a sense, the diode rectifier which clips off the negative half-cycles of an a-c wave may be considered a wave-shaping circuit. In addition, vacuum tubes may be used to change sine-wave alternating currents into square-, rectangular-shaped, or triangular waveforms. Any portion of the positive or negative half-cycles of some waveform may be clipped off by a vacuum tube, thus modifying its shape (see Fig. 1-8).

*Chapter 2*

# ELECTRONS AND ELECTRON EMISSION

In Chapter 1 we introduced the vacuum tube and gave a quick birdseye-view of its historical origins, its basic operations and applications. We had discussed how Sir J. J. Thomson had explained the mysterious *Edison effect* by the ingenious hypothesis that the emission of negatively charged particles, which he called *electrons,* from the hot filament accounted for the observed current through the empty space of the tube. We must go more fully into this remarkable *electron theory,* advanced by Thomson, which has since been completely verified and refined to a great degree. Once we understand the nature and behavior of these electrons, the process of emission will become crystal clear.

## ATOMS, ELECTRONS AND IONS

Everything in the world is composed of *atoms*—infinitesimally small particles of matter—each of them being less than a hundred-millionth of an inch in diameter. For simplicity we may think of atoms as tiny spheres, although they they could be more accurately described as bundles of balanced electrical energy, which make up the basic materials or *elements* on earth. There are 96 types of atoms—some of which are produced artificially—corresponding to 96 elements. Combinations of different atoms form into *molecules,* which are the smallest constituent parts of all the chemical *compounds* (combinations of elements) and substances in the physical world.

### Atomic Structure

Although atoms were originally thought to be indivisible ("atom" is the Greek word for "indivisible"), the work of the Danish scientist Niels Bohr in 1913, Rutherford, and others first revealed that the atoms actually had a complex structure. According to Bohr's theory, atoms resemble a miniature solar system, having a central kernel or *nucleus* of positive charge around which the negatively charged electrons revolve in much the same manner as the planets revolve around the sun. These inconceivably small whirling planetary systems make up all the elements, and hence all matter.

*The Electron.* It is the electron that accounts for the amazing performance of vacuum tubes. Billions of tiny electrons perform the fabulous work of the vacuum tube by carry elementary negative charges of electricity from the emitter (cathode) to the collector (plate) with remarkable swiftness. The electron is the lightest fundamental particle known, although not the smallest. Thirty thousand trillion trillion electrons weigh less than one ounce, and six million trillion (6,000,000,000,000,000,000) electrons are required to flow through the filament of a 100-watt bulb, each and every second, to keep it burning. Electrons measure about $\frac{1}{13{,}500{,}000{,}000{,}000}$ inch in diameter. To give you some idea how small this is, compare an electron with a 1-5/16 inch ping-pong ball. The electron is as small compared to the ping-pong ball, as the ping-pong ball is when compared to the huge orbit of the earth, which is 186,000,000 miles in diameter (Fig. 2-1). Electrons cannot be subdivided into anything still smaller, and they are so tiny that they will probably never be observed directly. Because of this, everything we know about the properties of the electron

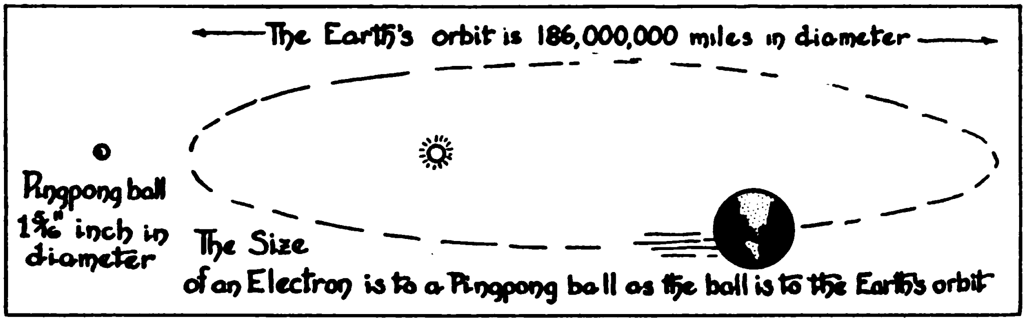



Fig. 2-1.

has been found by observation of the effects associated with them. Thus we can observe the heat which electrons generate when they suddenly strike a metal plate, giving up their energy to it, and we can observe the magnetic field associated with electrons in motion.

From all these facts, we can form some sort of mental picture of the electron as a particle, although not all scientists would go along with us on this. We might think of it as an extremely small, dense spherical ball, carrying a rather large negative charge for its size. All electrons are the same in size, weight and shape, and they all carry the same charge. An electric current may then be thought of as a directed motion of a tremendous number of these tiny charged balls. Although the picture of the electron as a solid ball is not quite correct, it will be adequate for our purposes.

*The Nucleus.* Strangely enough, the positively charged nucleus of the atom consists of additional fundamental particles. The two chief particles in the nucleus are the *proton* and the *neutron.* Although other subdivisions are suspected within the nucleus, their possible existence does not make any difference in the practical behavior of vacuum tubes. The *proton* is the companion piece to the electron, having the same magnitude of charge as the electron, but of positive sign. The proton is considerably smaller than the electron (about one-quarter of its size), but weighs about 1850 times as much (Fig. 2-2). Most of the mass (weight) of the atom is represented by the proton, although it is the smallest particle in the world. The proton rarely exists as an isolated particle and is not found frequently in vacuum tubes. The other fundamental particle in the nucleus is the *neutron,* which has the same mass (or weight) as the proton, but has no electrical charge whatso-

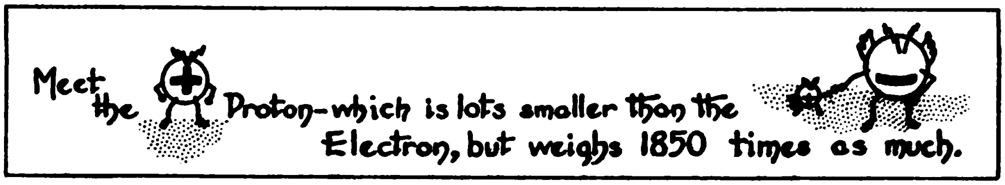



Fig. 2-2.

ever (Fig. 2-3). Being electrically neutral, the neutron has no practical effects on vacuum tubes, except to add weight to the atom. We will, therefore, ignore it in the future.

*All Atoms are Made Up of Protons, Neutrons and Electrons.* The difference between various types of elements, is the number and arrangement of the protons, neutrons, and electrons within their atoms. An ordinary atom is electrically neutral, the total positive charge of its nucleus exactly balancing the total negative

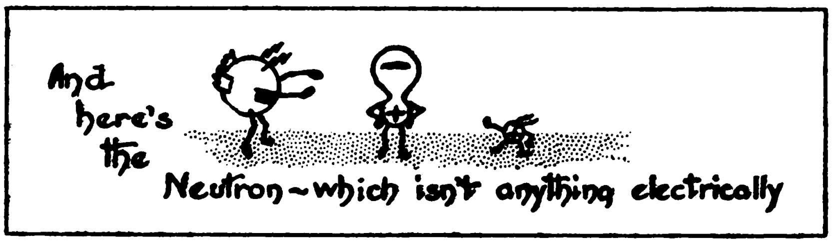



Fig. 2-3.

charge of the planetary electrons around it. In other words, the number of protons within the nucleus must equal the number of electrons around the nucleus, since the neutrons have no charge. The force of attraction between the positive nucleus and the negative electrons keeps the electrons in their orbits.

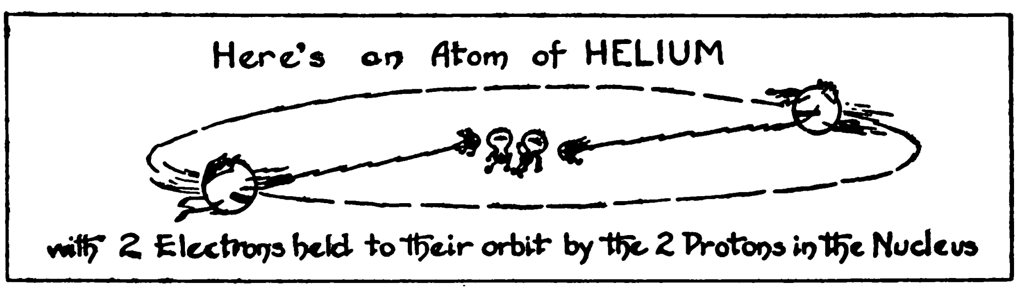



Fig. 2-4.

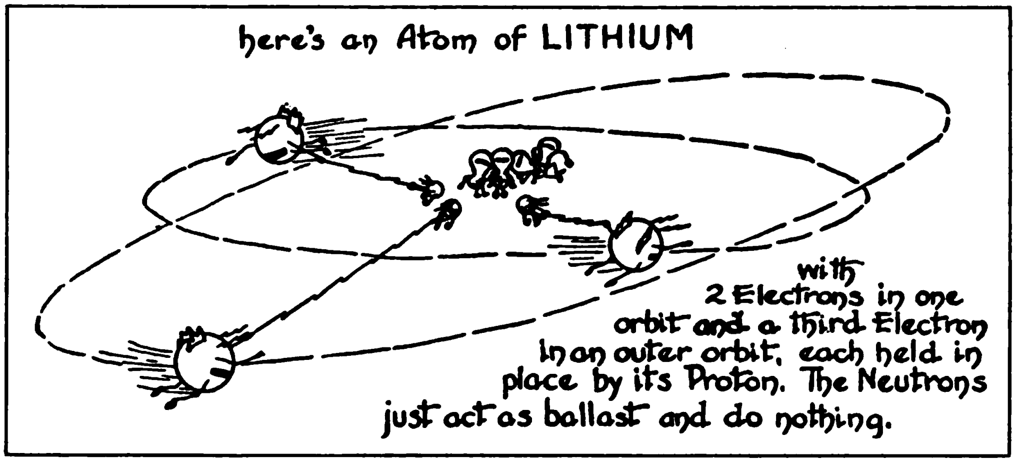



Fig. 2-5.

To understand these ideas better, let us look at some typical atoms. The simplest atom is the hydrogen atom. It has one proton in the nucleus and one planetary electron. Being like solar systems, atoms consist mostly of empty space. To get an idea of how much empty space there is in the hydrogen atom, assume that the proton is one inch in radius; the electron would then be spaced at a distance of about eight miles away from the proton. The next simplest atom is that of helium (Fig. 2-4). Its nucleus consists of two protons and two neutrons. Around the nucleus revolve two electrons which are held in their orbit by the two positively charged protons. As more electrons are added they establish new

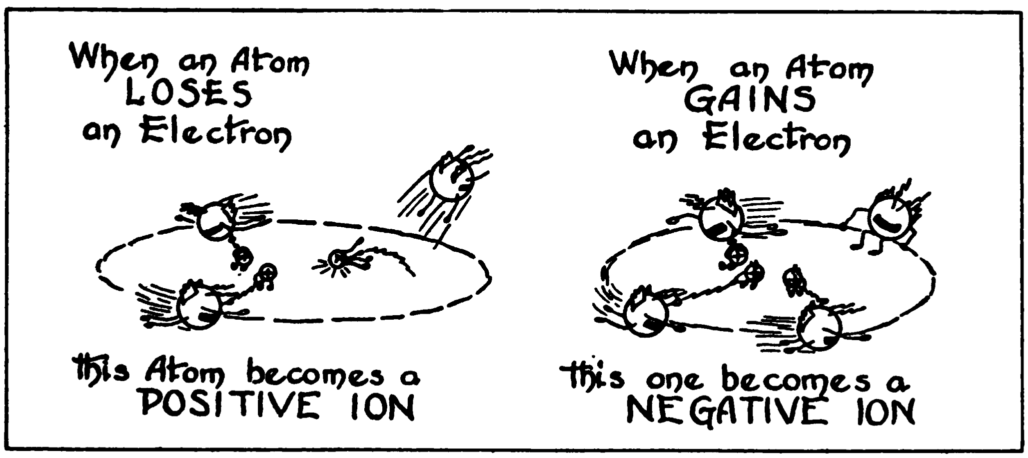



Fig. 2-6.

orbits around the nucleus. Thus in the lithium atom (Fig. 2-5) two electrons revolve in one orbit around the nucleus and a third electron revolves in a more distant orbit around the nucleus. These electrons are held in balance by three positively charged protons in the nucleus. In addition, the nucleus contains three neutrons which add extra weight but have no electrical effects. Other atoms are a bit more complicated. The carbon atom, for example, has six electrons swarming about a nucleus of six protons to balance the charge. In addition, the carbon nucleus contains six neutrons adding to the weight of the atom.

## Ions and Ionization

An ion is an atom which has become electrically unbalanced. If for some reason an atom loses an electron, the remaining electrons will no longer balance the positive charge of its nucleus and hence it acquires an excess of positive electricity. Such an atom is known as a *positive ion* (Fig. 2-6). On the other hand, if an atom gains an electron in some way, it acquires a excess negative charge, and is then known as a *negative ion*. The process of producing these ions is known as *ionization*.

Ionization does not change the chemical properties of an atom, but it does produce an electrical change. Since ionization is of some importance in vacuum tubes, we should understand how it can be brought about. The electrons in the outer orbit of an atom are rather loosely held to the nucleus and can be knocked

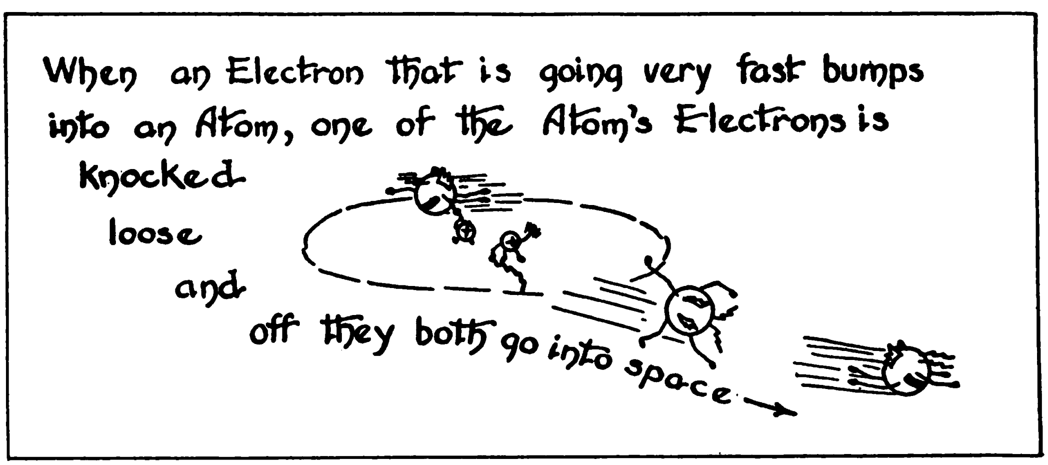



Fig. 2-7.

off easily by collision with another electron or atom, or by exposure to x-rays. For example, when an electron moving at rapid speed in a vacuum tube collides with an atom of gas, (there is always some gas left, since no perfect vacuum is possible) one of several things may happen. The electron may become attached to the gas atom and thus changes it into a negative ion. The electron may simply bounce off the atom without any effect. Finally, if moving at sufficient speed, the impact of the electron may knock off one or more of the outer electrons of the gas atom, thus creating a positive ion (Fig. 2-7). These positive ions are attracted to wards the negatively charged cathode or grid, moving in a direction opposite to that of the electrons. If a sufficient number of positive gas ions exist, they substantially affect the operation of the tube and may damage the cathode structure by their impact upon it.

Sometimes quantities of gas are deliberately introduced into a tube and then operation actually depends upon the ionization of the gas. As an interesting fact it may be noted that ionization of of gas atoms is usually accompanied by a characteristic glow of light, the color of which depends on the kind of gas used. The familiar neon advertising signs depend on this kind of action.

### Free Electrons

Thus far the electrons we have discussed were bound to the atom by the attraction of the positively charged nucleus. However, we have also seen that the electrons in the outer orbits are not so rigidly held and can be dislodged from the atom by collision with another particle. They are then known as *free electrons*. In most substances, a number of free unbound electrons are available. These are able to move from atom to atom. Ordinarily, these unbound electrons are in a state of continuous chaotic motion in all possible directions and are traveling at a speed that increases with temperature. Under the influence of an electric force, however, the free electrons become the agents by which an electric current is carried through a conductor. For example, if a wire is connected between the two terminals of a battery, the free electrons within the wire move in an orderly way, atom to atom, from the negative terminal towards the positive terminal (Fig. 2-8), thus constituting an electric current. Although this drifting motion from atom to atom is rather slow, the impulse is transmitted

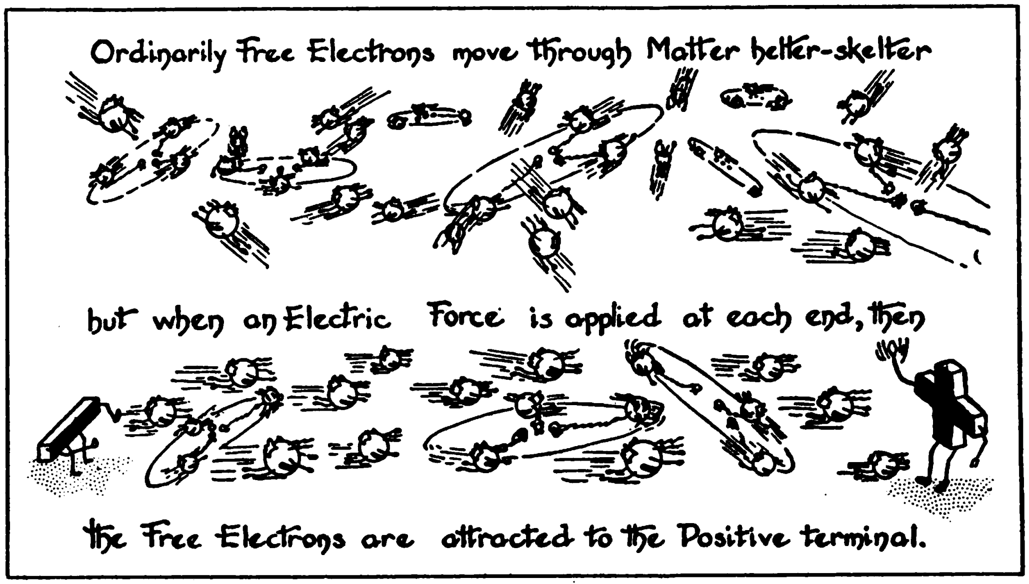



Fig. 2-8.

almost at the speed of light. The more free electrons are available within a material to carry an electric current, the better is the conductor. The fewer unbound or free electrons that are available, the poorer is the conductor. If very few electrons exist in a material and their degree of motion is highly restricted, the material is an insulator. Actually there are no perfect conductors and no perfect insulators; it is all a relative matter depending on the number and ease of motion of the free electrons.

## ELECTRON EMISSION

We have noted that a metallic conductor has a large number of free electrons which are in a state of continuous random motion. At ordinary room temperatures these roving electrons cannot leave the surface of the metal because of certain forces at the surface which act as a barrier. Most of the electrons, although in a state of agitated, haphazard motion, do not have sufficient *kinetic energy* (energy of motion) to break through the barrier. A relatively small number, however, at any particular time move at relatively high speed, and hence have sufficient energy to break through the barrier to the outside. The majority of the electrons move much too slowly for this to happen (Fig. 2-9).

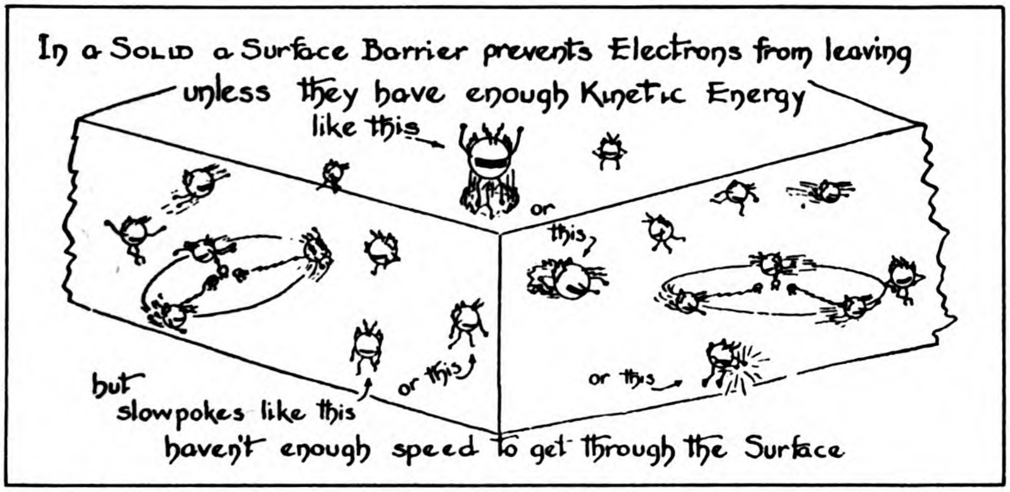



Fig. 2-9.

*Thermionic Emission.* Assume now that something is done to the metallic conductor which causes an increase in the speed of movement of all the electrons. As the electrons speed up, their energy of motion (kinetic energy) also increases until finally great numbers of them break through the surface barrier and escape

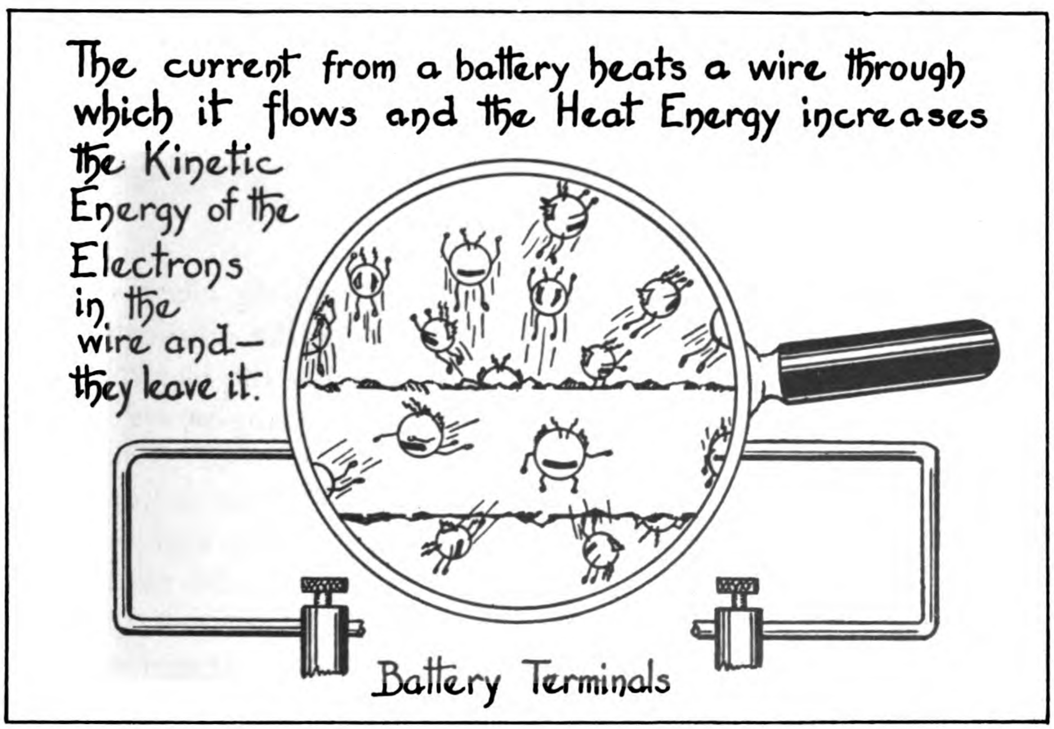



Fig. 2-10.

from the metal. This is the phenomenon of *electron emission.* Electron emission can take place in a number of ways. The electrons inside the metal may be speeded up by the application of heat. This may be done by sending a heavy current through a metal wire. As the metal is heated up the free electrons become more and more agitated and move faster and faster, until they finally reach sufficient energy to break through the surface barrier (Fig. 2-10). They are actually "boiled out" of the metal, like the evaporation of water molecules in the form of steam when a kettle of water is heated to the boiling point (Fig. 2-11). This process is known as *thermionic emission* and is most important in vacuum tubes.

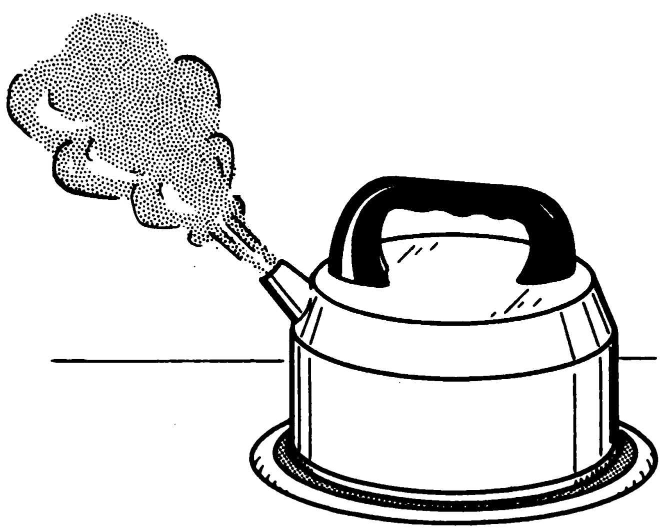


Fig. 2-11.

*Cold Cathode Emission.* In addition to boiling electrons out of a material, they may also be yanked out by the application of a high positive electrical voltage. In this method the electrons are literally pulled out of the material by the attracting power of the strong electrical field near the emitter (Fig. 2-12). This is done without applying any heat to the material, and hence is known as *cold-cathode* or *field emission.* Since an extremely high voltage is required, cold-cathode emission is not commonly used, and hence we shall not discuss it further in this book.

*Photoelectric Emission.* Electrons may also be "scared out" of some metals with a beam of light. In this process, known as *photoelectric emission,* the energy of the light radiation falling upon the metal surface is transferred to the free electrons within the metal, speeding them up sufficiently to leave the surface (Fig. 2-13). The number of electrons emitted depends upon the intensity (brightness) of the light falling upon the metal surface. The process may be understood better, if one considers the *particle nature of light.* Although generally thought of as a radiation, light sometimes acts like energy consisting of small particles, called *photons.* When these photons impinge upon a metal surface they may collide head-on with electrons near the surface and kick them out on the metal like billiard balls, How light can be both a particle and a wave is a mystery of advanced physics, which we cannot solve here. Photoelectric emission, however, is a fact and finds important application in the photoelectric tubes we have discussed in Chapter 1.

*Secondary Emission.* A fourth type of emission is called *secondary emission.* This is the liberation of electrons from a substance as a result of the bombardment of the substance with fast-

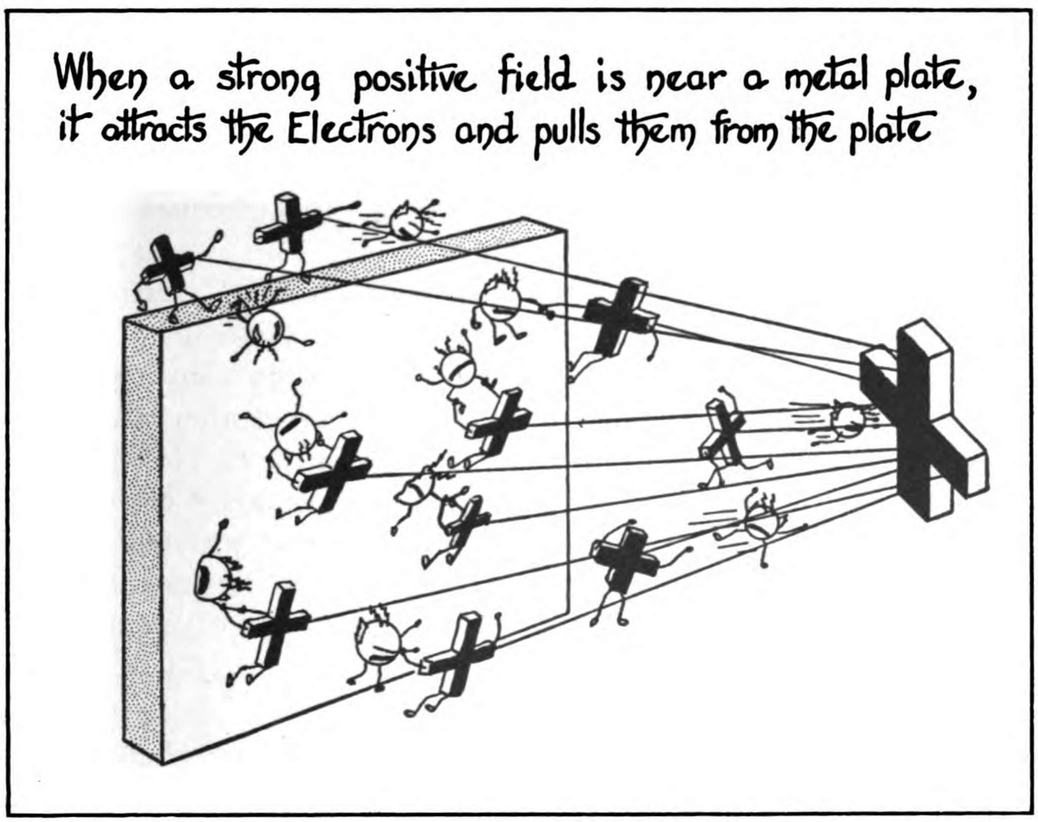



Fig. 2-12.

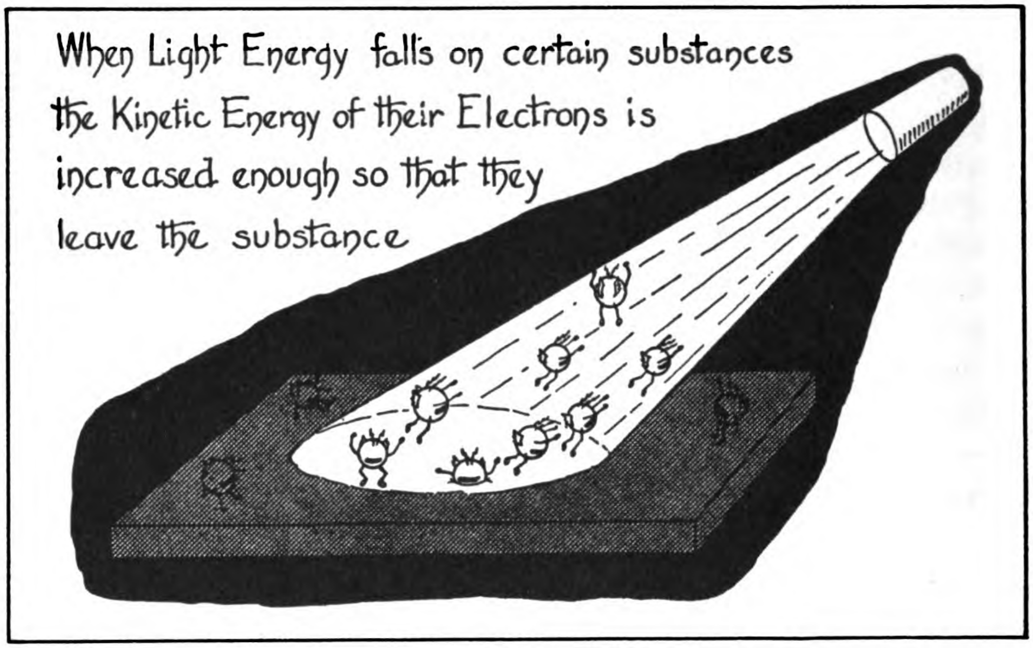



Fig. 2-13.

moving electrons. When high-speed electronic bullets suddenly strike a metallic surface, they give up their kinetic energy acquired during motion to the electrons and atoms which they strike. They may collide directly with free electrons and hence increase the energy of these electrons sufficiently to break through the surface barrier and leave the metal (Fig. 2-14). This is very similar to the billiard-ball collision between photons and electrons we have discussed in the last paragraph. The electrons that are knocked off are called *secondary emission* electrons, since primary electrons must first be made available from some other emitter to bombard the secondary electron emitting surface. You will see later on in the text that the existence of secondary emission is highly undesirable in certain vacuum tubes and provisions have been made to prevent it. Other tubes, however, depend for their operation on secondary emission.

## Thermionic Emission

Of the various methods of obtaining electron emission from a metal, that which employs heat is of the greatest interest to us, since most vacuum tubes depend on this kind of emission for their operation. Although it had been known for a long time that hot metals emits electrons more freely than cold ones, the systematic theory of *thermionic emission* was first worked out in brilliant fashion by O. W. Richardson in 1901 and it still holds good today. Richardson explained, as we have stated earlier, that the free electrons near the metal surface have a haphazard random motion, moving in all possible directions and at varying speeds. At normal temperatures very few of these roving electrons have sufficient speed, and hence kinetic energy, to break through the restraining force of the surface barrier. When the metal is heated, the heat energy adds to the vigor of the random motion and the speed of the free electrons increases rapidly. At a certain temperature, a very large number of electrons will attain sufficient speed and energy to break through the restraining barrier and leave the surface of the metal.

*Work Function.* We have talked a lot about the restraining force of the surface barrier which keeps the electrons from shooting out into free space at low temperatures, but we have thus far not explained the nature of this mysterious barrier. While this force is very complex and not yet completely understood, we can

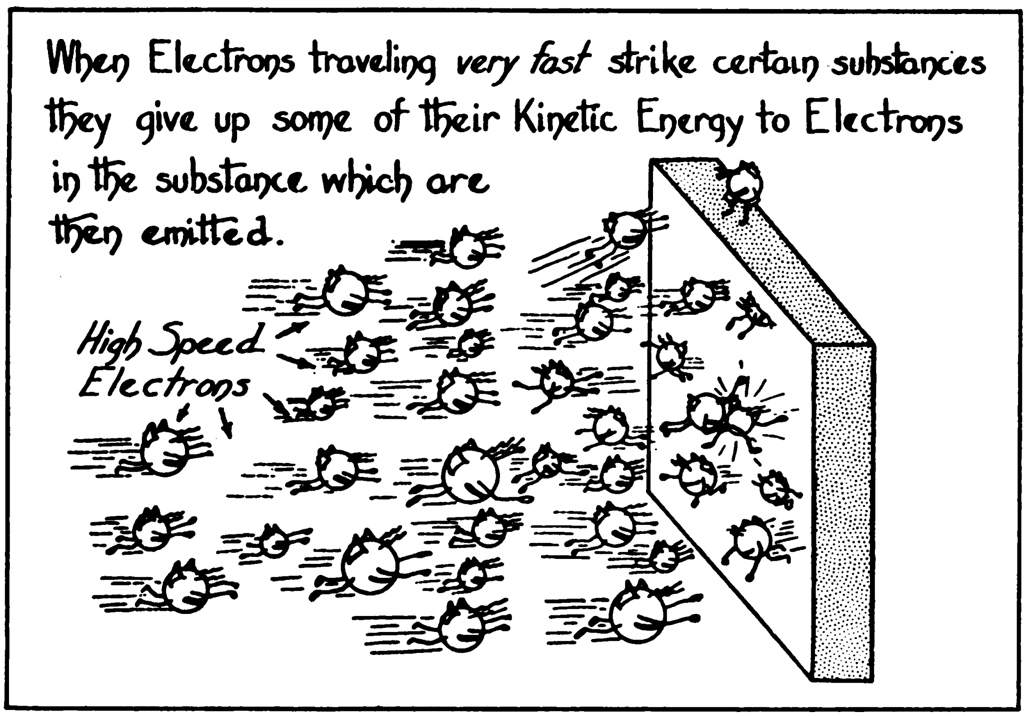



Fig. 2-14.

say that for the greater part it is the well-known force of electrical attraction between unlike charges. We all learned the basic fact of electricity that positive and negative charges attract each other. How does this explain the restraining force at the surface of a metal?

The answer is very simple. Before emission takes place, the metal surface is electrically neutral, that is, the number of negatively charged electrons just equals the positive charges of all the atomic nuclei on the metal surface. The fact that some of these electrons are bound to the atoms, while others are freely roaming around makes no difference; since the metal is uncharged, positive and negative charges must balance. Now assume that an electron—having a definite negative charge—has left the surface of the metal. As a result the charges remaining on the metal surface no longer balance, but an *excess positive charge* appears on the metal. This is similar to the process of ionization, where an atom becomes positively charged by removal of an electron from its orbit. The only difference in the present case is that the whole metal surface becomes positively charged to an amount that is equal to

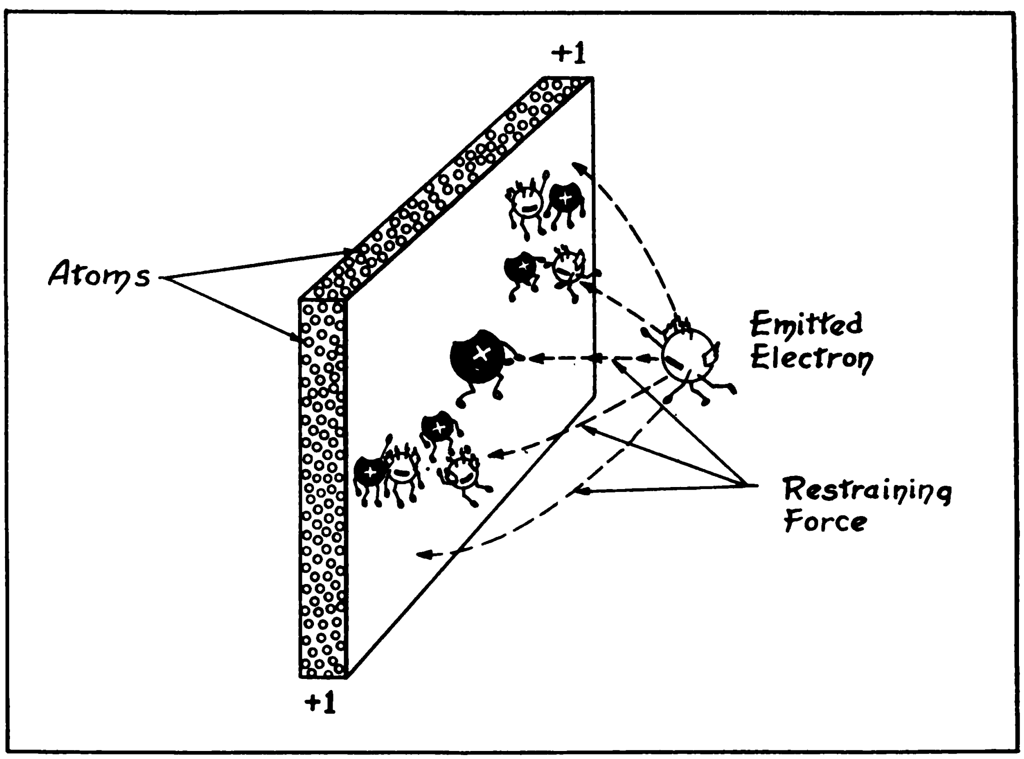



Fig. 2-15.

the negative charge of the electron which has left it. Naturally, the positively charged metal surface attracts the negative electron and tends to pull it back to the surface (Fig. 2-15). It is clear from this that an electron is not actually freed when it has left the metal surface, but that the attraction of the positively charged surface tries to pull back the electron like a stretched rubber band. The restraining force of the surface (sometimes called *potential barrier*) reaches a maximum after the electron has left the metal and has traveled a distance equal to the widths of several atoms. (This is such a small distance that for all practical purposes the electron is still at the surface of the metal.) If the electron succeeds in getting past this point of maximum restraining force, the "rubber band" appears to be broken, and the electron has little further difficulty in leaving the metal. Each electron has to go through the same ordeal to get away from the metal since it leaves the same positive charge at the surface.

We have seen that electrons must perform a certain amount of work to leave the metal surface against the restraining force of the electrical attraction caused by positive charge at the surface. The work an electron must do to escape from the metal surface depends on the type of metal. This characteristic is known as the *work function* of the metal. The work function can be measured by stating the amount of energy an electron would acquire by being attracted by a certain positive voltage, just equal to the energy needed to remove the electron from the metal.

For example, the work function of thoriated tungsten, which is commonly used as an emitter in vacuum tubes, is 2.63 volts. This means, that an electron traveling from rest to a metal plate charged to a potential of + 2.63 volts, will strike that plate with the same amount of energy as it would need to escape from the surface of thoriated tungsten. The lower the work function rating, the less energy– or voltage – is required, for an electron to penetrate the surface of the particular metal. Nickel coated with barium oxide, has a work function of only 1 volt, approximately. Hence it is frequently used an an emitter when a large electron flow is desired.

*Richardson's Equation.* Richardson explored not only the "why" of thermionic emission, but also derived an equation telling "how much". While this equation is too complicated to be stated here, we can give some of its results. Richardson's equation showed that thermionic emission, expressed in amperes per square-centimeter of emitter surface, depends chiefly on the temperature of the emitter and its work function. The lower the work function of a material, the higher is its electron emission at a given temperature. As the work function *decreases,* emission *goes up at an exponential rate.* By exponential rate, we mean a rate of increase about as fast as that of a snowball turning into an avalanche by rolling down a snow-covered slope.

On the other hand, for a given emitter material with a specific work function, thermionic emission *increases* extremely fast with *increasing temperature.* The rate of increase with temperature is even faster than the exponental rate stated for the work function. Relatively small changes in temperature can produce enormous changes in the amount of electron emission. For example, if pure tungsten metal is used, the emission is about a millionth of an ampere per square centimeter at a temperature of 2,400 degrees Fahrenheit. If the temperature is increased to 5,500 degrees Fahrenheit the emission increases incredibly to almost a hundred amperes per square centimeter. In this case, then, little more than doubling the temperature produces an enormous increase in emission of about a hundred million times.

### Types of Emitters

Our discussion of the Richardson equation has revealed that the ideal emitting substance will have as low a work function as possible, and should be able to operate at very high temperatures. Unfortunately, the materials capable of operating at very high temperatures usually also have fairly high work functions, thus partially cancelling their advantages. Among these materials are the pure metals tungsten, tantalum and molybdenum, all of which have very high melting points.

*Pure Metals.* Of all metals *tungsten* is most extensively used. because it can be raised to higher temperatures without melting than any other metal. However, since its emission is relatively low, tungsten is used as an emitter only in high-power transmitting tubes, where the emission of other metals would be destroyed by the effect of the high plate voltages. Tungsten is extremely rugged and durable, and hence can be subjected to very heavy overloads. Tungsten filaments are usually operated at temperatures of 4,000 to 4,500 degrees Fahrenheit, and glow with a white light. Although they have a comparatively long life, tungsten filaments gradually evaporate with time, becoming thinner and thinner. Eventually a part of the filament becomes too weak to carry the current and burns out. In order to attain long tube life, the voltage across a tungsten filament is kept constant, rather than the current through it. In this way the filament current adjusts itself naturally to the increase in resistance occuring with aging.

Another pure metal used as an emitter in transmitting tubes is *tantalum.* It cannot be heated to as high a temperature as tungsten, but its work function is lower and the emission is satisfactory. Unlike tungsten, tantalum can be worked in sheet form to produce special cathode shapes desired in some tubes. A disadvantage of tantalum is that it contaminates itself through the formation of gases which reduce emission.

*Atomic Film Emitters.* Somewhat more efficient than the pure metals are materials which use a layer of one atom thickness of one metal on top of another. In practice, the only material used is *thoriated tungsten,* which is manufactured by mixing tungsten metal with a small amount of thorium oxide. This reduces the work function, while at the same time permitting the tungsten to be heated above its own melting point.

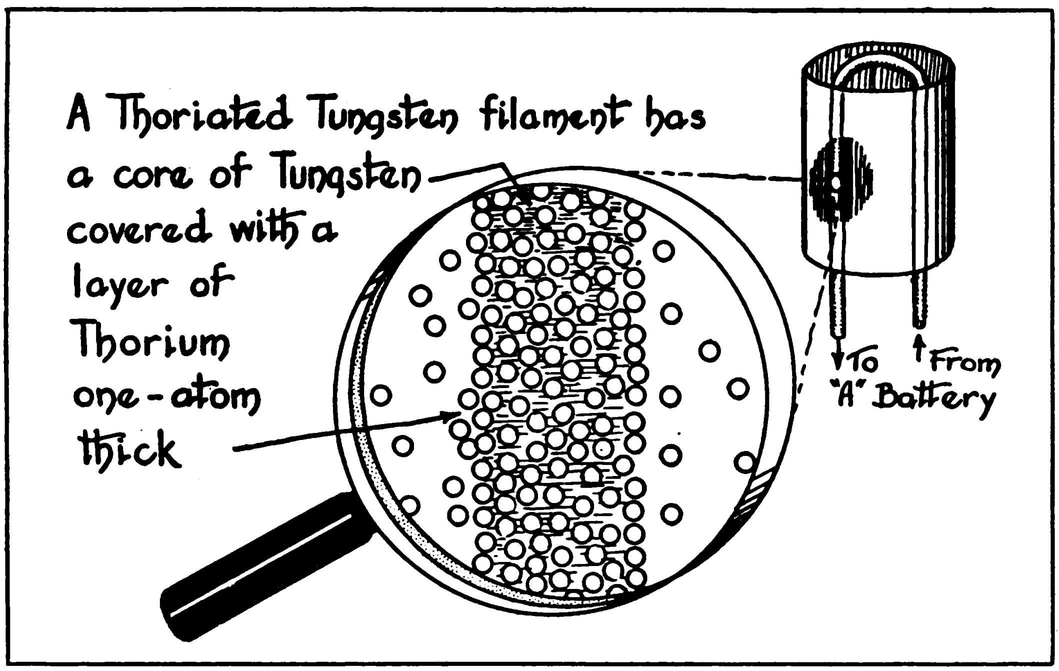



Fig. 2-16.

During operation, a small amount of the thorium diffuses to the surface of the tungsten filament and appears as a coating one atom thick (Fig. 2-16). This coating is an excellent emitter, but gradually boils off during use. As the layer evaporates, it is replenished from inside the tungsten filament. If the film of thorium is burned off by chance through excessive filament temperatures, the tube can be reactivated by *flashing* the filament at approximately three times its normal operating temperature and then operating it for several hours at about 50 percent above normal voltage. This restores the atomic film of thorium. Eventually, however, after about 5,000 hours of operation the filament wire evaporates and burns out, just like tungsten. Thoriated tungsten filaments are operated at a temperature of about 3,500 degrees Fahrenheit and glow a bright yellow. They are used chiefly in low- and medium-powered transmitting tubes.

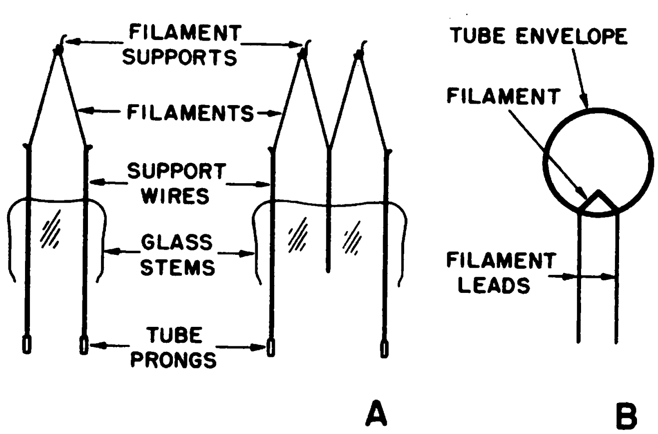



**Fig. 2-17. Directly heated filaments and their schematic symbol.**

*Oxide Emitters.* The most efficient electron emitters are oxide-coated filaments and cathodes. The oxide coating consists usually of a half-and-half mixture of barium and strontium oxides, coated on a metallic cylinder. After heat treatment, the active emitting surface of the cathode consists of a thin layer of barium and strontium, while the metallic core carries the heating current. Copious emission takes place from particles of free metal on the surface of the coating. Oxide-coated cathodes are operated at temperatures ranging from 1,500 to 2,000 degrees Fahrenheit, and they glow a cherry-red. Their operating life may be as high as several thousands hours and they are used in most receiving tubes.

#### Methods of Heating

All electron emitters are heated electrically, either *directly* or *indirectly*. In the direct method, the electric current is applied directly to a wire, called the *filament, filament-cathode,* or *directly-heated* cathode. In the indirect method, the electric current is sent through a separate *heater element,* located inside the emitting cathode. The cathode is heated *indirectly* through heat transfer from the heater element. The assembly is called the *heater-cathode.* Either ac or dc can be used in both methods of heating.

*Direct Heating.* Directly heated filaments are usually shaped in the form of an inverted *V,* or an inverted *W,* as shown in *Fig.* 2-17 (A). The schematic circuit symbol used is illustrated in part (B) of the figure. Directly heated filaments have the advantage that they can be operated at higher filament temperatures than those used with indirect heating, and they reach their operating temperature almost instantaneously, which is often of importance. All the emitters previously discussed may be used for directly heated filaments, including tungsten, thoriated tungsten, and oxide coatings. Directly heated oxide-coated filaments require very little heating power, and for this reason, are used extensively in battery-operated and portable electronic devices.

*Indirect Heating.* Indirectly heated cathodes are made in the form of a cylindrical sleeve surrounding the heater wire (Fig. 2-18). The cathode sleeve is coated with the emitting material, usually an oxide coating. The heat reaches the cylindrical cathode by radiation and conduction from the heater wire. With indirect heating the cathode can be electrically isolated from the heater and is at a uniform potential throughout its surface.

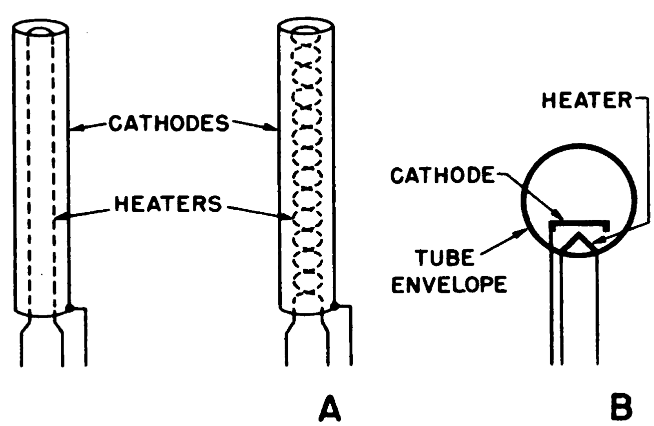
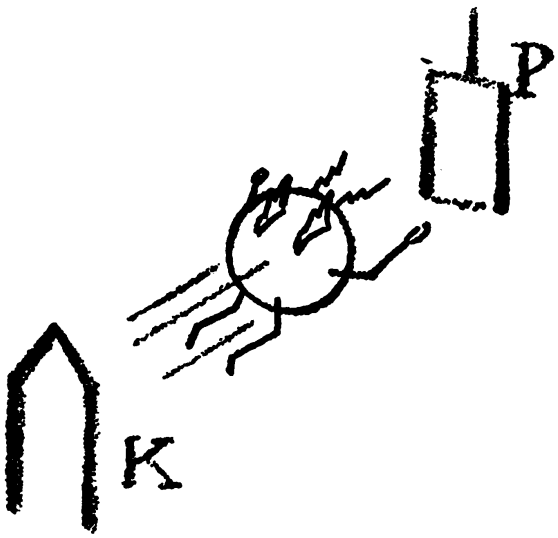



**Fig. 2-18. Indirectly heated cathodes and their schematic symbol.**

The majority of receiving-type vacuum tubes are indirectly heated because of the necessity of operating from an alternating-current supply. Since indirectly heated cathodes are slow in heating up and cooling off, their temperature (and hence emission) does not fluctuate much with the variations in heater current as the a-c input reverses direction. The rapid 60-cycle a-c heater variations are smoothed out by the heat inertia of the cathode and do not affect the tube's operation. With directly heated emitters, special circuits are required to adapt them to an a-c supply.




*Chapter 3*

# DIODES

We now understand why and how electrons are emitted from a cathode, but we do not yet know what happens to them after that. The behavior of electrons within the tube, their control and formation into a useful current, and the effects of this current on the circuits associated with the vacuum tube, will be subjects for discussion during the remainder of the book. Let us first look at the simplest combination of elements or electrodes which constitute a vacuum tube – the *diode.*

## Construction

The diode ("di-ode" means "two electrodes") consists of an *emitter of electrons* and a *collector of electrons,* enclosed in a highly evacuated envelope of glass or metal. The emitter may be a directly heated filament or an indirectly heated cathode. For convenience, all emitters are referred to as *cathodes,* regardless of the method of heating. The collecter of electrons is called the *plate*

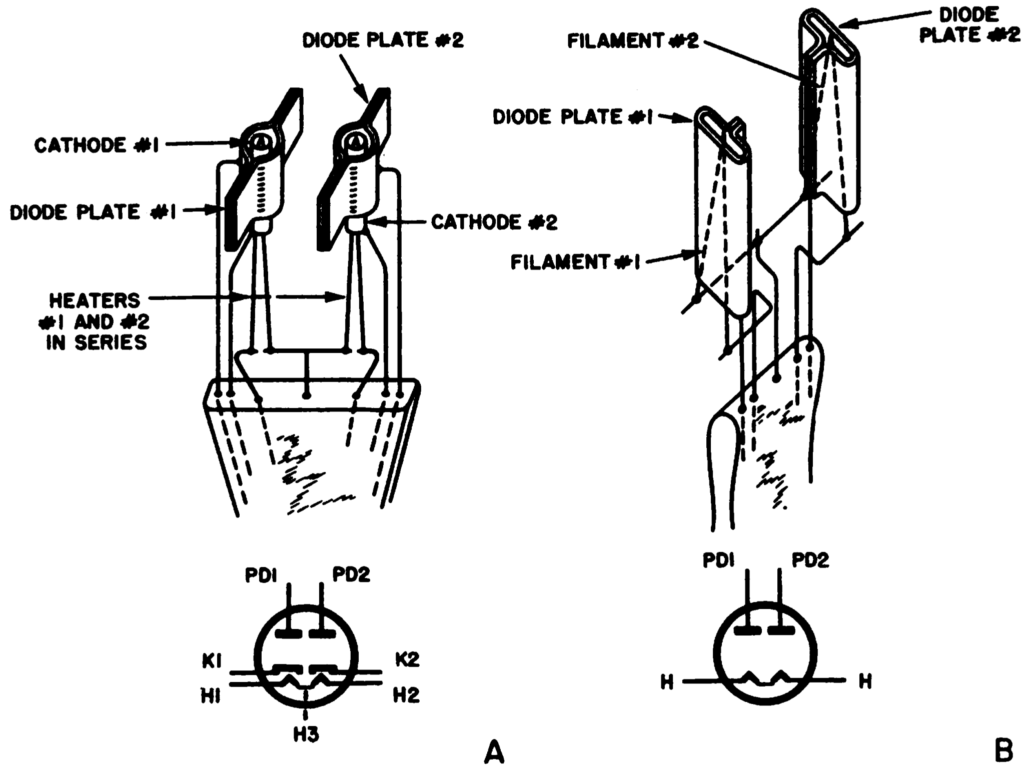



Fig. 3-1. Construction of a duo-diode and its schematic symbol.

and sometimes the *anode.* The plate is frequently constructed of a hollow metallic cylinder of circular or elliptical shape, which surrounds the cathode. Metals used for plates may be nickel, molybdenum, graphite, tantalum, monel, or iron.

Because of their ability to change alternating current to direct current, or *rectify* it, diodes are often referred to as *rectifiers.* A diode, containing a single cathode and surrounding plate within an envelope, may be known as a *half-wave rectifier,* because it is capable of rectifying only alternate half cycles of its a-c input, as we shall see later on. Depending on the specific functions a diode may fulfill within a particular circuit, it may also be referred to as a *detector, demodulator,* etc.

*Duo-Diodes.* Frequently two diode sections are contained inside a single glass or metal envelope, each section having its own separate cathode and plate, as shown in Fig. 3-1. Such a tube is called a *duo-diode,* or a *full-wave rectifier;* the latter term is used because the tube can be arranged in a circuit to rectify *both halfs* of an alternating-current input, as will be described later in the chapter. Part (A) of Fig. 3-1 shows the construction of a duo-diode with separate cathodes, but with their respective heaters being arranged in series. The lower part of the figure gives the corresponding schematic circuit symbol, with the commonly used labeling of each electrode. Here the letter "H" stands for "heater", "K" for "cathode", "P" for "plate", and "D" for "diode"; the numbers refer to section 1 or section 2 of the duo-diode, respectively.

Another type of duo-diode and its schematic symbol are illustrated in Fig. 3-1 (B). In this directly heated tube, the filaments are connected in series and no independently emitting cathodes are used. The plates, however, are independent of each other. This is the type of tube generally used in full-wave rectifier circuits. The other type with separate cathodes (Fig. 3-1A) is more versatile, and is used in a variety of radio signal circuits. Other modifications of duo-diode structure occur in practice, but it is

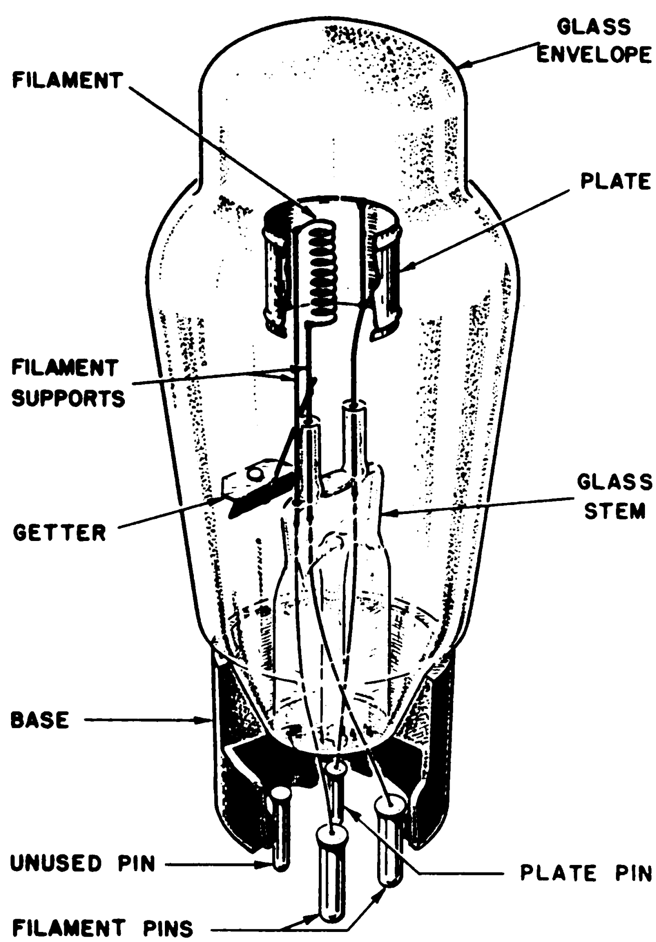



Fig. 3-2. View of a simple diode of filament type.

important to note that none of these make any difference as regards the basic operation of each diode section within the common envelope. Whatever we will have to say about the characteristics and operation of single diodes, will also apply to duo-diodes which are simply two tubes in one envelope.

*Getter.* The complete construction of a simple half-wave diode of the filament type is illustrated in Fig. 3-2. The figure clearly shows the base pins leading to the electrodes within the glass envelope, the spiral filament and the cylindrical plate surrounding it. You may wonder about the small metal receptacle, labeled "Getter" located near the glass stem inside the tube. This getter serves a very useful purpose in the manufacture of the tube, which we shall explain presently. We have mentioned that a tube must be highly evacuated to function properly. If a tube is not well evacuated, it is said to be *gassy*. In a gassy tube, the electrons emitted from the cathode collide with the numerous molecules of air, thus impeding their flow and producing positive ions by knocking off electrons from the outer orbits of the air molecules. These positive gas ions move in a direction opposite to that of the electrons (so-called *gas currents*) and lead to generally erratic operation of the tube. For this reason every precaution is taken during the manufacture of vacuum tubes to pump all the air from the tube, evacuating it as completely as possible. However, even the best available pumps leave more air in the tube than can be permitted. Additional measures are taken to remove the remaining air within the tube, which may be trapped in crevices and seams of the metal structure. By bringing tube elements to red heat during evacuation, most of these gases are driven off.

As a final step in degassing, a *getter* material, usually magnesium or barium, is placed on a small metal cup within the tube. After the tube is sealed off, this getter is flashed by an electrical heating process; the material evaporates and condenses on the inside walls of the tube as a silver or reddish coating. The getter coating tends to make the vacuum produced during manufacture more permanent by combining with any impurities that may be driven off during the life of the tube. Even in this highly efficient vacuum there may still be left as many as half a trillion air molecules within each cubic inch of the tube. This amount does not interfere with its proper operation, however.

## LAWS OF ELECTRON MOTION

Before going more fully into the operation of a diode, we must now review and expand our knowledge of the basic laws of electricity and *electrostatic fields.* This is necessary in order for us to predict how electrons in the diode will behave under various conditions of operation and voltages on the plate.

### Attraction and Repulsion

One of the basic laws of electricity states that *like charges repel each other* and *unlike charges attract each other* (Fig. 3-3). What is true about elementary charges, such as electrons, protons and ions, also is true about charged bodies or metal plates. We remember that a metal plate may be charged positively by removing negative charges (electrons) from it, or it may be charged negatively by adding negative charges to it. One way of charging metal plates is by connecting them to the terminals of a battery. In a battery, chemical action is utilized to maintain a surplus of electrons on the negative terminal and a deficiency of electrons on the positive terminal. (The deficiency is numerically equal to the surplus.) Thus, if we connect a metal plate to each of the two battery terminals, surplus electrons from the negative battery terminal will flow *to* the metal plate connected to it, while at the same time electrons *from* the other metal plate will flow to the positive terminal connected to it, where a deficiency of electrons

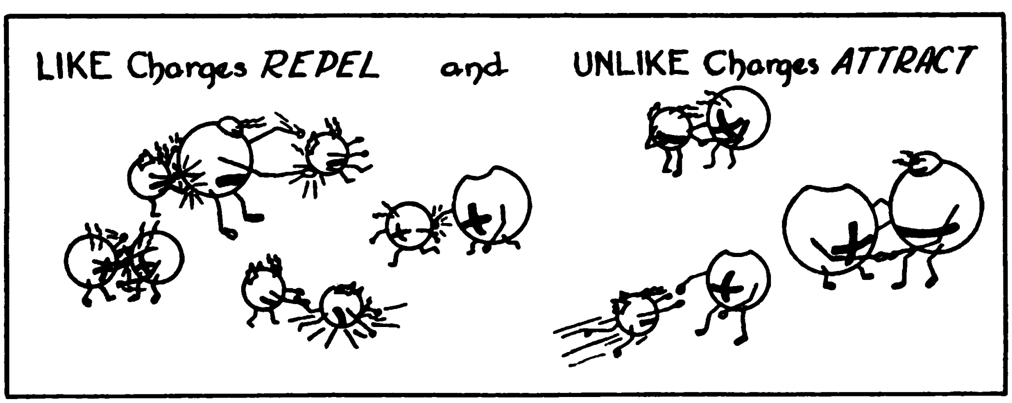



Fig. 3-3.

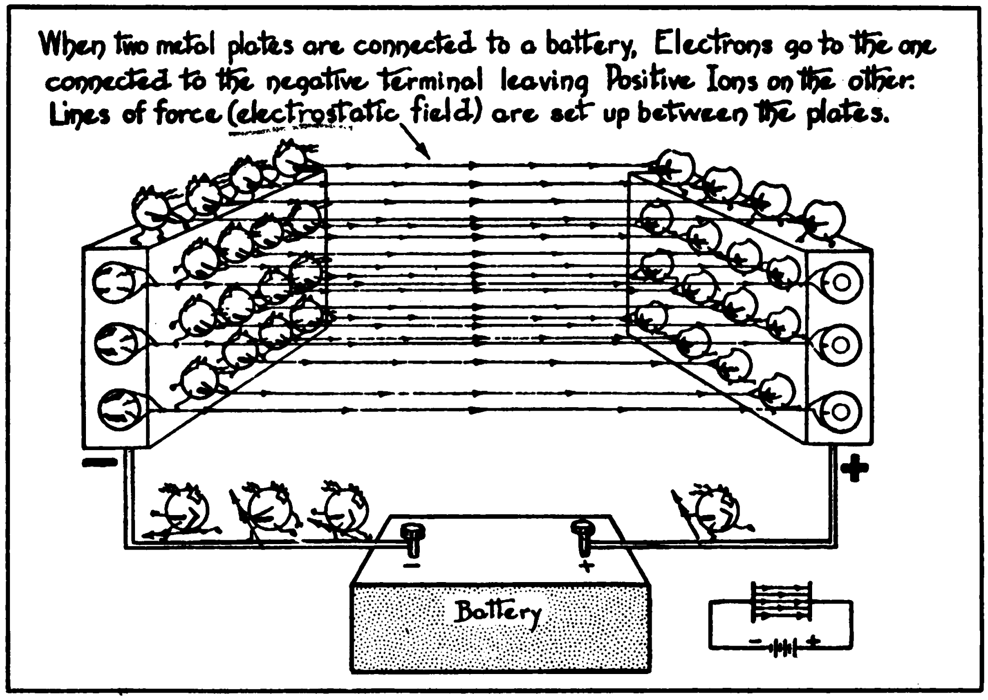



Fig. 3-4.

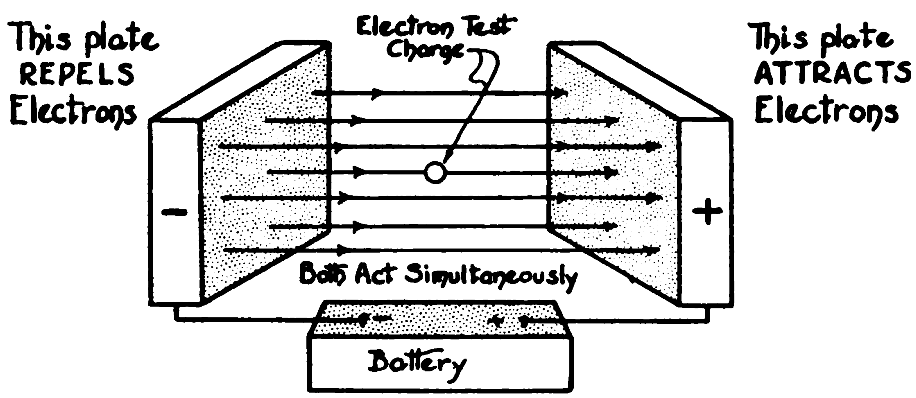
exists (Fig. 3-4). Hence, the metal plate connected to the negative battery terminal also will become negatively charged because of the excess of electrons flowing to it, while the metal plate connected to the positive terminal will become positively charged by the same amount because of its loss of electrons.

It is clear, then, that the charges on the two metal plates redistribute themselves in accordance with the charges on the two battery terminals, and the electrical relationship between the metal plates is the same as that between the terminals.

## Electrostatic Field

Figure 3-4 illustrates that as long as a *potential difference* (voltage) is maintained between the terminals of a battery, metal plates connected to the respective terminals will assume that same difference of potential between them and become equally positively and negatively charged. Being of unlike charge, the two metal plates in Fig. 3-4 tend to attract each other with a force which is directly proportional to the voltage between the plates (that is, the battery voltage). Although the plates may be unable to move, the force between their respective positive and negative charges nevertheless exists. This influence or force is called an *electrostatic field,* and it is indicated in the diagram by *lines of force* drawn between the two plates. We have drawn these lines of force between the excess electrons on the negative plate and the surplus positive ions on the positive plate to indicate that the force of the electrostatic field exists between the charges on the metal plates. Since the charges are uniformly distributed over each of the plates, this practice is not usually followed, but lines of force are arbitrarily drawn between the plates; their number per square inch indicating the strength of the electrostatic field between the plates.

*Electron Test Charge.* The lines of force are, of course, purely imaginary, and no actual lines exist between the two plates. However, it is easy to show that a force actually exists between the two plates, and that the lines of force do have real significance. Assume that a negative *test charge,* namely one electron, is inserted between the two charged plates, as shown in Fig. 3-5. This electron test charge will then be *repelled* by the *negative* plate and *attracted* to the *positive* plate, in accordance with the law of at-




The uniform field is due to the existence of two forces acting on the electron and the fact that the sum of these forces remains the same no matter where the electron may be located between the two fixed charged plates.

Fig. 3-5.

traction and repulsion. The electron test charge actually experiences two forces: one urging it toward the positive plate and one repelling if from the negative plate. The significance of the lines of force is that they are defined as the path and direction in which a negative test charge would move when placed in an electric field. (In some texts, a positive test charge is used, so that the direction of the lines of force are reversed. In this book, we will use a *negative* test charge however.)

In the illustrations of Figs. 3-4 and 3-5, we have drawn the lines of force as straight lines in the direction of the positive plate, as indicated by the arrows. This is the way a negative test charge would actually move, if placed anywhere in the space between the plates. This statement is completely true only if the two plates were of infinite size. In actual plates of limited size, the test charge would move in a straight line anywhere in the interior between the two plates, but would follow a slightly curved path near any of the edges of the two plates. This deviation from a straight path can be neglected for all practical purposes in vacuum tubes, and the lines can be assumed to be uniformly straight anywhere between the two plates.

*Force Between Plates.* Not only is the path an electron would follow anywhere between the two plates, a straight line perpendicular to the two plates, but the *force* acting on this electron is the same, no matter where it is inserted between the two plates. This may be hard to believe at first, but it is easy to explain. As we have said, there are actually two forces acting on the electrons: one repelling it from the negative plate, the other attracting it to the positive plate. The sum of these two forces is the total force acting on the electron, and it is the same throughout the space between the plates. If the electron is initially inserted near the negative plate, the force of repulsion from the plate will be very strong, while the force of attraction to the positive plate will be relatively weak. At the center between the two plates, both the force of repulsion and that of attraction will be exactly equal. As the electron moves near to the positive plate, the force of attraction of that plate becomes progressively stronger, while the force of repulsion from the negative plate becomes progressively weaker. It can be seen in a general way—and is easy to prove exactly—that the sum of these two forces acting on the electron remains always the same.

A field, such as we have described, where a test charge would move in straight lines under the influence of a constant force, is known as a *uniform field.* If we reverse the connections of the battery to the two plates in Figs. 3-4 and 3-5, the polarities will, of course, be reversed and the electron test charge would move in a direction between the two plates opposite to that shown. The direction of the lines of force would then have to be reversed also.

What does the magnitude of the force acting on a test charge between the plates depend on? One important factor is the potential difference, or voltage, established between the two plates. In a uniform field, the force acting on a test charge is *directly proportional to the magnitude of the applied voltage.* The other important factor that determines the intensity of the force acting on the unit test charge, is the distance between the two plates. The *smaller* the separation between the plates, the *greater* is the force exerted by the field for a given value of the voltage. The two factors affecting the *field strength* may be summarized by stating that the force acting on a unit test charge (an electron) anywhere between the two plates is *directly proportional* to the *voltage* between the plates and *inversely proportional* to the *distance* between the two plates. In effect then, the force on an electron between the plates may be doubled by either doubling the voltage or by cutting the distance between the plates in half. If both of these things are done, the force will be quadrupled.

*Velocity.* Another point of interest is the velocity with which an electron will hit the positive plate, when it gets there. If an electron is assumed to start off at rest (with zero velocity) near the negative metal plate, it will increase its velocity under the influence of the elecrostatic field at a constant rate, until it strikes the positive metal plate at a certain final velocity. Since the velocity is constantly increasing at the same rate, the electron in its flight is said to undergo *constant acceleration.*

The final velocity with which an electron strikes the positive plate depends *solely* on the difference of potential between the two plates, that is, the battery voltage to which the plates are connected. This is true regardless of the number of electrons introduced into the field which are moving toward the positive plate at the same time. The higher the voltage between the plates, the greater is the final velocity with which any number of electrons will hit the positive plate. The magnitude of the final velocity is *proportional* *to the square root* of the voltage applied between the plates. This means that whenever the voltage difference between the plates is *quadrupled,* for example, the final velocity of all electrons hitting the positive plate will be *doubled.* If the applied voltage is increased *nine times,* the final velocity of electrons will be increased three times. If all the electrons start off at the negative plate with the same velocity (zero velocity if they start from rest), they will all reach the positive plate with the same final velocity. Another way of saying this, is that the distance covered per unit time (which is the definition of *velocity*) is the same for all the electrons at any particular point between the plates, and depends entirely on the applied voltage.

*Electron Transit Time.* The example of the two metal plates (Fig. 3-5) is illustrative of the conditions existing between cathode and plate in a diode. Since electrons traveling between charged plates have a certain finite velocity, as we have just seen, it follows that they will require time to complete the journey from the negative to the positive electrode. In a vacuum tube, the time taken by an electron to travel from the cathode to the plate of the tube is known as the *electron transit time.* Since the distance between cathode and plate is very small, and the velocity of the electrons is quite high, the electron transit time is generally extremely short. Although this time can usually be neglected for practical purposes, it does become of importance when tubes are operated at very high alternating-current frequencies.

The ordinary a-c power line has a frequency of 60 cycles per second. This means that the current completes 60 positive and 60 negative alternations each second. Or we can say that it takes 1/60th of a second for the ordinary house current to go through one complete cycle, consisting of a positive and a negative half-cycle. The time taken by electrons to travel from cathode to plate in a tube is millions of times less than this. Hence, if ordinary power line a-c is applied to a vacuum tube, the electrons within the tube will be able to follow almost instantaneously the 60 cycle per second alternations, and the electron transit time can be neglected. However, vacuum tubes are often operated at radio frequencies as high as a hundred million cycles per second (100 megacycles) or higher. At a radio frequency of 100 megacycles, the time taken for each complete a-c cycle is only one hundred-millionths of a second. The electron transit time within a tube is comparable to this figure. Hence, if a 100-megacycle radio-frequency voltage is applied to the electrodes of a vacuum tube, the time taken by the electrons to travel from cathode to plate may consume an appreciable part of a cycle of the radio frequency. The electrons may then not be able to follow instantaneously the rapid alternations of the applied voltage.

This delay caused by the finite electron transit time becomes a very important factor when vacuum tubes are operated at very high frequencies. In certain instances, the transit time can be reduced substantially by either increasing the voltage on the plate of the tube, thereby speeding up the electrons, or by decreasing the spacing between the cathode and the plate, that is, decreasing the size of the tube.

## Simplified Operation of the Diode

Let us now apply the knowledge gained from our discussion of the electrostatic field between two charged plates to set up a simplified model of diode operation (Fig. 3-6). We shall learn later what has to be added to refine this elementary picture.

The emitter (cathode) of our elementary diode in Fig. 3-6 is indirectly heated, and a supply of heater voltage (*A*-battery or a-c voltage) must be furnished to drive current through the heater. When the *A*-battery is connected to the heater, the cathode of the diode will heat up and emit a copious supply of electrons into the space between cathode and plate. Apart from the heater circuit and cathode, our simplified systems consists of a *plate-voltage*

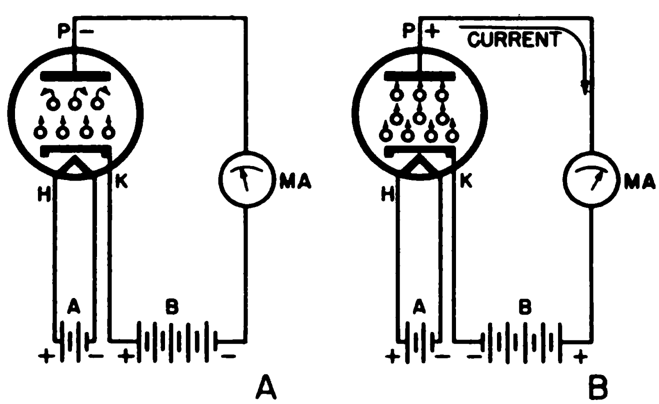



**Fig. 3-6 (A) When the plate is negative, no current flows; (B) When plate is positive, an electron current flows through tube and external circuit.**

*supply,* shown here as a $B$-battery (but it can be any d-c voltage source) and a milliampere meter to indicate the behavior of the current through the tube. The plate-voltage supply battery is connected between the plate and the cathode of the tube.

In part (A) of Fig. 3-6 we have connected the negative terminal of the $B$-battery to the plate and the positive terminal of the battery to the cathode of the tube. The plate is then made *negative* with respect to the cathode. What happens under these conditions to the electrons emitted into the space between cathode and plate? Based on our discussion of charged plates, the answer is very simple. Since like charges repel and unlike charges attract, the electrons will be strongly repelled from the negative plate and tend to fall back to the positive cathode from which they have been emitted. (However, since electrons continue to be emitted from the hot cathode, there will always be a supply of electrons in the space between cathode and plate.) With no electrons flowing from cathode to plate, the tube is the equivalent of an open circuit, and the milliampere meter shows no current flowing through it.

Now let us reverse the polarity of the $B$-battery, so that the positive terminal is connected to the plate and the negative terminal is connected to the cathode of the tube, as illustrated in part (B) of Fig. 3-6. Under these conditions, the plate is *positive* with respect to the cathode of the tube. What happens to the emitted electrons under such polarity conditions? Again, based on the laws of attraction and repulsion, the answer is very simple. The positively charged plate (having a deficiency of electrons) now exerts an attracting force on the electrons emitted by the cathode. Consequently, they advance across the space between cathode and plate and eventually hit the plate at a high velocity. Since moving charges comprise an electric current the stream of electrons through the tube *is* an electric current, occuring in this case without a wire conductor.

Upon reaching the plate the electron current continues to move through the conducting circuit between plate and cathode, made up of the connecting wire, the current meter, and the $B$-battery. After passing through the battery, the electrons return to the cathode of the tube, thus completing the circuit. The current flowing to the plate and through the circuit connected to the plate registers on the milliampere meter, and is identified as *plate current*. As long as the cathode is maintained at emitting temperature and the plate remains positive, plate current will continue to flow through the circuit. As shown in (B) of Fig. 3-6, under these conditions electrons continually flow from cathode to plate, filling the space within the tube. Outside the tube, the electrons return from plate to cathode through the external circuit, thus maintaining the current.

A number of important conclusions can be drawn from the simplified model we have just discussed:

(1) Current can flow in a diode only when the plate is positive with respect to the cathode, and no current can flow when the plate is negative with respect to the cathode.

(2) Current flow *within* a diode can take place only from cathode to plate, and never from plate to cathode. Because current can flow in one direction only, the action is called *unidirectional* or *unilateral* conduction.

(3) A diode can be made to act like a *valve*, automatically starting or stopping current, depending on whether the plate is positive or negative with respect to the cathode.

The conclusions stated above apply to other vacuum tubes also, as we shall see in later chapters.

## Space Charge

The simplified model of diode operation has been very useful in clarifying some basic characteristics of vacuum tube operation. However, in giving this rather crude explanation we have left out some important matters to which we must now turn. One of these is the behavior of the electrons in the space between cathode and plate. Regardless of the plate voltage and all other circumstances, once the cathode of a tube has been heated to its normal operating temperature, it will emit electrons at a constant rate. Even when the plate is positive, not all of these electrons immediately reach the plate; some actually return to the cathode, while others form an *electron cloud* in the space between cathode and plate. This electron cloud constitutes a negative *space charge* in the interelectrode region between cathode and plate. The negative space charge has a repelling effect on other electrons being emitted from the cathode which tends to force these electrons back into the cathode and generally impedes their movements to the plate. Whether or not the electrons emitted from the cathode actually reach the plate depends both on the applied plate-to-cathode voltage (that is, the electric field) and on the space charge between cathode and plate. We have described in detail the effect of the electric field set up by the plate-to-cathode voltage. We must now discuss the behavior of the negative space charge and its efect on the electric field between cathode and plate.

*Formation of Space Charge.* It would seem that even a very low value of positive plate voltage would immediately attract all the electrons emitted from the cathode. We have stated that this is not a fact, but we have not explained why. The reason actually is the repelling effect on newly emitted electrons of the electron cloud or *space charge* between cathode and plate. The space charge, in fact, limits or controls the amount of plate current. This still does not explain, however, why all the electrons emitted from the cathode are not immediately drawn off to the positive plate, instead of forming a negative space charge and repelling other electrons. It might appear confusing to say that the space charge is responsible for limiting electron flow, when we haven't explained what permitted the formation of this space charge in the first place.

To simplify our discussion initially, imagine for a moment, that we have heated the cathode of a diode to an electron-emitting temperature, but instead of applying a positive voltage to the plate we have connected the plate directly to the cathode by means of a wire. Since no voltage is applied to the plate, it exerts no attracting force on the emitted electrons, and hence its presence can be entirely ignored. Let us make some further simplifying assumptions. We know that if electrons are actually being emitted they must have had sufficient energy to overcome the work function of the cathode material. In breaking through the potential barrier, however, the electrons give up most of their initial energy and have very little left after leaving the emitter. Most of the electrons, therefore, leave the cathode with a relatively low velocity. Their speed is further reduced by two additional factors: One is the attraction of the positive ions the electrons leave behind in the cathode, which tends to pull them back. We have discussed this effect in the previous chapter. The other factor is the repelling effect of the electrons in the space charge, which appears after

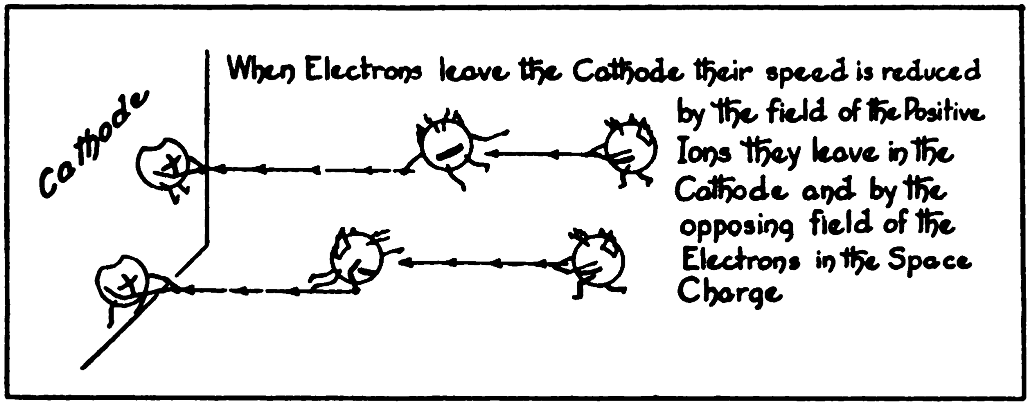



Fig. 3-7.

the tube has been placed into operation. The combined effect of these two factors is illustrated in Fig. 3-7. The result of all this is the fact that most electrons leave the cathode at a relatively low speed, although there may be some with sufficient initial energy and speed to complete the journey to the plate without any attracting pull from it. Let us ignore these high-speed electrons, and assume for convenience that all electrons are emitted from the cathode with a uniform, low velocity.

Another assumption we shall make is that the cathode is a straight plate or plane surface. Although the emitter is, in fact, a cylindrical surface the assumption does no harm, since it would be true for any particular plane or cross section of the cathode. Whatever we find out about the electrons leaving from this particular cross section of the cathode will then be true also for the whole surface of the cathode and area around it. Later we shall make the same assumption about the plate and treat it as a straight plane surface.

The final assumption is that the electrons leave the cathode in an orderly manner in single layers, something like the movement of troops in columns. This is not really true since electrons are emitted at different speeds and in all different directions, in a haphazard manner. However, for the purpose of illustrating the action, the assumption of uniformity of motion does no harm, and the end results are the same.

Let us start with the emission of the first row of electrons—a layer one electron thick—as illustrated in Fig. 3-8. This first layer of electrons traveling away from the cathode have nothing in front

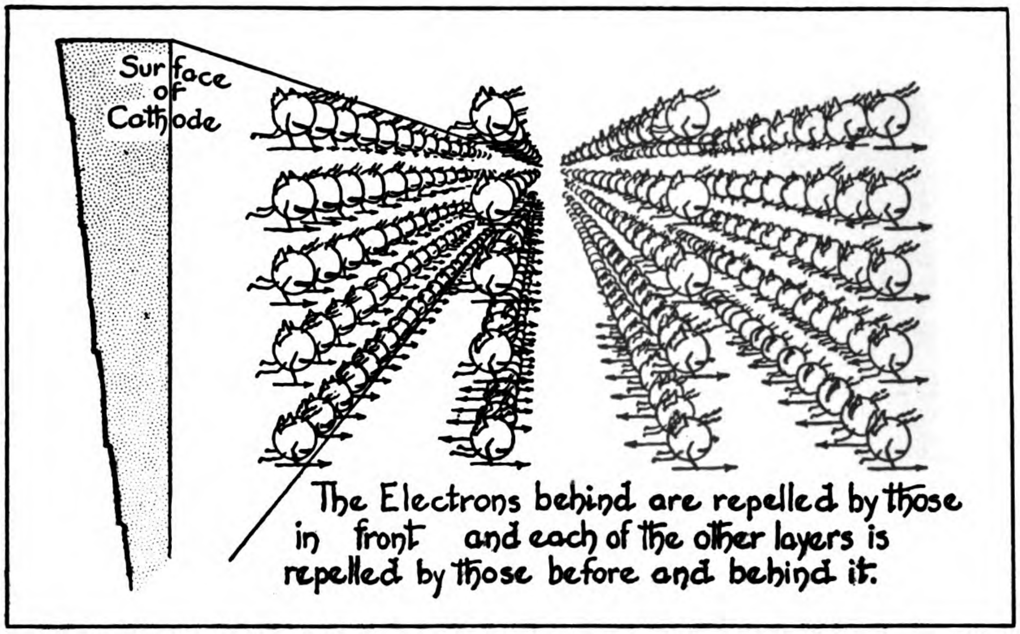



Fig. 3-8.

of them to retard them, except that they are limited by the low velocity of emission. The first layer of electrons is followed by a second layer in back of it, then a third layer in back of the second, a fourth layer in back of the third, and so on. Since like charges repel each other, the electrons in back of the first row are experiencing a repelling force due to the electrons in front of them, and the direction of this force is such as to retard the motion of the electrons away from the cathode. The third layer feels the repelling force of the two rows of electrons in front of it, as well as the repulsion of the electrons behind it. Successive layers of electrons feel these forces acting on both sides of them, with the repelling force of all the electrons in front of the layer steadily increasing.

The net result is that the electrons bunch together near the cathode in a cloud which constitutes the space charge. The layers of electrons leaving in the beginning have fewer repelling layers in front of them, and hence are distributed fairly loosely, while the electrons emitted at a later time experience the full repelling force of all the electrons in front of them, and consequently are crowded closely together near the cathode. We see, therefore, that the electrons occupying the space within the tube are not uniformly distributed, but are *relatively dense in the vicinity of the cathode and are less and less crowded as the distance from the emitter is increased.* (Fig. 3-9). An additional factor contributing to the crowding of electrons near the cathode is the attraction of the positive ions left behind in the cathode, illustrated in Fig. 3-7.

*Electrostatic Field Due to Space Charge.* The accumulation of negative charges in the vicinity of the cathode—called space charge—produces in effect an electrostatic field. This field has a direction so that it would tend to repel a negative test charge in the vicinity of the field (Fig. 3-10). The nature of this field is the same as that of the electrostatic fields previously discussed in connection with the two charged plates (Fig. 3-4). It may be difficult for you to visualize an electrostatic field associated with an accumulation of charges which is nonuniformly distributed from cathode to plate. No doubt you would be able to visualize this field better, if you imagined the space charge to be concentrated in a small area near the cathode, and then disregard the widely distributed electrons at a greater distance away. Since the actual density of electrons is very low near the plate and extremely high near the cathode, it is not a great departure from the truth to visualize the space charge as a concentrated layer or surface of electrons, located near the cathode of the tube. The lines of force emanating from the concentrated space charge would then be

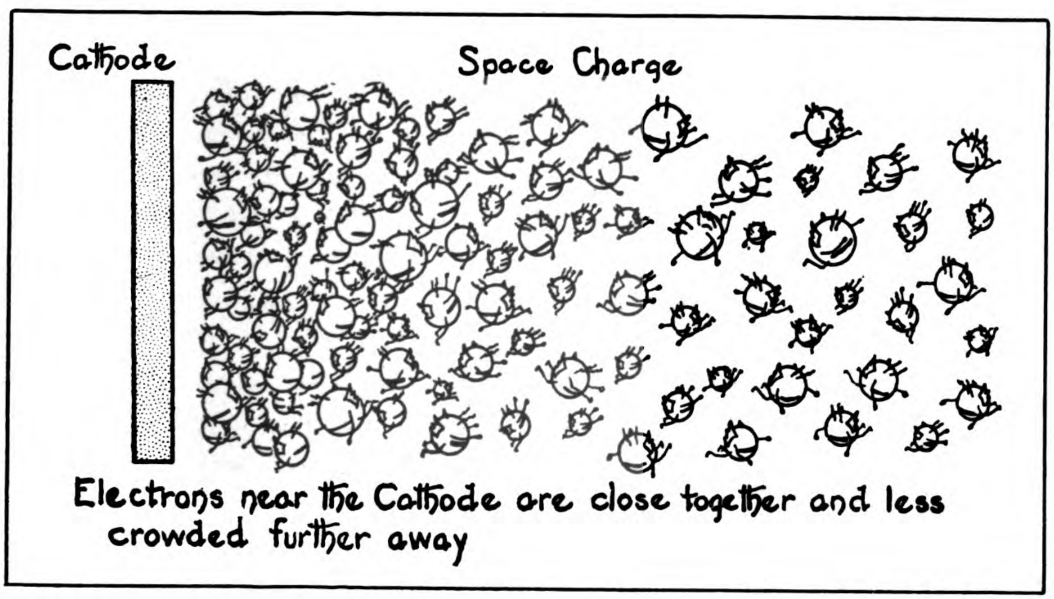



Fig. 3-9.

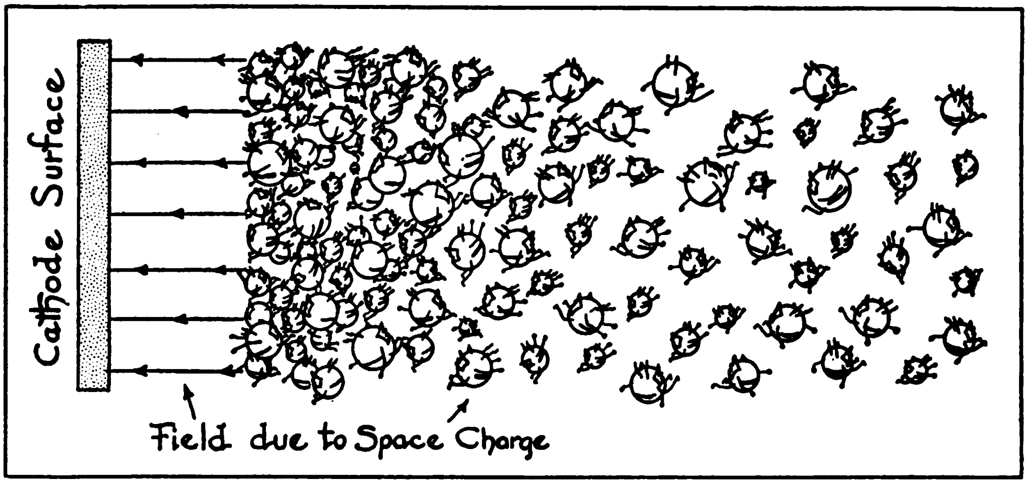



Fig. 3-10..

parallel straight lines between the space charge surface and the emitting surface, as shown in Fig. 3-10. The direction of the lines of force is away from the space charge.

*Emission Saturation.* It might appear at first glance that the amount and density of the space charge would increase as long as the cathode continued to emit electrons. Such is not the case, however. For any given cathode temperature—and hence possible emission—the amount of *actual emission of electrons and the density of the space charge is definitely limited.* The reason for this is the repelling action of the space charge. Having acquired a critical density for a particular cathode temperature and rate of electron emission, the space charge develops a field of such intensity as to *repel back into the cathode one electron for every electron which enters the space charge* (Fig. 3-11). This condition of equilibrium in the space charge is called *emission saturation.* That such an equilibrium between the rate of electron emission and the density of the space charge must exist, is easy to see.

Assume for a moment that more and more electrons would be emitted and attempt to join the already existing space charge. The result would be that the space charge would become increasingly negative and eventually would have such a repelling effect, as to shut off the flow of electrons entirely. If, on the other hand, the rate of electron emission would decrease for some reason, fewer electrons would join the space charge, and its density and negative charge would begin to decrease. As a result, the repelling effect of the space charge on newly emitted electrons would lessen, and more electrons would be encouraged to travel to the space charge. It is clear then, that there must be some condition of equilibrium between the rate of electron emission from the cathode and the density of the space charge, where the repelling effect of the space charge is just sufficient to offset further increases in electron emission. This does not conflict with the laws of electron emission discovered by Richardson. All the electrons predicted by Richardson's equation are actually emitted by the cathode, but at emission saturation, a certain percentage is returned to the cathode to maintain equilibrium.

There is a condition of emission saturation for every value of cathode temperature. If the temperature of the cathode is increased, the thermal agitation of the emitter material is increased, and more electrons with a *higher average speed* are emitted. This speed is sufficient to overcome the repelling force of the electrostatic field of the space charge, previously existent. Consequently, additional electrons will join the space charge and make it more dense. When this increase in density has again reached the point where the repelling force of the space charge can offset the higher average velocity of the electrons emitted at the increased cathode temperature, a new level of equilibrium is again established, and emission saturation exists at the increased cathode temperature.

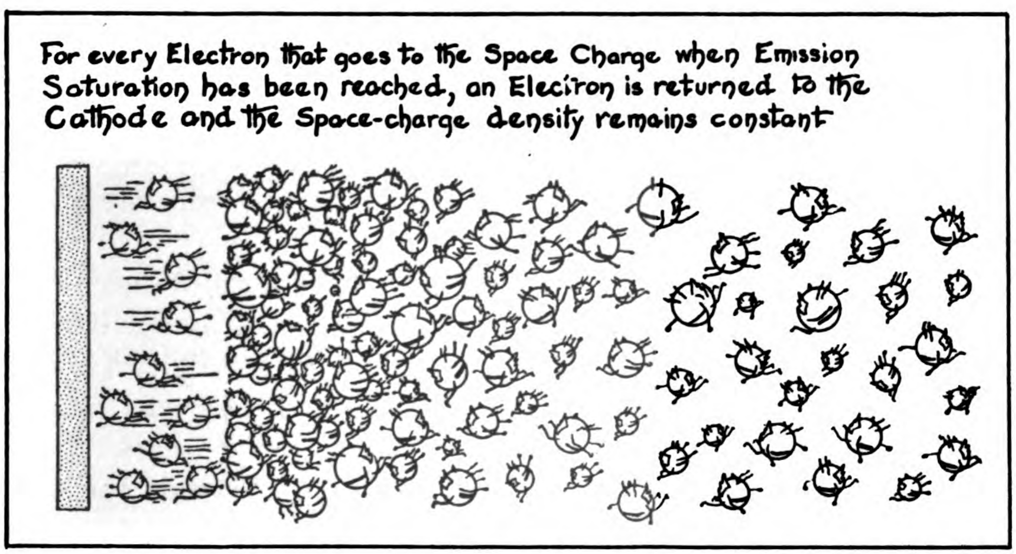



Fig. 3-11.

Summarizing we can say that the *space charge density increases with increased cathode temperature. For every fixed cathode temperature, a state of equilibrium—known as emission saturation—develops between the rate of emission and the space charge, so that the space charge density increases no further.* Similarly, a reduction in emitter temperature causes a reduction in the density of the space charge.

It is evident through this discussion that the space charge has a *controlling influence upon the emission of electrons from the cathode.* Although the average cathode emitter is capable of emitting many more electrons per unit time than are actually utilized in a vacuum tube, the space charge actually limits and maintains control over the amount of emitted electrons flowing to the plate. It thus exerts control over the plate current in a tube. For this reason, the plate current in diodes is described as being *space-charge limited* under certain conditions of operation.

*Plate Current.* Let us now put the emitted electrons to work by connecting a positive voltage to the plate of the diode. We have previously discussed the flow of plate current when the cathode is emitting and the plate is positive, but we have not yet described the effect of the space charge on the plate current flow. Since the plate is positive with respect to the cathode, it sets up an electrostatic field between plate and cathode. The strength of this field depends on the plate voltage. In addition, we have seen that the space charge in the interelectrode region sets up its own electrostatic field, as illustrated in Fig. 3-10. The strength of the latter field depends on the density of the space charge, and hence also on the cathode temperature. Two electrostatic fields, therefore, are present between cathode and plate of the tube: one between the cathode and the space charge, and the other between the space charge and the plate. (Fig. 3-12).

*Effects of Fields.* What are the practical effects of two fields between cathode and plate? This is made clear by an analysis of the lines of force emanate from the space charge in two direc-is negative with respect to both the cathode and the plate. Hence, the lines of force emanating from the space charge in two directions: one towards the cathode, and the other towards the positive plate (Fig. 3-12). The lines of force pointing in the direction of the cathode have a repelling effect on all electrons in the region between the cathode and the space charge. The lines of force di-

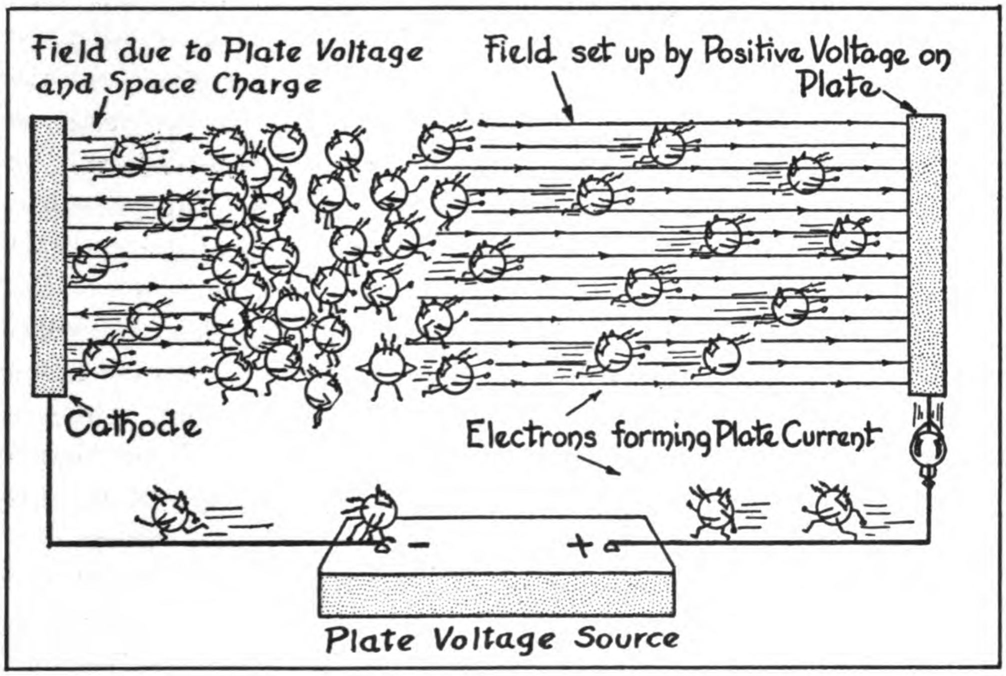



Fig. 3-12.

rected from the space charge to the plate, on the other hand, would tend to speed the electrons on their way to the plate.

Now let us turn to the field established by the plate voltage. Since the plate is positive with respect to the cathode, the lines of force of this field are directed from the cathode to the plate, tending to move the electrons uniformly from the cathode to the plate. It is clear, that in the region between the cathode and the space charge, the lines of force of the two fields oppose each other. In effect, the lines of force due to the positive plate voltage cancel those due to the space charge in the region between cathode and space charge. One effect of the space charge *is to neutralize the attraction of the positive plate upon the electrons leaving the cathode.* It may be thought at first glance, that the field due to the high positive plate voltage would outweigh the effect of the field due to the negative space charge. This is not so, provided a full space charge is present. As we shall see presently, *the density of the space charge regulates itself automatically to such a value as to offset completely the effect of the field of the positive plate voltage on the electrons emitted from the cathode.* Under these conditions, it is entirely correct to view the attracting force of the positively charged plate as acting on the electrons in the space charge, rather than directly on the electrons emitted from the cathode.

Summarizing what we have said, we find that there are two electrostatic fields set up in a diode, one due to the positively charged plate, the other due to the negative space charge. Furthermore, the field established by the positively charged plate acts upon the space charge, rather than directly upon the electrons emitted from the cathode.

*Electrons To and From the Space Charge.* We have previously said that for any given emitter temperature the density of the space charge is constant and in a state of equilibrium with the rate of emission from the cathode. What happens if we disturb this equilibrium by applying a positive voltage to the plate, thus drawing off electrons from the space charge in the region near the plate? Since the attraction of the positive plate removes electrons from the space charge, its density and hence the strength of its field will be reduced. The ability of the space charge to repel the electrons emitted from the cathode is, therefore, likewise reduced. Consequently, a number of electrons sufficient to restore the equilibrium will be added to the space charge in the region near the cathode (Fig. 3-13). Equilibrium will be reestablished when the space charge has again reached its previous density by

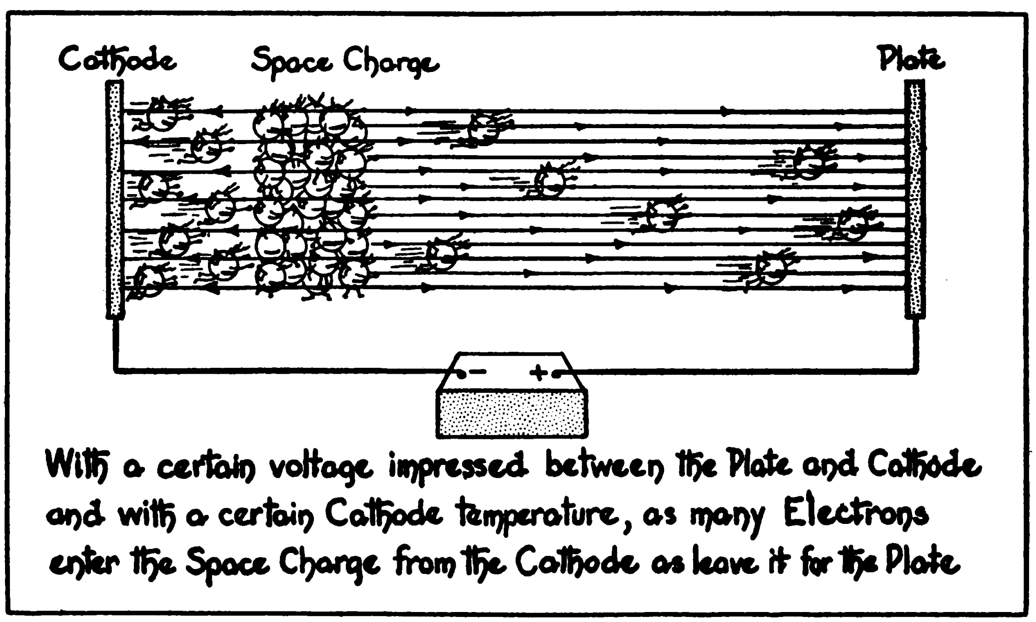



Fig. 3-13.

*adding exactly the same number of electrons emitted from the cathode as were removed by the positive plate voltage.* If more than this number were added, the increased space charge density would just repel a sufficient number of these additional electrons to reestablish the equilibrium; if less than this number of electrons were added, the space charge density would decrease and a sufficient number of additional electrons would be attracted to reestablish equilibrium.

Under the influence of a positive plate voltage, we may visualize the action of the plate as removing electrons from the space charge at a definite rate, while at the same time electrons emitted from the cathode are admitted into the space charge at the same rate. If one billion electrons move from the space charge to the plate each second (equivalent to a certain plate current), another billion electrons enter the space charge from the cathode each second. Thus, there is a progressive movement of electrons from the cathode into the space charge, through the space charge, and out of the space charge to the plate *without altering the density of the space charge.*

Such a directed movement of electrons may be described as being the flow of plate current between the cathode and the plate. The function of the space charge may be visualized as a *reservoir of electrons* from which are drawn the negative charges required to equal the instantaneous plate current. The cathode is the supply which replenishes the space charge. This is similar to a water-supply system in which the consumers draw water from a local reservoir, and a stream or lake automatically supplies the equivalent amount of water needed to maintain the predetermined level.

*Saturation.* For a given value of plate voltage and a constant cathode temperature, a fixed number of electrons per unit time are drawn from the space charge. This results in a plate current of a certain value, which is measured in amperes or milliamperes. A change in plate voltage changes the rate of electron flow, and hence the plate current. Specifically, an increase in plate voltage increases the rate at which electrons are drawn off from the space charge, and consequently increases the plate current. As we have explained, the electrons drawn off from the space charge are replenished by the emission of the cathode. As long as the cathode emits a surplus of electrons capable of maintaining a full space charge, any increases in plate voltage are accompanied by corresponding increases in the rate of electron flow and hence in the resulting plate current. Under these conditions, the plate current is said to be *space-charge limited.*

What happens, however, when the plate voltage is made so high that it draws off all the electrons from the space charge which the cathode is capable of emitting at a certain temperature. Under these conditions, the total plate current is equal to the *emission current* of the cathode, by which is meant the total number of electrons emitted by the cathode per unit time and at a definite temperature. In effect, all the electrons emitted by the cathode are attracted to the plate. If the plate voltage is further increased beyond this point, the space charge no longer receives and hence is no longer capable of supplying the additional electrons needed, and no further increase in plate current results. Under these conditions, *voltage saturation* is said to occur and the maximum plate current (emission current) is also known as *saturation current.* A tube operated at saturation is said to be *emission-limited.* The plate voltage at which saturation sets in depends, of course, on the emission of the cathode, which in turn depends on the emitter material and the cathode temperature. If the cathode temperature is increased, more electrons are liberated, and voltage saturation occurs at a higher plate voltage.

## DIODE CHARACTERISTICS

We have discussed in considerable detail the behavior of the diode electron flow under the influence of the electrostatic fields of the positive plate voltage and the negative space charge. Although we have learned what actually happens when the plate voltage and the cathode temperature are varied, we do not as yet have a quantitative idea of the magnitude of the *changes in plate current* as a result of the variation in *operating voltages* of the tube. By operating voltages we mean the filament or heater voltage, which determines the cathode temperature and emission, and the positive plate voltage, which determines the strength of the electrostatic field between cathode and plate. As we have seen, a definite relationship exists between plate voltage and plate current, that is between the magnitude of the attracting force exerted by the positively charged plate and the number of electrons actually attracted to the plate. Furthermore, there is a definite relationship between the heater or filament voltage and the plate current for a fixed plate voltage. The manner in which these variable factors influence the operation of a tube characterize the particular type of tube and are therefore known as the *characteristics* of the tube. The various characteristic relationships are most easily illustrated by a series of graphical representations, known as *characteristic curves*. A characteristic curve, then, shows the relationship between two quantities, such as between plate voltage and plate current, filament voltage and plate current, filament voltage and electron emission, etc.

### Characteristic Curve

In what manner do we obtain such a characteristic curve and how do we read and interpret it? Figure 3-14 shows an imaginary characteristic curve which we use for the purpose of illustration. This does not represent the behavior of any particular vacuum tube. Clearly, the curve portrays the relation between applied

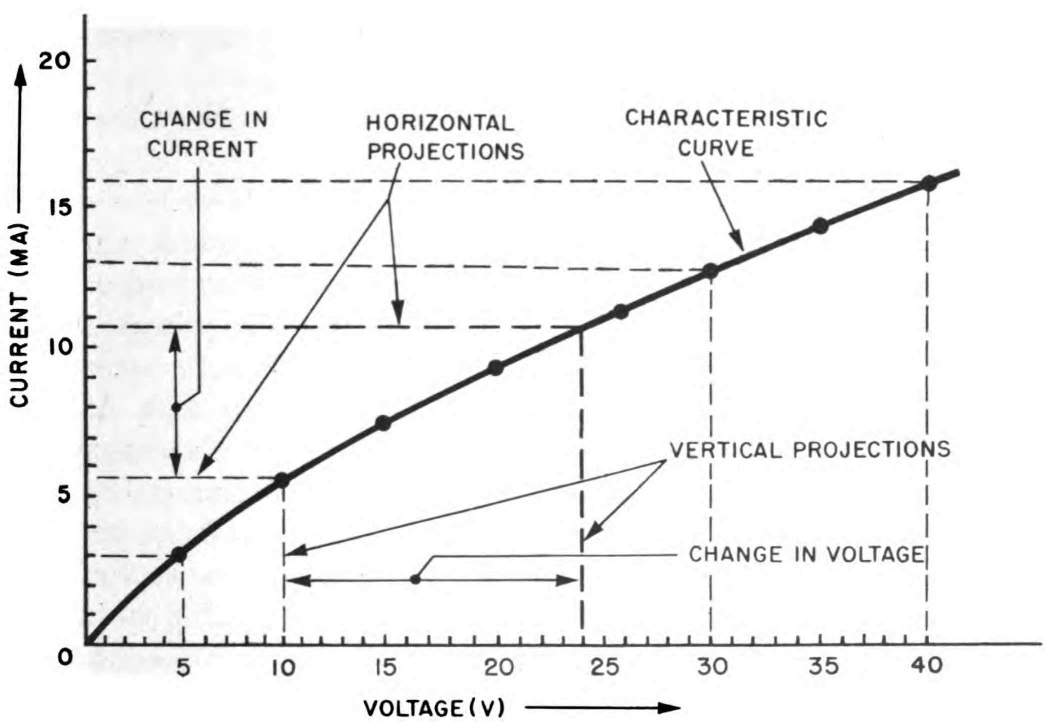



Fig. 3-14. Plot of a simple characteristic curve.

*voltage* (V) and *current* in milliamperes (MA) in some device or circuit. We shall see later in greater detail, how such a curve is obtained, but for now let us show in the simplest terms how it could be done. Let us assume that the voltage applied to the device was increased in 5-volt steps, and the current (in ma) through the device was measured for each value of the voltage. We thus have obtained a series or table of values which shows the resultant current for a variation in the voltage at fixed intervals, and we now know the effect on the current caused by a change in voltage. Since we varied the voltage (or *cause*) at will, it is also known as the *independent variable,* while the current (or *effect*)—which depends on the voltage—is also referred to as the *dependent variable.*

*Plotting The Curve.* By plotting this cause-effect relationship on paper, we can show it graphically. To do this we draw a scale on paper along a horizontal axis, which represents the independent variable or cause (that is, voltage in this case) and another scale along a vertical axis to represent the dependent variable or effect (current, in this case). We are now ready to plot the series of values we have previously obtained by measurement. Imagine our table of values looks like this:

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Voltage (V): (independent variable) | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | volts |
| Current (MA): (dependent variable) | 0 | 3 | 5.6 | 7.5 | 9.3 | 11.1 | 13 | 14.2 | 16 | milliamps. |

Since the current was zero for zero voltage, we mark a point at the common zero of both scales, which is the intersection of the two axes. At 5 volts we draw a vertical line from the voltage (horizontal) axis, and since the current was 3 ma at 5 volts, we draw a horizontal line at 3 ma from the current (vertical) axis. At the intersection of the two lines we mark a point, which represents the values 3 ma at 5 volts. Next we draw a vertical line at 10 volts from the voltage axis and a horizontal line at 5.6 ma from the current axis. Again we mark a point at the intersection of the two lines to represent 5.6-ma current at 10 volts. Proceeding with the graph, we draw a vertical line from the voltage axis at every 5-volt interval to intersect horizontal lines drawn from the current axis at the values determined from our table. At each intersection we mark a point to represent the two corresponding values. In this way, we obtain a series of points on paper which graphically represent our table of values. For simplicity, we have only drawn vertical and horizontal lines (in Fig. 3-14) at 5, 10, 30 and 40 volts, but the procedure is evident. If you use ruled or square paper, you will be able to see the intersections of corresponding values at a glance and can mark the points without having to draw vertical and horizontal lines.

Having plotted the points of our table, we now draw a smooth curve connecting all the points and passing through them. This curve is the desired characteristic curve, showing the relation between voltage and current. The interesting thing about this characteristic curve is the fact that it represents not only our table of measured values, but *all* values of voltage and the corresponding current between the limits of measurement; that is, between 0 and 40 volts. Barring any erratic, unpredictable behavior by the device, it is reasonable to assume that even if we had taken many more measurements between 0 and 40 volts, the resulting points would have fallen somewhere on the curve, or a least very close to it. Of course, the more measurements we take the more accurate becomes the characteristic current-voltage curve.

*Reading The Curve.* Having obtained a characteristic curve, how do we interpret it, and of what use is it? For one thing, as we have pointed out, we can now find the current for intermediate values of voltage, between the 5-volt steps. What is the current corresponding to a voltage of 24 volts, for example? To find this current, we first draw a vertical line from the 24-volt point on the voltage scale to the curve. Such a vertical line is known as a *vertical projection* of the curve. At the point where this vertical projection meets the curve, we draw a horizontal line (called *horizontal projection*) to the current scale, and read off 10.6 ma. Hence, at 24 volts applied voltage, the resultant current is 10.6 milliamps. If the curve were shown on ruled graph paper we would be able to estimate the vertical and horizontal projections without actually having to draw the lines.

A second and more important use of the curve is that it tells us what *changes in* current correspond to a given *change* in voltage between two definite values. For example, what is the *change* in current, when the voltage is changed from 10 to 24 volts. Having previously drawn the vertical and horizontal projections, we remember that the current at 10 volts is 5.6 ma, while at 24 volts it is 10.6 ma. Thus a change of 14 volts results in a change in current of 5 ma. If we had picked a 14-volt change between two different voltage points on the voltage scale, the current change would *not* have been 5 ma, but some other value. (Try it between two other values!) The reason for this is that the characteristic is a curve and not a straight line. A relationship where the same changes in the cause (voltage) do not result in the corresponding proportional changes in the effect (current) is known as *non linear.* Vacuum-tube characteristics are generally *nonlinear,* but we shall have a lot more to say about this later on.

A third important use of a characteristic curve is that *it permits us to determine what change must be made in the independent variable* (*or cause*) *to bring about a certain required change in the dependent variable* (*or effect*). In our present example, the curve can tell us what change in applied voltage has to be made to obtain a required change in the resulting current from a certain reference point. To use our previous illustration (Fig. 3-14), let us say that the device is operated at 10 volts and draws a current of 5.6 ma, as we have determined before. To what value does the voltage have to be increased to obtain a 5-ma increase in current? From the previous example it is clear that the voltage has to be increased by 14 volts to 24 volts to obtain the 5-ma increase. Evidently characteristic curves work in both directions, telling us either what happens to the current when the voltage is changed, or what has to be done to the voltage to obtain a required change in current. As we shall see later on, the versatility of characteristic curves is not limited to these examples.

### Plate-Current Emitter-Temperature Characteristic

*Circuits.* To establish the manner in which the plate current of a diode varies with emitter temperature, a circuit is set up which permits operating the emitter at various temperatures, while holding the plate voltage constant. Such a circuit is shown in part (A) of Fig. 3-15. An indirectly heated tube is shown, although a filament-type could be used equally well. The heater current through the tube is adjusted by means of a variable resistor, *R,* connected in series with a constant voltage *A*-battery and a milliampere meter (MA). The filament meter indicates the

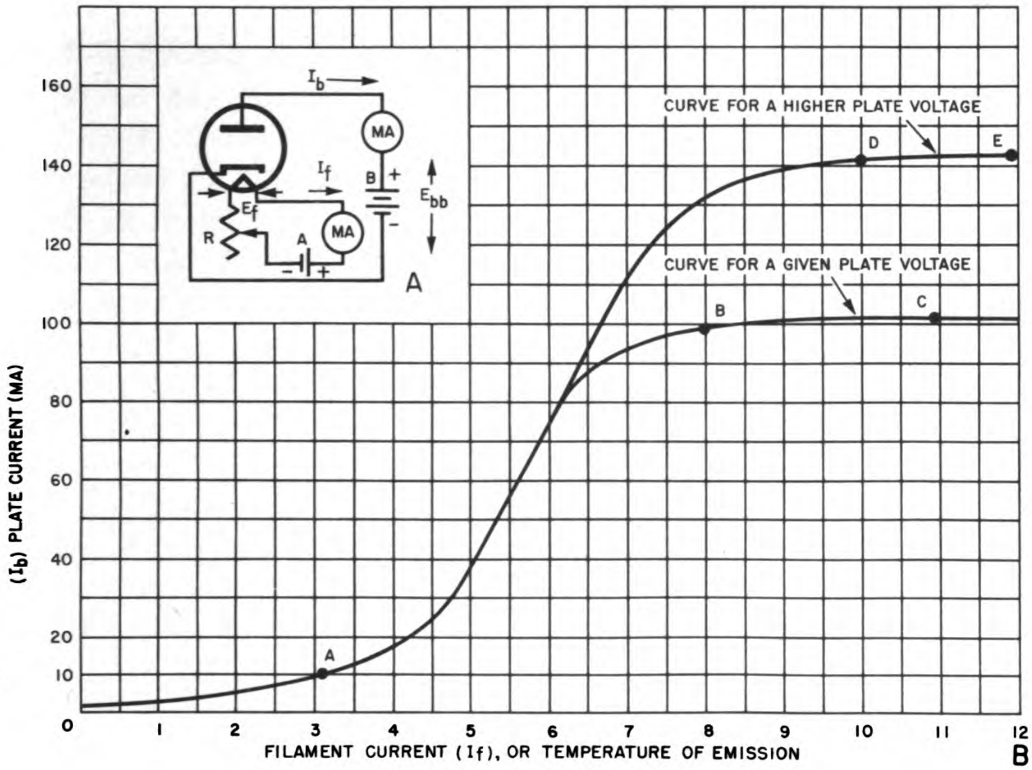



**Fig. 3-15. Plate-current emitter-temperature characteristic.**

flow of current, $I_f$, through the heater circuit; the value of this current can be used as indication of the emitter temperature. The plate of the tube is supplied from a *B*-battery, its voltage usually being labeled by the symbol $E_{bb}$. The plate current, resulting from the application of these voltages, is labeled $I_b$ and is measured by another milliampere meter (MA).

*Shape of Curve.* The curves shown in Fig. 3-15 are obtained by increasing the filament current $I_f$ through the tube heater in fixed steps and measuring the plate current $I_b$ for each of these steps. It does not matter whether the filament current $I_f$ or the filament voltage $E_f$ is used as an independent variable, since the temperature of the emitter is proportional to both of these quantities. For this reason, we have arbitrarily numbered the horizontal scale from 0 to 12 (rather than indicating actual current values) and labeled it "Filament Current or Temperature of Emission." The curve would have been the same, if we would have used "Filament Voltage" for the horizontal scale. The plate-current values

($I_b$) are laid off on the vertical scale of the figure; the values are also arbitrary and do not refer to any specific tube.

The general shape of the $I_b$-$I_f$ curve can be predicted from what has been said about the conditions of emission and the space charge. We would expect the plate current to be zero when the filament current (and hence the emission) is zero, as borne out in Fig. 3-15. As the filament current is increased, electron emission also increases—and the plate current for a fixed plate voltage rises correspondingly. The emission and the resulting plate current rise slowly at first for low cathode temperatures (low values of $I_f$) and then very steeply as operating temperatures are reached and the supply of electrons becomes plentiful. This is borne out by the curves of Fig. 3-15. The sharply rising portion corresponds to the region *A-B* in the lower curve (for one value of plate voltage) and the region *A-D* in the upper curve (for a higher value of plate voltage). In this region of the characteristic, a full space charge is not yet present in the tube, and consequently the plate current is *limited by the emission from the cathode.*

As the filament current and emission of the tube is further increased, a full space charge is developed and *emission saturation* sets in. We would expect, therefore, that the plate current would *flatten out,* since for a given plate voltage and a full space charge present, no more than a certain fixed number of electrons can be pulled out of the space charge, regardless of the cathode temperature. This is borne out by the flattened portions of the characteristics (*B-C* in the lower curve and *D-E* in the upper curve). Although a slight rise in plate current with increased filament current is evident from the graphs, it is practically negligible. Hence we can state accurately that *after emission saturation sets in, the plate current is limited by the space charge at a given plate voltage, and is independent of cathode temperature.* Modern tubes are designed to provide a full space charge at normal operating temperatures. Their plate current, therefore, is *space-charge limited,* and cannot be increased by raising the cathode temperature.

If the plate current is to be further increased after normal emitter temperatures have been reached and emission saturation has set in, it can be done only by reducing the effectiveness of the space charge. As we have seen previously, this is accomplished by increasing the plate voltage, thus pulling more electrons away from the space charge. When this happens, more electrons are supplied by the cathode to restore equilibrium to the space charge. The end result of this action is an increased plate current. This is shown by the curve *A-D-E* in Fig. 3-15, where the plate voltage has been increased over that used in curve *A-B-C*. As is evident, emission saturation now sets in at a higher value of plate current. The plate current which flows after the *saturation point* (points *D* and *B* in Fig. 3-15) has been reached, is also known as *saturation current.*

*Family of Curves.* We could have plotted several more plate-current emitter-temperature characteristic curves in Fig. 3-15 for successively higher plate voltages. These would have shown higher values of saturation current for increasing plate voltages, demonstrating the control of the plate voltage over the plate current. Each of these curves represents an $I_b$-$I_f$ (or $I_b$-$E_f$) characteristic at a fixed value of the plate voltage. A group of such curves, showing the relationship between two variables for different fixed values of a third quantity (held constant for each plot), is called a *family of curves.* In vacuum tube manuals, a variety of families of curves are encountered, generally showing the relationship between the plate current and one of the operating voltages, while another

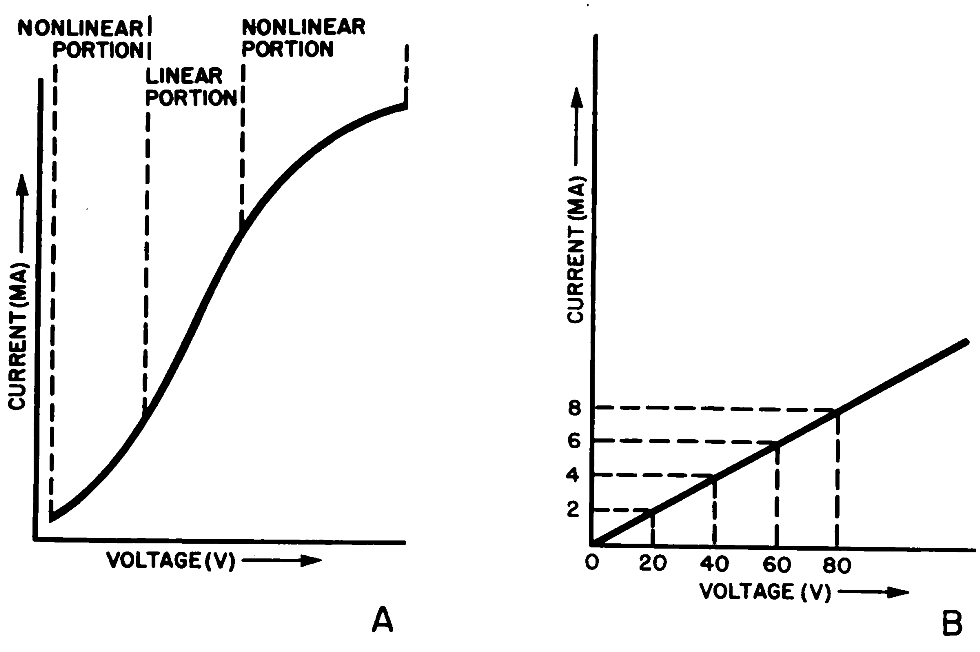



Fig. 3-16. Nonlinear and linear characteristic curves.

operating factor (also called *parameter*) is held constant for each curve.

*Nonlinear Characteristic.* Looking over the general shape of the characteristics in Fig. 3-15, we note that they may be divided into a straight-line portion near the center of each graph, and two curved portions, near the extremes of each graph. The center portion is also called the *linear portion,* while the ends of each graph are called the *nonlinear portions.* Apart from the appearance of the graphs, the terms *linear* and *nonlinear* characterize a very important relationship. Refer to Fig. 3-16 (A), which illustrates a simple current-voltage characteristic with linear (straight-line) and nonlinear (curved) portions. A relation between two variables is called *linear* if a change in the independent variable (or cause) produces a *directly proportional change* in the dependent variable (or effect); a relationship in *nonlinear* if a *cause does not produce a directly proportional effect.*

The characteristic of Fig. 3-16 (A) is linear near the center and nonlinear at the extremes of the graph. Most vacuum-tube characteristics are similar to this general curve, having only a limited region where operation is linear; that is, where the plate current changes in direct proportion to changes in the applied voltage. This limited region represents a certain range of voltage values where operation is *undistored,* as we shall see later. Part (B) of Fig. 3-16 further illustrates the meaning of linearity. A change in voltage always causes a proportional change in current in this graph. Whenever the voltage is changed by 20 volts, the current changes by 2 ma. This is true, whether the voltage is changed from 20 to 40 volts, or from 60 to 80 volts, etc.

**Plate-Current Plate-Voltage Characteristic**

*Circuit.* Another important relationship is that between the voltage applied to the plate and the resultant plate current, when the emitter temperatures (filament voltage) is held constant. This so-called plate-current plate-voltage characteristic is far more frequently employed than the plate-current-emitter temperature characteristic, since it approaches the actual operating conditions of the tube. The circuit used for obtaining this characteristic is shown in (A) of Fig. 3-17. A variable voltage source, $E_{bb}$, applies a voltage between plate and cathode of the tube, its value being indicated by a voltmeter (VM). The plate current, $I_b$, resulting for various values of the plate voltage is indicated on a milliammeter (MA), which is in series with the plate and the voltage source. The heater (or filament) circuit is not shown, since the cathode

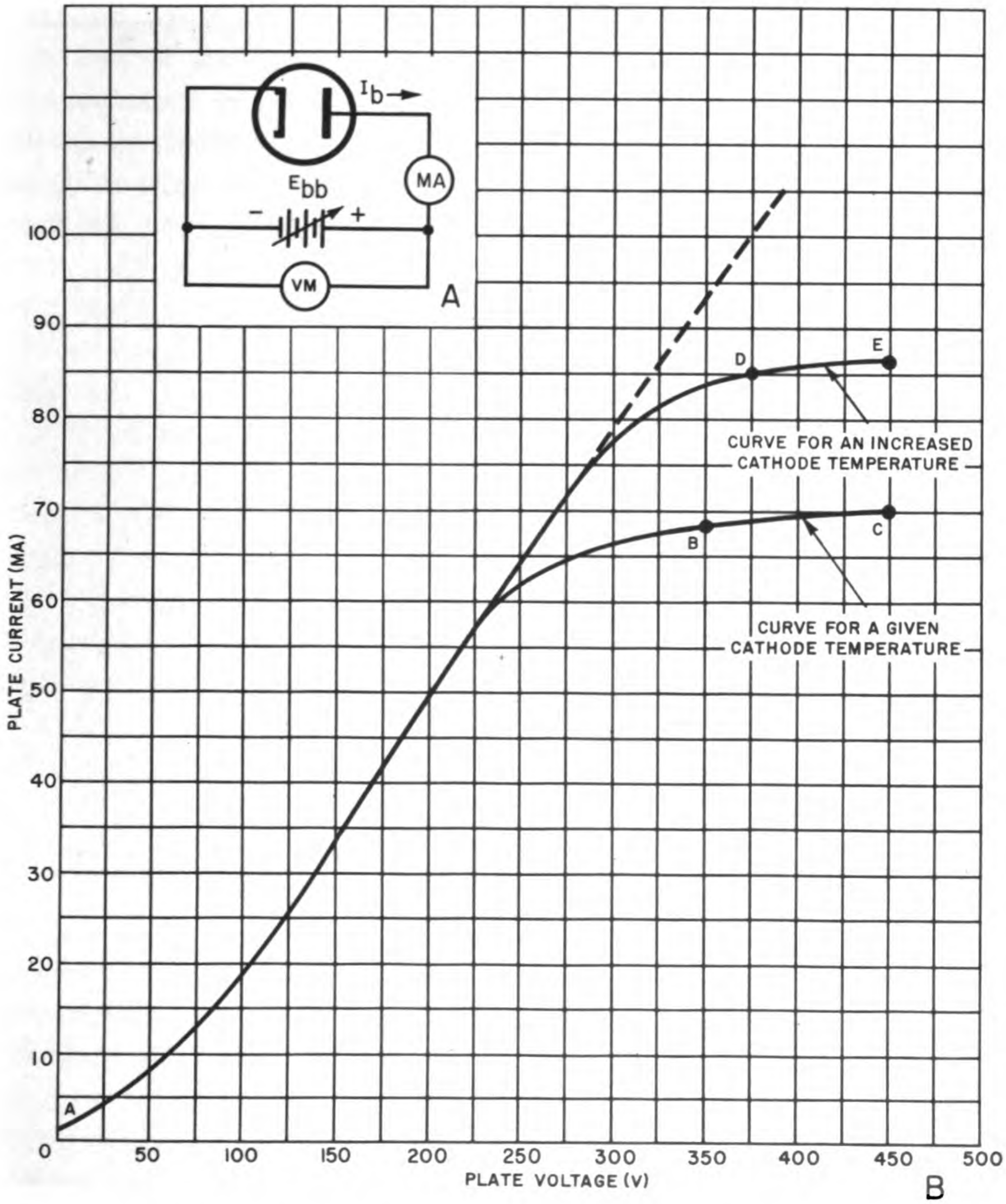



Fig. 3-17. Plate-current plate-voltage characteristic curves.

temperature is held constant during the plotting of any one plate-current plate-voltage characteristic. The lower curve *A-B-C* of Fig. 3-17 is obtained by operating the tube at a certain heater voltage (or cathode temperature), and then increasing the plate voltage $E_{bb}$ from 0 volts to 450 volts in a series of equal steps, noting down the plate current indicated by the milliammeter each time. The upper curve *A-D-E* is obtained in the same way, but the heater voltage—and hence emitter temperature—has been increased by a certain amount. The resulting plate-current plate-voltage values are representative for certain types of high-current diodes, but they are not based on any actual tube.

*Space-Charge Limiting.* Again our knowledge of emission and space charge effects permits us to predict the general shape of the characteristic curve. We would expect the plate current to be *almost* zero at zero plate voltage (and a definite emitter temperature), but this is not actually so, since we remember that some high-speed electrons emitted from the cathode reach the plate even when no voltage is applied to it. This is borne out by *A* of the characteristic curve in Fig. 3-17. Furthermore, we expect the plate current to rise rapidly with increasing plate voltage, as more and more electrons are pulled out of the space charge, and more are admitted into the space charge from the cathode in a proportional relationship. This is shown by the portion *A-B* of the lower curve and portion *A-D* of the upper curves. This portion of the plate-current plate-voltage characteristic is said to be *space-charge-limited,* since the plate current is effectively held down by the repelling field of the space charge, which permits only a limited number of electrons to enter the space charge, as the plate voltage is increased. We remember that these electrons are admitted into the space charge, and pulled out of the space charge to the plate without decreasing the density of the space charge.

*Emission Limiting.* As the plate voltage continues to be increased, the neutralizing effects of the space charge are gradually overcome, until finally all the electrons emitted by the cathode—at a certain temperature—are drawn over to the plate of the tube. We would expect very little further increase in plate current with increasing plate voltage, since all the emitted electrons are already being utilized. This condition of *plate voltage saturation* is reached at about 350 volts plate voltage for the lower curve of Fig. 3-17, and the saturation point is indicated by *B*. Raising the plate voltage from 350 to 450 volts (portion *B-C*) increases the plate current by about 2 ma only; a value so small that it may be neglected. In portion *B-C* of the curve, the plate current is said to be *emission limited.*

To obtain an increase in plate current for plate voltages in excess of 350 volts, a greater flow of electrons must be provided. This can be accomplished by increasing the emission through raising the cathode temperature. Curve *A-D-E* of Fig. 3-17 shows an increased saturation current occuring at a plate voltage of about 375 volts (point *D*) at the increased cathode temperature. In portion *D-E* of the upper curve the plate current is again limited by the now increased emission. The discussion thus far shows us that for a tube operated at a fixed cathode temperature there is a certain value of plate voltage beyond which further increases are useless, since all the electrons emitted from the cathode are already moving to the plate. It further shows us that below this plate-voltage saturation value, the cathode temperature makes little or no difference since the plate current is limited strictly by the space charge.

We remember from Fig. 3-15 that a contrasting condition existed in the plate-current emitter-temperature characteristics, when the tube was operated at a fixed plate potential. We found then that it was useless to increase the emitter temperature beyond the point of emission saturation—at a fixed plate voltage—since the space charge limited the flow of electrons and hence the resulting plate current. Below the point of emission saturation, the value of the plate voltage made little difference, since the available cathode emission fixed the amount of plate current available. We can summarize these findings by stating *that at low plate voltages (below plate voltage saturation) the plate current is controlled by the plate voltage and is largely independent of cathode temperature, while at high plate voltages (beyond saturation) the plate current is almost independent of the plate voltage and is determined chiefly by the cathode temperature.*

*Effect of Different Emitters.* There is another factor influencing plate voltage saturation which occurs in practice. The curves in Fig. 3-17 were obtained with a tungsten filament, which shows pronounced saturation effects. If a thoriated-tungsten cathode had been used, saturation effects also would have been present, although to a lesser degree. However, if an oxide-coated emitter had

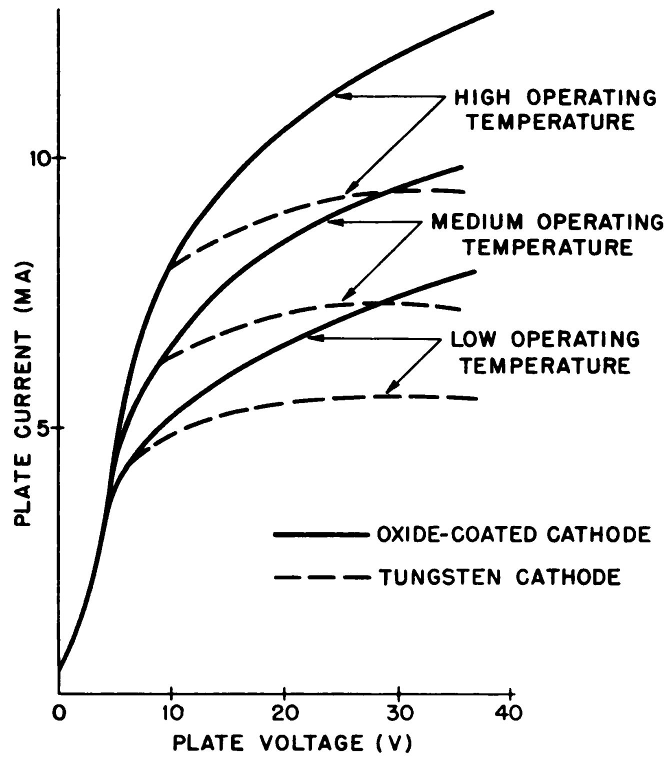



**Fig. 3-18. Plate-current emitter-temperature characteristic for different types of emitters.**

been used (Fig. 3-18), it would have been next to impossible to find a value of plate voltage capable of drawing off all the electrons to the plate—that is, a saturation point. Although there is a certain range of saturation, emission continues to increase slowly with increasing plate voltage in this range, as shown by the solid graphs in Fig. 3-18. Emission in oxide-coated cathodes is so plentiful—with added emitting material being freed at high plate voltages—that saturation cannot be obtained in practice without ruining the tube. Furthermore, increases in operating temperature have a greater effect on oxide-coated cathodes at high voltages than on tungsten emitters, as is evident from Fig. 3-18.

## D-c Plate Resistance of Diode

Since the application of a positive voltage to the plate of a diode tube results in the flow of a definite plate current, and inasmuch as the plate current varies with the plate voltage, it is reasonable to assume that the tube has some value of resistance. This resistance signifies the opposition the tube offers to the flow of plate current; if there were no resistance, the plate current would be infinite as soon as a small plate voltage were applied. We already know some of the reasons why this is not so. Among the factors which limit the plate current, we have discussed the amount of emission for a given cathode temperature, the condition of the space charge, opposition to the electron flow by some remaining air molecules, etc. Other factors which influence the opposition to the electron flow are the spacing between the electrodes and their physical size. All these factors contribute to the

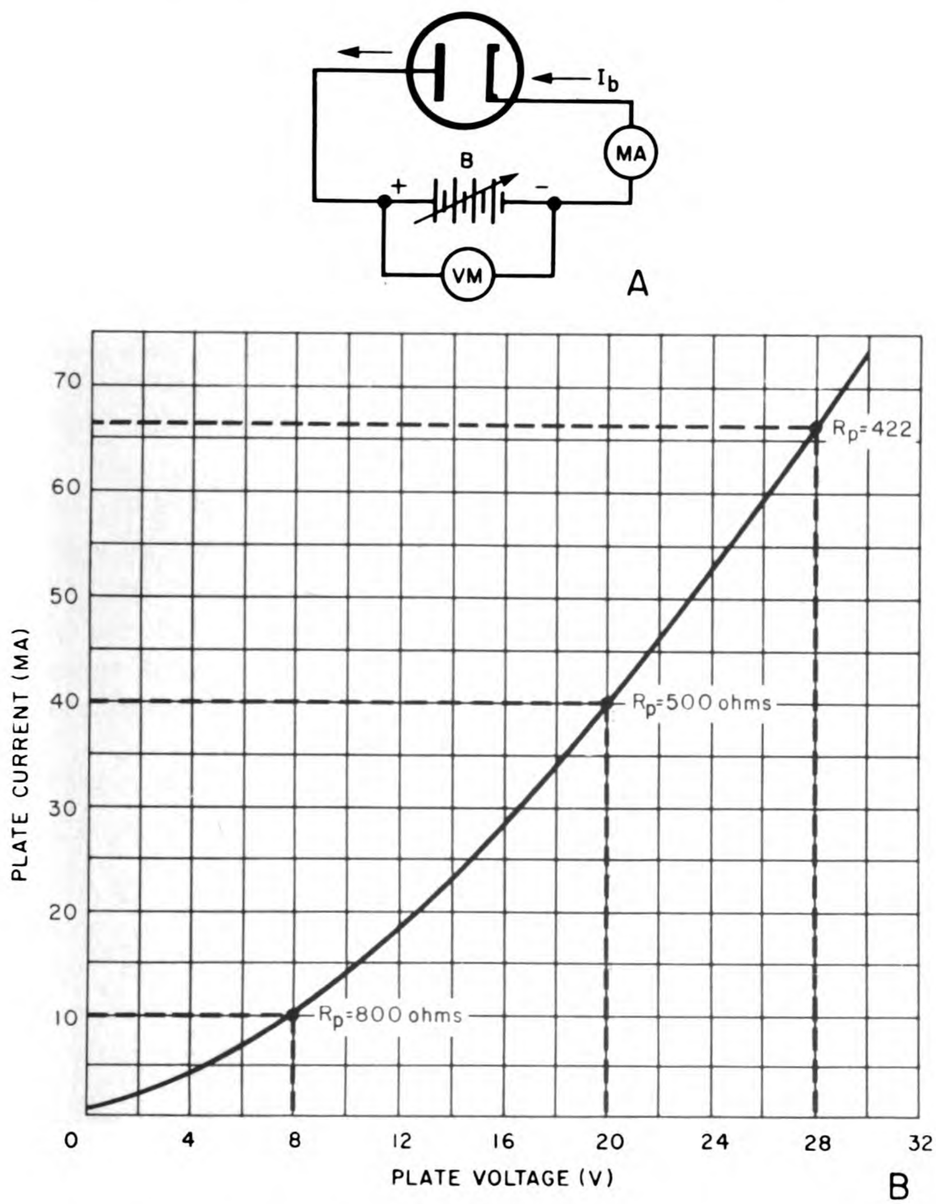



**Fig. 3-19. Plate-current plate-voltage characteristic for type 6H6 tube, using only one diode section.**

tube's opposition to electron flow, which is called the *plate resistance* of the tube.

As the name indicates, the d-c plate resistance of a diode is the opposition to the flow of plate current which is offered by the tube when a d-c voltage is applied to the plate. As we shall see later, the tube also offers a resistance when an a-c voltage is applied to the plate, and the latter is in fact more important than the d-c plate resistance. The symbol $R_p$ is generally used for the d-c plate resistance. The plate resistance can be calculated from Ohm's law, R=E/I, using the plate voltage and the plate current as the known factors in the equation.

As an example, Fig. 3-19 illustrates a typical plate-current plate voltage characteristic for a type 6H6 duo-diode tube, using only one cathode and its associated plate. (The tube contains two pairs of elements inside the envelope.) The 6H6 uses an oxide-coated cathode, and it is evident from Fig 3-9 that plate voltage saturation is a long way off. More likely than not, the tube would be damaged long before anything the plate voltage saturation could be obtain. At 30 volts on the plate, the plate current is very high (73 ma) and apparently it would increase even more steeply if the plate voltage were raised.

Let us determine the d-c plate resistance (symbol $R_p$ from the characteristic curve for various values of applied plate voltage. With 8 volts dc applied to the plate, the plate current $I_b$ is seen to be 10 milliamperes, or 0.01 ampere. Applying Ohm's law for d-c circuits, these values of plate voltage and plate current represent a d-c plate resistance of

$$R_p = \frac{E_b}{I_b} = \frac{8}{0.01} = 800 \text{ ohms}$$

(In the equation above we have used the symbol $E_b$ to stand for the plate voltage—that is, the actual voltage present between plate and cathode of the tube. The symbol $E_{bb}$ which we have previously used, represents the voltage of the plate-supply source, or *B*-battery. Since the battery is connected directly between cathode and plate, in this case, $E_{bb}$ is the same as $E_b$; but this is not always true.)

Similiarly, with 20 volts dc applied to the plate, the curve shows a plate current of 40 ma, or 0.04 ampere. This corresponds to a d-c plate resistance of 20/0.04, or 500 ohms. With 28 volts dc applied to the plate, the plate current from the curve comes out to 66.4 ma, or 0.0664 ampere, and the corresponding d-c resistance is 28/0.0664, or 422 ohms.

Examination of these figures and of the shape of the characteristic curve reveals that the resistance offered by the tube to the flow of plate current is *not* constant, as is the case for an ordinary resistor. Our calculations and the shape of the curve show that the resistance of the diode *decreases* as the plate voltage is *increased,* and *increases* as the plate voltage is *decreased.* It is evident from Fig. 3-19, that the plate resistance is *high,* where the slope of the characteristic $I_b$—$E_b$ curve is *shallow;* and the resistance is *low,* where the slope of the curve is *steep.* Hence, the d-c plate resistance exhibits a *non-linear behavior.* We know from our previous discussion on linearity, that the plate resistance would be *linear* (that is, it would remain constant over the whole range of plate-voltage values), if the characteristic $I_b$—$E_b$ curve were a straight line.

It is also of interest to note in connection with Fig. 3-19, that the plate current over the entire range of plate-voltage values would have been *doubled* if both sections of the 6H6 duo-diode had been connected in *parallel.* The sections are paralleled by connecting together the two plates and also joining the two cathodes. By apply ing the plate voltage to both sections in parallel, the plate current for each value of plate voltage is doubled, or equivalently, the *d-c plate resistance is cut in half.* This holds true for all multiple-section diodes.

## A-c Plate Resistance of Diode

In most instances the voltage which is supplied to the plate of a diode is of a varying or alternating character, rather than dc. For this reason, the resistance the tube offers to a *change* in plate voltage is of much greater interest than the resistance at a constant plate voltage. The a-c plate resistance (sometimes called *dynamic plate resistance*) represents the opposition the tube offers to *small variations or changes in the plate voltage.* Defined more accurately, the a-c plate resistance is the *ratio of a small change in plate voltage to the small change in plate current which it produces.* This may be written as an equation, as follows:

$$r_p = \frac{\Delta\ e_p}{\Delta\ I_p}$$

where $r_p$ is the a-c plate resistance in ohms. (A small "r" is used to distinguish it from the d-c plate resistance $R_p$; in general, capital letters are used to identify *constant or d-c quantities,* while small letters are used to indicate *varying or a-c quantities.*)

$\Delta\ e_p$ represents a small change in plate voltage and $\Delta\ i_p$ represents a small change in plate current, produced by the change in plate voltage. (In general, the symbol $\Delta$ signifies "a small change in".)

In practice, a small change in plate voltage is obtained by picking some fixed d-c plate voltage, and then varying the plate voltage by a small amount on both sides of the fixed or average value. This, in fact, simulates a small a-c voltage superimposed on a fixed d-c value. An alternating voltage which actually reverses polarity cannot be used to measure a-c plate resistance, since during the negative halfcycles the diode would not permit any plate-current

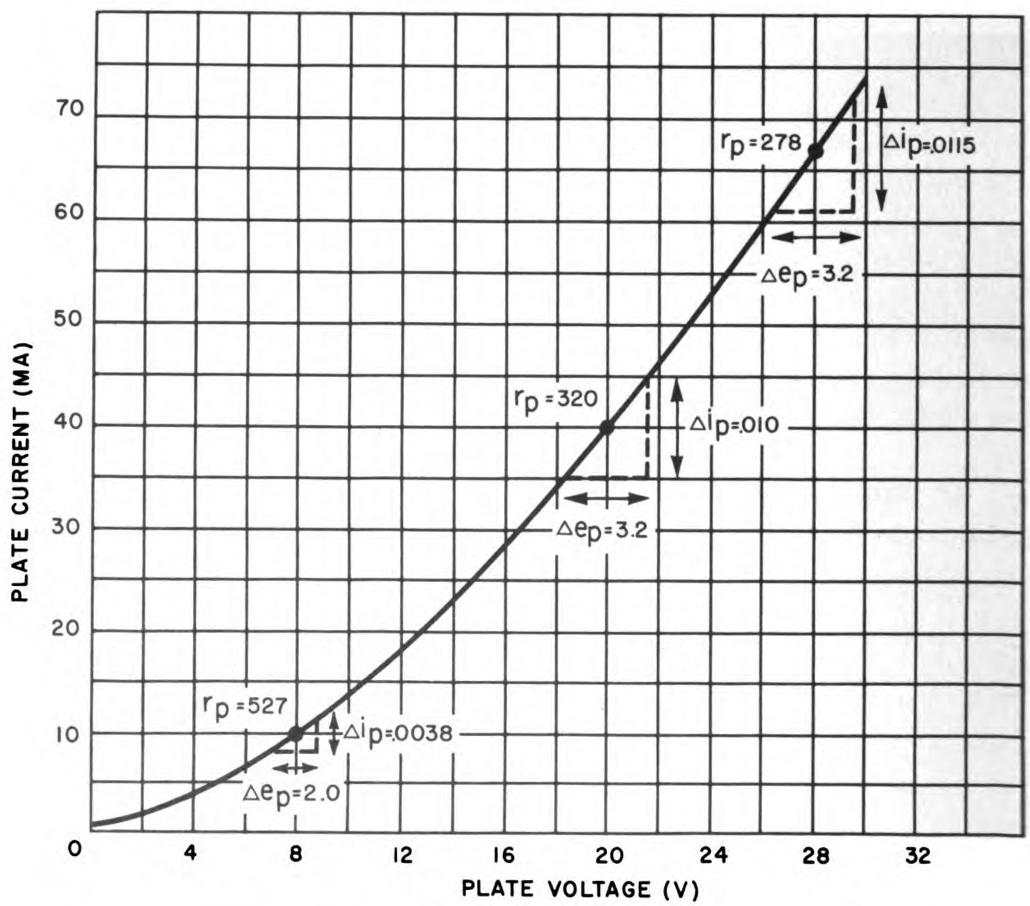



**Fig. 3-20. Determination of a-c plate resistance from plate-current plate-voltage characteristic (type 6H6).**

flow whatsoever, and hence the resistance would be infinite half of the time.

Figure 3-20 shows a plate-current plate-voltage characteristic curve, identical to the one shown in Fig. 3-19 for one 6H6-diode section. To determine the a-c plate resistance at any point along the curve, we vary the plate voltage by a small amount on both sides of this point. The smaller we make the variation, the more accurate is the value we obtain. We know from Fig. 3-19 that the d-c plate resistance of the tube is 500 ohms when the plate voltage is held constant at 20 volts dc. What is the a-c resistance for this *mean* or average value of 20 volts? Suppose we arbitrarily vary or *swing* the plate voltage by 1.6 volts on each side of the 20-volt point. For this swing $\Delta e_p$ equals 3.2 volts.

To compute $r_p$, we must first find the change in plate current resulting from the 3.2-volt variation in plate voltage. At 21.6 (20 plus 1.6) volts the plate current is 45 ma, or 0.045 ampere. At 18.4 (20 minus 1.6) volts the plate current comes out as 35 ma, or 0.035 ampere. The change in plate current, therefore, is 10 ma, or 0.01 ampere. Consequently, the a-c plate resistance is

$$r_p = \frac{\Delta e_p}{\Delta i_p} = \frac{21.6 - 18.4}{0.045 - 0.035} = \frac{3.2}{0.01} = 320 \text{ ohms}$$

Thus, for a plate voltage fluctuating between 18.4 and 21.6 volts, the a-c plate resistance is 320 ohms, while for a constant plate voltage of 20 volts, the d-c plate resistance is 500 ohms. Using the same method of computation, an a-c resistance of 278 ohms is obtained at the 28-volt plate-voltage point, using a swing of 1.6 volts on each side of 20 volts. The d-c resistance at the same point is 422 ohms, with the plate voltage fixed at 28 volts. Similarly, at the 8-volt point of the curve, the a-c plate resistance comes out as 527 ohms for a variation of *1 volt* on each side of the 8-volt average value. If a swing of 1.6 volts is used instead of 1 volt, the value of $r_p$ still remains close to 527 ohms. A small swing is generally preferred, since it usually results in a more accurate value of $r_p$. As larger swings are taken, the nonlinearity of the characteristic produces erroneous values.

We find as a result of our calculations that the d-c plate resistance and a-c plate resistance differ appreciably. As a rough approximation, the a-c plate resistance is only about one-half of the value of the d-c plate resistance in this case. Furthermore, as Fig. 3-20 shows, the a-c plate resistance also *decreases* as the plate vol-

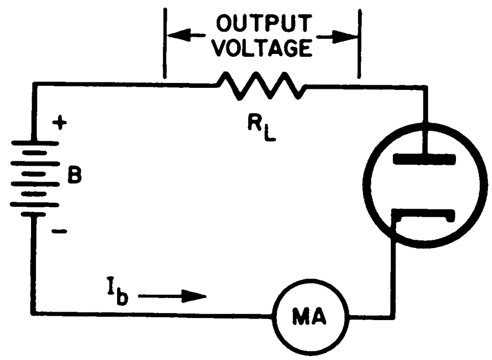



**Fig. 3-21. Adding a load resistor, $R_L$, in series with the diode plate circuit to obtain an output voltage.**

tage is *increased,* and it *increases* as the plate voltage is *decreased.* The *exact value of the a-c plate resistance depends on the point of operation selected on the characteristic curve.* As the operating point on the plate-voltage scale is moved up, the a-c plate resistance decreases. These conclusions concerning the a-c plate resistance generally hold true for all types of vacuum tubes—not only for diodes —as we shall confirm later on.

It is also well to bear in mind that the a-c plate resistance is considered much more significant than the d-c plate resistance. Hence, when the term *resistance* is used with reference to a vacuum tube, and is not further qualified, the a-c plate resistance is usually meant.

### Static and Dynamic Diode Characteristics

Thus far we have discussed the characteristics of a diode under so-called *static conditions,* that is, no demands were made upon the tube to deliver an actual output and perform useful work. Practical circuits, however, must contain a *load* to which the tube can deliver useful power. By making the diode plate current flow through a load resistance outside of the tube, *it develops a voltage drop across this load, which then represents the useful output of the tube.*

When such a load resistor—identified by $R_L$ in Fig. 3-21—is added in series with the diode plate, and a voltage source, the operating characteristics of the tube change materially, as shown in Fig. 3-22. The plate-current plate-voltage characteristic curves obtained with a load in the circuit are known as the *dynamic characteristics* of the tube. In general, the word "dynamic" is used in vacuum-tube terminology to denote *actual operating conditions,* rather than theoretical conditions imposed to study tube behavior, which are called *static* conditions.

*Effect of Load.* With no load in the circuit (Fig. 3-19), or when $R_L$ equals zero, the current through the circuit is determined by the resistance of the tube itself, plus the very small resistances of the battery and the meter, which may be neglected. However, when an external *load resistance* is added (Fig. 3-21), the total opposition to the flow of plate current includes that of

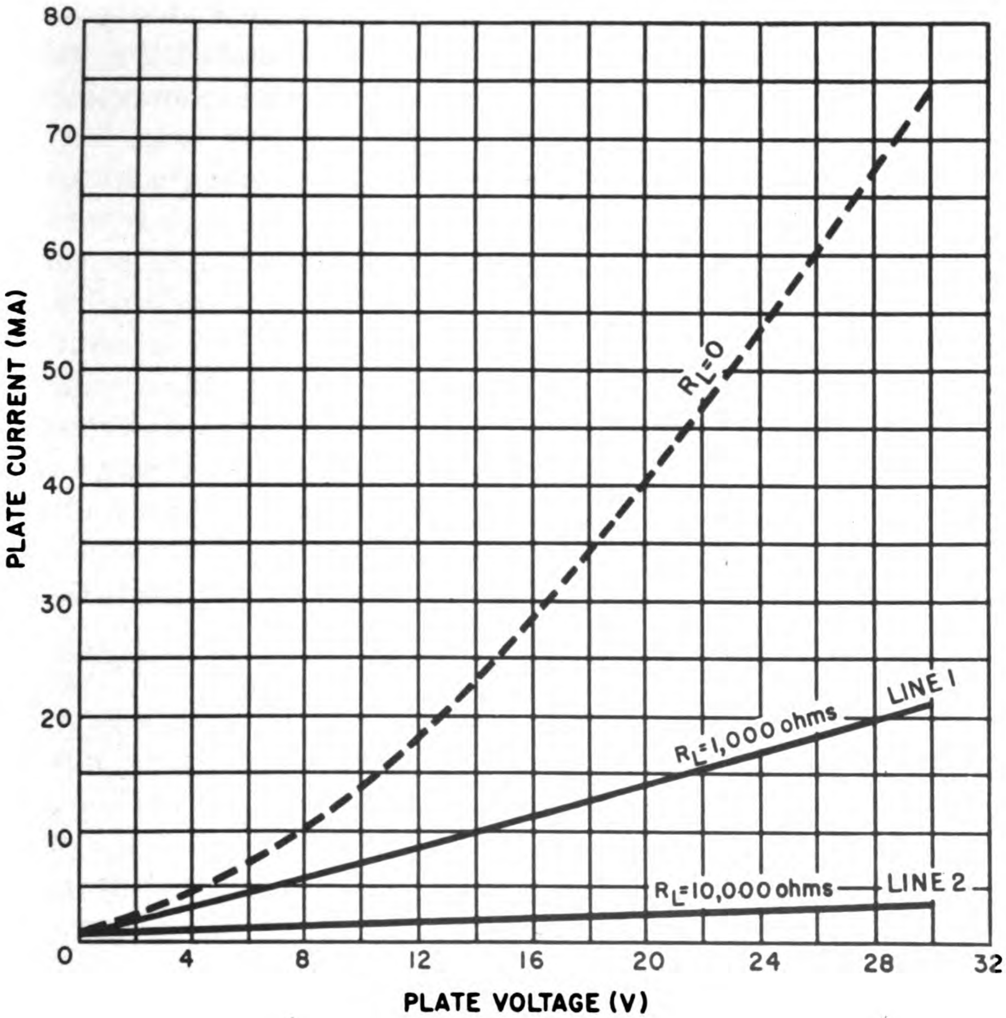



Fig. 3-22. Effect of different load resistance values on plate-current plate-voltage characteristics of a diode.

the tube itself (the plate resistance), as well as that of the load resistance. When a load resistance is selected which is many times the value of the internal plate resistance of the tube, the opposition to current flow stems chiefly from the external load resistance, and the effect of the plate resistance is almost negligible. Consequently, if the load resistance maintains its value regardless of the amount of current flowing through it (that is, if it behaves *linearly*), the plate-current plate-voltage characteristic of the circuit is changed from a curved line into a substantially straight line. In other words, for high values of the external load resistance, plate-current flow is determined chiefly by this linear load resistance, and hence the circuit behaves linearly.

The effect of different values of the load resistance upon the plate-current plate-voltage characteristic of the 6H6 duo-diode is shown in the separate graphs of Fig. 3-22. The dashed line in the figure is the *static* characteristic of the tube (same as shown in Figs. 3-19 and 3-20)—that is, for the condition when there is no load resistance ($R_L$ equals zero). Solid *Line* 1 illustrates the voltage-current relationship when a load resistance of 1,000 ohms is used in the circuit of Fig. 3-21. This graph still has some degree of curvature, but it is considerably less than that of the static line. Solid *Line 2* is obtained with a load resistance of 10,000 ohms, which is many times the value of the plate resistance. It is evident that this graph is almost straight; a very small degree of curvature is exhibited in the region of low plate voltages, where we remember that the internal resistance of the tube is highest. A line representing a load resistance of 100,000 ohms is so straight throughout its length and lies so close to the horizontal axis that it would have been impractical to draw it.

*Uses.* We see from these curves that the higher the value of the load resistor, the straighter is the dynamic characteristic of the tube, and also the smaller is the amount of plate current flowing in the circuit. If the current demands on the tube are small, a high value of load resistance can be used with a consequent straightening in the dynamic characteristic. A straight characteristic is desired in some radio circuits, where distortion must be kept to a minimum. (You may recall that a nonlinear characteristic produces distortion.) In other circuits—mainly for power conversion—a high load current is desired, and the distortion due to a nonlinear characteristic is of no consequence; in these cases a relatively low value of load resistance is utilized. The main point to bear in mind, however, is that some load resistance must be used if the diode is to be of practical use. When a load is used, the characteristic is automatically straightened and the amount of plate current is limited to values which cannot damage the tube, even at relatively high plate voltages.

## DIODE APPLICATIONS

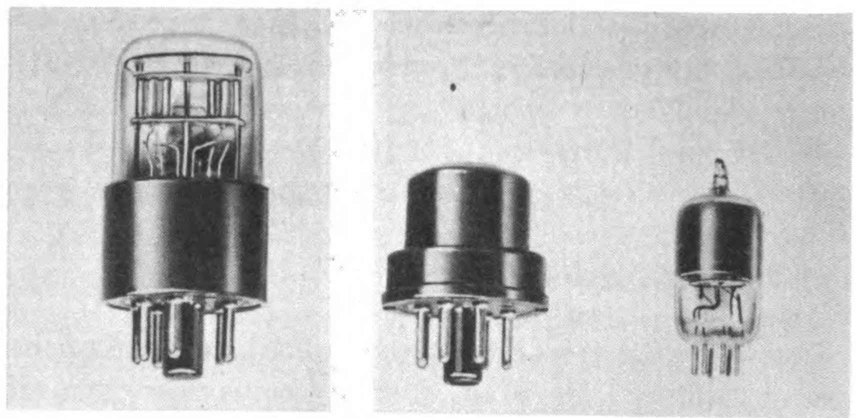
### Types of Diodes Available

We have discussed in considerable detail the fundamental facts underlying the operation of all diodes. Let us now turn briefly to some of the main applications for which diodes are used in practice. Diodes are employed primarily in two types of circuits. The first category are the so-called *signal circuits,* which handle radio signals of relatively low power, and require small plate currents. The second type are the *power circuits,* which handle high values of voltage and current. Accordingly, practical diodes in use fall into the categories of *signal diodes* and *power diodes.* The two types, illustrated in Fig. 3-23, differ chiefly in size, shape and the physical dimensions of the electrodes. The fundamental arrangement of the electrodes inside the tube is the same for both types. However, larger dimensioned and heavier electrodes are required in the power diodes (or *rectifier*) which must be capable of handling larger plate currents and voltages than are necessary in the signal diodes, which work with tiny signal voltages.

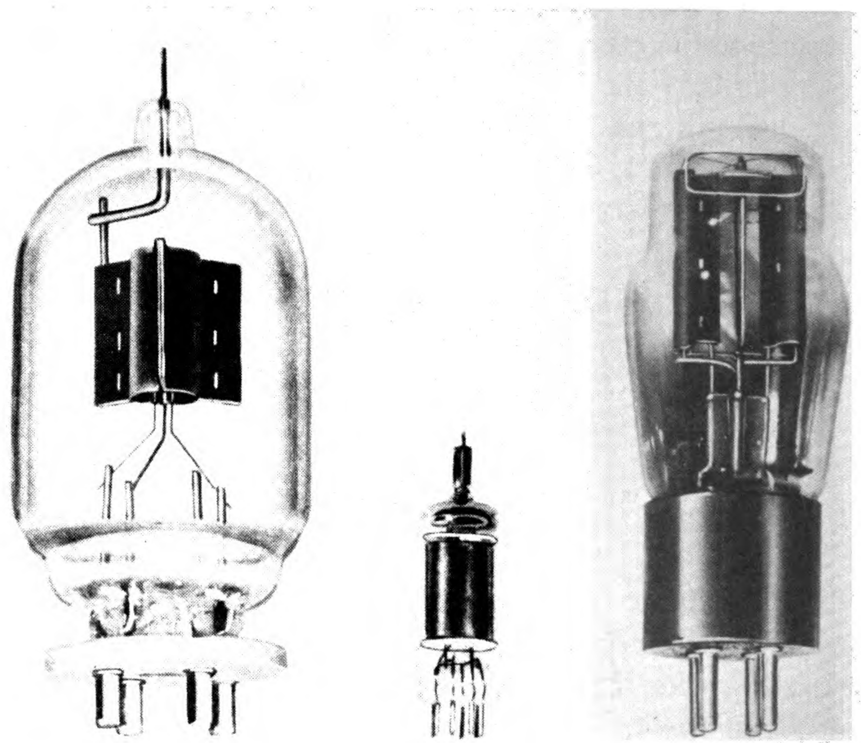
### The Diode as Power Rectifier

One of the basic functions of the diode is to convert a-c power into d-c power. Practically all tubes are operated from d-c supply voltages, and diode rectifiers are commonly used to furnish this voltage. A number of circuit configurations exist to rectify ac, but we shall be concerned here only with the two most fundamental circuits, known as the *half-wave rectifier* and *full-wave rectifier,* respectively.

*Half-Wave Rectifier.* Since a diode will permit current to flow only when its plate is positive with respect to its cathode, the positive half-cycles of an applied a-c voltage will pass through the tube,



SIGNAL DIODES



POWER DIODES

Fig. 3-23. Various types of high-vacuum diodes.

and the negative half-cycles will be cut off. It is for this reason that a single diode is known as a *half-wave rectifier.* A practical circuit and its waveforms are shown in Fig. 3-24 (A). An a-c input voltage is applied in series with the diode rectifier and a load resistance $R_L$. Plate current $i_p$ flows through the tube and load resistance during the positive alternations of the input voltage—that is, every other half-cycle, and is blocked during the negative half-cycles. Consequently, plate-current flows through the load always in the same direction. During the time that the current flows, its instantaneous amplitude follows exactly the changes in the applied voltage. The shape of the plate-current waveform, therefore, is an exact replica of the input voltage waveform during positive half-cycles. The current flowing through $R_L$ develops an output voltage across it, which may be used for the desired d-c application. The output voltage waveform is seen to be exactly the same as that of the input voltage, but only the positive half-cycles $A$ and $A'$ are reproduced. Because it loses one-half of the input voltage, the efficiency is low. In practice, the series of positive pulsations are too rough to be used directly, but must first be *smoothed out* by passing them through a *filter.* You may note in Fig. 3-24, that we have indicated the tube heater, but have not shown its circuit. The heater may be fed either from an a-c or d-c voltage source; the type of voltage supply makes no difference in the operation of the basic rectifier circuit, or any other application.

*Full-Wave Rectifier.* Plate current can be made to flow during the full cycle of the a-c supply voltage by employing two diode rectifiers in the so-called *full-wave rectifier* circuit, shown in Fig. 3-24 (B). Sometimes both diodes are included in the envelope of a single tube, having two plates and a common cathode or filament. Such a tube is then simply known as a *full-wave rectifier.*

You will note that the cathodes of the two rectifier tubes are tied together and the common junction is tied to one end of the load. We have shown a box for the load, since it rarely is a simple resistor, but generally includes the resistance of a smoothing filter and the plate resistances of several tubes, supplied from the rectifier circuit. The other end of the load is connected to the center tap of the secondary winding of a step-up transformer. We have labeled the center tap junction as "O", since we shall measure the transformer secondary voltages with respect to this zero reference point. It is clear that only *one-half* of the transformer secondary voltage

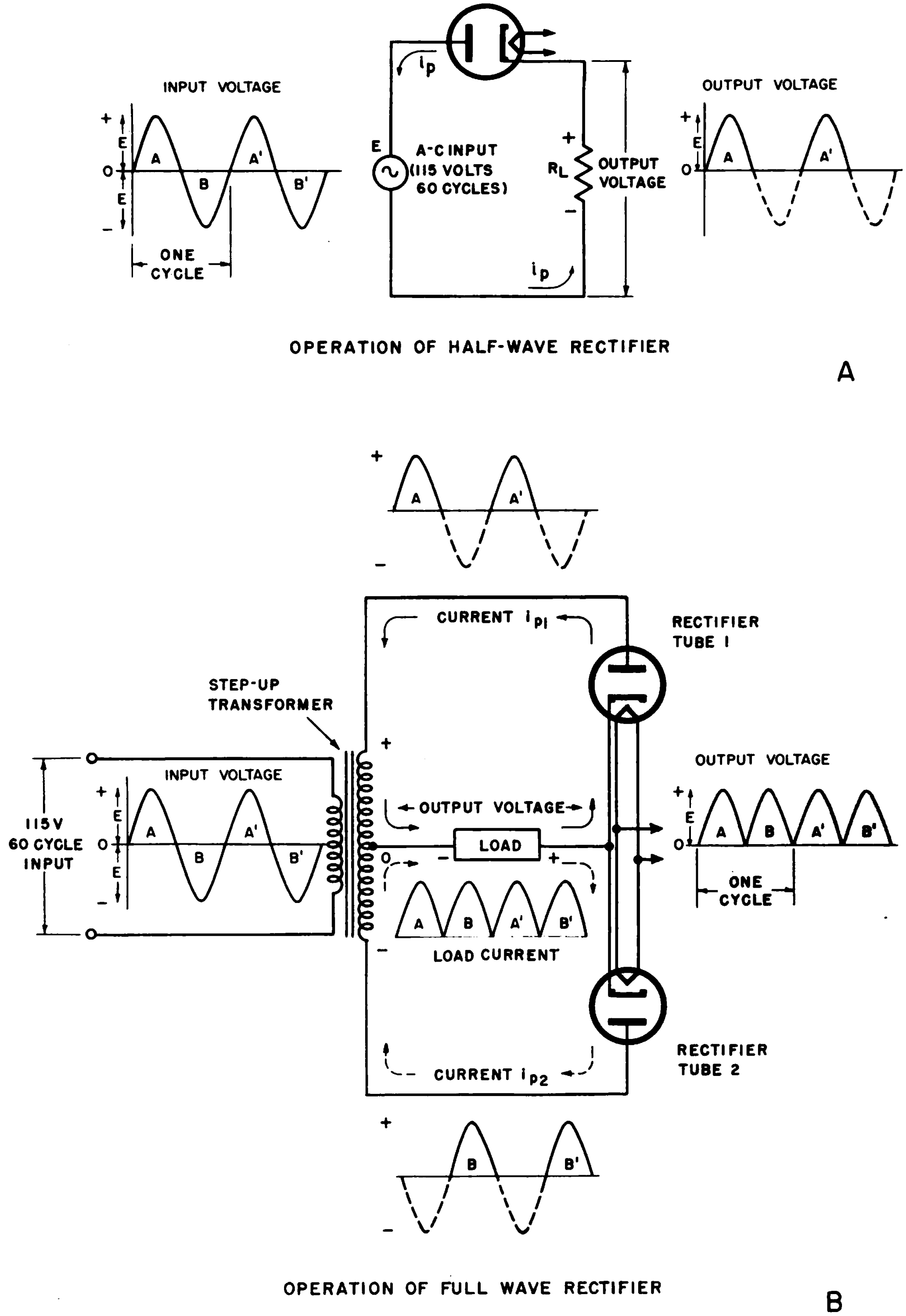



Fig. 3-24. Applications of power diodes (Rectifiers).

appears between plate and cathode of each of the rectifier tubes, since each is connected between one end of the winding and a point midway in voltage, (the center tap). To make up for this loss in voltage, and provide as high a plate voltage as possible a step-up transformer is used at the input of the circuit.

When an a-c voltage is applied to the primary winding of the step-up transformer, a voltage of the same shape (shown in Fig. 3-24B) but enlarged in amplitude appears across the secondary winding of the transformer. This secondary voltage is split in half with respect to the center-tap point ("O"), one-half appearing across tube 1 in series with the load, the other half appearing across tube 2 in series with the load. Whenever the top of the secondary winding is instantaneously positive with respect to the center tap, the bottom of the winding is negative with respect to the center tap, and vice versa. Since the plates of the tubes are connected to the ends of the winding, they show the same instantaneous polarity.

Assume, that the polarities are such that the top of the transformer secondary winding (and hence the plate of tube 1) is initially positive during the first half-cycle, *A*, of the applied a-c voltage. The plate of tube 1 will then be positive with respect to the cathode junction, and a plate current, $i_{p1}$, will flow from cathode to plate of tube 1, through the top half of the secondary winding and through the load, in the direction shown by the solid arrows. This current developes a voltage drop across the load, indicated by the half-cycle *A* in the output voltage waveform (Fig. 3-24B). Since electron current always flows in the direction from minus to plus, the cathode end of the load is positive, and the center-tap end of the load is negative. During this first half-cycle (*A*) of the a-c input voltage, the bottom of the transformer secondary winding —and hence the plate of tube 2—is negative with respect to "O" and no plate current flows through tube 2.

During the second half-cycle, *B*, of the applied voltage the top of the transformer secondary winding will be negative with respect to the center-tap ("O") point. Hence the plate of tube 1 is negative with respect to its cathode, and no plate current flows. During this same half-cycle, however, the bottom of the secondary winding is positive with respect to "O", and hence the plate of tube 2 also is positive with respect to the cathode junction. Consequently, a plate current, $i_{p2}$, flows from cathode to plate of tube 2, then through the bottom half of the transformer secondary and through the load, in the direction indicated by the dotted arrows. It is evident, that this current flows in the same direction through the load as the previous half-cycle, and hence again a positive current pulse, *B*, is shown flowing through the load. The current develops a voltage drop across the load, indicated by the positive output voltage pulse shown in Fig. 3-24B.

During the next half-cycle, *A'*, of the applied voltage tube 1 conducts again, developing positive output voltage pulse *A'*, while tube 2 is nonconducting. Finally, during half-cycle *B'* of the applied voltage (completing the second full a-c cycle) tube 2 conducts, resulting in output voltage pulse *B'* while tube 1 is nonconducting. It is evident from this analysis, that the tubes conduct alternately, each permitting current flow during the half-cycle where its plate is positive with respect to the cathode junction. The resulting current through the load is a series of unidirectional pulses, called a *pulsating dc.* Since there are two output current pulses for each complete cycle of the input voltage, the frequency of the pulsations, called the *ripple frequency,* is twice that of the applied a-c voltage. That is, if the input frequency is 60 cycles per second, the ripple frequency will be 120 cycles per second. Since the current is less discontinuous than for the half-wave rectifier, the pulsations, or ripple, is more easily smoothed out by a suitable filter circuit. Furthermore, the efficiency of a full-wave rectifier is far better than that of the half-wave rectifier, inasmuch as both halves of the a-c input cycle are utilized. It is for these reasons that full-wave rectifiers are widely utilized in electronic circuits.

### Signal Applications of Diodes

We shall consider two of the most important applications of diodes in signal circuits. The first is the use of a diode for *detection* of a radio signal, and the second is its use for modifying the waveshape of an a-c voltage. This latter application is of great importance in *pulse circuits,* such as used in television receivers and radar sets.

*The Diode as a Detector.* Before we can explain the action of a diode in rectifying—or *detecting*—a radio signal, we must first get an idea what a radio signal looks like. The electrical equivalents of ordinary speech and music are slowly varying a-c voltages of relatively low frequency (20 to 20,000 cycles per second) the so-called *audio frequencies.* These audio frequencies cannot be sent out directly by a radio transmitter. However, much higher frequencies—so-called radio frequencies (extending from about 100,000 cycles upward) may be sent out easily. An ingenious trick—called *modulation*—is employed to saddle these radio frequencies (called *carriers*) with the lower audio frequencies containing the information to be transmitted.

We cannot go here into the details of modulation, but it is enough to say that in one type of modulation the amplitudes of the radio-frequency carrier waves are modified in exact correspondence with the audio signals to be transmitted. If a pure sine wave of audio frequency (that is, a pure tone) is used to *amplitude-modulate* a radio-frequency carrier signal, the result looks like the waveform shown in *1* of Fig. 3-25 (A). As is seen, both the positive and negative half-cycles of the radio-frequency carrier wave follow in amplitude the audio frequency, which represents the modulating signal.

In the radio receiver, the information contained in the modulated radio-frequency signal must be extracted in order to become audible in the radio loudspeaker. This job is done by a detector circuit of which one type is shown in 2 of Fig. 3-25 (A). After suitable amplification, the modulated signal is applied to the detector by means of a high-frequency transformer, which is tuned to its exact frequency with an associated tuning capacitor. Passing through this transformer does not change the waveform of the modulated input signal applied to the diode detector as is evident from the figure. The signal is then applied to the diode, which acts exactly like the half-wave rectifier that we have just discussed. Consequently, the modulated signal is rectified, and only the positive half-cycles remain, as shown in *2* of Fig. 3-25 (A). These rectified current pulses, however, are still much too rapid to be heard in a loudspeaker.

The final step in detection is to apply the rectified radio-frequency pulses to a filter, consisting of a capacitor, *C,* and a load resistor, *R.* When the tube conducts during positive half-cycles, the capacitor quickly charges up to the maximum or *peak value* of the pulse. The value of the capacitor and load resistor are chosen so that the capacitor is able to discharge only very slowly through the resistor as the voltage across it decreases. Hence, as

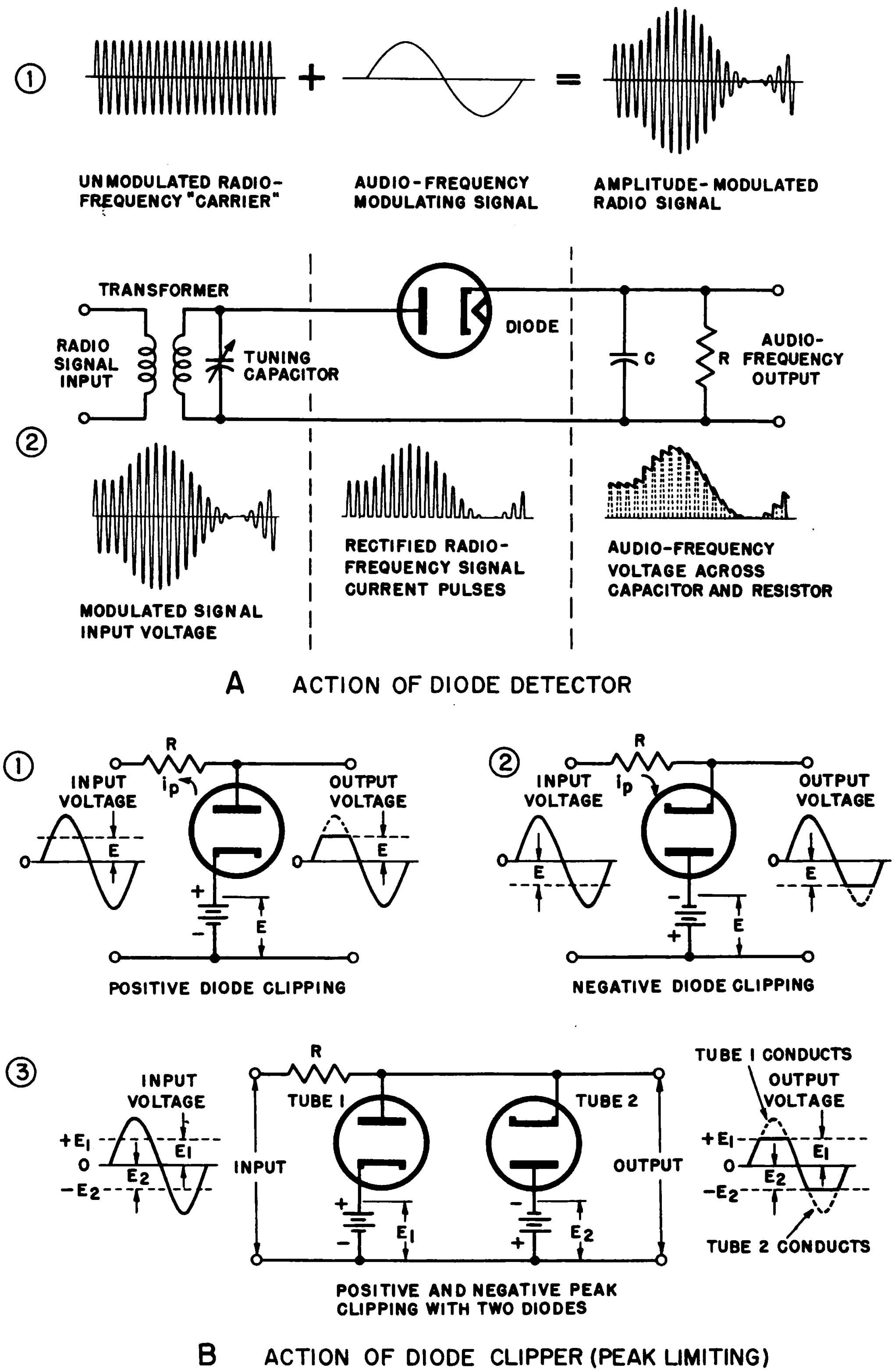



Fig. 3-25. Applications of signal diodes.

the positive pulse across $C$ falls away rapidly at the radio-frequency rate, the capacitor is incapable of discharging at the same rate. It essentially holds its charge and cannot follow the rapid radio-frequency variation. By the time the next r-f (radio-frequency) pulse comes along, the charge on the capacitor has fallen off only slightly, but it is now quickly recharged to the peak value of the new r-f pulse. As each r-f pulse appears across the capacitor,. it charges up to its peak value, and then discharges very slowly through $R$ between pulses.

The result is that the voltage across the capacitor (or across $R$) follows only the *peak values* of the r-f pulses in a series of jagged variations, which we have greatly exaggerated in the figure. Actually, the r-f pulses are spaced so closely together that the output voltage across $C$ follows the peak values quite smoothly. But as we remember, the maximum amplitudes or peaks of the r-f signal contain the audio-frequency modulation with the desired information to be recovered. By smoothing out the radio-frequency variations, but following the audio-frequency modulation represented by the peak values of the positive pulses, the original information which is to be made audible is recovered.

*The Diode as a Limiter* (*Clipper*). In pulse circuits it is often required to shape a waveform for a specific purpose and to limit its positive or negative amplitudes. The wave to be modified may be originally a sine wave, a square wave, triangular or some other shape. Circuits which permit modifying a waveform are called *wave-shaping circuits* and specifically those which limit the peaks of the positive and/or the negative half-cycles of an a-c waveform are known as *limiters* or *clippers*. Diodes make very efficient clippers.

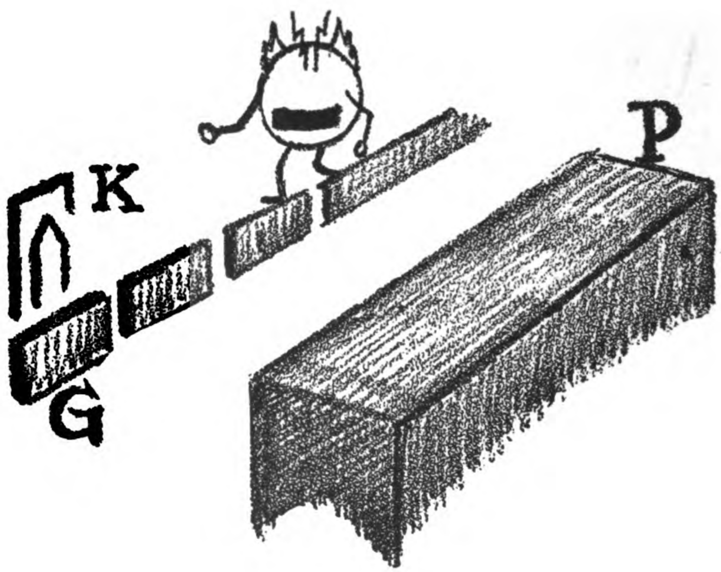
In *1* of Fig. 3-25 (B) one type of a diode clipper circuit is shown which limits the positive peaks of an a-c input waveform. A sine wave is shown for the input waveform, but any other alternating waveform would be affected by the circuit in the same manner. The action of all diode limiter circuits is based on the fact that the tube will permit current flow only when its plate is positive with respect to the cathode.

In *1* of Fig. 3-25 (B) the cathode of the diode is connected to the positive terminal of a battery having a voltage $E$. Hence, when no signal is applied to the input, the cathode of the diode is more positive than the plate by the value of $E$, or equivalently, the plate is negative with respect to the cathode by the value of $E$. As long as the input voltage is less positive than the battery voltage, $E$, the plate of the diode remains negative with respect to the cathode and the *tube acts as an open circuit or switch.* Under these conditions the output voltage is equal to the input voltage. No voltage drop occurs across resistor $R$, since no current flows through it. If the input voltage increases to a value greater than $E$, however, the plate of the diode becomes positive with respect to its cathode, and the tube conducts. The value of series resistor $R$ is chosen to be many times greater than that of the tube's internal (plate) resistance (about 10 to 20 times as high). Hence, when current flows through $R$ and the tube in series, practically the total voltage drop is developed across $R$ and very little appears across the tube. With the voltage drop across the diode being very small, the upper output terminal is essentially at the same voltage as the positive terminal of the battery. The tube now behaves as a closed switch, connecting the output to the fixed voltage, $E$. During this portion of the input cycle, then, the output voltage is equal to $E$, regardless of the amplitude of the input voltage. You may wonder what happened to the *difference* between the input voltage and the output voltage, which is shown by dotted lines in *1* of Fig. 3-25 (B). The answer is simple. Since the tube draws a current through resistor $R$, the difference appears as a voltage drop across $R$ equal to $i_p \times R$. In other words, the sum of the output voltage and the $i_pR$ drop across the resistor equals the input voltage. (A tiny voltage also appears across the diode, but it may be neglected).

Summarizing, if an input voltage wave is applied to the circuit of Fig. 3-25 (B), part *1*, the output voltage follows the input whenever the input voltage is less than $E$, but the output is limited to $E$, whenever the input voltage exceeds $E$. If $E$ is made zero (battery shorted out), the entire positive half-cycles will be shaved off. The process of cutting off the tops of waveforms is known as *clipping.*

A negative diode clipper is illustrated in *2* of Fig. 3-25 (B). Its action is just the reverse of the positive clipper, shown in *1*. The plate of the diode is negative with respect to the cathode by the value of the battery voltage, $E$. Thus, as long as the input voltage is positive, or less negative than $E$, the diode acts as an open switch, no current flows, and the output voltage is equal to the input voltage at any instant. When the input voltage becomes *more negative than E,* however, the tube conducts and effectively connects the upper output terminal to the negative terminal of the battery (the small voltage drop across the diode may be neglected.) During this portion of the input cycle, then, the output voltage is limited to $E$, and the difference between input and output voltage appears as a voltage drop across resistor $R$. In this circuit, then, the output voltage follows the input, whenever the input voltage is more positive than $E$, but the output voltages equals $E$, whenever the input voltage becomes *more negative than E.* If $E$ is made zero by shorting out the battery, the entire negative half-cycles of the input waveform are clipped off.

When it is desired to clip both the positive and the negative peaks of a voltage waveform, two diodes are placed in parallel in head-to-toe relation, as shown in *3* of Fig. 3-25 (B). Here a positive and a negative diode clipper work together to limit the output voltage between two values, $E_1$ and $E_2$. Whenever the input voltage becomes more positive than the value of $E_1$, tube 1 conducts and short-circuits the upper output terminal to the positive battery terminal, $E_1$; thus positive half-cycles are limited to the value of $E_1$. Whenever the input voltage becomes more negative than the value of $E_2$, tube 2 conducts, and short-circuits the output terminal to the negative battern terminal, $E_2$; hence negative half-cycles are limited to the value of $E_2$. This double limiter circuit illustrates one way of obtaining an approximate square-wave output from a sine-wave input voltage.




*Chapter 4*

# TRIODES

Up to 1907, the diode was the only vacuum tube used in radio-communication systems. While the unidirectional characteristic of diodes made them efficient detectors of radio energy, their inability to *amplify* the weak radio signals held the state of radio communication at a primitive level for a number of years. But when in 1907, Lee De Forest added a third element—the *control grid*—between the cathode and plate of a diode, he provided a missing link to radio and wire communications which made the astounding present-day development of electronics possible. With his new three-element tube—called a *triode* (he named it "audion") —De Forest was able to use a tiny voltage to control the flow of a relatively large current furnished by a battery. Here, was the magic wand that made it possible for radio transmitters and telephone communications to girdle the globe, and led to the series of dazzling inventions which at present influence the daily life of every human being.

**Physical Construction of Triode**

Figure 4-1 shows the construction of a typical triode with an indirectly heated cathode. The grid is seen to be an ovally shaped structure of wire which completely surrounds the cathode, but does not impede the electron flow because of its open construction. The particular type of receiving tube shown does not differ fundamentally in construction from a diode, except for the presence of the grid. Other triodes differ from that shown in Fig. 4-1 in size and in the dimensions and spacing of the electrodes, in accordance with their intended function.

*Control Grid Structure.* The control grid is a metal structure which may take any number of different shapes (see Fig. 4-2), depending on the design and intended application of the tube. In most cases, the grid has a helical form, consisting of a number of turns of fine wire wound in the grooves of two vertical metal supporting members. The grid is generally spaced more closely to the cathode than to the plate. Metals used for grids may be molybdenum, nichrome, iron, nickel, tungsten, tantalum, and iron-nickel alloys. We will become familiar later on with the reasons for

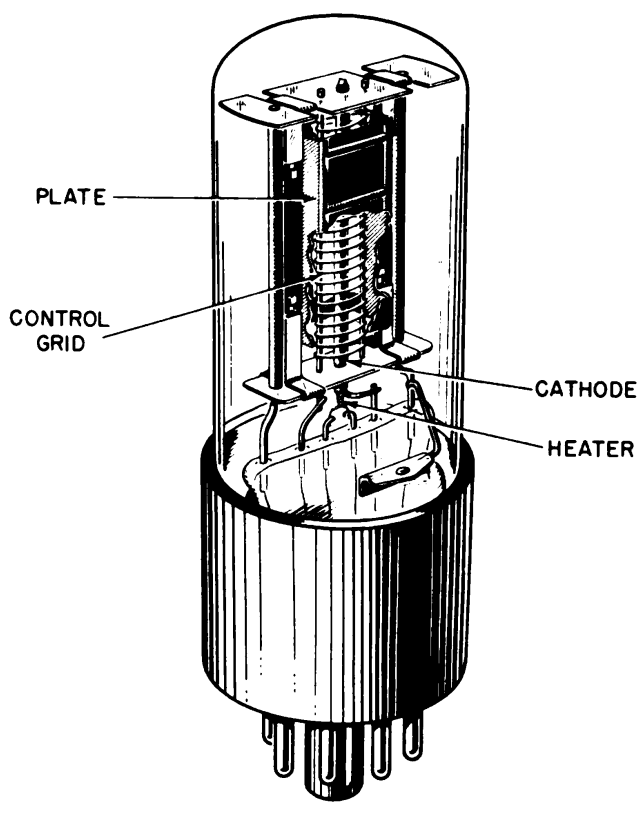



**Fig. 4-1. Construction of a triode showing cathode, control grid, and plate arrangement.**

the different sizes and spacing of the control grid wires. The cathodes and plates of triodes are constructed in the same way as those used in diodes. The standard schematic circuit symbols for triode tubes are shown in Fig. 4-3. The letter "G" stands for the control grid.

## Effect of Control Grid

We have said that a very tiny voltage applied to the grid has a controlling effect upon the plate current flowing between cathode and plate of the tube. A small negative voltage applied to the grid is capable of completely nullifying the attractive force of a many times greater (20 to 100 times) positive plate voltage, causing complete stoppage of the electron movement to the plate. Let us

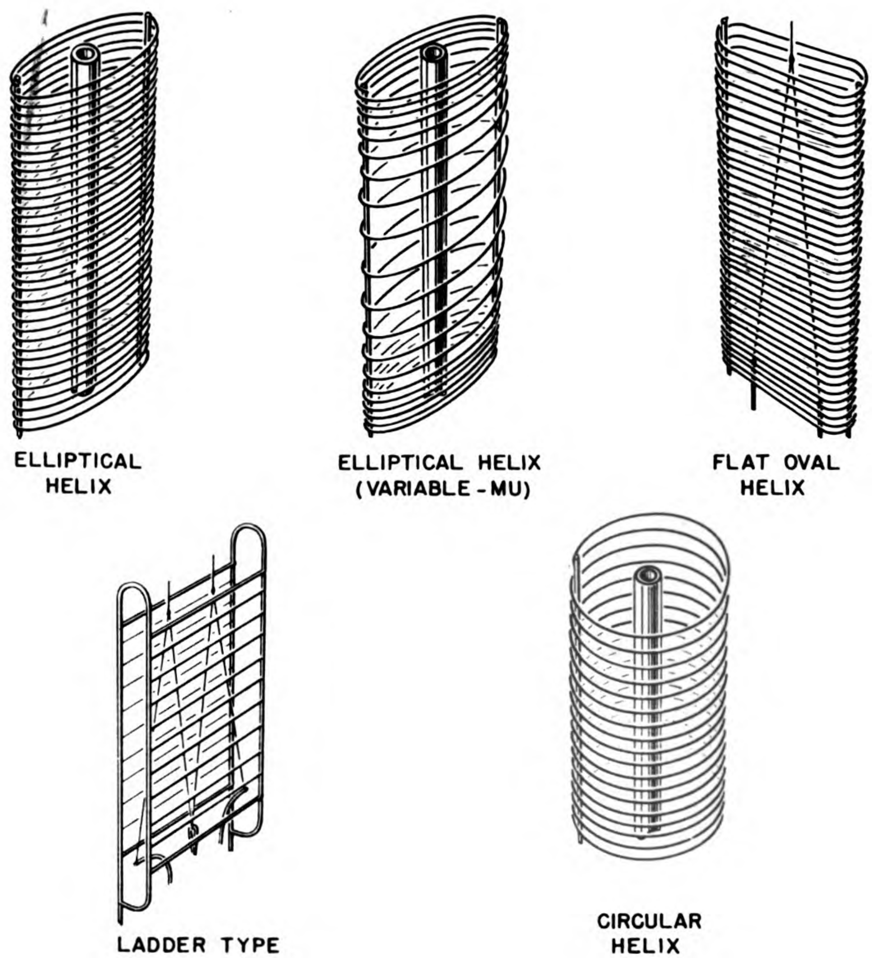



Fig. 4-2. Typical control-grid structures.

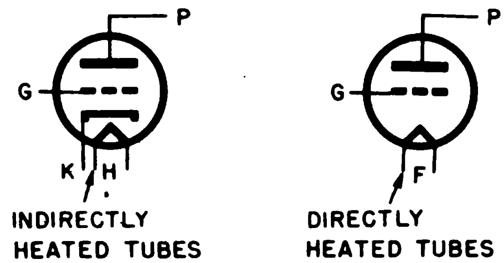



**Fig. 4-3. Schematic symbols for directly and indirectly heated triodes.**

first look briefly at the practical consequences of this control grid action before going into the reasons behind it.

*Supply Voltages.* To operate properly, a triode requires the application of three voltages, one to each of the electrodes. An *A*-battery or *A*-supply provides a source of filament or heater voltage to heat the emitter to operating temperatures. Further, a *B*-battery or plate voltage supply is needed to furnish the positive operating potential to the plate of the tube. Finally, a *C*-battery or grid voltage supply (also known as *grid bias*) must be connected between the control grid and the cathode of the tube. For normal operation, the grid is usually made negative with respect to the cathode, as shown in Fig. 4-4. The reasons for this shall be seen presently. In practice, batteries are not used to supply the operating potentials to the tube, except in some portable equipments. The heater or filament voltage is usually obtained from an a-c transformer, while the plate and grid supply voltages are furnished by one of the types of rectifier circuits discussed in the last chapter. All d-c supply voltages of the tube are measured with respect to the *cathode,* which is the common junction point of the voltage sources.

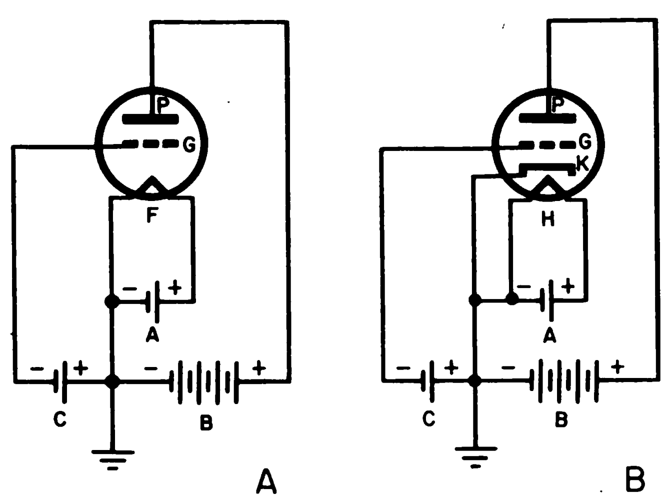



**Fig. 4-4. D-c operating voltages of directly and indirectly heated triodes.**

In Fig. 4-4, this common junction has been shown connected to *ground*—a general practice. To measure any of the operating voltages of the tube, a voltmeter may be connected between the particular electrode and the common ground junction.

*Cut-off Grid Bias.* Since the grid is closer to the cathode than the plate, the grid voltage, or *bias,* has a greater effect upon the plate current of a triode than does the plate voltage. Let us explore now the effects of various grid voltages and polarities when the tube is emitting electrons at a normal rate and is operated at a fairly high plate voltage to attract these electrons to the plate.

If there were no voltage connected to the grid (or no grid present), we would normally expect the flow of a substantial plate current under these conditions. Now assume, however, that the grid has been made negative with respect to the cathode by connecting it to the negative terminal of the *C*-battery. With the grid at a negative potential, it has a repelling effect on the electrons, and consequently retards their motion toward the plate. If the grid is made more and more negative, progressively fewer electrons will reach the plate, until finally all the electrons are repelled back to the cathode and none reach the plate. Under these conditions, the tube ceases to conduct and the plate current is zero. The negative grid voltage required to stop the flow of plate current is called the *cut-off voltage* or *cut-off bias.* This condition is illustrated in Fig. 4-5 (A).

*Negative Grid Bias.* If the grid is made less negative with respect to the cathode than required for plate current cut-off, some electrons get past the grid mesh and move on to the plate, producing a moderate flow of plate current (Fig. 4-5 (B). As the amount of negative grid voltage is further reduced (that is, made less negative), more and more electrons are able to pass through the grid, and the plate current continues to increase. However, as long as the grid is negative with respect to the cathode, no electrons are attracted to the grid and hence no current flows through the grid-to-cathode circuit, as indicated in Fig. 4-5 (B).

*Zero Grid Bias.* At zero grid voltage with respect to the cathode, the electrons do not experience any retarding effect from the grid, and the action is similar to that of a diode (Fig. 4-5C). A fairly large plate current flows, depending on the plate voltage, its value being about the same as for a diode of a similar construc-

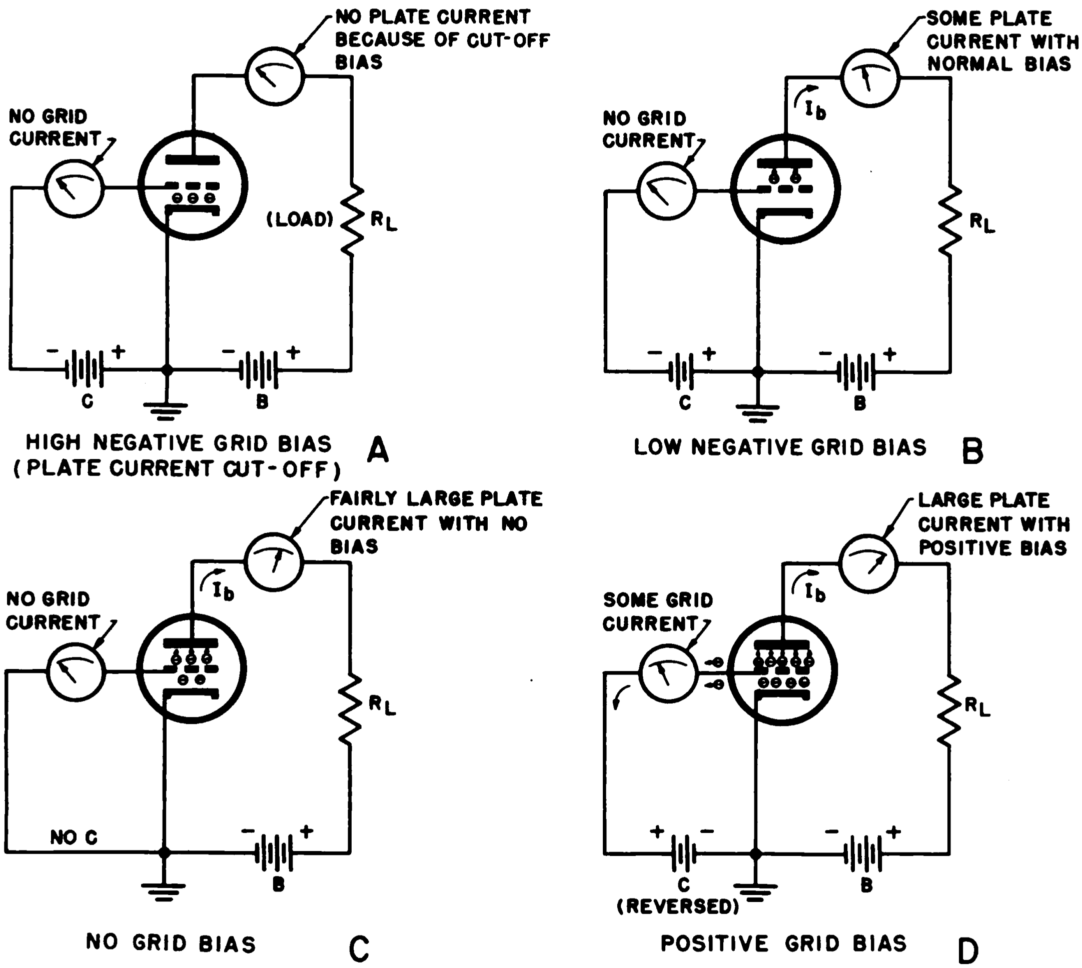



Fig. 4-5. Action of control grid: (A) high negative grid bias (plate current cut-off); (B) low negative grid bias; (C) zero grid bias; (D) positive grid bias.

tion. Since electrons are not influenced by the grid and are not attracted to it, no grid current flows with zero grid bias.

*Positive Grid Bias.* In Fig. 4-5 (D), the *C*-battery has been reversed in polarity, making the grid *positive* with respect to the cathode. With the grid positive, it exerts an accelerating force upon the electrons, which adds to that exerted by the plate. Consequently, electrons are pulled away from the cathode and space charge at a very high rate and the plate current increases to a large value. Further, some of the electrons moving toward the plate are attracted by the positive grid causing a *grid* current to flow between grid and cathode. This type of operation is generally undesirable, since large plate current may eventually damage the tube.

### Electrostatic Fields in the Triode

We have now reached that point in the discussion of the triode where we can explain the manner in which the control grid achieves its remarkable results. In order to describe the action we shall refer you back to the diode. The triode is essentially an elaboration of the diode, with a third element—the grid—added between the emitter and the plate. The part played by the emitter in the triode is the same as it is in the diode, and the effect of the positively charged plate on the space charge is the same in both tubes. It follows that the basic electrostatic fields which exist in the diode are likewise to be found in the triode. These are two in number as you will recall: one due to the space charge and the other due to the voltage on the plate. You shall soon see that these two electrostatic fields are not the only ones existing in the triode.

Furthermore, we showed how the plate current in a diode operated below plate-voltage saturation (the normal condition), was always space charge limited. This, too, is a basic condition for the triode in almost all applications. The control grid may determine the exact value of plate current by adding or bucking the action of the positive plate, but this does not alter the fact that the plate current is space-charge limited. Similarly, if a triode is operated in such a manner that all the electrons emitted are drawn to the plate, the value of the plate current is then limited by the electron emission, or equivalently, by the emitter temperature. Once more, the grid—through the voltage applied to it—may aid the plate in creating this state, but this does not alter the fundamental condition of saturation, described in connection with the diode.

From these considerations you can see that there is much similarity between the diode and the triode in the basic conditions existing within the tube. The control grid in the triode does not alter their basic relationships, but it is *capable of controlling the extent to which the electrostatic field due to the positive plate voltage acts upon the space charge.* The control grid is simply another charged surface with an electrostatic field of its own, which is interposed between the plate and the space charge. The effect on the space charge and the resulting plate current depends upon the relative intensities of the grid and plate electrostatic fields near the cathode. In other words, *the plate current in a triode is for all practical purposes determined by the electrostatic field that the combined action of the grid and plate voltages produce at the space charge (near the cathode)*. Let us see just what this means when the grid is at various potentials with respect to the cathode.

*Negative Voltage on Grid.* Let us first examine the electrostatic field conditions when a negative potential is placed at the grid. Refer to Fig. 4-6. In this illustration we show the grid as a series of dots, the spaces between the dots indicating the open portions of the grid. The separation between the grid wires (dots) is ample to allow electrons to travel through the grid toward the plate. Note that the control grid is much closer to the cathode (and hence to the space charge) than to the plate. The space charge is shown by the tiny dots between the cathode and the control grid. The greatest space-charge density is near the cathode, and so few electrons are located between grid and plate that we can assume the entire space charge to exist between cathode and grid, as shown in Fig. 4-6. The field between the space charge and the cathode is not shown, since we are aware of its action of supplying additional electrons from the emitter to the space charge in the same proportion as they are drawn off to the plate.

A battery marked "C" in Fig. 4-6, applies a small voltage to the grid so as to make it negative with respect to the cathode. An additional *B*-battery supplies a positive potential to the plate, its value being many times that of the negative potential on the grid. (If the plate voltage is about 100 volts, the negative grid voltage may be from −1 to −10 volts.)

Let us examine the electrostatic fields existing within the tube under these conditions. The positive plate voltage establishes

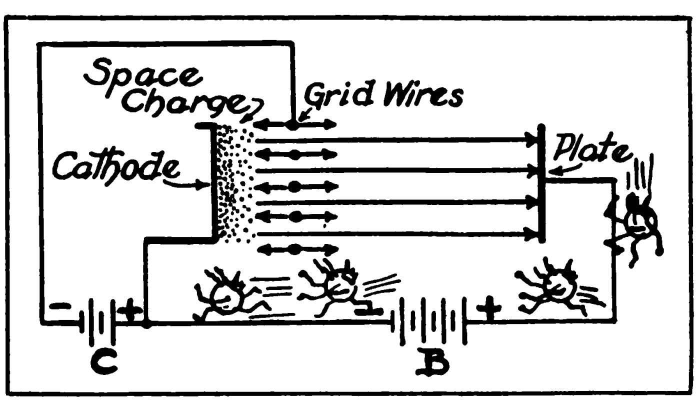



**Fig. 4-6. Electrostatic fields in the triode for negative bias.**

a strong electrostatic field, directed from cathode to plate through the grid wires. This field tends to pull electrons away from the space charge and attract them to the plate. In addition, we have the field set up by the negative voltage on the grid. Since it repels electrons (unlike charges repel each other), its lines of force are directed *away* from the control grid, both toward the plate and toward the space charge. It is clear, that in the space between grid and plate, the lines of force of the grid field *aid* those of the plate electrostatic field, while in the region between grid and cathode the lines *buck* those of the plate field.

Examining the region between control grid and plate, it is evident that once an electron has traveled past the grid into that area, all the forces acting on it pull it toward the plate; that is, the electron is both repelled from the negative grid and also attracted toward the positive plate. There is nothing to block the path of electrons in this area.

Much more important is the area between the space charge and the grid where the controlling action takes place. It is evident from the direction of the lines of force that the field set up by the negative control grid voltage, tends to repel electrons back into the space charge, thus reducing the number of electrons which would normally move toward the plate. In fact, the negative grid increases the density of the space charge and makes it more concentrated near the cathode. Again, this would decrease the number of electrons admitted into the space charge, and those traveling from the space charge toward the plate. Consequently, considering the field set up by the negative grid *alone,* there would appear to be a definite reduction in the number of electrons reaching the plate, and hence in the resulting plate current.

However, we must deal also with the field set up by the plate voltage, whose lines of force oppose those of the field due to the grid, in the region between space charge and control grid. The field set up by the plate tends to attract electrons from the space charge to the plate *through* the grid wires. Thus we have an attracting and a repelling field opposing each other at the space charge. *The movement of electrons through the openings between the grid wires will be determined by the field which predominates.* It would appear that the field set up by the high positive plate voltage (over 100 volts) would easily overwhelm the effect of the field set up by the small negative grid voltage (less than 10 volts), and hence the electrons would freely move to the plate. This is not so, however. You may remember as we explained in the last chapter, that the intensity of an electrostatic field is *directly proportional to the voltage between two charged plates* and *inversely proportional to the distance between them.* This means that the electrostatic field between two plates, separated by 10 inches and having a potential difference of 100 volts between them, will have exactly the same strength as that of a field between two plates, separated by one inch and having only 10 volts potential difference between them.

This is exactly the situation which applies to the fields within a triode tube. Although the plate voltage is normally much higher than the grid voltage, the grid is located much closer to the space charge than the plate. Consequently, the opposing fields at the space charge may be quite comparable in strength, and even if the grid is only a few volts negative its field may actually nullify that due to a very high positive plate voltage.

Furthermore, it is evident that due to the closeness of the grid to the space charge, a *small change in the grid voltage will have a much greater effect on the electron flow* (and hence the plate current) *than an equal change in the plate voltage.* Just how much greater the effect of the grid voltage on the plate current is than that of the plate voltage, depends on the physical design of the particular tube; chiefly on the distance between grid and plate. In one tube, the negative grid voltage required to offset completely the attracting force of the plate may be 1/10 of the plate voltage, while in another tube it may be only 1/100 of the plate voltage. This ratio of the relative effectiveness of the grid and the plate, is a measure of the *control* the grid exerts over the plate current, and is also known as the *amplification factor*. From what has been said already, it is evident that the *outstanding feature of the triode is its amplifying action, which permits a tiny voltage on the grid to exert control over relatively large plate currents, without drawing any current itself*. Since a negative grid repels electrons, no current flows in the circuit between grid and cathode of the tube, and hence no *power* is required from a voltage source applied to the grid. We shall have to say much more about this amplifying action and the amplification factor later on.

We have seen that a negative voltage on the grid tends to neutralize the effect of the positive plate voltage, and hence re-

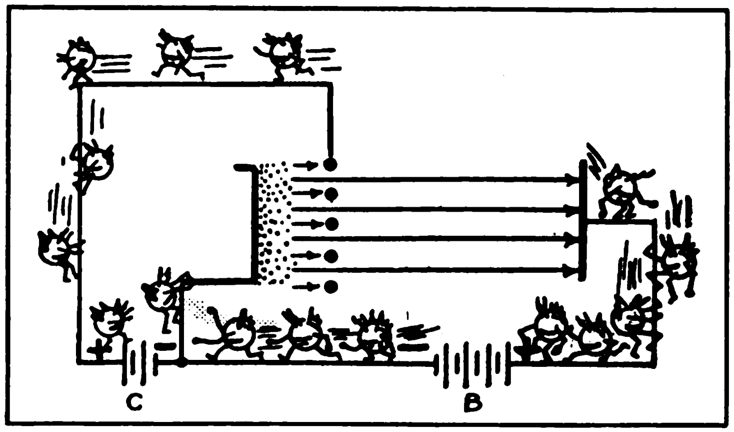



Fig. 4-7. Reversed field for positive bias and flow of grid current.

duce the flow of plate current through the tube. No matter how small a negative voltage is applied to the grid, the effect will be a reduction of plate current below the value which would exist if the grid were absent. Moreover, if the grid voltage is made sufficiently negative, it will completely overcome the effect of the positive plate voltage, and stop the flow of plate current entirely. The negative grid voltage required to cut off the plate current is called the *cut-off bias.* Its value depends on the plate voltage and the relative effectiveness of the grid over the plate called the *amplification factor.*

*Positive Voltage on Grid.* What happens if the voltage applied to the control grid is positive with respect to the cathode? Although this mode of operation is not frequently used, it warrants an explanation.

Reference to Fig. 4-7 shows that with the grid positive, its electrostatic field is reversed in direction (compared to Fig. 4-6), and it now aids the field due to the positive plate voltage. The electrons in the space charge are now acted upon by *two attracting fields,* one due to the positive grid and the other due to the positive plate. The net result of this combined action is two-fold. Electrons are attracted by both grid and plate, and pour in great numbers through the grid openings toward the plate. The effect of this is to increase the plate current far above the value which would have been possible with the grid absent. Another result of the positive grid voltage is that a substantial number of electrons which are attracted toward the grid, strike the grid wires and flow back to the cathode through the external circuit and *C*-battery.

This flow of electrons through the external circuit constitutes a *grid current* and a consequent loss of power in the grid-to-cathode circuit occurs.

The effect of a positive grid in increasing the plate current compared to the effect of the plate voltage, is similar to what was discussed for a negative grid. Since the grid is much closer to the space charge than the plate, a small positive voltage on the grid has a much greater effect in raising the value of the plate current than increasing the plate voltage by the same amount. As a matter of fact, the ratio of effectiveness of a positive grid over that of a positive plate in increasing the plate current is the same as was described for a negative grid; namely, the amplification factor. You will recall that its values depends on the dimensions and spacing of the grid and plate.

It would seem that increasing the value of the positive voltage applied to the grid would result in a steady increase in plate current, for the greater the positive grid voltage, the greater is the number of electrons drawn from the space charge to the plate. This is true, but only to a limited extent. As the positive grid voltage is increased, the plate current also increases — at first rapidly and then more slowly. With further increases in grid voltage, the plate current tends to flatten off, similar to the plate current of a diode at saturation. The reason for this flattening off is twofold. First of all, as the grid is made increasingly positive, it begins to draw a substantial grid current itself, diverting a large number of electrons from the plate current. Although the grid and plate current together (called the *space current*) may still be increasing rapidly, the *fraction* of the increase in grid current becomes larger, while that of the increase in plate current becomes smaller. Another reason for slower rate of increase in plate current is the tendency for saturation, especially if the plate voltage is large. With the grid voltage highly positive, and the plate voltage also fairly high, all the electrons emitted from the cathode may be drawn off to plate and grid. We shall later see that there may be additional reasons for the grid to draw a greater fraction of the space current, as the grid voltage is made more positive.

*Zero Voltage on Grid.* Figure 4-8 illustrates an arrangement where the grid is directly connected to the cathode, and hence is at zero voltage with respect to the cathode. What is the action under these conditions? It stands to reason that when the grid vol-

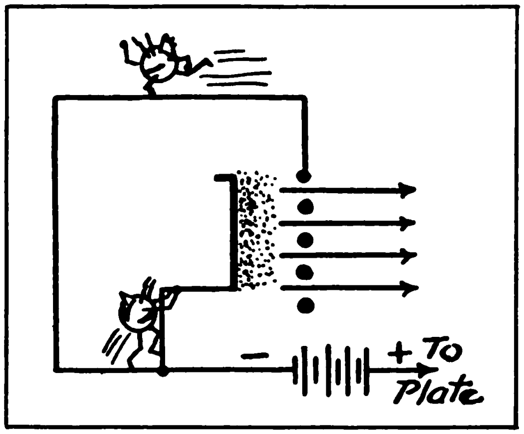



**Fig. 4-8. Even without bias, a few electrons on their way to the plate are intercepted by the grid and go into the input circuit.**

tage is zero, there can be no electrostatic field set up by the grid, and hence there is no repelling effect on the electrons in the space charge. In this case, the control grid contributes very little to the behavior of the triode. The fact that the grid is present, and acts as a rather ineffective wire shield, does have a slight retarding effect on the electrons traveling to the positive plate, and a small reduction in plate current results over the value which would exist without the grid. Furthermore, some of the electrons drawn over the plate are intercepted by the solid grid wires, giving rise to a slight grid current from grid to cathode, generally in the order of a few microamperes. However small, this grid current is generally considered undesirable, since it leads to a loss of power in the grid circuit and possible distortion.

*"Free" Grid.* While speaking about zero grid voltage, let us briefly refer to another condition which is frequently confused with it. This is the absence of an operating voltage on the grid, because the grid circuit is open (Fig. 4-9), and not connected to any other element. This condition is known as a "free" or "floating" grid. Assuming that proper emission takes place and a positive plate voltage is applied, a "free" grid creates a peculiar condition, which must be distinguished from the case where the grid is connected to the cathode.

With electrons being emitted, some are intercepted by the grid wires, just as in the case of zero grid voltage. In contrast to the previous case, however, the electrons which strike the metal portions of the grid have no place to go, and consequently, they lodge themselves or rest upon the grid. As electrons pile up on the grid, it assumes a negative charge. The amount of the negative charge on a free grid depends on the magnitude of the space charge, the plate voltage, the fields near the tube and possible leakage of electrons from the grid inside and outside the tube. Having a negative charge, the free grid has a repelling effect on electrons from the space charge, and substantially reduces the plate current over the value existing with zero grid voltage. For very low values of the plate and/or heater voltage, the accumulations of electrons on the grid and the resultant negative charge may become sufficiently large to reduce the plate current to a negligible quantity. Because of its erratic behavior, this type of operation is practically never employed.

*Summary of Control-grid Action.* As we have seen, the plate current in a triode is governed by the electrostatic field resulting from the combined action of the grid and plate voltages on the space charge. Since the grid is located closer to the space charge than the plate, the plate current is very effectively controlled by the grid voltage. With the grid voltage going negative, the plate current is reduced far more than a similar decrease in plate voltage would produce. At a sufficiently large value of the negative grid voltage, the plate current is completely cut off. With the grid voltage going positive, the plate current is increased by far more than a similar increase in plate voltage would produce. Furthermore, as the grid is made more positive, an increasing fraction of the total space current is diverted to the grid, resulting in undesirable grid current and a reduction in the rate of increase of plate current. With the grid at zero voltage, the plate current is reduced slightly over its value when the grid is absent, and a small amount of grid current is produced.

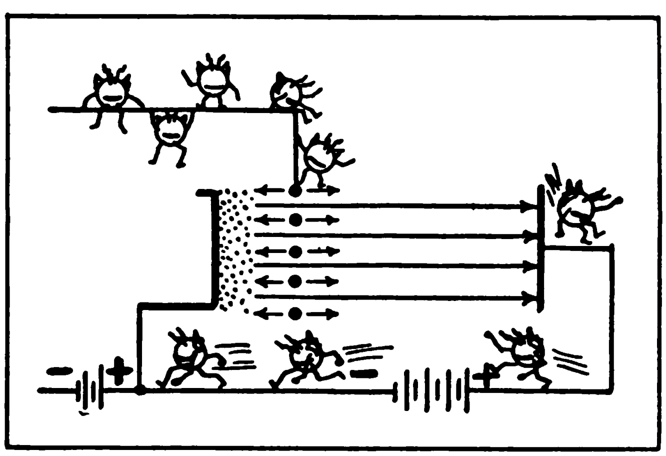


**Fig. 4-9. With a "floating" grid, electrons accumulate on the grid and charge it up negatively.**

The most important point to remember is the ability of the grid to control the flow of plate current without itself drawing any current (when the grid voltage is negative), or consuming power. A tiny change in grid voltage can produce a large change in resulting plate current, giving rise to a valve action or amplification.

## CHARACTERISTIC CURVES

We have discussed the action of a triode in a very general way, but have not given a quantitative picture by which different types of triodes are distinguished from each other. As in the case of diodes, the behavior which characterizes a particular type of triode is described in terms of *characteristic curves.* We recall that the basic factors controlling the plate current in a triode are the cathode temperature (or heater voltage), the plate voltage, and the control grid voltage. Since the cathode temperature (and voltage) is generally fixed at a value to provide sufficient emission for normal conditions of operation, we need not concern ourselves any further with it. The proper filament or heater operating voltage for all types of triodes is listed in available tube manuals.

This leaves the control grid voltage and plate voltage as the two variable factors which govern the amount of plate current flowing in a triode. Since these variables cannot be portrayed in a single curve at the same time, it is customary to show the relationships between grid voltage, plate voltage, and plate current by two types of characteristic curves: (1) the effect on the plate current caused by varying the grid voltage, while holding the plate voltage constant at a fixed value; this is the so-called *plate-current grid-voltage characteristic curve*: (2) the effect on the plate current caused by varying the plate voltage, while holding the grid voltage constant at a fixed value; this is the so-called *plate-current plate-voltage characteristic curve.* These two types of curves are the most important characteristics we shall have to deal with.

### Triode Circuit Notation

Before going into the details of triode characteristics, it is necessary to state briefly a consistent method of designating the

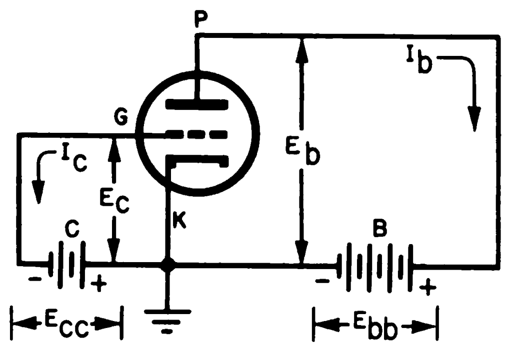



**Fig. 4-10. Basic triode circuit, showing d-c supply voltages and resulting currents.**

various currents and voltages by abbreviations or symbols. For the moment, we shall deal only with fixed or d-c voltages and currents at the various tube elements, while later we shall have to develop the appropriate notation for handling varying or a-c signals applied to the tube. Figure 4-10 shows the basic triode circuit for supplying the required operating voltages with the appropriate notations marked. (The heater voltage is not shown, since it is not a variable factor in developing the characteristics.) The explanation of these steady-state or d-c symbols is as follows:

$E_{bb}$ = the plate-supply voltage, also known as *B*-supply voltage.

$E_b$ = the total plate voltage between plate and cathode. (In Fig. 4-10, $E_b$ equals $E_{bb}$, since there is no voltage drop in the absence of a plate-load resistor.)

$I_b$ = the total, steady (or d-c) plate current.

$E_{cc}$ = the control grid supply voltage, grid bias, or *C*-supply voltage.

$E_c$ = the total grid voltage between grid and cathode. (In Fig. 4-10, $E_c$ equals $E_{cc}$, since there is no voltage drop in the absence of a grid resistor.)

$I_c$ = the total, steady (or d-c) grid current.

In general, capital symbol letters are employed when dealing with d-c (steady) voltages and currents.

## Static Plate-Current Grid-Voltage Characteristics

We shall discuss first the *static* characteristic curves of a triode, by which we mean the characteristics obtained when applying various steady voltages to the tube electrodes, but when neither an alternating input signal is applied to the grid of the tube, nor a load resistor is inserted in the plate circuit to obtain useful work from the tube. The construction of a static plate-current grid-voltage characteristic is a simple matter. The tube is operated at a fixed heater and plate voltage. We then apply different values of grid voltage to the tube, advancing from zero volts in both the positive and negative directions, and measure the plate current for each value of grid voltage. The data thus obtained is plotted on graph paper, laying out the grid-voltage scale (independent variable or cause) along the horizontal axis, and the plate-current scale (dependent variable or effect) along the vertical axis. The intersections of the various pairs of grid-voltage plate-current values determine the points of the characteristic curve, as we have explained previously in detail for the case of diode characteristics. After obtaining this particular static characteristic curve, we can pick another value of the plate voltage, repeat the whole procedure, and obtain a second characteristic curve. If we repeat this for a sufficient number of plate voltages, we shall eventually obtain the whole *family* of static grid-voltage plate-current characteristic curves for the particular type of triode used in the experiment.

*Tungsten Filament Characteristic.* Figure 4-11 shows a typical static plate-current grid-voltage characteristic together with the circuit used for obtaining it. The grid-voltage source, $E_{cc}$, is so arranged that varying values of grid voltage, either positive or negative, can be tapped off to the grid. A voltmeter between grid and cathode measures the applied grid voltage, while the plate current is measured by a milliammeter in the plate circuit. The plate voltage is held fixed at 100 volts.

Referring to the characteristic curve, it appears that plate current begins to flow when the grid voltage is about –6 volts. For voltages more negative than this value, the plate current is cut off entirely. As the control-grid voltage is made less negative, the plate current increases, but in a *nonlinear manner,* to about –2.75 volts on the grid. From about –2.75 volts up to about 0 volts grid voltage, the plate current rises in direct proportion to the reduction of the negative grid voltage. This is the straight or *linear portion* of the characteristics. As the control-grid voltage becomes increasingly positive, the plate current continues to increase, but again in a *nonlinear* manner. Beyond point *A* on the characteristic curve, the plate current begins to flatten off, and if the grid voltage is made still more positive, the current actually begins to decrease, as indicated by the dashed portion of the curve.

The characteristic curve tells the whole story of the tube's operation for the particular plate voltage (100 volts) we have

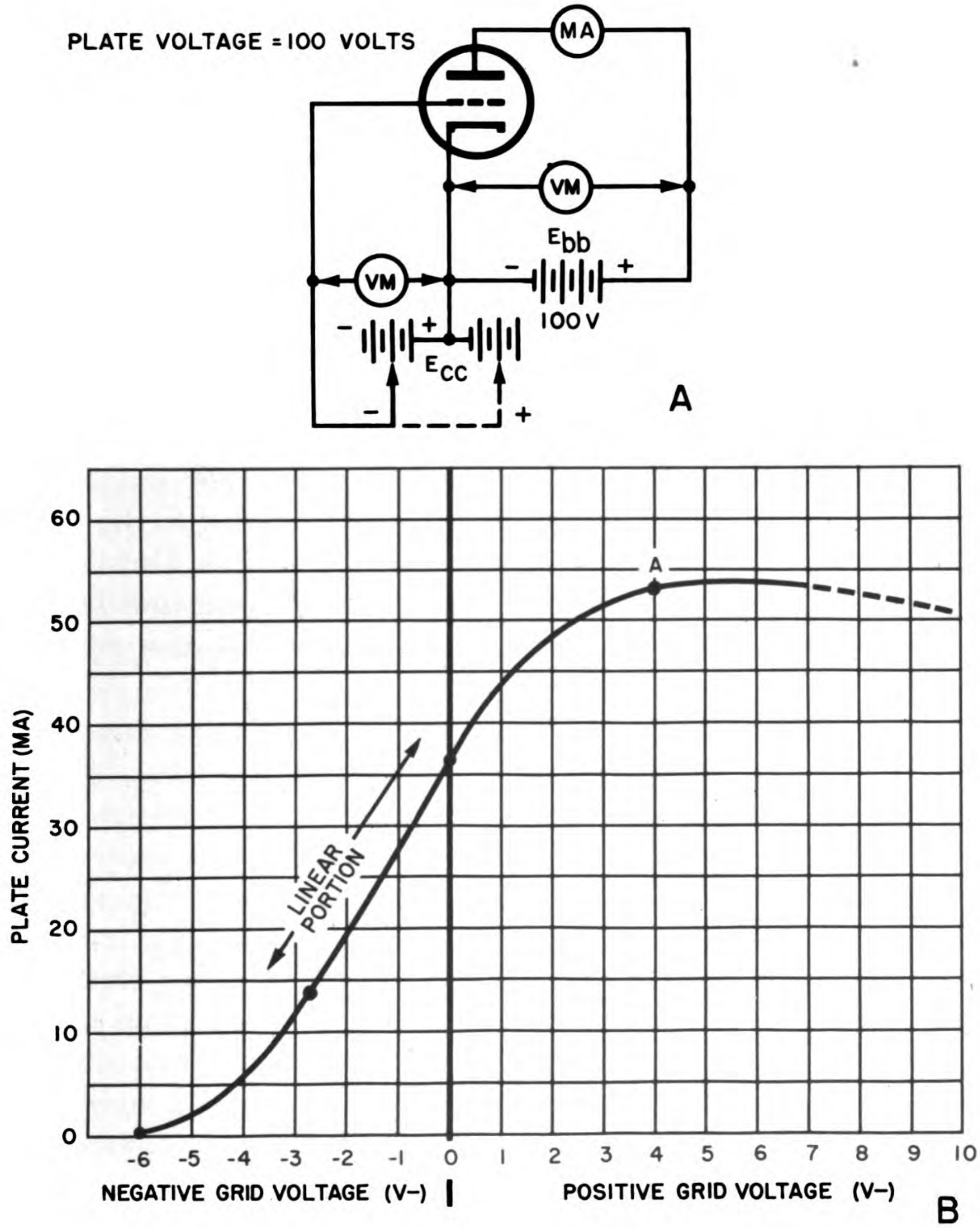



Fig. 4-11. Plate-current grid-voltage characteristic curve for a typical

chosen. It tells us that for grid voltages more negative than −6 volts, the plate current will be cut off, while the current reaches about 54 ma for a grid voltage +5 volts, and flattens off for higher grid voltages. For practical purposes, the tube is generally operated in the linear portion of the negative grid-voltage region from about −2.75 to 0 volts, since nonlinear operation results in distortion, as you may recall.

The flattening off and decrease of the plate current beyond point *A* on the characteristic deserves some comment. It is typical for tubes having tungsten filaments. You will remember that the supply of electrons emitted from a tungsten filament is not as copious as that supplied from an oxide-coated emitter, and that because of this, *saturation* sets in with tungsten emitters at high plate voltages. Even when the plate voltage is not extreme, saturation may set in at high positive grid voltages, when all the electrons emitted from the tungsten filament are drawn off to the plate. This is one reason for the levelling off of the plate current at high positive grid voltages. Another reason is the fact that at high positive grid voltages grid current begins to flow and diverts a substantial portion of the electrons normally moving to the plate. As the grid is made more and more positive, the total space current levels off due to saturation, and with the grid drawing an increasing fraction of the space current, the plate current may actually begin to decrease.

*Oxide-Coated Emitter Characteristic.* Figure 4-12 shows the plate-current grid-voltage characteristic curve for a triode having an oxide-coated (indirectly heated) emitter. You will note immediately on curve *A-B-C* that no plate current saturation occurs, even for high positive values of the grid voltage. Although the plate voltage is held constant at 100 volts for obtaining this curve; raising the plate voltage to higher values, would show the same condition; the plate current would continue to rise and no saturation would be noticeable. You may recall that oxide-coated emitters have such a profuse electron emission, that even at high plate or grid voltages there remains an ample supply of electrons to draw upon. Essentially, then, with oxide-coated emitters, the plate current is space-charge limited throughout the whole characteristic, and no saturation can be detected. If the plate voltage were made very high, saturation would eventually occur, but the tube would probably be damaged, or burn out, before this happened.

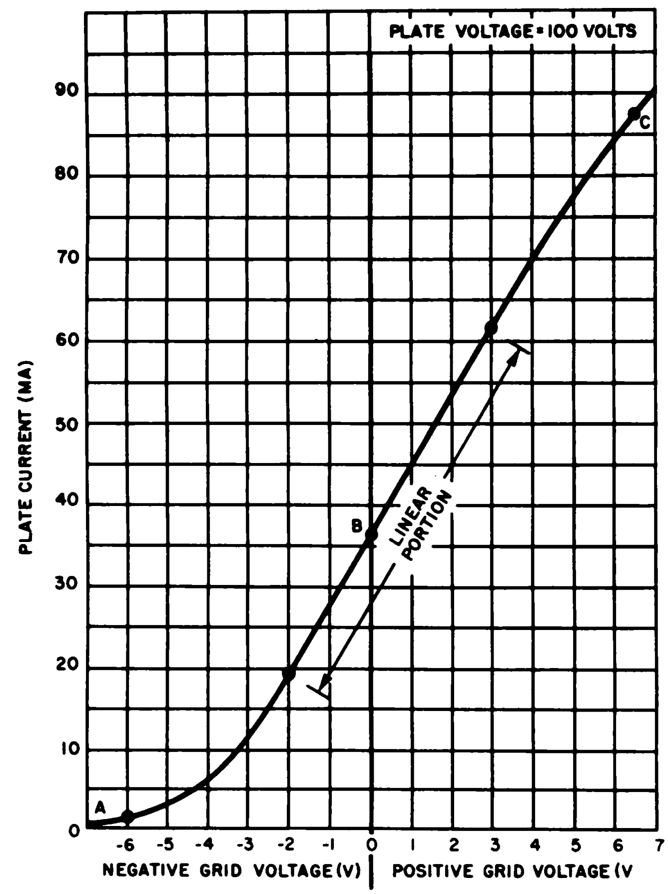



**Fig. 4-12. Plate-current grid-voltage characteristic curve for triode with oxide-coated cathode.**

The shape of the characteristic curve in the negative grid-voltage region is seen to be very much like that for the tungsten emitter triode. This is to be expected because the fundamental relationships between the tube electrodes, when a full space charge is present, are the same for both types of tubes, regardless of the type of emitter. It is also apparent that because of the absence of plate-current saturation, the oxide-coated emitter characteristic is linear over a substantial portion, including part of the positive grid-voltage region. This is one of many reasons why oxide-coated tube types are preferred for practically all receiving applications. Nevertheless, the tube is usually *not* operated in the positive grid-voltage region, since grid current does flow, leading to a loss of power in the grid circuit, which is undesirable for voltage amplification applications.

## Grid Family of Characteristic Curves

A number of static plate-current grid-voltage characteristic curves, each obtained for a different value of the plate voltage, is

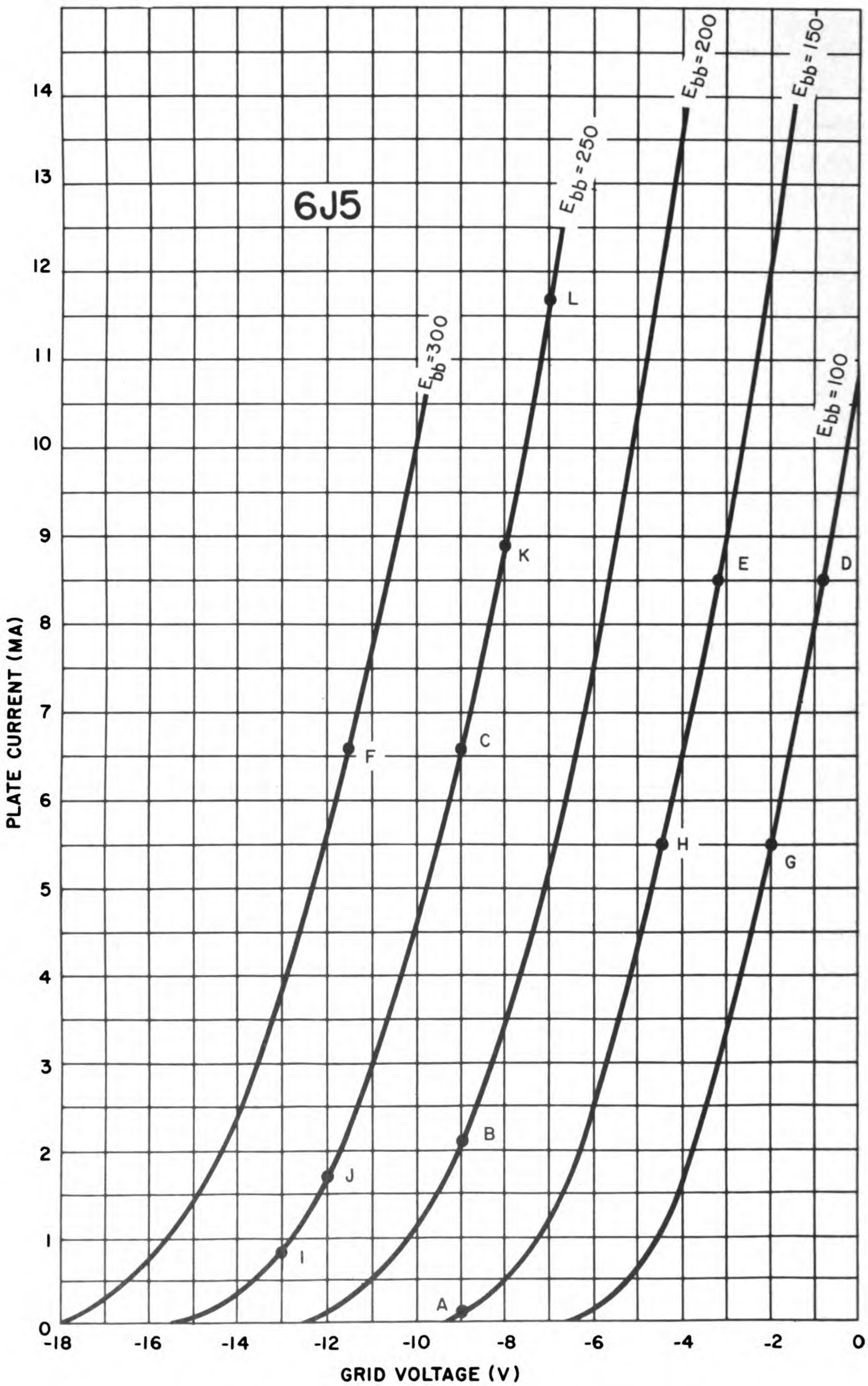



Fig. 4-13. Grid family of characteristic curves for 6J5 triode.

usually referred to as the *grid family* of characteristic curves, or the *static transfer characteristic*. Essentially, each of these curves is like that of Fig. 4-11 or 4-12, but when a number of these curves are correlated into a family, far more information can be secured than is possible with one individual curve.

A grid family of characteristic curves is shown in Fig. 4-13 for a type 6J5 tube, which is typical of many receiving triodes. As is evident, the curves are not carried into the positive grid-voltage region. For most triode applications, the grid is not driven into the positive region to avoid grid current, and hence the curves do not have to be extended into this region. The general appearance of the curves is similar to that of Fig. 4-12. The circuit used to develop the data shown in Fig. 4-13 is similar to that of Part (A) in Fig. 4-11, except that the plate voltage, $E_{bb}$, is made variable over a considerable range. The curves are obtained in the same way as previously explained for each fixed value of the plate voltage.

*Interpretation of Curves.* It is apparent that there is a close similarity between the general shape of the characteristic curves. Each has a linear and a nonlinear part. Furthermore, each plate-current curve has a cut-off point on the grid-voltage axis, showing the negative grid voltage required to stop the flow of plate current. It can be seen that the value of the negative bias required to cut off the plate current is increased as the plate voltage increases. For example, only −6.5 volts grid bias is required to cut off the plate current when the plate voltage is 100 volts, whereas −12.6 volts are required when the plate voltage is increased to 200 volts.

The grid family further discloses an increase in plate current for an increase in plate voltage when the grid bias voltage is held constant. For example, −9 volts bias (point *A*) results in 0.1 ma plate current with 150 volts applied to the plate, while a 2.1-ma plate current (point *B*) flows when the plate voltage is increased to 200 volts, and a 6.55-ma (point *C*) plate current flows with 250 volts applied to the plate.

You can determine from the grid family, the amount of grid voltage change required to offset a change in plate current because of a plate voltage change. This graphically illustrates the interaction between the various electrostatic fields within the tube, which we have discussed previously in a general manner. For example, point *D* in Fig. 4-13 corresponds to 8.5 ma plate current with a negative bias of 0.8 volt and a plate voltage of 100 volts. If the plate voltage is increased to 150 volts, what must be done to the bias to hold the plate current constant at 8.5 ma? It is evident from the family of curves, that the plate current can be held at 8.5 ma if the negative bias is increased to −3.2 volts (point *E*). This shows, then, that a plate-voltage increase of 50 volts is offset by an increase in grid bias of 2.4 (3.2 −0.8) volts. Similarly, points *C* and *F* for 6.55 ma plate current show that an increase in bias of 2.5 volts (from −9 to −11.5 volts) is able to offset a plate voltage increase of 50 volts.

The grid family may also be worked in reverse fashion. You can find out how much to change the plate voltage to offset a change in grid voltage if the plate current is to be held constant. For example, starting with point *G*, representing 5.5 ma plate current for −2 volts bias and 100 volts on the plate, what must be done to the plate voltage to hold the plate current constant at 5.5 ma if the bias is increased to −4.5 volts? A vertical projection from the −4.5 volt bias point to 5.5 ma plate current intersects the 150-volt plate-voltage curve at point *H*. This shows that the plate voltage must be increased by 50 (from 100 to 150) volts for a change in grid bias of 2.5 (from −2 to −4.5) volts, in order to hold the plate current at a constant value.

You can get still more information from the grid family of characteristic curves. You may determine, for example, the change in plate current for a given change in grid voltage at different operating regions of a particular plate-voltage curve. Depending on the linearity of the curve, we know that this is not always the same. For example, on the 250-volt plate-voltage curve, a bias change of 1 volt from −13 to −12 volts (points *I* and *J*), produces a plate-current increase of 0.9 ma (from 0.8 to 1.7 ma). The same 1-volt grid bias change higher up on the curve from −8 to −7 volts produces a plate-current change of 2.8 ma, going from 8.9 ma to 11.7 ma (points *K* and *L*).

If the same 1-volt change had been tried in different operating regions of the 300-volt plate-voltage curve, a greater change in plate current would have resulted. On the other hand, if the 1-volt bias change is tried on the 200-volt plate-voltage curve, it results in a smaller plate-current change. You can find this out for yourself, by plotting the −7 and −8 volt bias points on the 200-volt curve. It turns out that the plate current changes from 3.5 ma at –8 volts to 5.3 ma at –7 volts, or an increase of only 1.8 ma, as against the increase of 2.8 ma obtained on the 250-volt plate-voltage curve. We shall see later on that it is generally true for any type of vacuum tube, that at higher plate voltages a greater change in plate current is obtained for a given change in grid voltage. All these illustrations demonstrate convincingly the importance of choosing a correct *operating point* for the tube along the plate-current grid-voltage characteristic curves.

**Static Plate-Current Plate-Voltage Characteristics**

Having dealt with the grid voltage as the variable factor, we shall now make the plate voltage the variable quantity while holding the grid voltage fixed at different values. The circuit used

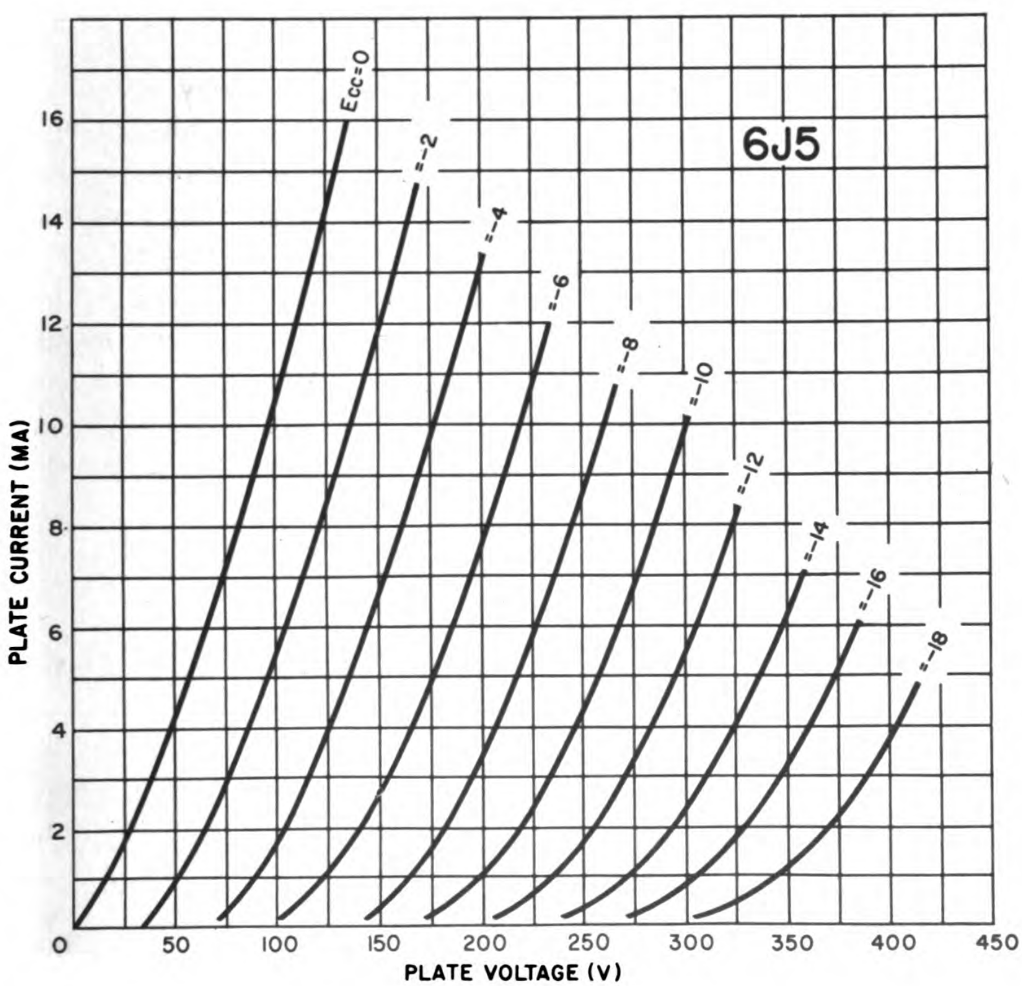



**Fig. 4-14. Plate family of characteristic curves for 6J5 triode.**

to obtain the resulting plate-current plate-voltage characteristics is the same as that employed in (A) of Fig. 4-11, except that the plate-supply voltage is made continuously variable. Figure 4-14 shows a *static plate family* of characteristics for the same 6J5 triode, obtained by a series of measurements with the circuit of Fig. 4-11 (A). Each characteristic curve covers a continuously variable range of plate voltage for a fixed grid voltage. Adjoining curves are obtained by changing the grid voltage in steps of 2 volts (from 0 to −18 volts), and repeating the plate-current measurements for a plate-voltage range of about 135 volts. Each curve starts at a point along the plate-voltage axis where the negative grid bias causes plate-current cut-off, and is carried to the maximum permissible plate-voltage plate-current combination which the tube can handle. (The power rating of the tube is determined by the product of plate voltage and plate current, and is fixed at a certain maximum value.)

In general, the grid family and the plate family of characteristics furnish the same information about the tube, but in slightly different forms. The grid family displays the effect on the plate current of a continuous variation in grid voltage and fixed differences in plate voltage, while the plate family displays the effect on the plate current of a continuous variation in plate voltage and fixed differences in grid voltage. If you have either complete family for any tube, it is a rather simple matter to plot the complementary family of characteristics from the same data. Both types of families present the relationships between the triode electrode voltages under static conditions.

### Tube Constants

Now that you have been introduced to the two basic families of characteristic curves, we are ready to deal with more specific information which these curves can supply. The families of curves which show the characteristic manner in which each tube behaves are not a result of accident. Rather they exhibit the outcome of purposeful design to give the tube specific characteristics and make it behave in a certain way. The design takes into account the geometric organization of the tube's electrodes, the spacing between them, their dimensions, power dissipation capabilities, and many other factors. It is these factors which determine the maximum voltages which can be applied to the electrodes, the maximum permissible plate current through the tube, the conditions for plate-current cut-off, as well as other tube ratings. The design factors of the tube are expressed by a group of numbers, known as the *tube constants.*

The tube constants are based partly on the geometrical design of the tube. We have seen, for example, that the *amplification factor* is a measure of the relative effectiveness of the control grid in overcoming the electrostatic field of the plate, and that this factor depends to a large extent on the spacing between the grid and plate electrodes. Since the geometry of the tube is known, the tube constants can be mathematically predicted for each type of tube, before it is put into operation. However, a more accurate and practical way of determining the tube's constants is to obtain them from the actual performance of the tube, as measured or displayed in the family of characteristic curves. The three most important tube constants which we shall determine in this way are the *amplification factor,* the *a-c plate resistance,* and the *transconductance* (sometimes also called *mutual conductance*).

#### Amplification Factor

The amplification factor expresses numerically how much greater the effect is that the electrostatic field of the control grid exerts upon the space charge than that exerted by the electrostatic field set up by the plate (assuming that the same value of voltage is used on both electrodes). It thus shows the effectiveness of the grid voltage in controlling the plate current compared with that of the plate voltage. This relative effectiveness in plate-current control could be measured by changing the grid voltage by a certain amount, and recording the change in plate current which occurs, and then changing the plate voltage by an amount just sufficient to restore the previous plate current. The ratio of the required change in plate voltage to the change in grid voltage to keep the plate current at a constant value, would then show the relative effectiveness of the two electrode voltages, or simply the amplification factor. Accordingly, we define the amplification factor by the formula:

$$\text{amplification factor} = \frac{\text{small change in plate voltage}}{\text{small change in grid voltage}}$$

*for the same change in plate current.* The changes have to be small, since the nonlinear tube characteristics would lead to erroneous results for large changes. Using the system of abbreviations we devised for the plate resistance of a diode (in Chapter 3), we may rewrite the above formula for amplification factor, as follows:

$$\mu = \frac{\Delta\ e_b}{\Delta\ e_c} \text{(with } i_p \textit{ constant)}$$

where the Greek letter $\mu$ (pronounced "mu") stands for the amplification factor

$\Delta\ e_b$ = a small change in plate voltage
$\Delta\ e_c$ = a small change in grid voltage

(We use small letters for the plate and grid voltages, since changing or alternating quantities are involved. As in the last chapter, the symbol $\Delta$ indicates *a small change in.*)

The amplification factor, $\mu$, is a pure number and has no reference to any units. Thus a tube may have a $\mu$ of 10, which means that a change in grid voltage is ten times as effective in controlling the plate current as the same change in plate voltage. To illustrate further, suppose that a plate-current change of 1 ma is produced by a plate-voltage change of 10 volts, and that a grid-voltage change of only 0.1 results in the same 1-ma plate-current change. Then the amplification factor is:

$$\mu = \frac{\Delta\ e_b}{\Delta\ e_c} = \frac{10v}{0.1v} = 100$$

Only the *changes* in plate and grid voltage are important, not their individual values. It is apparent where the amplification factor derives its name If the $\mu$ is 10, for example, a changing voltage on the grid of the tube (that is, an input signal) will be ten times as effective in producing plate-current changes, than a changing voltage of equal magnitude on the plate of the tube. Thus, the grid-voltage changes are *amplified* by a factor of ten in their effect on the plate current, as compared with equal plate-voltage changes.

*Finding the Amplification Factor from the Grid Family.* The amplification factor can be obtained either from the grid or the plate family of characteristic curves. We shall first use the grid family, shown in Fig. 4-15, which is the same as that of Fig. 4-13 for the 6J5 tube. Assume that it is desired to find the amplification factor of the 6J5 when it is operated with 250 volts on its

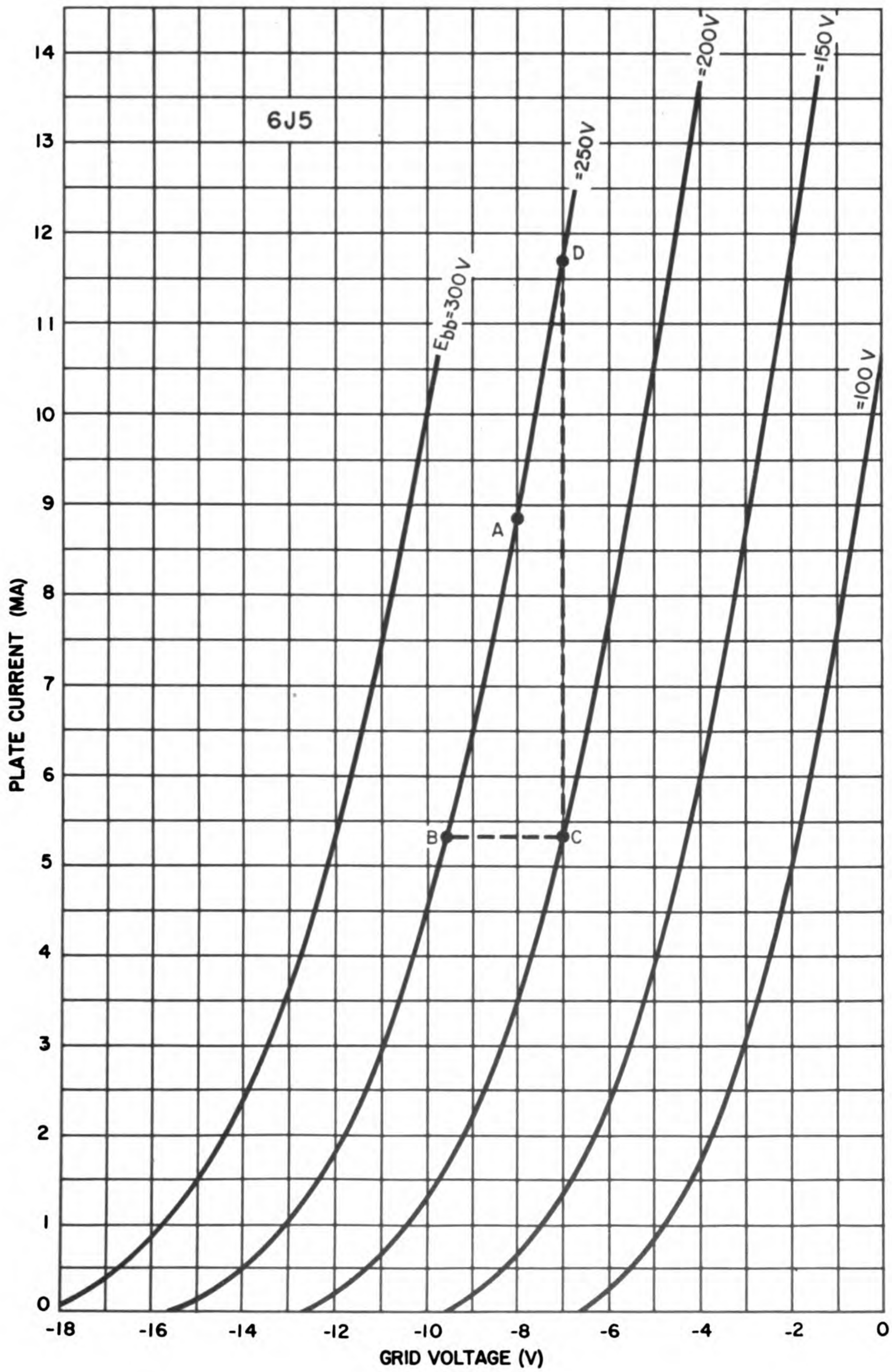



Fig. 4-15. Determination of amplification factor from grid family.

plate and –8 volts on the grid, corresponding to point $A$ in Fig. 4-15. Since we are interested in determining $\mu$ near point $A$, we select some convenient point, such as $B$, on the 250-volt curve for the grid-voltage change. For a convenient plate-voltage change, we draw a horizontal line from $B$ on the 250-volt curve until it intersects the adjoining (200-volt) plate-voltage curve at point $C$. To determine the plate-current change for this 50-volt plate-voltage change, while holding the grid voltage constant, we draw a vertical line from point $C$ along a constant grid voltage (–7 volts), until it intersects the 250-volt plate-voltage curve again at point $D$. This completes the construction.

To interpret this experiment on paper, assume that we started at point $B$ with a plate voltage of 250 volts, a plate current ot 5.35 ma, and a grid voltage of 9.6 volts. We then changed the grid voltage, while holding the plate voltages constant, moving upward on the 250-volt curve past point $A$ (the desired operating point) until we reached point $D$ for a grid voltage of –7 volts, and plate current of 11.7 ma. Thus a grid-voltage change of 2.6 (9.6 –7) volts produced a plate-current change of 6.35 (11.7 –5.35) ma. To return the plate current to its previous value of 5.35 ma, while holding the grid voltage constant, we must obviously reduce the plate voltage. Hence we move downward from point $D$ along the –7 volt grid voltage curve, until the plate current is again 5.35 ma. This occurs at point $C$ for a plate voltage of only 200 volts. Thus we note that the same 6.35 ma plate-current change (from 11.7 to 5.35 ma) was produced by a 50 volt change in plate voltage, as had previously been produced by a grid voltage change of only 2.6 (9.6 –7 volts). In other words to keep the plate current constant at 5.35 ma, a 2.6-volt reduction in the negative grid bias must be offset by a 50-volt reduction in the positive plate voltage. Hence, by our previous definition, the amplification factor is:

$$\mu = \frac{\Delta\, e_b}{\Delta\, e_c} = \frac{50}{2.6} = 19.2 \text{ (near the operating point } A.)$$

We might have obtained a more accurate value for $\mu$, if we had used much smaller changes in plate and grid voltage near point $A$. Because of the nonlinearity of the characteristics, the "constant" $\mu$ is not the same everywhere on the characteristics. However, our value of 19.2 compares very well with the value of

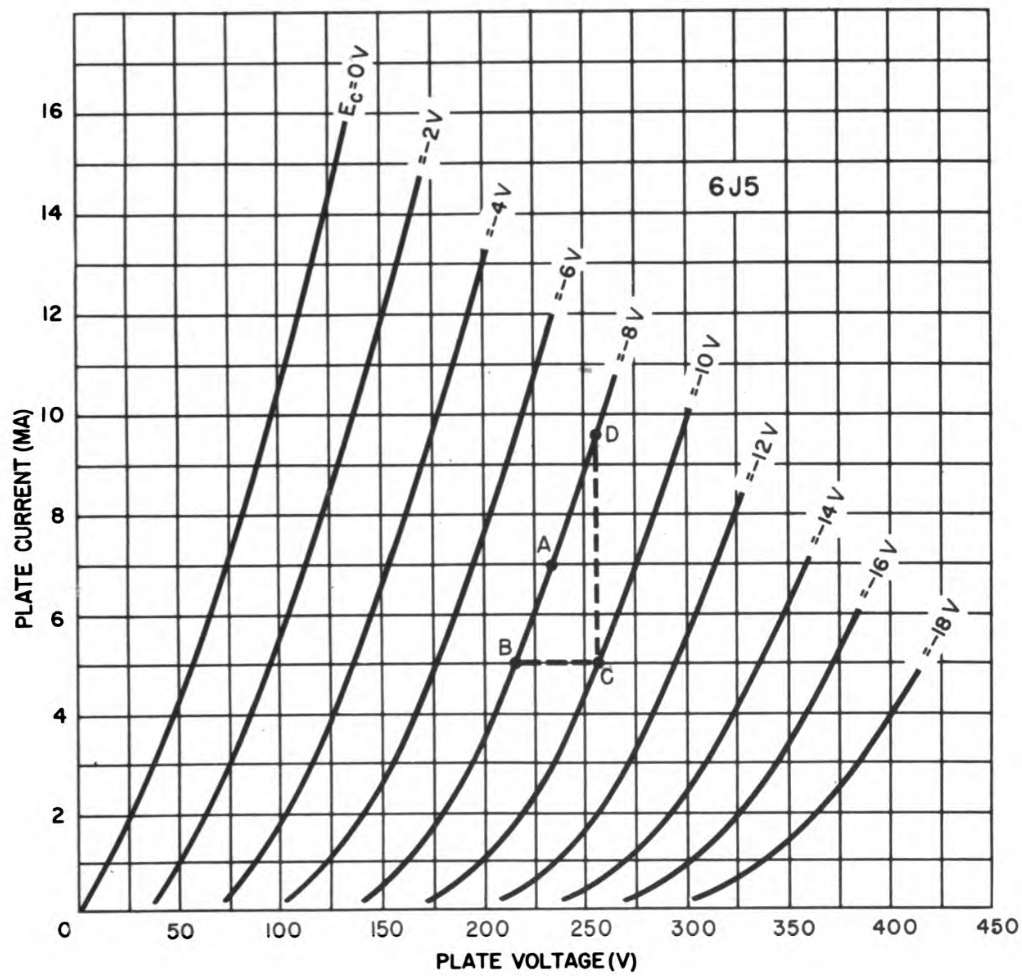



**Fig. 4-16. Determination of amplification factor from plate family.**

20 for the amplification factor of the 6J5, stated in the manufacturer's literature.

*Finding $\mu$ from the Plate Family.* The amplification factor may also be determined from the plate family of characteristics, which are more frequently available in manufacturer's literature than the grid family. The simple construction is shown in Fig. 4-16, which shows the same plate family for the 6J6 tube as Fig. 4-14. Suppose, we want to find the amplification factor near point *A* in Fig. 4-16, for a grid voltage of —8 volts, a plate current of 7 ma, and a plate voltage of about 235 volts. First, we move down on the —8 volt curve to a convenient point *B*. We draw a horizontal line from point *B* (along a constant plate current of 5 ma) until it hits the next grid-voltage curve ( —10 volts) at point *C*. We then draw a vertical line for constant plate voltage, until it intersects the –8 volts grid-voltage curve again at point *D*.

This construction may be interpreted as follows: Moving from point *B* to *C* along the –8 volt curve, we have kept the grid voltage constant, but have increased the plate voltage from 214 volts to 255 volts, or a change of 41 volts in plate voltage. At the same time the plate current has increased from 5 ma to 9.6 ma. To return the plate current to its previous value of 5 ma, while keeping the plate voltage constant, we increased the negative grid voltage from –8 volts at point *D* to –10 volts at point C, by moving along the vertical line of constant plate voltage from *D* to *C*. Hence, a 2-volt change in grid voltage had the same effect on the plate current as the 41-volt change in plate voltage. Therefore, the amplification factor is:

$$\mu = \frac{\Delta\, e_b}{\Delta\, e_c} = \frac{41}{2} = 20.5$$

which is substantially in agreement with the previously obtained value, as well as the one given by the manufacturer. (Note that if the operating points chosen had been exactly the same and if we could have read both graphs with the same degree of accuracy, *identical* results would have been obtained.) The value is somewhat more accurate this time, because we have used smaller increments in plate and grid voltage. Of course, if we did not have either the plate or the grid family of characteristics, we could still have obtained the value of the amplification factor by simply performing the measurements indicated in the above data.

*Triode Amplification Factors.* Triodes are often classified according to the value of their amplification factor into *low-mu* triodes, *medium-mu* triodes, and *high-mu* triodes. In a low-mu triode, the amplification factor is less than 10 (such as type 2A3), in a meduim-mu triode it is between 10 and 30 (such as type 6J5), and in a high-mu triode the amplification factor is more than 30, and may be as high as 100 or more (type 6SF5 has a $\mu$ of 100). In some special tubes the amplification factor varies with the applied grid bias; these tubes are known as *variable-mu* tubes.

### Plate Resistance

The plate resistance is a tube constant which describes the *internal resistance* or opposition of the tube to the flow of electrons from cathode to plate. The type of emitter, the space charge, the dimensions of the various electrodes are among the factors which determine its value. As we have discussed for diodes (In Chapter 3), there are two types of plate resistance: one for dc and one for ac. The d-c plate resistance signifies the internal opposition to electron flow when *steady* values of voltage are applied to the tube electrodes, and it is determined simply by an application of Ohm's law:

$$R \text{ (ohms)} = \frac{E \text{ (volts)}}{I \text{ (amperes)}}$$

In the case of a triode, the d-c plate resistance can be determined at any point of the plate-current characteristic, and the above equation in this case becomes:

$$\text{D-c plate resistance } (R_p) = \frac{E_b}{I_b} \text{ (ohms)}$$

Suppose you want to find the d-c plate resistance at point M of Fig. 4-17, which show again the plate-current plate-voltage characteristic of the 6J5 tube. At this point the plate voltage is 250 volts, the grid voltage is –8 volts, and the plate current is 8.9 ma, or 0.0089 amps). Hence, by Ohm's law, $R_p$ is 250/0.0089, or 28,100 ohms. Again, if the plate resistance at point *N* of Fig. 4-17 is required, simply divide the plate voltage of 225 volts by the plate current of 6 ma (0.006 amp) to obtain a plate resistance of 37,500 ohms at this point. As a final example, the plate resistance at point *0,* where the plate voltage is 195 volts and the plate current is 3 ma, is 195/0.003, or 65,000 ohms. (You may ignore the various triangles in Fig. 4-17; they are used for determining the a-c plate resistance.)

*Finding the A-C Plate Resistance.* The a-c plate resistance of a triode (or any tube, in general) is the internal opposition of the tube to the flow of plate current, when varying or a-c voltages are applied to the electrodes. It is measured by the small change in plate current occuring when the plate voltage is changed by a small amount, while the *grid voltage is kept at a constant value.* In the form of an equation, this may be expressed as follows:

$$\text{a-c plate resistance } (r_p) = \frac{\Delta\, e_b}{\Delta\, i_b} \text{ (with } e_c \text{ constant)}$$

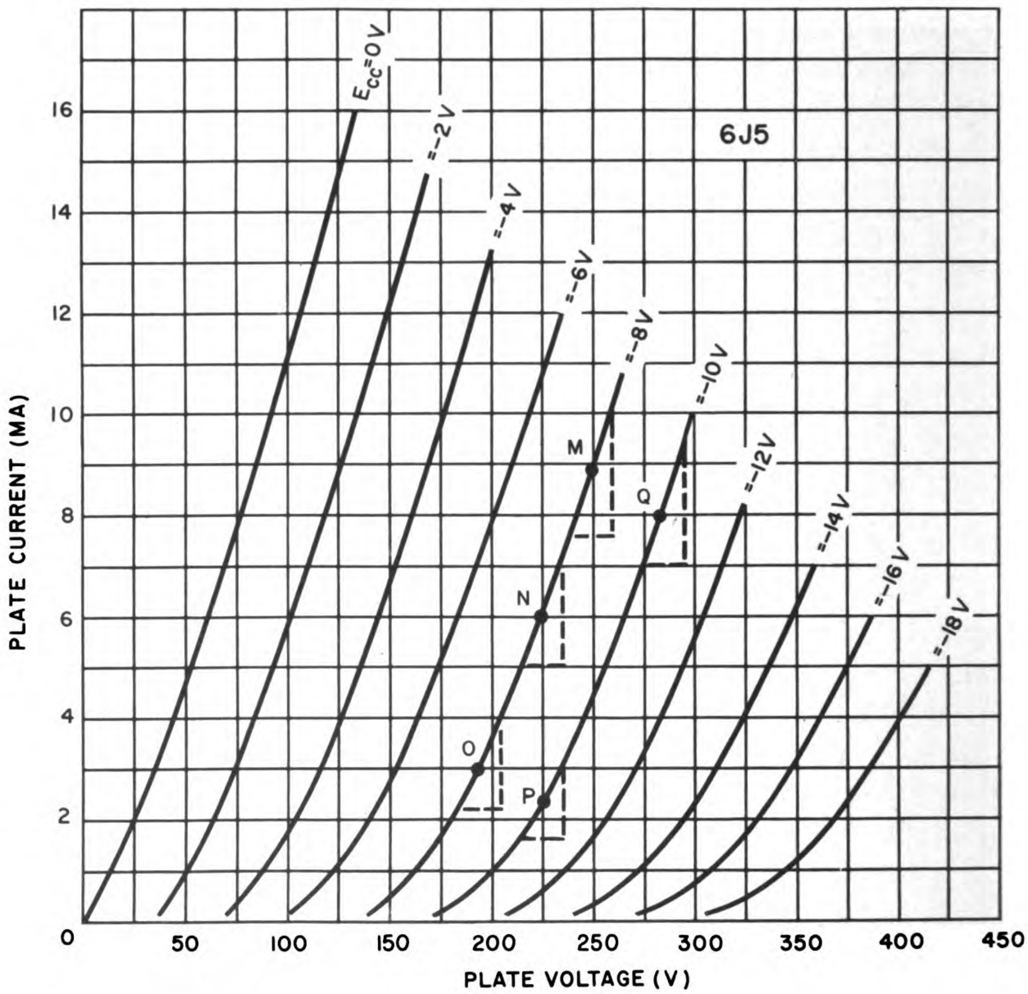



Fig. 4-17. Determining plate resistance of 6J5 triode from plate family.

Again small letters are utilized to indicate varying quantities. Whenever the term *internal plate resistance* is employed, the a-c plate resistance of the tube is invariably meant; it is also sometimes referred to as the *plate impedance* of the tube.

Finding the a-c plate resistance from the plate family of curves in Fig. 4-17 is somewhat more involved than for the d-c resistance, but it is not difficult. Imagine you want to find the plate resistance at point *Q* of Fig. 4-17, where the grid voltage is −10 volts, the plate voltage is 285 volts and the plate current is 8 ma. Using Ohm's law, the *d-c plate resistance* at this point is simply 285/0.008, or 35,625 ohms. To find the *a-c plate resistance* we must vary the plate voltage above and below point *Q*. Assume we vary the plate voltage by 20 volts around point $Q$, from 275 volts to 295 volts. We, therefore, draw a horizontal line from the $-10$ volt curve at the 275-volt plate-voltage point to the 295-volt plate-voltage point. But, since we are interested in finding out what happens to the plate current while keeping the grid voltage *constant,* we now draw a *vertical* line for 295 volts plate voltage back to the $-10$ volt grid-voltage curve. The two intersections with the $-10$ volt curve show that the plate current has changed from 7 ma for 275 volts on the plate to 9.4 ma for 295 volts on the plate, or a change of 2.4 ma in plate current for a 20-volt change in plate voltage, with the grid voltage fixed at $-10$ volts. Consequently, the a-c plate resistance is:

$$r_p = \frac{\Delta\, e_b}{\Delta\, i_b} = \frac{295-275}{0.0094-0.007} = \frac{20}{0.0024} = 8{,}333 \text{ ohms}$$

This value does not agree exactly with the manufacturer's rating of 7,700 ohms, but is sufficiently close for practical purposes. Discrepancies in a-c plate resistance calculations must be expected, since the resistance is a function of the operating point along any particular grid-voltage characteristic. To illustrate this point, the a-c plate resistance has been calculated at three different points, *M, N,* and *O* along the $-8$ volt grid-voltage curve in Fig. 4-17, as indicated by the triangles. Each of these points presents a different condition of operation which may be used in practice. The plate voltage has been changed by 20 volts around each of these points, and the resulting plate-current changes were determined from the curves by the method just discussed. If you carry through the calculations, you will discover that the a-c plate resistance at point *M* turns out to be about 8,300 ohms, that at point *N* equals about 10,000 ohms, the a-c plate resistance at point *O* is about 11,100 ohms, and the a-c plate resistance at point *P* (on the $-10$ volt curve) is about 14,000 ohms.

A comparison of the a-c plate resistance calculations at points *M, N, O,* and *P* of Fig. 4-17 leads us to the following conclusions, which happen to be generally true for all types of triodes: As the applied plate voltage is increased, the a-c plate resistance decreases (compare points *O, N,* and *M.*) Furthermore, a reduction in the negative grid voltage (or an increase in the positive voltage) is also accompanied by a decrease in the a-c plate resistance (compare point *P* with point *N.*) From this it would appear that several values of the a-c plate resistance would have to be given in the ratings. This is not so, however. In practice, the manufacturer states the a-c plate resistance for a typical set of operating conditions, for normally rated plate and grid voltages.

### Transconductance (Mutual Conductance)

We have seen that changing either the plate voltage or the grid voltage, or both, causes changes in the plate current. We have further shown that changes in plate voltages are related to changes in plate current by the plate resistance of the tube, with the grid voltage held constant. We shall now introduce the tube constant which relates *changes in plate current to changes in grid voltage,* while the plate voltage is held constant. This tube constant is known as the *transconductance* or *mutual conductance* of the tube.

Transconductance is abbreviated by the symbol $g_m$, and it is defined as the ratio of a small change in plate current to the small change in grid voltage which produced it, *with the plate voltage held constant.* In the form of an equation, the transconductance is:

$$g_m = \frac{\Delta\ i_b}{\Delta\ e_c}\ \text{(with } e_b \text{ constant)}$$

Since $g_m$ is the ratio of a current to a voltage, it has the form of a conductance and may be interpreted as the ampere change in plate current per volt change in grid voltage. The unit of transconductance is the *mho* (*ohm* spelled backward), but since this unit is too large for vacuum tube usage, the *micromho,* ($\mu$mho) or the millionth part of a mho, is generally used. By multiplying mhos by 1,000,000, micromhos are obtained. A vacuum tube, in which a one-volt change in grid voltage produces a 1-ma change in plate current, has a transconductance of 1,000 micromhos (0.001 amp/1 volt, times 1,000,000). The transconductance is often stated as a number without units, in which case micromhos are implied.

*Finding Transconductance from the Plate Family.* Since plate families of characteristics are more readily available than grid families, we shall show how to find the $g_m$ from the plate family, although it may be found equally well from the grid family. Suppose it is desired to find the transconductance of the 6J5 from the plate family at an operating point $A$ (Fig. 4-18), where the grid

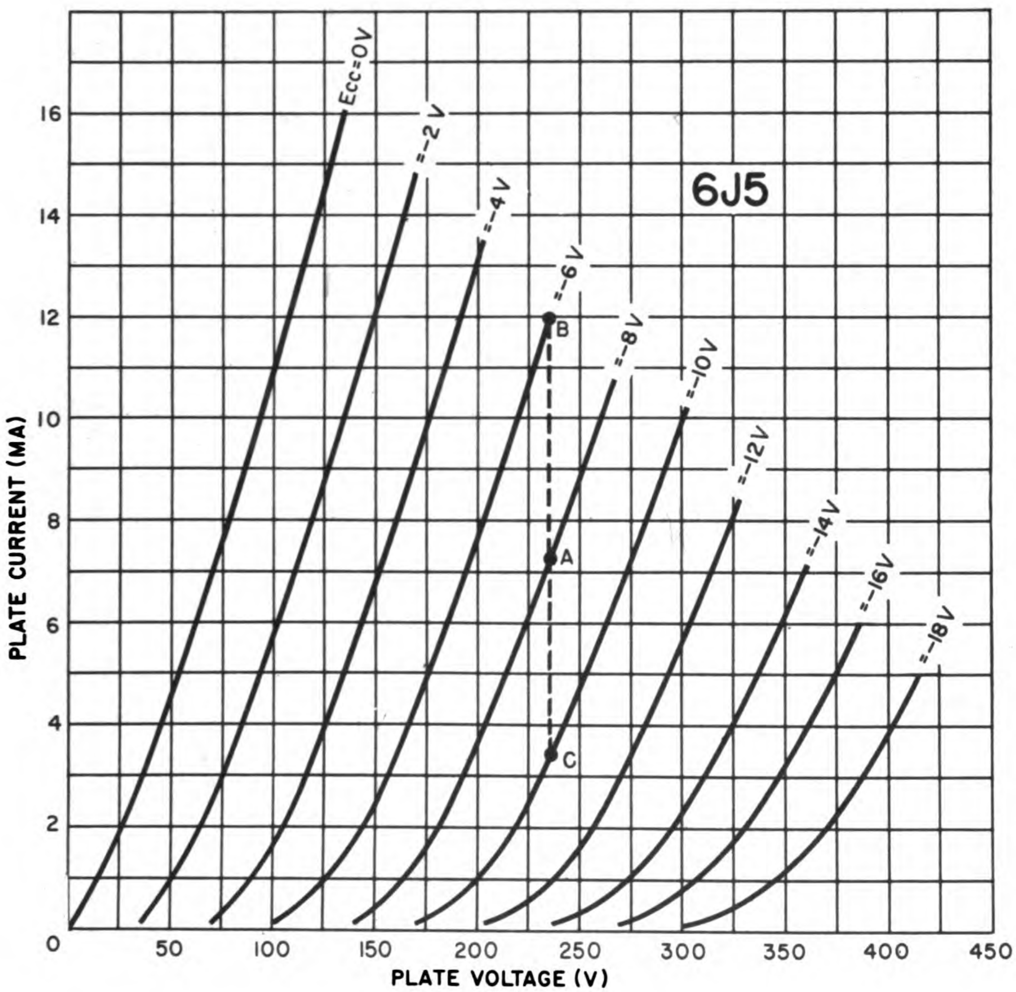



**Fig. 4-18. Use of plate family of curves to determine transconductance of 6J5 triode.**

voltage is —8 volts, the plate current is 7.2 ma, and there are 235 volts on the plate. Since by the definition of transconductance, we want to find the change in plate current resulting from a change in grid voltage while holding the plate voltage constant, we can project from point *A*, upward and downward along a line of constant plate voltage, to adjacent grid-voltage curves. At point *B*, the plate current is 12 ma for the grid voltage of —6 volts (the plate voltage remains constant at 235 volts), and at point *C* the plate current is 3.5 ma for the grid voltage of —10 volts (plate voltage still 235 volts). Consequently, the transconductance is:

$$g_m = \frac{\Delta\, i_b}{\Delta\, e_b} = \frac{0.012 - 0.0035}{10 - 6} = \frac{0.0085}{4} = 0.002125 \text{ mho,}$$

$$\text{or } 2{,}125 \text{ micromhos.}$$

This is equivalent to a 2.125 ma per volt (abbreviated ma/v) change in plate current. The manufacturer states the value of $g_m$ for the 6J6 to be 2,600 micromhos, which is in fair agreement with the value we have calculated. The discrepancy is due to the non-linearity of the grid-voltage curves, the largeness of the changes in current and voltage used in the example, and to the fact that a somewhat different operating point was chosen for the calculation. In general, the transconductance of a triode increases at higher plate voltages, or at less negative grid voltages.

*Importance of Transconductance.* By revealing the effectiveness of the grid in securing changes in the plate current, and hence in a signal output, the transconductance proves to be the most important of the three tube constants. The transconductance is frequently used as a "figure of merit" for comparing different tubes in the same general classification. A tube with a transconductance of 2,000 is better than one rated at a transconductance of 1,000, since the tube with the higher value of $g_m$ is capable of furnishing a greater signal output with the same signal input, and in the same circuit. Many tube testers compare the value of $g_m$ of a tube with its rated value when new, to determine whether the useful life of the tube is over. However, it is a good idea to keep in mind that the use of the transconductance for comparing the relative merit of different tubes, is appropriate only for tubes intended for the same general service.

### Relation Between $\mu$, $R_p$, and $g_m$

We have seen that each of three tube "constants" for any particular tube depends on the choice of operating voltages on the electrodes. Through these operating conditions the tube constants are related to each other, and they vary in magnitude with respect to each other. To give a clear picture of these relative variations, we have plotted the variations in tube "constants" for the 6J5 on a single chart, shown in Fig. 4-19. In this chart, a separate vertical scale is given for each of the constants, as indicated, while all three have the same horizontal scale, namely the plate current in

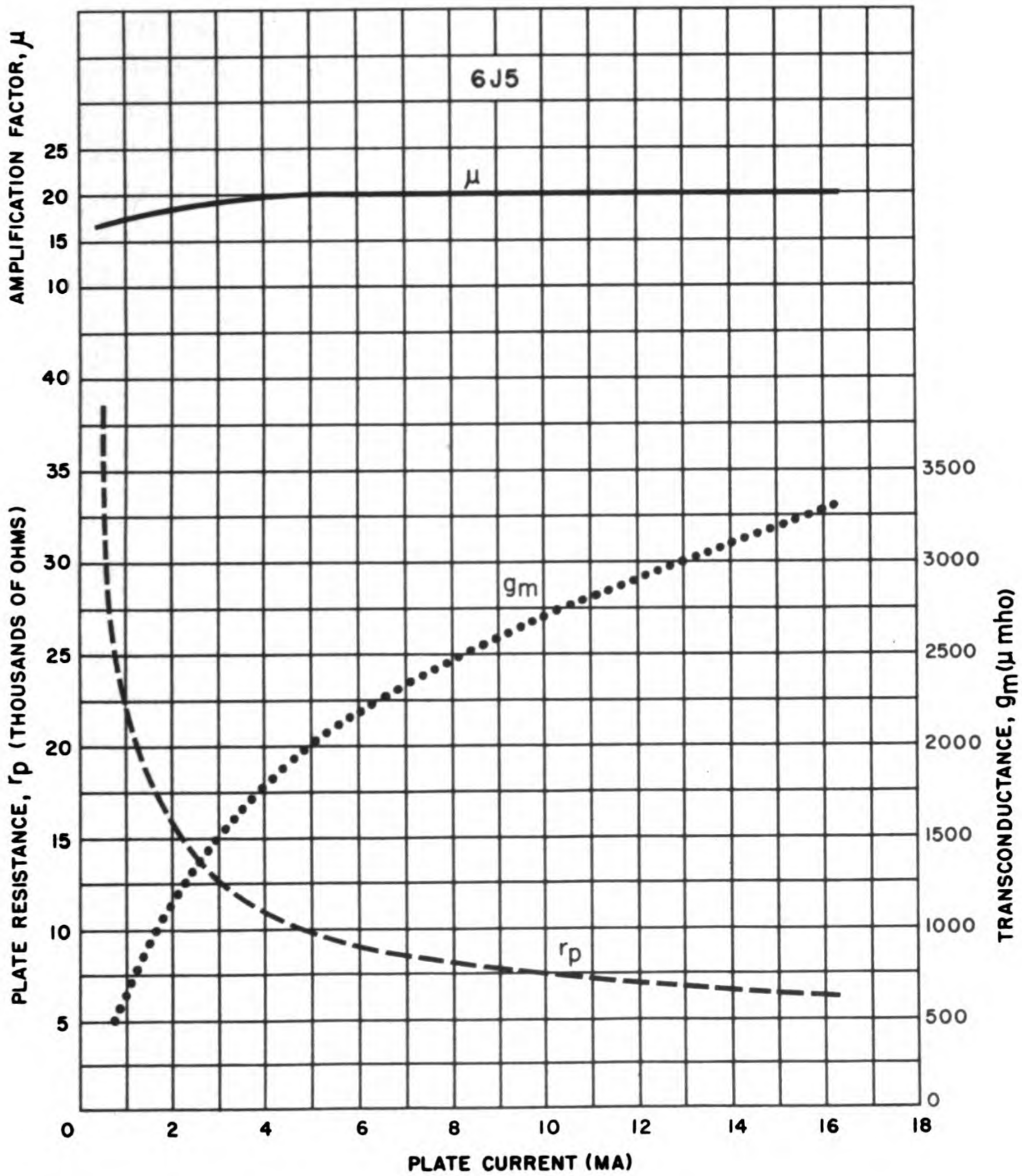



**Fig. 4-19. Curves illustrating relation between $\mu$, $g_m$, and $r_p$ for 6J5.**

ma. To obtain this uniform plate-current scale, we have kept the plate voltage constant at 250 volts. Hence, as the plate current increases toward the right on the horizontal scale, the negative grid voltage decreases, or becomes more positive. Its exact value for each plate current value may be determined from the plate family, shown in Fig. 4-18.

You will note from the chart, that the amplification factor, $\mu$, is essentially constant throughout the entire operating range of the tube above a few milliamperes. This is reasonable since, as we have explained, the amplification factor is basically a property of the geometry of the tube. The plate resistance, on the other hand, varies greatly over the operating range, being very high at low plate currents and low at high currents, or equivalently, at high plate or positive grid voltages. Again this is to be expected, since at plate-current cut-off, the tube does not conduct at all, and its plate resistance is infinite, while at saturation current, a maximum of electrons is transported toward the plate, resulting in a relatively low internal resistance. It is interesting to note that the amplification factor increases as the physical separation between grid and plate in a triode is made larger; at the same time the a-c plate resistance also increases as the grid-to-plate spacing is made greater. Consequently, it is generally true that the higher the amplification factor of a triode, the greater is its a-c plate resistance.

The transconductance is seen to increase rapidly with increasing plate currents, being very high at high plate currents, or equivalently at high plate voltages or low negative grid voltages. Also, you will note that the plate resistance goes down as the transconductance goes up, both acting in a complementary fashion. For any particular tube, the higher the transconductance, the lower is the plate resistance, and vice versa. It is also generally true that triodes with a high transconductance rating, have a low plate resistance, a combination of high transconductance with high plate resistance not being available among triode tubes.

*Mathematical Relationships.* The interdependence between $g_m$, $\mu$, and $r_p$ which we have just demonstrated graphically is not accidental, but in fact follows from their mathematical definitions. According to these definitions:

$$\textit{amplification factor } (\mu) = \frac{\Delta\, e_b}{\Delta\, e_c} \quad (i_b \textit{ constant})$$

$$\textit{a-c plate resistance } (r_p) = \frac{\Delta\, e_b}{\Delta\, i_b} \quad (e_c \textit{ constant})$$

$$\textit{transconductance } (g_m) = \frac{\Delta\, i_b}{\Delta\, e_c} \quad (e_b \textit{ constant})$$

Let us multiply the plate resistance by the transconductance, and see what happens. Accordingly, we find:

$$r_p \times g_m = \frac{\Delta\ e_b}{\Delta\ i_b} \times \frac{\Delta\ i_b}{\Delta\ e_c}$$

Cancelling out the terms $\Delta\ i_b$, which appears in both numerator and denominator, we obtain

$$r_p \times g_m = \frac{\Delta\ e_b}{\Delta\ e_c}$$

But this ratio is exactly the same as the definition of the amplification factor ($\mu = \frac{\Delta\ e_b}{\Delta\ e_c}$), and hence we see that the product of the plate resistance and the transconductance equals the amplification factor. Thus, we can write

$$\mu = r_p \times g_m$$

which is a very important relationship to remember. By simple transformations, we can state equivalent forms of this equation, namely

$$r_p = \frac{\mu}{g_m}, \text{ and } \quad g_m = \frac{\mu}{r_p}$$

From the last equation, which expresses the transconductance as the ratio of the amplification factor to the plate resistance, we see why $g_m$ serves as the figure of merit of a tube. It is obviously desirable to have a high amplification factor to obtain large output voltages from low input signals, while a low plate resistance permits large plate currents, resulting in high output power. You can also appreciate the difficulty of designing a tube with a high transconductance, remembering that the plate resistance increases as the amplification factor is made larger.

It is evident now that it suffices to find two out of three tube constants from the characteristics, since the third constant may always be determined from the equation relating the constants, which we have just stated. To check up on this, suppose we wanted to find the amplification factor of the 6J5 from the values of the a-c plate resistance and the transconductance given by the manufacturer for identical operating points. A value of 0.0026 mho is given for the transconductance, and a value of 7,700 ohms is given for the plate resistance. (When used in an equation, equivalent units must be used; that is, ohms and mhos, *not* micromhos.) Consequently,

$$\mu = r_p \times g_m = 7{,}700 \times 0.0026 = 20$$

This is in agreement with the value for $\mu$ which is given. If the values found in our previous examples are used instead (8,333 ohms and 0.002125 mho), then the value obtained for $\mu$ is about 18. The discrepancy is due to the somewhat different operating points for each of the calculations, to the relatively large changes in voltages and currents used, to the inaccuracy of reading from the graphs, and not carrying out the calculations to the same significant figure in each case.

You should remember from our discussion that tube constants serve to compare different tubes with each other, and permit the selection of the appropriate tube for each specific need. It is also well to keep in mind that the tube constants are not restricted to triodes alone, but that they apply to all vacuum tubes containing three or more electrodes. The values for the 6J5, which we have given in this chapter, are of course only one example from a great variety of tube constants occuring in practice.

**Dynamic Characteristics of the Triode**

Thus far we have not seen a triode do any useful work. We have varied the voltages applied to the grid and plate of the tube, and have observed the amount of plate current flowing through the tube to the plate and from there through the external circuit and back to the cathode, but we have not seen any results that this current has produced. In fact, we have only studied the behavior of a triode under *static* conditions, and have developed a number of interesting families of characteristics, which up to now have served no useful purpose. In order that a vacuum tube can be of any practical use, a *load resistance* must be inserted in its plate circuit. Once a load resistance is present, the plate current will develop a voltage drop across it, which may be transferred to the input of another tube, or the tube can be used directly to do useful work. If an input signal is applied to the grid of a tube, the plate current will create an amplified version of this signal — or output signal — across such a load resistor.

The presence of a load resistor in the plate circuit of a triode gives rise to the so-called *dynamic characteristics* of the tube, which are the actual conditions of operations used in practice, and hence far more important than the static characteristics we have studied. The dynamic characteristics are then a graphic portrayal of tube behavior under load, as shown in Fig. 4-20. In part (A) of this figure we have illustrated a basic triode circuit with a load inserted into the plate circuit, assigning typical values to the plate voltage and load resistor, and then for comparison we have also shown the same circuit without a load (part B), similar to that of Fig. 4-10.

*Voltage Drop Across Load.* The load resistor, $R_L$, is in series electrically with the plate-supply voltage, $E_{bb}$, and with the tube itself. Consequently, the electrons on their way back to the cathode of tube must flow through this load resistor and develop a voltage drop across it. This voltage is known as the output voltage of the tube, and is indicated by the abbreviation $E_{RL}$. By Ohm's law, the voltage drop across $R_L$ ($E_{RL}$) is then $I_b \times R_L$ (voltage equals current times resistance). You remember that the sum of the voltage drops around a series circuit must be equal to the voltage source, or supply voltage. Evidently, then, the plate voltage supply, $E_{bb}$, must be equal to the *sum* of plate-to-cathode

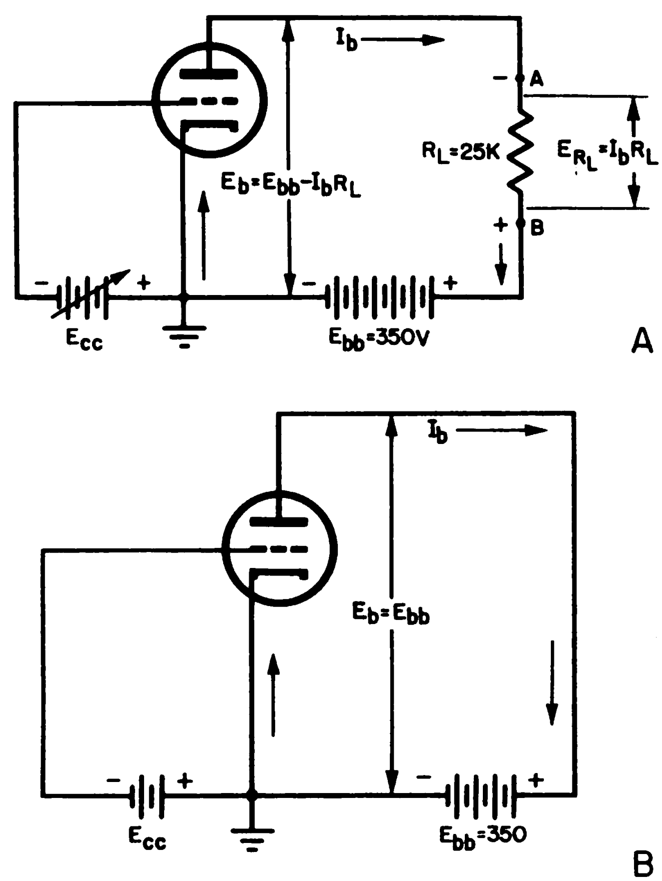



**Fig. 4-20. Basic Circuit of triode with and without load.**

voltage $E_b$, *plus* the voltage drop across the load resistor, $E_{RL}$. Stated in the form of an equation, we have

$$E_{bb} = E_b + E_{RL} = E_b + I_b \times R_L$$

By a simple transposition, we find that

$$E_b = E_{bb} - I_b \times R_L$$

In other words, the plate voltage across the tube is the *difference* between the plate-supply voltage, $E_{bb}$, and the voltage drop across the load, $E_{RL}$ (equal $I_b R_L$). This is a very important relation to remember. It shows that the *plate voltage* ($E_b$) *decreases as the plate current increases,* since the plate-supply voltage, $E_{bb}$, and the load resistor, $R_L$, are both fixed in value. This is the main difference between the static condition of operation, where the plate voltage equals the plate-supply or battery voltage ($E_b = E_{bb}$), since no load is present, and the dynamic condition of operation with a load, where the plate voltage is the difference between the plate-supply voltage and the voltage drop across the load ($E_b = E_{bb} - I_b R_L$).

As an example, let us assume various conditions of operation in the circuit of Fig. 4-20 (A). Imagine, at first, that the grid bias, $E_{cc}$, is adjusted to such a high negative value as to cut off the plate current ($I_b$) entirely. In the absence of plate-current flow there is no voltage drop across the plate resistor, $R_L$, and the plate voltage equals the plate-supply voltage, or $E_b = E_{bb} = 350$ volts.

Now assume that the bias is changed to allow 1 ma of plate current to flow through the plate circuit. With a 0.001-ampere plate current, we find that the plate voltage is:

$$E_b = E_{bb} - I_b R_L = 350 - 0.001 \times 25{,}000 = 325 \textit{ volts}$$

In this case, the voltage drop across the load is relatively low, and the internal drop across the plate resistance is high (i.e. 325v).

Imagine now that the grid bias is adjusted to a less negative value, to allow as much as 12-ma of plate current to flow through the circuit. With a 0.012-ampere plate current, the plate voltage is then:

$$E_b = E_{bb} - I_b R_L = 350 - 0.012 \times 25{,}000 = 50 \textit{ volts}$$

For this operating condition we see that most of the voltage drop from the *B*-battery occurs across the load resistor, $R_L$, and very little appears across the internal resistance of the tube; that is, the plate voltage (between the tube's plate and cathode) is relatively low. This example demonstrates convincingly that there is an opposing relationship between the plate voltage and the drop across the load. When the plate current is high (generally because of a high input voltage, or a large signal), the plate voltage is low, and the drop across the load resistor— or output voltage— is high. On the other hand, the lower the plate current, the less the voltage drop across the load, and the higher is the voltage between plate and cathode of the tube.

**Introducing the Load Line**

The insertion of a load resistance in the plate-circuit of a triode *does not alter* the three basic constants of the tube, but we have seen that it does greatly affect the operating conditions of the tube (for example, the plate voltage), and hence it modifies the basic characteristics. The effect of the load can be predicted in advance by adding to the static plate family of characteristic curves, a graphical representation of the load, known as the *load line.* The load line automatically furnishes the division of the plate-supply voltage, $E_{bb}$, between the load and the internal resistance of the tube for different values of the plate current and grid voltage. From the dynamic characteristics resulting from the addition of a load line to the plate family, a so-called *dynamic transfer characteristic* can be developed, which shows the dependence of the plate current on the grid voltage *with a load present.*

*Construction of Load Line.* In Fig. 4-21 we have drawn a load line representing a load resistance of 25,000 ohms and a plate-supply voltage of 350 volts. The values have been chosen arbitrarily to correspond with the circuit of Fig. 4-20; any other pair of values would have been equally suitable for the purposes of illustration. We shall see later, however, that there are practical limits on the range of values for the load resistance.

How was the load line of Fig. 4-21 arrived at, how did we know that it would be a straight line, and what determined its limits? The answers to these questions are fairly simple. First of all, since we are dealing with an ordinary resistor in the plate circuit, we know that it will obey Ohm's law, that is, there will be a *linear* relationship between the current through the load and the voltage across it. A linear relation between cause and effect means that a *straight* line can be used to represent it graphically. Furthermore two points are sufficient to define a straight line, since no more than one line can be drawn between two points.

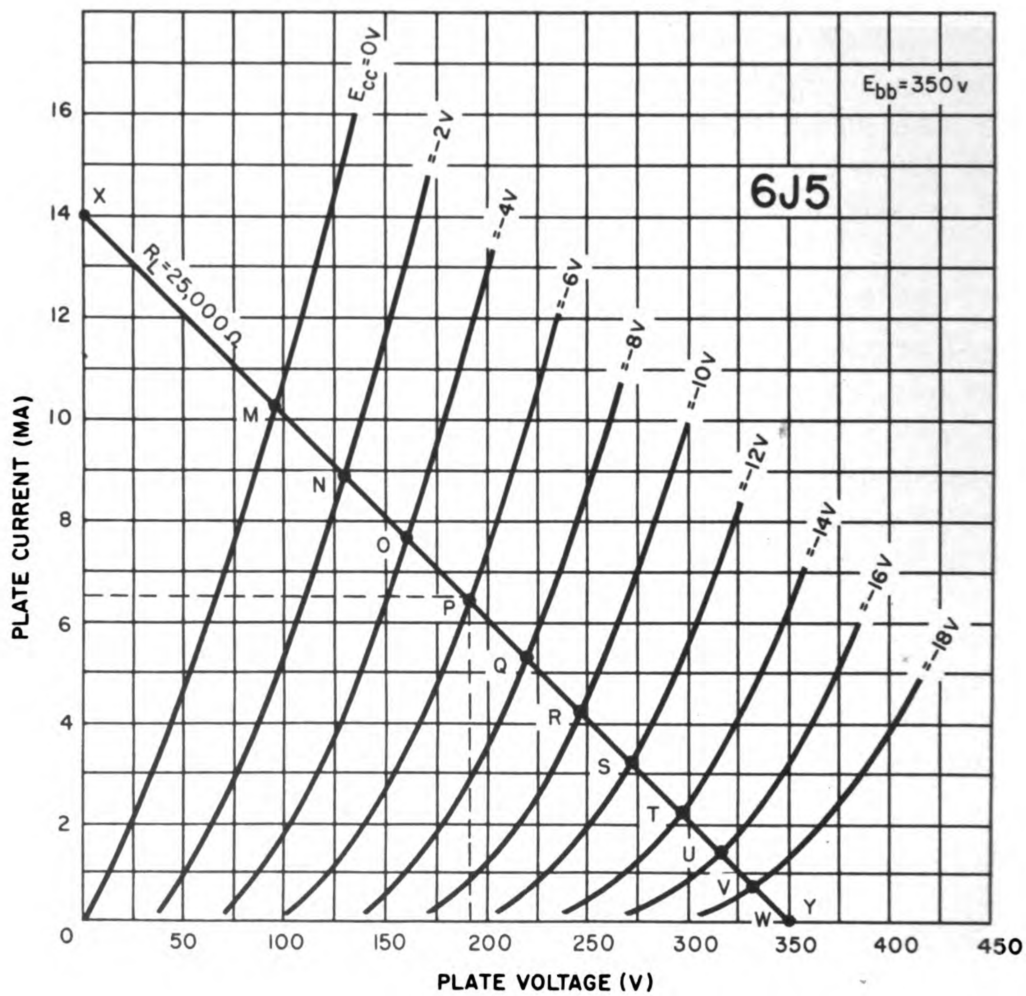



**Fig. 4-21. Load line (25,000 ohms) drawn on plate family of 6J5.**

Thus, all we need to draw any load line are two points along its length. Any number of conditions can furnish these two points, but the simplest thing is to remember that the *load line is a graphic representation of the distribution of the plate-supply voltage across the load and across the internal resistance of the tube.* We have previously derived an equation to represent this voltage division, and we restate it here for convenience:

$$E_b = E_{bb} - I_b \, R_L$$

Since we have assumed a plate-supply voltage of 350 volts, and a load resistance of 25,000 ohms for our example, we can substitute these values and obtain

$$E_b = 350 - I_b \times 25{,}000$$

The load line is an exact graphic representation of this plate-voltage equation, and has essentially nothing whatsoever to do with the plate family of characteristics of any tube. However, by drawing a load line on such a family of curves, we combine the information given by the load line with that known about the tube, and thus obtain a complete picture of dynamic conditions. If we arbitrarily assume different values for the plate voltage, $E_b$, in the above equation (no more, of course, than 350 volts, since that is all that is available), and solve the equation each time for the plate current $I_b$, we will obtain a series of values which when plotted result in the straight line of Fig. 4-21. This laborious process is not necessary, however, since we only need two points. Let us therefore assume two extreme conditions to obtain the end points or terminations of the line. Imagine first that the plate voltage is *equal* to the plate-supply voltage, that is,

$$E_b = E_{bb} = 350 \text{ volts.}$$

Substituting in the equation, we have:

$$350 = 350 - I_b \times 25{,}000$$

Solving for the plate current, we obtain:

$$I_b = 0$$

This is to be expected, of course, since the only way the plate voltage can be equal to the plate-supply voltage is when the plate current is zero, and no voltage drop occurs across the load, $R_L$. Hence, our first and obvious end point of the line is for the condition, where $E_b = 350$ volts, and $I_b = 0$ ma. This point is 350 volts on the horizontal plate-voltage axis.

The second extreme condition is the assumption that the full plate-supply voltage is developed across the load resistors, and none appears between plate and cathode of the tube; that is, the plate voltage equals zero. This condition can't actually occur in practice, since as long as some plate current is flowing, a voltage drop must be developed across the tube, however tiny. However, the assumption that $E_b$ equals zero is useful for setting up a theoretical limit of operation, and hence an end point for the load line. Substituting $E_b = 0$ in the equation, we obtain:

$$0 = 350 - I_b \times 25{,}000$$

and solving for the plate current, $I_b$, we get:

$$I_b = \frac{350}{25{,}000} = 0.014 \text{ ampere, or } 14 \text{ ma}$$

Thus, the other termination of the load line is for the condition, where $E_b = 0$ and $I_b = 14$ ma. Marking this point down at 14 ma on the vertical plate-current axis, we have two end points and can now draw the load line $X - Y$, as shown in Fig. 4-21.

The procedure for constructing a load line we have just outlined is actually very simple: All you have to do in practice is to remember the two conditions for the end points of the line. One condition occurs when the plate current is zero, and hence the plate voltage is equal to the plate-supply voltage. This point is defined by $I_b = 0$, and $E_b = E_{bb}$ (whatever its value is). The other condition occurs when the plate voltage is zero, and the voltage across the load is equal to the plate-supply voltage. This second condition defines the other end point of the load line; namely, $E_b = 0$, and $I_b = \frac{E_{bb}}{R_L}$ (whatever values you chose for the plate-supply voltage, $E_{bb}$, and the load resistor, $R_L$).

Knowing the complete equation ($E_b = E_{bb} - I_b R_L$) is very useful, nevertheless, for checking up on other points on the load line, and for experimenting with different loads and plate-supply voltages. Thus, if you want to know, for example, the value of the plate current in the circuit of Fig. 4-20 (A) when the plate voltage is 200 volts, you can simply substitute in the equation:

$$200 = 350 - I_b \times 25{,}000$$

and obtain by solving for the plate current:

$$I_b = \frac{350 - 200}{25{,}000} = \frac{25{,}000}{150} = 0.006 \text{ ampere or } 6 \text{ ma}$$

An inspection of Fig. 4-21 reveals that the load line passes through the point where $E_b = 200$ volts, and $I_b = 6$ ma. Again, you see, that the load line is simply a graphic description of this equation for all possible points. If you substitute different values for the plate-supply voltage, $E_{bb}$, and the load resistor, $R_L$, you will obtain a series of different load lines, which permit investigating the tube's operation under various operating conditions.

*Information Obtained from Load Line.* Now that we have constructed a load line on the plate family of characteristics, what does it indicate and what are its uses? In brief, it gives us complete information on the tube's behavior for the conditions of operation we have chosen. There is only one more thing we must do before we can investigate the performance: we must choose a value of grid bias, $E_{cc}$, at which we want to operate. For the 6J5 tube in our example, we have chosen a grid bias voltage of –6 volts, or point $P$ on the load line of Fig. 4-21. This is a convenient point, since it is nearly mid-way on the tube's normal operating range on the more linear part of the characteristics. That is, if we wanted to avoid grid current for positive grid voltages, and the nonlinearity due to the curvature of the characteristics at high negative grid voltages, we would normally operate the tube with grid voltages varying between 0 and −12 volts. Hence, we put our initial operating point in the center of this range, or at –6 volts grid bias. Drawing a horizontal line from the –6 volt point $P$ to the plate-current axis, we obtain a plate current of 6.35 ma. Dropping a vertical line to the plate-voltage axis, we see that the plate voltage is about 190 volts. Consequently, our operating point, $P$, may be completely described as follows:

$$E_{cc} = -6 \textit{ volts}$$
$$E_b = 190 \textit{ volts}$$
$$I_b = 6.35 \textit{ ma}$$

The vertical (dashed) line dropped from point $P$ divides the plate-voltage scale in accordance with the division of the plate-supply voltage between the tube and the load. The distance to the left of the intersection of this line with the horizontal axis indicates the 190-volt plate-to-cathode voltage across the tube. The distance to the right of the intersection up to the 350-volt point indicates the voltage drop across the load. In other words, the difference between the plate-supply voltage (350 volts) and the plate voltage (190 volts) is the voltage dropped across the load, or 350 − 190 = 160 volts. This last statement may be checked by a simple calculation, since we know that the plate current at the operating point ($P$) is 6.35 ma. Hence the voltage drop across the load:

$$E_{RL} = I_b\, R_L = 0.00635 \times 25{,}000 = 159 \textit{ volts}$$

which is in close agreement with the value we obtained graphically.

If we change the voltage on the control grid of the tube, we can obtain similar complete data on the tube's operation for any point of intersection between a grid voltage on the load line. Suppose we try this for two extreme grid voltages, −12 and 0 volts, which represent the practical operating range of the tube. For zero volts on the grid, point $M$ on the load line gives all the relevant data:

$$E_{cc} = 0 \text{ volt}$$
$$I_b = 10.1 \text{ ma}$$
$$E_b = 97 \text{ volts}$$
$$E_{RL} = 253 \text{ volts} \quad (350 - 97 = 253)$$

At the other extreme, with −12 volts on the grid, point *S* on the load line yields the following information:

$$E_{cc} = -12 \text{ volts}$$
$$I_b = 3.1 \text{ ma}$$
$$E_b = 272 \text{ volts}$$
$$E_{RL} = 78 \text{ volts} \quad (350 - 272 = 78)$$

From the data obtained from these three points, we see that changing the grid voltage from −6 to 0 volts has resulted in a plate-voltage change ($E_b$) from 190 to 97 volts, or 93 volts, while the voltage across the load changed at the same time from 160 to 253 volts, or again by 93 volts. We shall find it always true that the change in plate voltage is the same as the change in load voltage, since as the plate voltage drops in value, the load voltage increases correspondingly, both always adding up to the total plate-supply voltage ($E_{bb}$).

Changing the grid voltage from −6 volts to −12 volts, however, resulted in a plate-voltage change from 190 to 272 volts, or a change of only 82 volts. Similarly, the load voltage changed from 160 to 78 volts, or again by 82 volts. Evidently, then, a positive-going (less negative) grid-voltage change from −6 to 0 volts produced plate and load voltage changes of 93 volts each, while an equal negative-going grid-voltage change, from −6 to −12 volts, produced a smaller plate and load voltage change of only 82 volts, each. Under ideal conditions—with perfectly linear characteristics—the rise and fall in plate voltage, as well as the drop across the load, would be the same in both directions of grid voltage changes. However, because of the increasing curvature of the characteristics for high negative grid voltages, nonlinear (or nonproportional) operation takes place, which produces distortion in the signal output, as we have mentioned previously.

*Grid and Plate Voltage Swing.* The operating conditions we have discussed thus far were for various *fixed* operating voltages, which we changed in definite steps. Thus, we changed the grid bias from −6 to 0 volts, and from −6 to −12 volts; at the same time the plate and load voltages went through definite changes produced by the fixed grid-voltage changes. However, these voltage changes need not necessarily be in fixed steps by changing taps on a battery. They could be *continuously changing or alternating quantities.* If we varied the grid voltage, for example, continuously and at a definite speed by some manual means between 0 and −12 volts, and back again, the changes in plate voltage and the drop across the load would occur at the same rate. No matter how slowly or rapidly we vary the grid voltage back and forth between 0 and −12 volts, the plate and load voltages follow instantaneously and at the same speed. Looking at the voltage changes as continuous variations, we can speak of a total *grid-voltage swing* of 12 volts (from 0 to −12 volts), with a positive *peak* amplitude of +6 volts (at zero grid voltage) and a negative peak amplitude of −6 volts (at −12v grid voltage). Similarly, we may talk of a corresponding total *plate-voltage swing* of 175 volts (93 plus 82), with a peak amplitude of 93 volts in one direction, and 82 volts in the other direction. Finally, the total change in voltage across the load resistor, or *load-voltage swing* is from 78 volts at −12 volts grid voltage to 253 volts at zero grid voltage, or again 175 volts.

You will have the proper conception of the meaning of the dynamic characteristics if you think of the grid-voltage variations as being brought about by an a-c voltage between grid and cathode of the tube (that is, a *signal voltage*), rather than by a mechanical variation of the taps on the grid-voltage supply battery. Any particular point on the load line will then represent the *instantaneous conditions* of grid, plate, and load voltage and the plate current for an alternating grid-voltage signal. We shall have to refer to these a-c conditions more fully later in the chapter.

### Dynamic Transfer Characteristic

Granting the importance of the load line when it is added to the static plate family, it does not tell the story of dynamic operation as conveniently as does the static grid family with the effect of the load superimposed. If this is done, the resulting plate-current grid-voltage characteristic is known as the *dynamic transfer characteristic.* In Fig. 4-22 (B), we have repeated the static plate family with the 25,000-ohm load line of Fig. 4-21, while part (A) repeats the static grid family of Fig. 4-13, but with the dynamic characteristic added. Although this dynamic curve can be

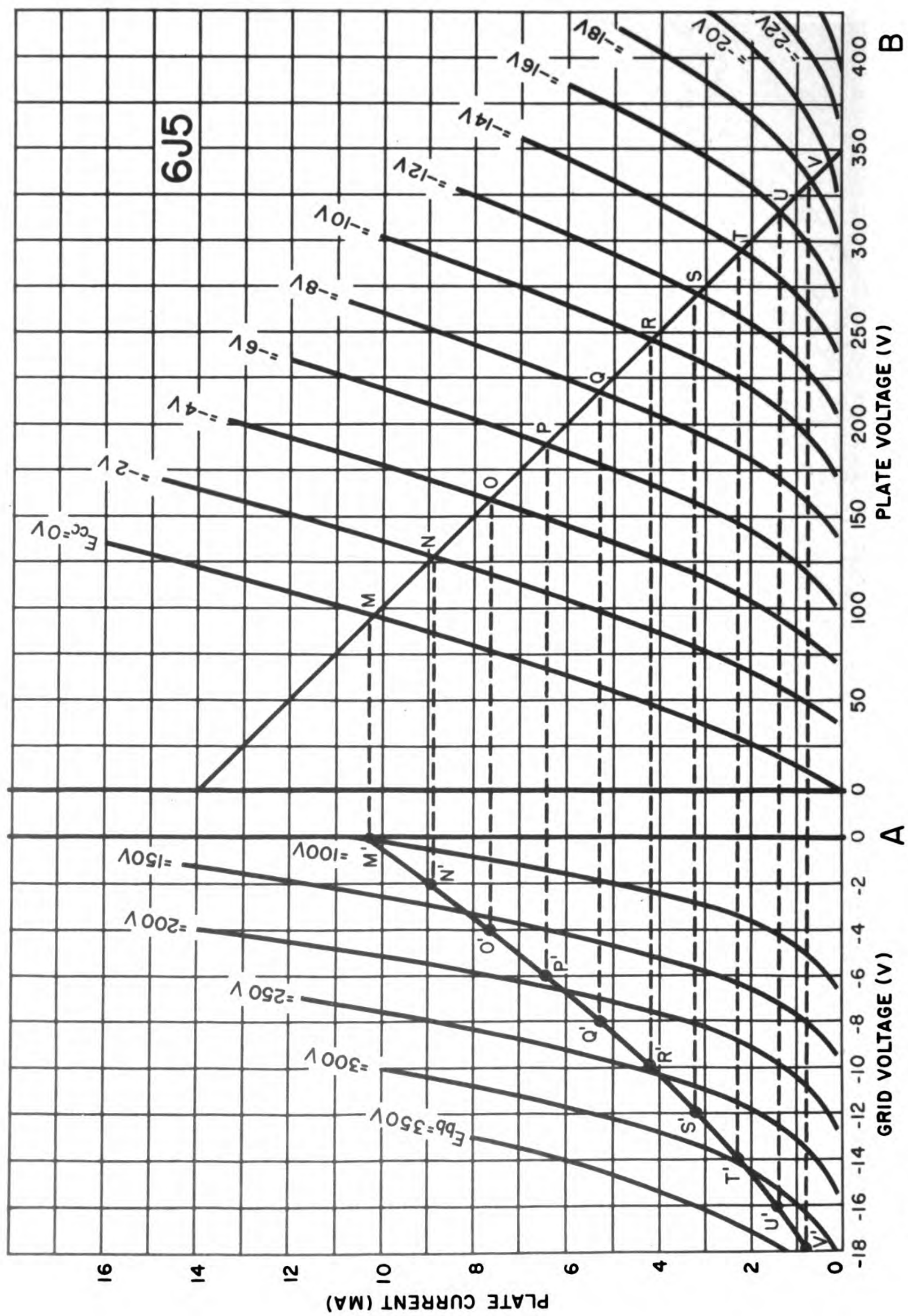



Fig. 4-22. Construction of dynamic transfer characteristic for 6J5 from plate and grid families of curves.

developed directly by the appropriate measurements, we have taken the easy way of simply transposing the information from Fig. 4-21 onto the static grid family. Both figures have a common plate-current (vertical) axis, but the horizontal axis for part (A) is the *grid voltage,* while for part (B) it is the *plate voltage*. It is, therefore, simply necessary to plot the plate-current values for any particular grid voltage from the load line of part (B) (Fig. 4-22) onto the corresponding plate-current grid-voltage points of the graph in part (A).

Taking point *M* in the plate family of Fig. 4-22 (B) as the starting point, we see that it represents a grid voltage of zero volts and a plate current of 10.1 ma. Finding the same conditions on the characteristics of Fig. 4-22 (A), we locate point *M′* at the intersection of the 0-volt vertical grid-voltage line and the 10.1 ma horizontal plate current line. Similarly, point *N* in part (B) with a grid voltage of −2 volts and a plate current of 8.9 ma, corresponds to point *N′* in part (B), located at the intersection of the −2 volt vertical line and the 8.9 ma horizontal plate-current line. You will note that in the actual construction, we simply draw a horizontal line from any grid-voltage intersection on the load line of part (B) until it hits a vertical line in part (A) which represents the same negative grid voltage. One horizontal line represents the same plate current for both graphs, since the vertical scale is the same. Furthermore, we need not worry about the value of the plate voltage at any point, since its correct location at the corresponding point in (A) takes care of itself.

Proceeding in this fashion, points O, P, Q, R, S, T, U, and V are transferred onto the grid family of part (A), leading to the corresponding points O′, P′, Q′, R′, S′, T′, U′, and V′. Finally, drawing a smooth curve through all the primed points in Fig. 4-22 (A), we obtain the *dynamic transfer characteristic* (from V′ to M′) for a 25,000-ohm load.

Notice that the dynamic characteristic in Fig. 4-22 (A) is much less steep and less curved than the static plate-current grid-voltage curves. The insertion of a load in the plate circuit has resulted in *straightening out* the static characteristics and has made them *more linear* than before. This is of importance with respect to the amount of distortion occuring during operation. While the curve is more linear, we also note that changes in grid voltage now result in smaller changes in plate current than on the static characteristics. The increased linearity, however, more than compensated for this apparent disadvantage. A further difference between the load line in (B) and the transfer characteristic in (A) is revealed in the fact that we have in (A) a continuous series of values in plate current for all values of grid voltage between 0 and −18 volts, while the load line in (B) gives us information only in 2-volt grid-voltage steps.

### Effect of Different Loads

Some questions have probably arisen in your mind by now. Why was a 25,000-ohm load used—however arbitrary — rather than one of 50,000 ohms or some other value? What effect would a higher or lower load resistance have on the operation of a triode? In general, we can give the answer that the value of the load resistance has two effects: (1) it affects the *linearity of operation* of the tube, and (2) it affects the *amount of amplification* of a signal voltage possible with the tube. We can state generally that the *higher the value of the load resistance, the straighter is the dynamic transfer characteristic and the greater is the possible amplification of the tube.*

We shall have to defer the proof for the last half of this statement until later on, but we can easily show the straightening in the dynamic transfer characteristic. In Fig. 4-23, we have plotted a number of dynamic transfer characteristics for different loads inserted into the plate circuit of a 6J5 tube. It is evident that the transfer characteristics become progressively straighter as the value of the load resistor is increased. The curve for a load of 100,000 ohms (curve *D*) is substantially straight for almost its full length, while curve *A* for a load of 15,000 ohms is curved throughout most of its length. It should be apparent to you why this happens. As the load resistance is made higher and higher in comparison to the fixed plate resistance, it has an increasingly important effect in determining the total plate current through the circuit, while the effect of the nonlinear plate resistance is of less consequence. With the load made very high, the circuit approaches *linear operation* in accordance with Ohm's law, while the nonlinear plate resistance can be practically neglected.

It might appear from the above that the load could be increased without limit to attain the advantages of increased linear-

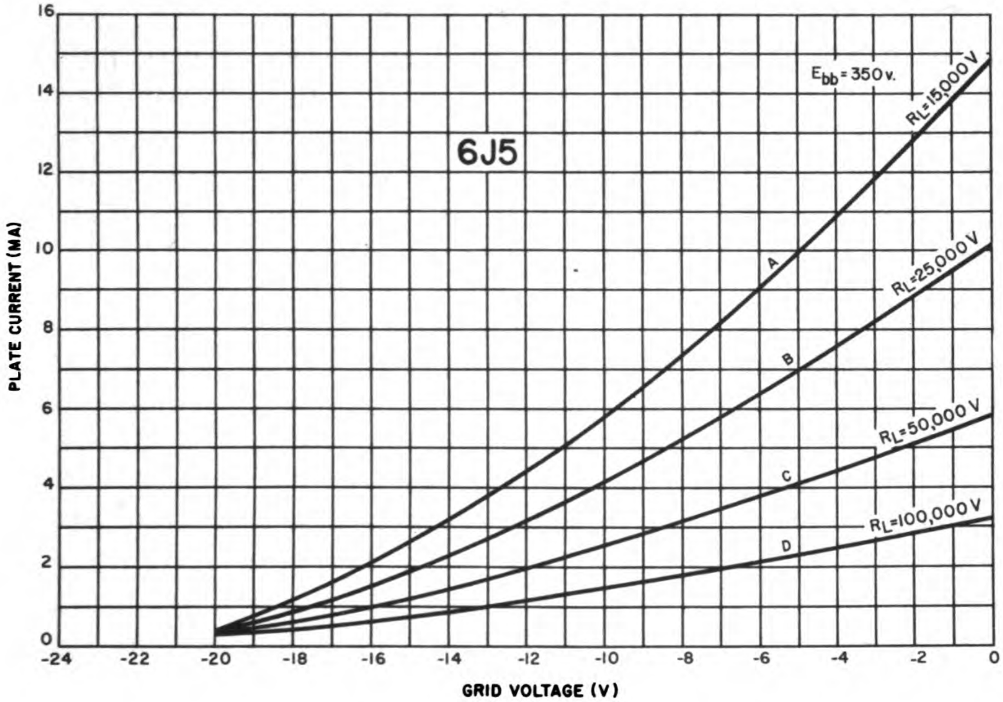



**Fig. 4-23. Dynamic transfer characteristics of 6J5 for different loads.**

ity and higher amplification. This is, however, not so for several reasons. While the linearity continues to increase, other forms of distortion take place, which we cannot describe here. Furthermore, the amplification can increase only to a theoretical value fixed by the amplification of the tube, as we shall see later, and increases in load resistance above some reasonable value have practically no further effect on the available amplification. Finally, with the plate-supply voltage fixed at some value, the voltage drop across a very high load resistor would become excessive, and the voltage left over at the plate of the tube may become insufficient to operate the tube properly. Increasing the plate-supply voltage does not solve the dilemma, either, since it would only result in exceeding the maximum permissible voltage ratings of the tube (at high negative grid voltages) and would be highly uneconomical to boot.

## TRIODE APPLICATIONS

We have reached a most important point in our discussion of the triode; specifically, what makes it a practical amplifier. Most triode applications are based on the amplifying properties of the tube, which we have discussed in a theoretical manner without giving a practical example. We must, therefore, turn now to the fundamental operation of a simple triode amplifier and some of its ramifications. After we have gained a basic understanding of the triode amplifier, we shall discuss some other applications of the tube without going into great detail, since the scope of this book has been limited to the "basic vacuum tube."

### Simple Triode Amplifier

Thus far we have considered the fundamental triode circuit (Fig. 4-10) operated with d-c potentials, although we have on occasion varied these potentials in a more or less mechanical manner to observe the effect on the plate current. In most applications, however, the triode is operated with an alternating voltage (usually called the *exciting* or *signal voltage*) applied to the grid circuit, in addition to the d-c grid bias voltage. The effect of this is to vary the grid-to-cathode voltage of the tube and cause a corresponding variation in the plate current. The plate-current variations, in turn, generate a varying voltage across the load resistor, the so-called *output voltage* of the tube. We shall have to explore how this output voltage is amplified with reference to the input signal or exciting voltage. In order to understand this dynamic amplifying process, we shall have to modify our thinking toward an *alternating-current* viewpoint of the triode tube. Actually, the triode is no different from the diode, in that it is capable of passing a current in only one direction, from cathode to plate, and only when the plate is positive with respect to the cathode. Hence the varying plate current and voltages of the tube are all unidirectional—and they never reverse their polarity to negative. This may sound paradoxical, but the proper way to consider the varying plate current and voltages—with a grid signal voltage present—is to imagine them composed of *two components*. One component is the *d-c or quiescent value* of the current of voltage (as shown in Fig. 4-10) for a fixed grid bias and with no signal voltage present in the grid circuit. *Superimposed on this d-c component is* a second component of the current or voltage under consideration, namely *the varying or alternating component caused by the exciting voltage or signal in the* grid circuit of the tube.

In Fig. 4-24 we have shown a very simple fundamental triode amplifier circuit with an a-c signal (sine wave) in the grid circuit and an output load resistor in the plate circuit. The circuit is essentially the same as that of Fig. 4-20 (A), except that an a-c exciting signal of 6 volts peak has been added in series with the bias battery of 6 volts. We have indicated the *a-c components* in the illustration with small letters, while the d-c components have been marked with capital letters, as in previous figures. These latter components have been defined before (see Fig. 4-10), but we have yet to give meaning to the symbols for the a-c components

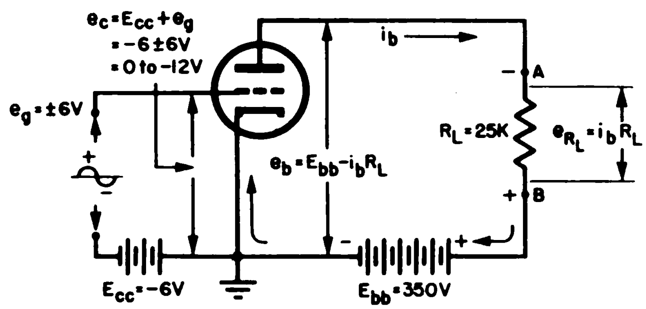



**Fig. 4-24. Basic triode amplifier circuit, including input signal and output load.**

of the currents and voltages (small letters). The a-c currents and voltages acting in the grid and plate circuits, are defined as follows:

$e_g$ = the instantaneous value of the *signal* or *exciting voltage*. (This is the a-c component of the total grid voltage $e_c$.)

$e_c$ = the instantaneous total voltage between grid and cathode. (This is the sum of the bias voltage and the a-c signal voltage; that is, $e_c = E_{cc} \pm e_g$.)

$i_b$ = the instantaneous total plate current. (This includes the total d-c plate current $I_b$ plus the a-c component of the plate current, $i_p$.)

$i_p$ = the instantaneous value of the varying or a-c component of the plate current.

$e_b$ = the instantaneous total plate voltage. (This is equal to the plate-supply voltage *less* the voltage drop across the load; that is, $e_b = E_{bb} - i_b R_L$.)

$e_{RL}$ = the instantaneous total voltage across the load resistor (that is, $e_{RL} = i_b R_L$).

The small letters all signify *instantaneous values,* by which we mean the value of the a-c voltage or current at any particular chosen moment or *instant.* This is contrasted to the d-c voltages and current, signified by capital letters, which always remain the same. The profusion of symbols and definitions may appear confusing to you at this moment, but their application will soon clarify their meaning.

*Grid Bias.* It is evident from the circuit of Fig. 4-24 that the a-c signal voltage is inserted *in series* with the bias battery, $E_{cc}$. The question arises, why this bias-supply voltage is still necessary, since we have a separate exciting or signal voltage present in the grid circuit.

The answer is fairly simple. In its basic application as an amplifier of tiny signal voltages, the triode is operated so as to *consume no power in the grid circuit,* because generally no power is available from the extremely weak radio signals. This is the great advantage of the tube; that it is capable of being *purely voltage-operated in the grid circuit, although power may be available from the plate circuit.* In order to consume no power in the grid circuit, it is *essential that no grid current should flow;* a current flowing from the grid to the cathode of the tube and through an external grid circuit would obviously consume some amount of power, however small. It follows from our previous discussion, that – in order to avoid any grid current – the tube must be operated at a *negative grid voltage,* or at least a voltage which never rises above zero to positive values, since under those conditions grid current would flow and power would be consumed. This is the real *purpose of the negative grid bias*: *It is to prevent the control grid voltage from ever rising to positive values, with grid-current flow resulting.* In addition to power loss, the linearity of operation of the tube is reduced so that signal distortion may occur.

In Fig. 4-24 we have chosen an a-c sine-wave signal voltage for grid excitation which rises to a *positive peak amplitude* or +6 volts, and has a negative peak amplitude of –6 volts. In series with this alternating signal voltage we have applied a d-c grid bias of –6 volts. (From now on we shall always reserve the term *Bias* for the d-c grid voltage). The total voltage acting between grid and cathode of the tube ($e_c$) is the *algebraic sum* (that is, with regard to the sign of the a-c signal) of the a-c signal voltage and the d-c grid bias thus we have:

$$e_c = E_{cc} + e_g = -6 \pm 6v = 0 \text{ to } -12 \text{ volts}$$

The numbers have been inserted for extreme values of the a-c signal. When the a-c signal voltage is at its extreme negative value of −6 volts, the total grid-to-cathode voltage is −12 (−6 plus −6) volts, while for the extreme positive value of the a-c signal of +6 volts, the total grid-to-cathode voltage ($e_c$) is 0 volts (−6 +6=0).

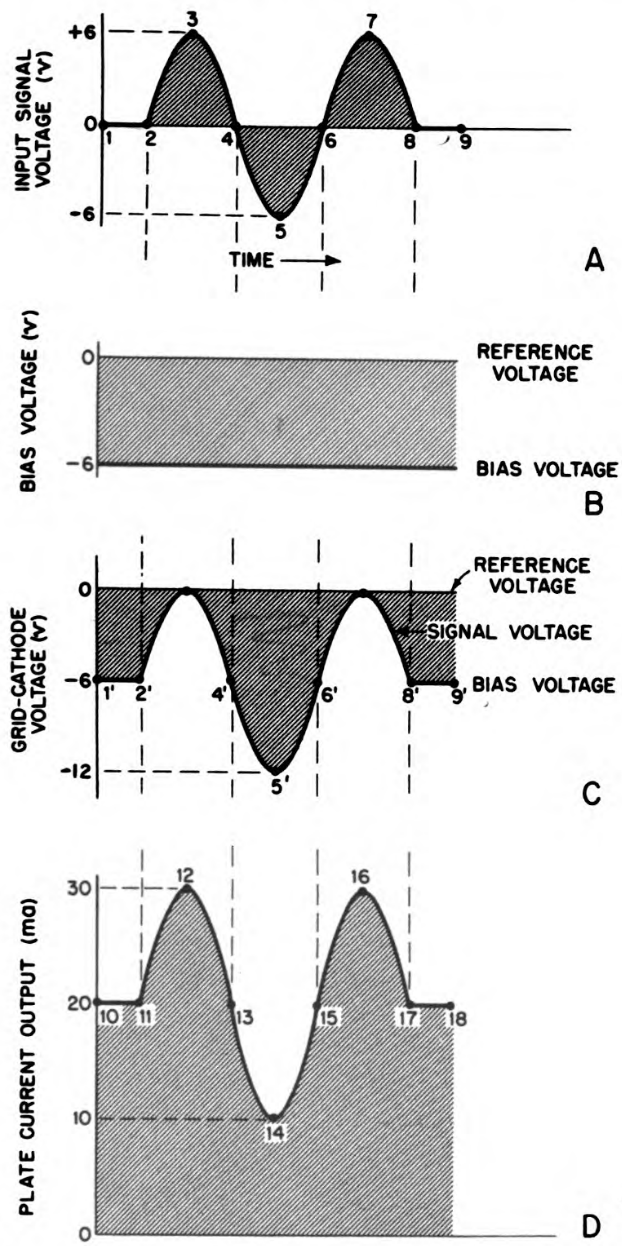



**Fig. 4-25. Waveforms illustrating relation between grid bias, signal voltage, and plate current.**

These conditions have been graphically portrayed in Fig. 4-25. Curve (A) represents the a-c input signal of 6 volts peak, which in this case is a simple sine wave, although any other waveform could have been chosen. It can be seen that the signal voltage varies between the limits +6 and –6 volts. The bias voltage of –6 volts has been represented by a straight line, 6 volts below zero-voltage reference line, in (B) of Fig. 4-25. The algebraic addition, or *resultant* of the a-c signal voltage and the d-c bias voltage is shown in curve (C), where points corresponding to curve (A) have been marked by the same numbers. Between points *1* and *2,* no signal is applied, and hence the total grid-to-cathode voltage is simply the bias voltage, or –6 volts. At points *3* and *7* the a-c signal rises to +6 volts peak, while the resultant total grid voltage reaches a value of zero volts. At point *5* the a-c signal falls to its negative peak of –6 volts, while the resultant grid voltage falls to –12 volts. Between *8* and *9,* when the signal is zero, the total grid voltage returns to its *quiescent* bias value of –6 volts. It is seen that the grid is at no time at a positive voltage.

The plate current variations corresponding to the variations in total grid-to-cathode voltage are shown by curve (D). The plate-current variations between 10 and 30 ma are arbitrary values, and do not apply to any particular tube. Between points *10* and *11,* and *17* and *18,* when no a-c signal is present on the grid, the plate current has a *quiescent* or d-c value of 20 ma, corresponding to the –6 volts grid bias and a fixed plate voltage. When the total grid voltage goes in the positive direction, and reaches zero for the positive peak of the a-c signal, the plate current rises to its maximum value of 30 ma, at points *12* and *16*. When the a-c signal and the total grid-to-cathode voltage reach their negative peak (–6 and –12 volts, respectively), the plate current falls to its minimum value of 10 ma. Since the plate current rises by the same value on positive peaks of the a-c signal as it falls on negative peaks (that is, 10 ma in each direction), its variation is *linear,* which is a very desirable condition. The chief purpose of the discussion up to this point is to show the addition of the bias and signal voltages, and to bring out the point that the total grid voltage never rises above zero—and no grid current flows—if the value of the negative bias is chosen to be at least equal to the positive peak of the a-c input signal.

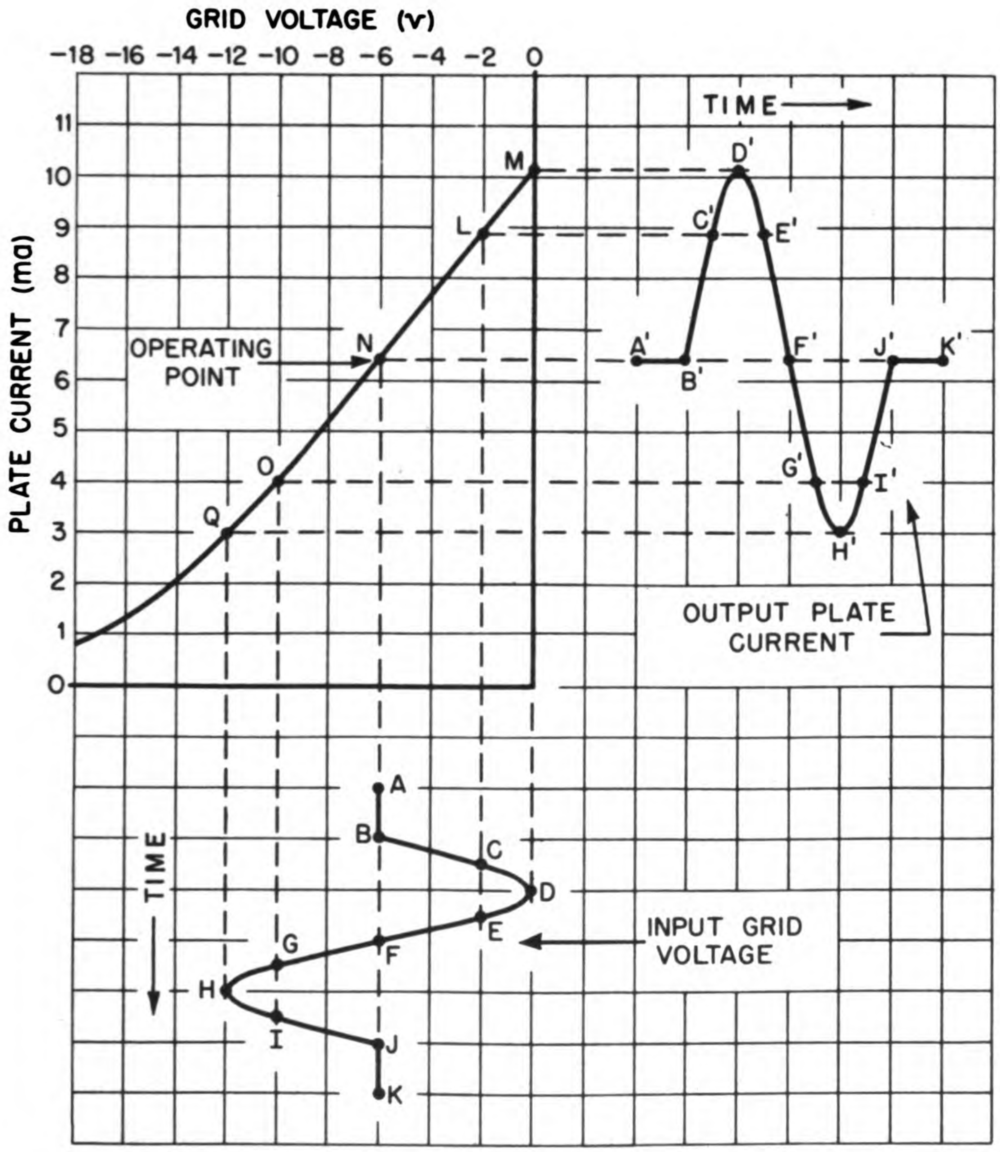



**Fig. 4-26. Operation on linear portion of 6J5 dynamic transfer characteristic (25,000-ohm load resistance).**

## Operating Point

We have explained how the correct value of the grid bias is chosen with reference to the peak signal voltage, but we have not yet said anything about the value of the plate-supply voltage and the load resistance. These factors together determine the *operating point* and operating region of the tube. In Fig. 4-26 we have repeated the dynamic transfer characteristic of Fig. 4-22 (A) for the

6J5 with a 25,000-ohm load resistor and 350 volts plate-supply voltage, but we have omitted the static curves, because they are not necessary for our purpose. The dynamic transfer characteristic alone is sufficient to portray graphically the variations in output plate current produced with a varying input grid voltage. The curve actually predicts the behavior of the plate for a given input signal voltage and a fixed *operating point.*

*Quiescent Conditions.* Given the plate-supply voltage 350 volts and the load resistance of 25,000 ohms, we obtained the dynamic transfer characteristic shown in Figs. 4-22 and 4-26. We still have to chose an operating point on this particular curve; that is, a fixed value for the grid bias. In accordance with our previous considerations that the maximum grid swing should not drive the grid positive, we select point *N* at –6 volts as our operating point. This is the *quiescent* or *d-c value* of the grid voltage (the bias). As we have seen for this value the positive peak of the a-c signal (+6 volts) will not drive the grid positive, and hence no grid current is drawn. For –6 volts bias, corresponding to zero volts input voltage, we obtain a plate current of 6.4 ma from the dynamic characteristic; this is known as the *quiescent, no signal,* or d-c value of the plate current.

*Plotting Input and Output Waveforms.* Having chosen an operating point, let us see how the dynamic transfer characteristic can be used to give a picture of the plate current variation for a given grid-voltage swing. The instantaneous values of both the grid voltage and the plate current must be plotted point by point to obtain the complete waveforms. Starting with the grid voltage, we fix its base line so that its zero voltage points *A-B* and *J-K* coincide with the –6 volts fixed bias by drawing a dashed line to operating point *N.* This fixes the base line for the varying grid voltage at –6 volts for no input signal. Along this base line we plot the a-c signal sine wave against time through points *A, B, C, D, E, F, G, H, I, K.* The positive peak of the a-c signal (+6 volts) occurs at point *D,* corresponding to zero volts total grid voltage, as indicated by the dashed line going to zero volts grid voltage on the transfer characteristic. The negative peak (–6 volts) of the a-c signal occurs at point *H,* corresponding to –12 volts grid voltage on the dynamic transfer characteristic. The units along the time axis (that is, the distance between points) are arbitrary, but for a correct representation, the same time units must be chosen for both the grid-voltage and the plate-current waveforms. Having plotted the waveform of the input grid voltage, we now obtain the corresponding plate-current waveform directly from the dynamic transfer characteristic. We start out by drawing a horizontal base line for the plate current from point *N* to the right. This fixes the quiescent (no-signal) plate current at the value of 6.4 ma, as previously determined. Place point *A'* somewhere along this horizontal plate-current base line to start the plate-current wave. Then lay off a distance *A', B',* equal in length to distance *A-B* of the grid-voltage wave. This means that during the time interval *A'-B',* corresponding to A-B when no signal is present, the plate current remains at its quiescent value of 6.4 ma. Now vertically project point *C* from the grid voltage until it intersects the transfer characteristic at point *L* (for a grid voltage of −2 volts and a plate current of 8.9 ma). From *L* draw a horizontal line to point *C'* on the plate-current wave to indicate a plate current of 8.9 ma for the grid voltage of −2 volts.

The location of point *C'* along the horizontal base line is fixed by measuring off the time distance *B-C* on the grid voltage wave and making *B'C'* the same *horizontal* length along the plate current base line. Similarly, a projection from point *D* on the grid-voltage wave at its positive peak intersects the characteristic at *M* and indicates a plate current of 10.1 ma for a grid voltage of 0 volts (when the signal is +6 volts). A horizontal line from *M* to *D'* on the plate-current wave fixes the peak plate current at 10.1 ma. Point *D'* is located at the same time distance from *C'* as point *D* is away from C.

As you will see the distance in time units between any points on either waveform (*not A-B, A',-B', J-K,* and *J'-K'* which are one unit long each) is always equal to one-half the side of a square unit. Hence the other points on the plate-current waveform may simply be plotted by making vertical projections from each point on the grid-voltage wave to the characteristic, and then drawing a horizontal line from the intersection point with the characteristic to the corresponding point on the plate-current wave, one-half unit square distant (in time) from the last point. Thus, the complete plate-current waveform *A'-B'-C'-D'-E'-F'-G'-H'-I'-J'-K'* is obtained, which is an accurate representation of what the plate current of the tube would look like, if we measured the plate current at each of these instants and plotted the values. It can be further seen, that the waveform of the plate current appears identical with that of the grid input voltage. It is evident, therefore, that the waveform of the voltage appearing across the load resistor (that is, the product of the plate current times the load resistance) is also an accurate replica of the grid input voltage waveform. All three, the input signal, the plate current and the load voltage are faithful renditions of a typical a-c sine wave in this case.

*Linearity.* We have previously stated that for low distortion and a faithful rendition of the input waveform, the plate current changes must be linear, that is, they must be *directly proportional* to the grid-current changes. Let us see how well the plate-current waveform of Fig. 4-26 fulfills this condition of linearity. When the grid input voltage goes through the first quarter cycle and reaches its positive peak of 0 volt (at $D$), the plate current increases from its quiescent value of 6.4 ma to a value of 10.1 ma at $D'$, or a change of 3.7 ma. During the time when the grid voltage decreases from its reference value (at $F$) to its negative peak of $-12$ volts at $H$, the plate current falls from the quiescent value of 6.4 ma (at $F'$) to its minimum value of 3 ma (at $H'$), or a change of 3.4 ma. We see, therefore, that the plate-current rise during the time the signal goes positive differs by only 0.3 ma (that is $3.7 - 3.4 = 0.3$ ma), or less than 10 percent from the plate-current fall when the input signal goes negative. Ideally, the plate-current rise would equal the plate-current fall, but the waveform distortion due to the 10 percent discrepancy between these two is still tolerable, and the output waveform can be called a fairly satisfactory rendition of the input. Even this slight *distortion could have been avoided by increasing the load resistance and reducing the input signal voltage, so as to further straighten out the transfer characteristic and operate entirely along its linear portion.*

*Choice of Operating Point.* To illustrate the importance of choosing the proper operating point, we have shown one case of distortion in Fig. 4-27. In this case nothing has been changed except the operating point on the dynamic transfer characteristic. The plate-supply voltage is 350 volts and load resistor is 25,000 ohms as before. The a-c input signal still has peak values of $+6$ and $-6$ volts, but we have now moved the operating point from $N$ in the curved portion of the characteristic in Fig. 4-26 to point $P$ on Fig. 4-27. This corresponds to a grid bias of $-12$ volts, and a quiescent value of the plate current of 3 ma when no signal is

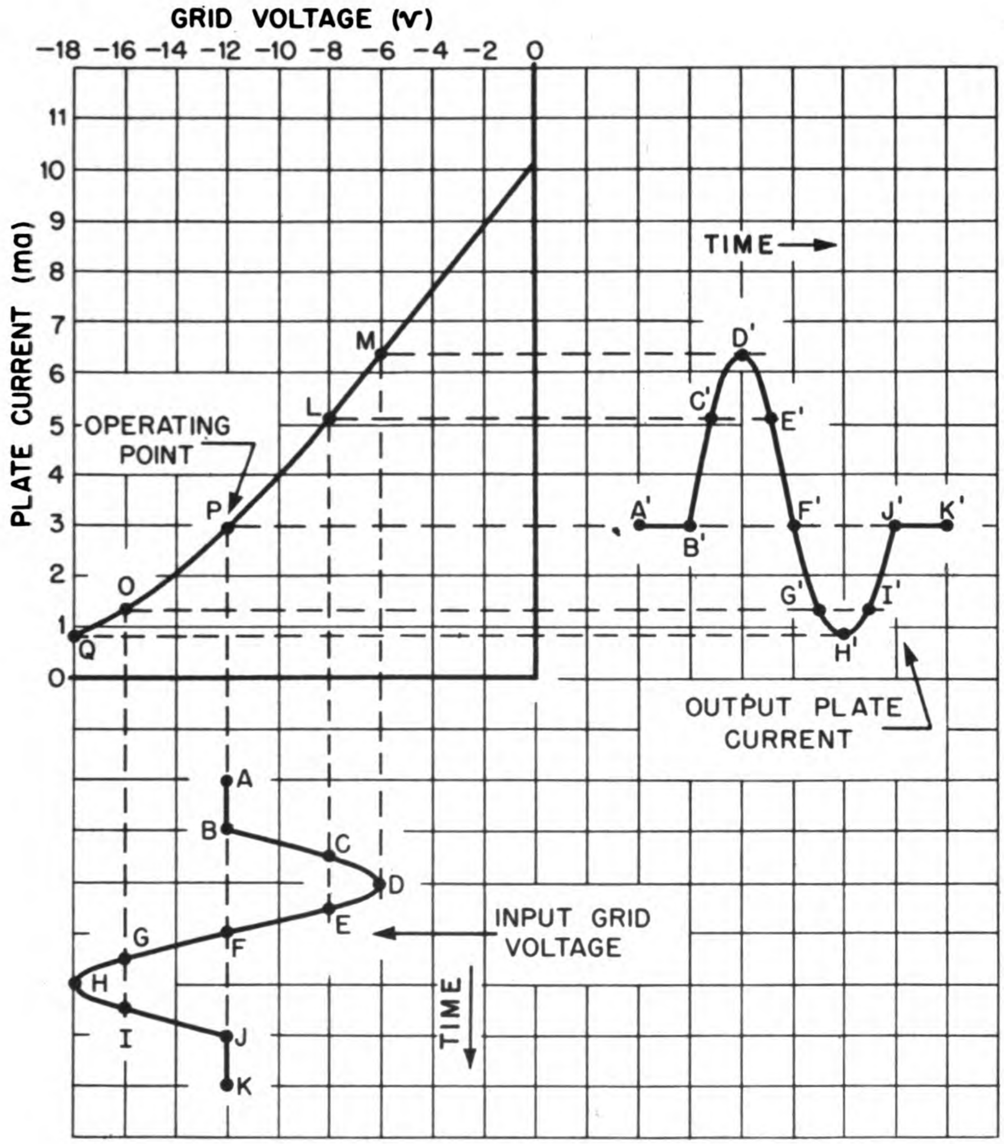



**Fig. 4-27. Operation on nonlinear portion of 6J5 dynamic transfer characteristic (25,000-ohm load resistance).**

present. It is evident that negative swings of the input grid voltage drive the tube far into the curved, nonlinear portion of the transfer characteristic, and even a casual look at the output plate-current waveform shows it to be highly nonuniform and distorted, with the negative peaks apparently flattened out.

The plate-current waveform was obtained by the same plotting process as was explained in connection with Fig. 4-26, and we do not need to repeat it again. Let us see, just how bad the *non-*

*linear distortion* of the plate-current waveform really is. The quiescent (no-signal) value of the plate current is 3 ma, in this case. When the grid voltage rises to its positive peak at point *D*, the plate current rises to its maximum value of 6.4 ma at point *D'*, which amounts to a change of 3.4 ma (6.4 −3 = 3.4). When the grid voltage reaches its negative peak at point *H*, the plate current falls to its minimum value of about 0.9 ma at point *H'*, or a change of 2.1 ma (3—0.9 ma = 2.1) from the quiescent value. The difference between the rise and fall of the plate current is 1.3 ma (3.4 −2.1), which is discrepancy of almost 40 percent. This amount of distortion could never be tolerated in most applications, where it is desired to reproduce exactly the input waveform. As you will discover when you read more advanced texts, nonlinear waveform distortion leads to the introduction of entirely new frequencies in the output which were not present in the input wave.

Summarizing, we see that the location of the operating point is not only determined by the consideration that the maximum positive grid swing should not exceed the value of the bias, but also by considerations of linearity, or what amounts to the same thing, the amount of permissible distortion. The higher the value of the load resistor, the more linear is the dynamic transfer characteristic, and, providing we have chosen an operating point on the linear portion of the characteristic, the smaller the input grid-voltage swing (that is, the signal amplitude), the more linear and undistorted is the output plate-current waveform.

### Amplification

We have not yet shown how much the simple triode amplifier of Fig. 4-24 has amplified the input signal voltage in the grid circuit. Although the plate-current waveform in Fig. 4-26 *looks bigger* than the grid-voltage waveform, this is no indication of the amount of amplification taking place, since we cannot compare the magnitude of a current with that of a voltage. To obtain the correct amplification, we must compare the magnitude of the output voltage developed as a result of the drop across the load resistor with that of the input or signal voltage applied to the grid of the tube. Hence, we can define the amount of *voltage amplification,* also known as *voltage gain,* as the *ratio of the output voltage to the input voltage*. Stating the same thing as an equation, we have for the voltage gain:

$$A = \frac{e_{out}}{e_g}$$

where $A$ = the voltage amplification, or voltage gain
$e_g$ = the instantaneous value of the input signal, or exciting voltage
$e_{out}$ = the instantaneous value of the a-c output voltage across the load resistor

You will note that the equation deals strictly with instantaneous values of a-c quantities.

There are two ways we can determine the output voltage ($e_{out}$). One simple way is to multiply the a-c plate current ($i_p$) by the load resistance ($R_L$); in other words, the a-c voltage across the load:

$$e_{out} = i_p \times R_L$$

In our present example of the 6J5 (Fig. 4-26), we have just seen that the plate current rises from its quiescent value of 6.4 ma for no signal to a maximum of 10.1 ma at point $D'$ for the 6-volt positive peak of the a-c input signal. The peak value of the a-c plate current ($i_p$), then, is the total *change* in the plate current, which is 3.7 ma (10.1 −6.4 = 3.7). Multiplying this value by the load resistance, we obtain the peak value of the a-c output voltage:

$$e_{out} = i_p \times R_L = 0.0037 \times 25{,}000 = 92.5 \text{ volts}$$

Taking the ratio of the a-c output voltage to the grid voltage, we obtain:

$$\frac{e_{out}}{e_g} = \frac{92.5}{6} = 15.4 = \text{the voltage amplification}$$

Thus we see that the voltage amplification in the present case is 15.4, which means that any value of the input signal voltage will be multiplied by a factor of 15.4 due to the tube's amplification. (In the present case we have compared the *peak values* of the output to the input voltage—points $D'$ and D in Fig. 4-26; this is not essential. Any other two corresponding points of the output and input voltage wave could have been compared with the same result.)

The second way of determining the output voltage is directly from the load line and does not involve any calculations whatsoever. Referring back to Fig. 4-21, where we used the same operating point ($P$) for −6 volts bias and 6.4 ma quiescent plate current, we remember that the voltage across the load ($e_{RL}$) changed from

160 volts for –6 volts bias (zero signal voltage) to 253 volts for 0 volts grid voltage (+6 volts signal voltage). The a-c output voltage is the *change in load voltage,* or in this case 253 –160 = 93 volts. We could have obtained the same figure by considering the plate voltage which – as you will recall – changed from 190 volts at –6 volts grid voltage (no signal) to 97 volts at 0 volts grid voltage (+6 volts signal voltage). Again the *change* in plate voltage is the a-c output voltage, and amounts to 190 –97 – 93 volts.

Substituting in the equation, we see that the voltage gain in this case amounts to:

$$\frac{e_{out}}{e_g} = \frac{93}{6} = 15.5 = \textit{amplification.}$$

This value is in excellent agreement with the previous value of 15.4 obtained by the first method of calculation, and also with the manufacturer's data. Note also, that the amplification is always somewhat *less* than the value of the amplification factor (20 in this case), which represents a theoretical limit.

**Phase Relations**

In preceding pages we have seen how the signal applied to the grid of a triode is amplified by the tube, causing a magnified replica of the input signal waveform to appear in the output, (plate circuit) of the tube. We have further shown that the plate current – and hence the output voltage – faithfully duplicates the waveform of the input signal, provided the operating point of the tube is properly chosen. We have not yet considered the timing, or *relative phase,* between the various input and output voltages and currents,

Figure 4-28 shows five sine waves which illustrate the phase relationships occuring in a triode amplifier circuit. Our previous example for –6 volts bias, 350 volts plate-supply voltage, and 25,000 ohms load resistance has been chosen again for continuity, but the *phase relations are true regardless of the particular values of the voltages and currents.* The dashed vertical lines passing through the waveforms compare corresponding points at the *same instant in time* for each of the waveforms. In addition we have shown the general nature of the various waveforms and their relative phase, superimposed on the circuit of Fig. 4-24 in the slighty modified circuit of Fig. 4-29.

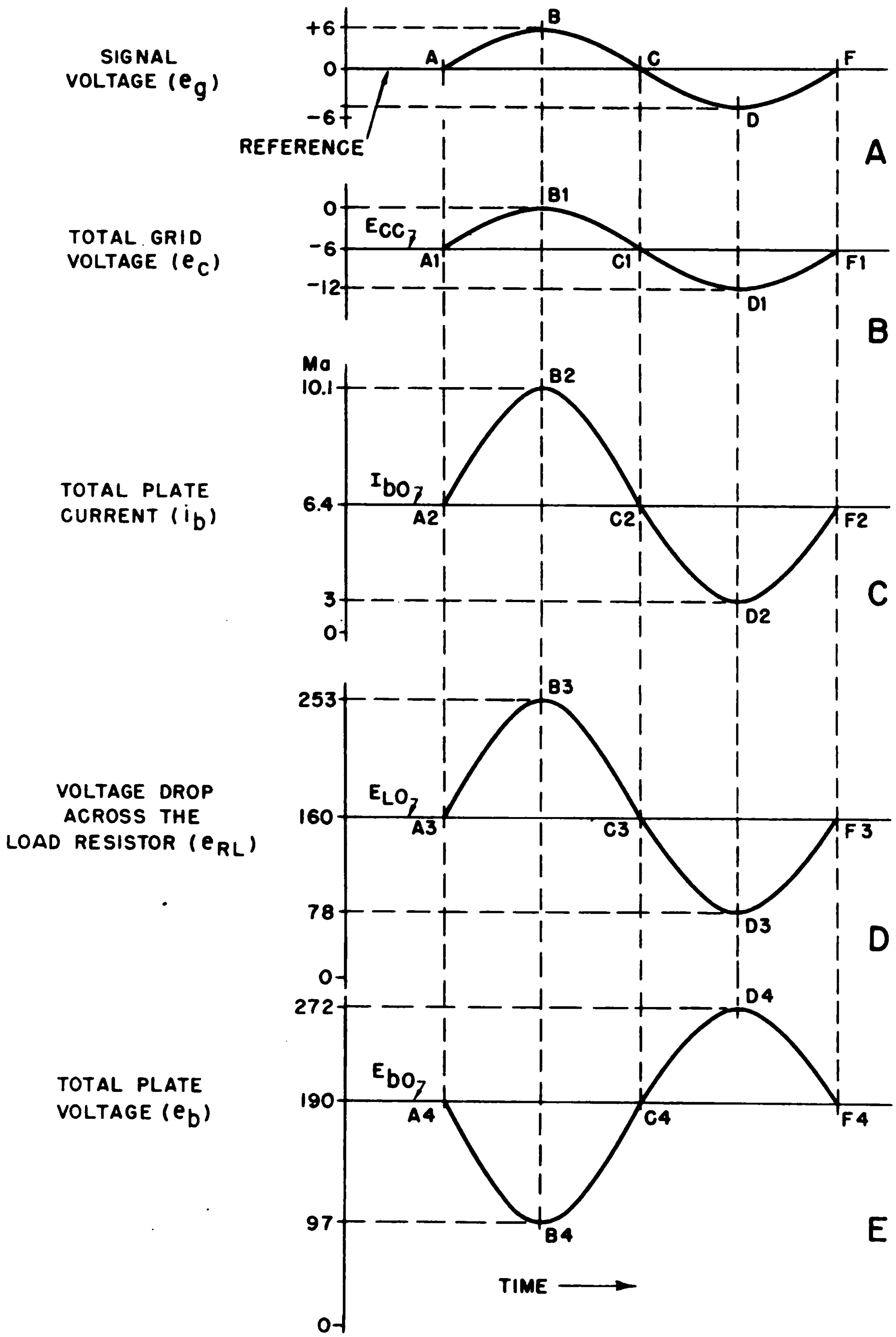



Fig. 4-28. Waveforms illustrating phase relations in triode amplifier circuit.

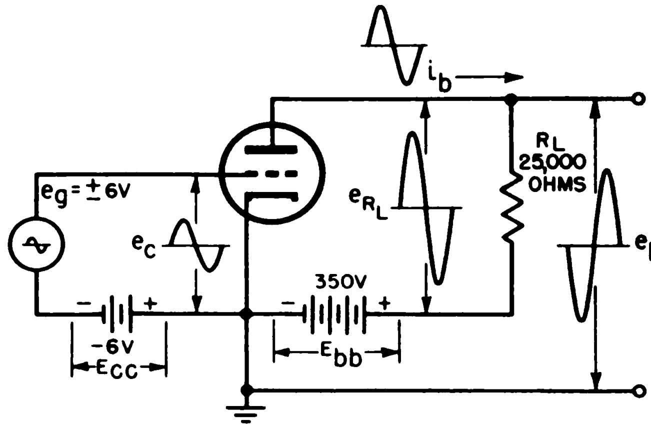



**Fig. 4-29. Basic triode amplifier circuit, showing phase relations of current and voltage waveforms.**

Curve (A) in Fig. 4-28 represents the signal voltage, $e_g$, which is seen to vary between peak values of +6 and –6 volts. Curve (B) represents the total grid voltage, $e_c$, which you will recall is the algebraic sum of the grid bias and the signal voltage (that is, $e_c = E_{cc} + e_g$). With a grid bias, $E_{cc}$, of –6 volts, the total grid-to-cathode voltage, $e_c$, is seen to vary between a maximum of 0 volts (for +6 volts signal swing) and a minimum of –12 volts (for –6 volts signal swing.) Its quiescent value is equal to the bias, or –6 volts.

Curve (C) shows the variation in the plate current, $i_b$, *for* the varying grid voltage. Its quiescent, or no-signal value, is 6.4 ma and has been labeled $I_{bo}$, to indicate the zero signal voltage. Its maximum value is 10.1 ma for +6 volts signal voltage, while its minimum value is 3 ma for –6 volts signal voltage. Its positive peak is a little larger than the negative peak, but the peaks coincide in time with the positive and negative maxima of the signal and total grid voltages, and hence are all *in phase.*

The total voltage drop across the load resistor, $e_{RL}$, is illustrated by curve (D). You may recall that its quiescent value for no signal voltage is 160 volts, designated by $E_{Lo}$, while it reaches a maximum of 253 volts when the signal voltage is +6 volts, and a minimum of 78 volts when the signal voltage reaches its negative peak of –6 volts. Again, the maxima and minima of the load voltage drop coincide with those of the signal and grid voltages, and those of the plate current, and hence all these waves are *in phase.*

As you can see the phase relations are entirely different for the fifth waveform, (E), which represents the total instantaneous plate voltage, $e_b$, existing between plate and cathode of the tube.

You will remember the equation $e_b = E_{bb} - i_b R_L$, which shows that for a fixed plate-supply voltage ($E_{bb}$) the total plate voltage ($e_b$) decreases as the plate current ($i_b$) and total voltage drop across the load increase. This is so, you recall, because with increasing plate current and load voltage drops, less of the supply voltage is available at the plate of the tube. On the other hand, the lower the plate current, the smaller is the voltage drop across the load, and hence the more plate voltage is left over from the fixed supply voltage. It is evident, therefore, that the total plate voltage is in an opposing, or *out-of-phase relation* to the plate current and the input signal. This is brought out by the shape of curve (E) in Fig. 4-28. From Fig. 4-21 you can ascertain that the quiescent value of the plate voltage (for no signal) is 190 volts for a bias of –6 volts and load of 25,000 ohms. This value has been marked $E_{bo}$ in Fig. 4-28. When the grid voltage rises to 0 volts for a signal of +6 volts, the plate voltage *falls* to a minimum value of 97 volts, while the *drop* in grid voltage to –12 volts for a signal of –6 volts produces a *rise* in total plate voltage to its maximum value of 272 volts. Thus, whenever the signal voltage, $e_g$, is at its maximum positive value, the plate voltage, $e_b$, is at its minimum value, and vice versa. It appears as if the plate voltage has been shifted by one-half cycle, or 180 degrees, (a cycle corresponds to 360 degrees) with reference to the grid voltage. We can sum up our conclusions by stating that *the plate current is in phase with the grid voltage, but the plate voltage is 180 degrees out of phase with the grid voltage*. This is generally true for all types of vacuum tubes which have a control grid.

### Supply Voltage Sources

While for convenience we have shown batteries as voltage sources for the d-c operating potentials of the tube, other supplies are generally utilized in practice. The fixed plate supply voltage and fixed grid bias are most frequently secured from a rectifier power supply. A low-voltage winding on the power transformer in this power supply supplies the heater current for the tubes. Simple rectifiers were discussed in Chapter 3 (on diodes). In the case of the necessary grid bias, fixed voltages are not always used, but the tube sometimes supplies its own bias – known as *self-bias* by the insertion of appropriate resistors either in the cathode circuit or grid circuit. Plate current flowing through a cathode resistor develops a voltage which may be used to bias the tube, or sometimes grid current flowing through a grid resistor can serve the same purpose.

### Interelectrode Capacitances

Although it appears at first glance that all the electrodes in a triode tube are perfectly well isolated from each other, and that they cannot possibly influence each other except through the flow of plate current, this is not quite correct. You will remember that we discussed the electrostatic fields existing between the charged electrodes of a triode, such as the field between plate and cathode, plate and grid, and grid and cathode. You may also recall from

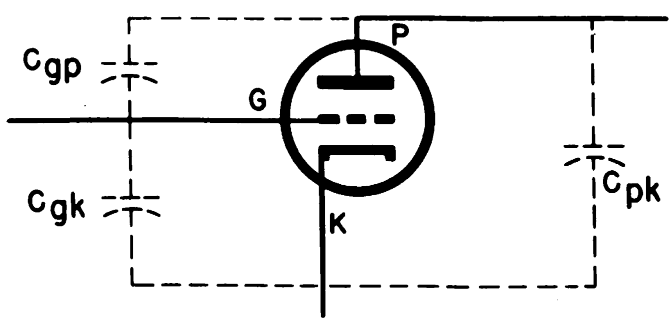



Fig. 4-30. Interelectrode capacitance of a triode.

elementary electricity that an electrostatic field between any two charged metal plates is the equivalent of an electric capacitor; capable of holding a certain charge. Thus it is evident that definite capacitances exists between all the metal electrodes of a triode, which however tiny — do affect the operation of the tube.

Figure 4-30 illustrates the chief capacitance existing between the metal electrodes, the so-called *interelectrode capacitances*. The most important of these is the capacitance between the control grid and the plate of the tube, which is labeled $C_{gp}$. There is also capacitance between the control grid. and cathode, $C_{gk}$, and a capacitance between the plate and the cathode, $C_{pk}$. The values of these capacitances are very small; generally somewhere in the order of 2 to 10 micromicrofarads ($\mu\mu f$). At low, audio frequencies (between 20 and 15,000 cps) the effect of these tiny capacitors is almost negligible, but at the higher radio frequencies (from 100 kilocycles up), when their reactance becomes low they play an important role in influencing the tube's operation. Especially the capacitance petween plate and grid, $C_{gp}$, may have the very undesirable property of coupling the output (plate) circuit back to the input (grid) circuit, resulting in the feedback of energy from the plate to the grid.

While sometimes useful, this feedback of energy as a result of interaction between the grid and the plate circuits frequently presents serious problems in achieving circuit isolation. A reduction of the interelectrode capacitances by additional shielding electrodes is achieved in multielectrode tubes. How these tubes successfully overcome the undesirable coupling and feedback effects between the plate and grid circuits, is discussed in the next chapter.

### Triode Detectors

Let us now explore briefly some other applications for which triodes are frequently used. In the last chapter we described a simple diode detector circuit which made use of the unidirectional (rectifying) ability of the diode to detect a radio signal. A triode, too, is a unidirectional device, since it does not conduct unless its plate is positive with respect to the cathode, and it has the advantage of amplification as well.

Figure 4-31 (A) illustrates how a triode tube can be utilized to rectify an a-c voltage. An operating point is chosen with a value of negative grid bias approximately at plate-current cut-off. Evidently this places the operating point in the lower bend of the dynamic transfer characteristic. Hence with no a-c input signal at the grid, a negligible plate current flows. When an a-c voltage is applied to the grid, its negative half-cycles — which drive the grid even more negative — are cut off, since the plate current can not be less than zero. On positive half-cycles of the signal voltage, however, the total grid voltage rises above the cut-off value, and the plate current reproduces the waveform of the positive half-cycle of the grid voltage. There is some distortion, of course, since the tube is operated on the nonlinear portion of the characteristic. It is apparent that the rectifying ability of the diode and the triode are very similar. The

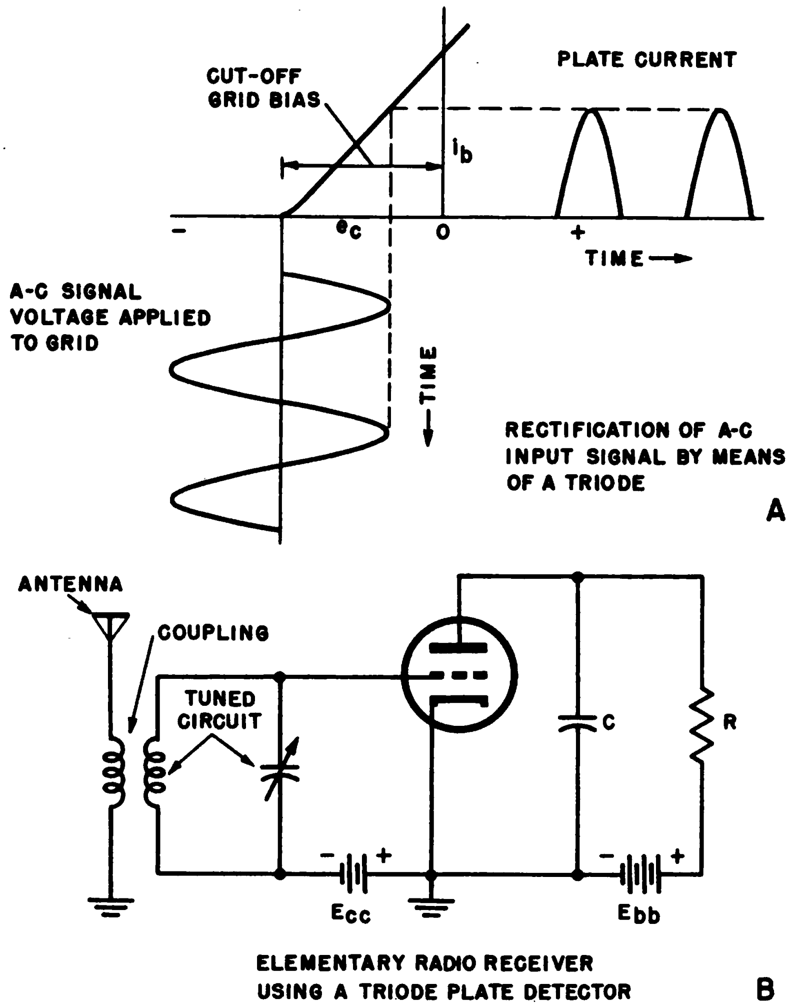



Fig. 4-31. Operation and circuit of triode plate detector.

big advantage of the triode is the fact that in addition to rectifying the a-c signal voltage, it also amplifies it in the plate circuit – something which the diode cannot do.

One form of triode detector circuit, the so-called *plate detector*, is shown in Fig. 4-31 (B). This circuit is really equivalent to the diode detector circuit shown in Chapter 3, provided that the triode and the diode have the same plate resistance. The chief difference is that the triode circuit amplifies the signal at the grid, while no amplification takes place in the diode circuit. The tube is operated at cut-off through the bias battery, $E_{cc}$. The modulated signal voltage is fed through the tuned circuit to the grid of the tube. It is rectified by the plate circuit, as shown in part (A). The action taking place in the output circuit across $C$ and $R$ is essentially the same as discussed for the diode detector and need not be repeated here. The circuit of Fig. 4-32 (B) actually represents a very elementary radio receiver. A radio signal fed in through the antenna and the tuned input coupling circuit is detected by the tube, and could be made audible if a pair of headphones were inserted into the plate circuit. There are other types of triode detector circuits which will not be discussed here. However, the one circuit shown will serve to illustrate one example of this important vacuum tube application.

### Cathode Followers

Another very popular application of the triode is the cathode-follower circuit, illustrated in Fig. 4-32. Instead of inserting the load resistor in the plate circuit, as was done in the case of the simple triode amplifier of Fig. 4-24, we have inserted a 25,000-ohm load resistor into the cathode circuit of the tube. This apparently simple change has some remarkable effects on the behavior of the circuit. The plate current of the tube now flows through the cathode resistor, $R_k$.

Assume that the signal voltage, $e_g$, is going positive, at first. This will result in an increased plate current, which in turn produces an increased voltage drop, $i_b \times R_k$, across the cathode load resistor $R_k$. Since electrons flow from minus to plus, the increased plate current will make the cathode end of resistor $R_k$ more positive than before. The polarity of the voltage across $R_k$, therefore, is the same as that of the a-c signal voltage. A rise in signal voltage produces an increase in the output voltage across $R_k$ of the same polarity. Similarly, when the signal voltage, $e_g$, goes negative, the plate current and hence the voltage drop across $R_k$ both decrease,

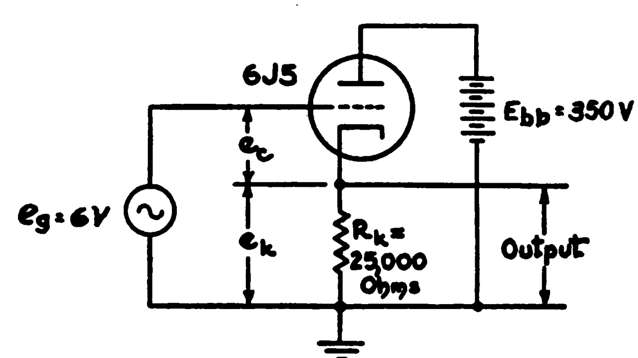



Fig. 4-32. Basic cathode follower circuit (6J5).

and the cathode becomes less positive (or more negative). It can be seen, therefore, that the *output signal is in phase with and follows the input signal,* a fact from which the circuit derives its name.

*Feedback.* If you look at Fig. 4-32 more closely you will discover that the cathode resistor, $R_k$, is part of both the plate and the grid circuits. It is part of the plate circuit, because the plate current flows through it. It is also part of the grid circuit, because the output voltage (across $R_k$) is in series with the signal voltage, $e_g$. The cathode resistor, therefore, couples the plate and grid circuits together, and an interaction takes place. What is this interaction?

We have seen that with the a-c signal voltage ($e_g$) going positive, the cathode end of resistor $R_k$ will also become more positive. This is equivalent to saying that the *grid will become more negative with respect to the cathode.* It can be seen therefore, that the total grid-to-cathode voltage, $e_c$, decreases, although the signal voltage, $e_g$, is increasing. It is clear, that the output voltage, $e_k$, bucks the signal voltage, tending to wipe it out. This opposing relationship can be stated thus:

$$e_c = e_g - e_k, \text{ where } e_k = i_b \times R_k$$

You will realize now that the common cathode resistor has the effect of reducing the total grid voltage, $e_c$, in an action known as *degenerative feedback.*

What are the effects of this degenerative feedback action of $R_k$? One effect is that it greatly reduces the distortion in the output of the tube. Furthermore, you will realize that by almost wiping out the signal voltage, the feedback action greatly reduces the amplification of the tube. As a matter of fact, no amplification takes place at all, and the *output voltage is always a little less than the input signal voltage.* In the circuit of Fig. 4-32, with a peak signal voltage of 6 volts, the output voltage will only be about 5.6 volts, and hence the voltage "gain" is $\frac{5.6}{6} = 0.93$. In other words no amplification takes place at all, and the voltage gain is less than unity. In contrast, the amplifier circuit of Fig. 4-24 has a voltage gain of 15.4, and produces an output voltage of 93 volts for a 6-volt signal voltage. Clearly, the cathode follower is not used as an amplifier circuit.

One advantage of the cathode follower is its low distortion. Its more important advantage is that it is capable of *lowering an impedance,* acting somewhat *like a matching transformer.* The feedback action tends to reduce the internal resistance, $r_p$, of the tube greatly — by a factor equal to $\mu + 1$. While the plate resistance of the 6J5 in the circuit of Fig. 4-24 was found to be about 7,700 ohms, in the circuit of Fig. 4-32 it is only $\frac{7{,}700}{20 + 1}$, or 367 ohms. The output resistance of the tube — also known as *output impedance* — is the parallel combination of this reduced plate resistance and the cathode resistor, $R_k$. In the present example this amounts to about 360 ohms. Since the input resistance of the tube is several millions of ohms, the cathode follower can be used to match a high impedance source at the input of the tube to a low-impedance device in the output, without using a transformer.

### Phase Inverter

We have previously discovered that any simple triode amplifier has an output of opposite polarity to the input. A positive-going signal at the grid produces a negative-going 180-degree out-of-phase signal at the plate, as indicated in Fig. 4-28. However, in many applications it is desired to have *two* output signals, which are of equal amplitude, but 180 degrees out-of-phase with each other. Such a dual signal is used in the so-called *push-pull amplifiers* (consisting of two tubes whose grids are driven in opposite directions), and in other applications.

Since we have just seen that an output voltage taken from a cathode load resistor is *in phase* with the input signal voltage, it is a simple matter to devise a circuit which will have two output voltages, one taken from the plate, the other from the cathode of the tube. The circuit shown in Fig. 4-33 does just that. We have now split our output load into two parts. One load resistor (25,000 ohms in this case) is placed in the plate circuit, while the other load resistor of equal value (25,000 ohms) is placed in the cathode circuit. The output signal (1) taken off at the plate-load resistor $R_L$ is 180 degrees out-of-phase with the input signal, while the output signal (2) taken off at the cathode-load resistor $R_k$ is in phase with the input signal. Consequently, the two output signals are of opposite polarity or 180 degrees out of phase with each

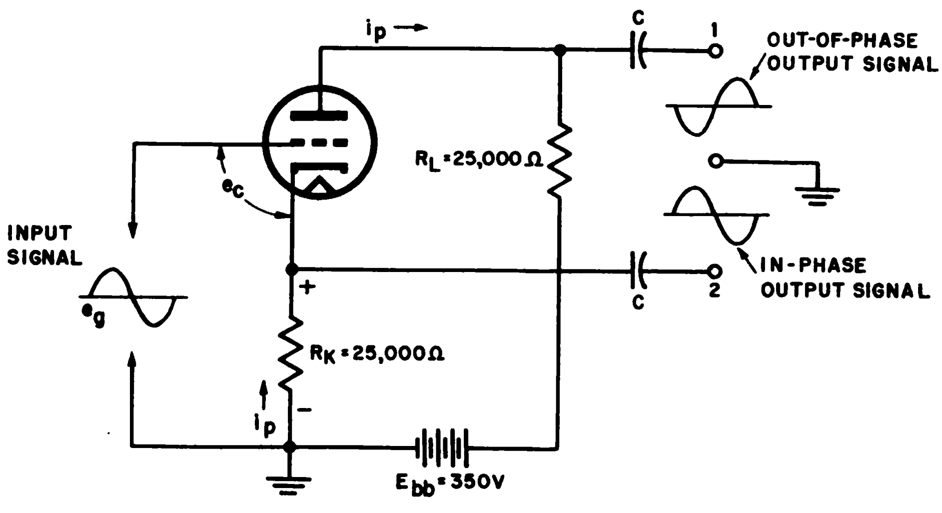



Fig. 4-33. Simple phase inverter for obtaining two 180-degree out-of-phase voltages of equal amplitude.

other. Since the total output voltage is split evenly between the two equal resistors, the two output signal voltages are also of equal amplitude. A capacitor, *C*, is placed in each output lead to block the d-c voltages at the plate and cathode of the tube from reaching the output terminals, so that only a-c output signals are present between each terminal and ground.

As in the case of the cathode follower, a degenerative feedback action takes place in the cathode circuit, and the voltage gain is again a little less than unity. Each output voltage, therefore, is a little smaller than the input signal voltage. The total output voltage, however, (between the two extreme output terminals) is a little less than *twice* the value of the input signal. Since phase inversion is the desired aim, the lack of amplification does not matter. Other phase inverter circuits exist, but the circuit of Fig. 4-33 serves to illustrate the general idea.

## Production of Square Waves (Overdriven Amplifier)

You will recall that when we placed the operating point of our simple 6J5 amplifier into the lower curved portion of the dynamic transfer characteristic by selecting a high negative grid bias (see Fig. 4-27), the output plate current became highly distorted, its negative peaks being considerably *flattened out*. If we had made the bias still more negative, or else had increased the signal amplitude, the negative peaks of the plate current would have been further flattened, taking on an almost square appearance. (If we had made the bias equal to plate-current cut-off, the negative half-cycles of the signal would have been shaved off completely, of course.) Furthermore, you may remember in connection with our discussion of the static plate-current grid-voltage characteristic (see

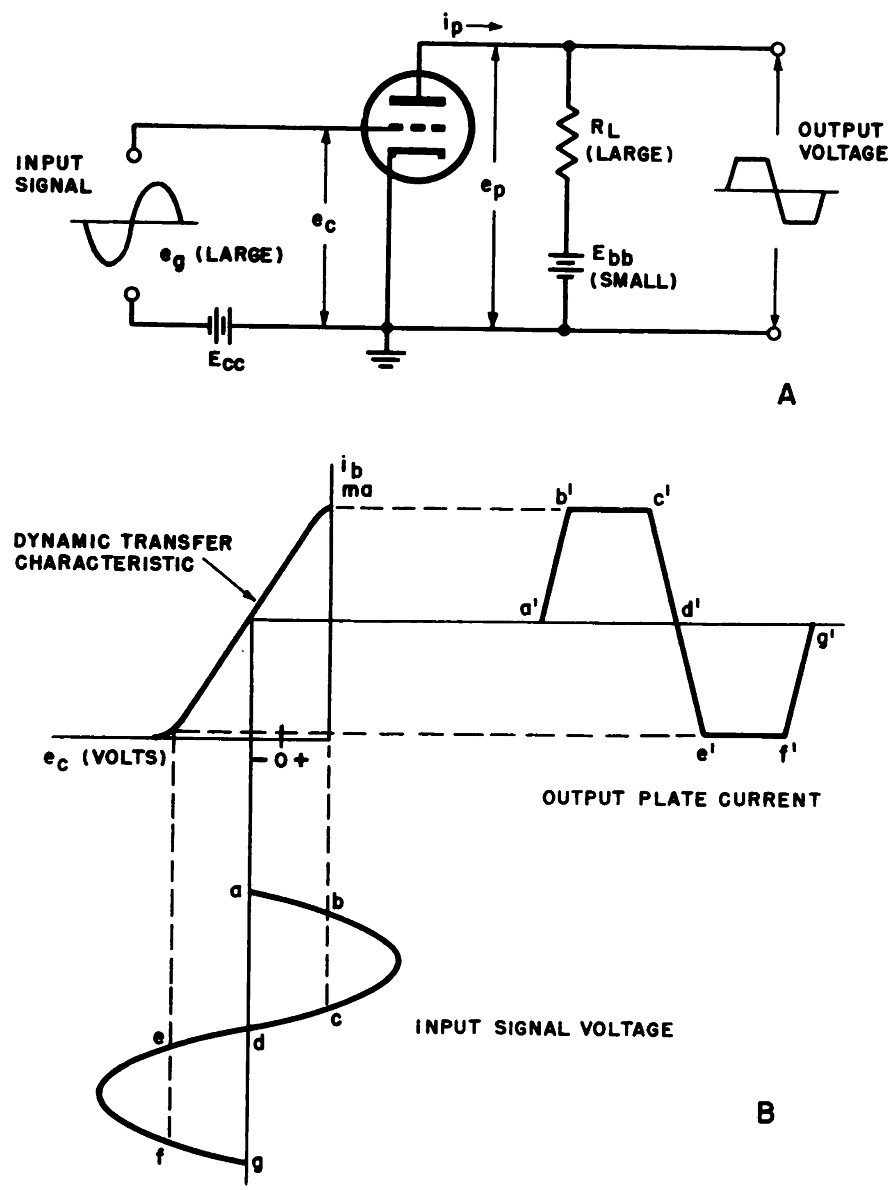



**Fig. 4-34. Production of square waves by an overdriven amplifier.**

Fig. 4-11) that *plate-current saturation* set in for relatively low positive grid voltages, provided the plate-supply voltage was sufficiently low. As is evident from an inspection of Fig. 4-11 the characteristic curve flattens out rapidly for low positive grid voltages at the low plate voltages of 100 volts. If the tube is biased at zero volts, an a-c signal voltage of about 7 volts positive peak would have the effect of *flattening out the positive peaks of the plate current,* since the plate current at saturation could not rise to reproduce the positive peaks of the input signal.

Although both types of distortion due to the curvature of the characteristic at high negative and positive grid voltages are generally highly undesirable, they are sometimes deliberately used to obtain a desired waveform, such as a square wave from an input sine wave. The circuit shown in Fig. 4-34 (A) purposely utilizes *plate-current cut-off for high negative swings of the input signal and plate-current saturation for large positive signal swings in order to clip off the tops from the negative and positive half-cycles of the plate current.* In this way, a sine wave at the input is converted into a waveform at the output which approximates a square wave.

The circuit of Fig. 4-34 (A) utilizes a large plate resistor, $R_L$, and a low value of the plate-supply voltage, $E_{bb}$. This produces plate-current saturation for relatively low positive values of the grid voltage. Most of the plate-supply voltage appears across the load resistor $R_L$ and very little across the tube, with the result that the value of the plate current is limited approximately to $E_{bb}/R_L$. The effect of this circuit on a large input signal voltage is illustrated in part (B). The negative peaks of the plate current are leveled off by plate-current cut-off, while the positive peaks are clipped by plate-current saturation.

## Oscillators

An electrical oscillating system, consisting of an inductance coil $L$ and a capacitor $C$, is shown in Fig. 4-35 (A). The action of these electrical elements is analogous to the mechanical pendu-

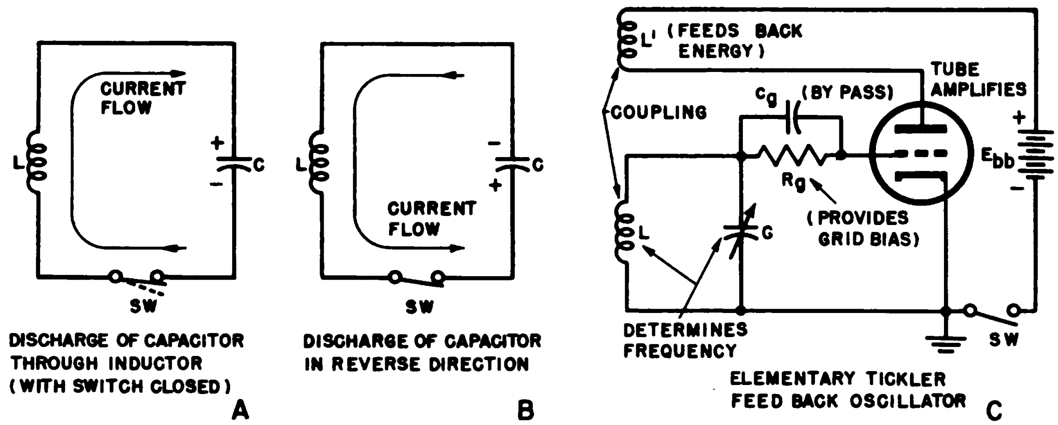



**Fig. 4-35. Operation of oscillators.**

lum. Assume that the switch is initially open and the capacitor has been previously charged to a certain voltage, so that an electric field exists between its plates. This electric field holds a certain amount of energy. Now let's see what happens, when we close the switch:

(1) Electrons move from the negative plate through inductance coil *L* to the positive plate, initiating a current flow. The flow of current through *L* creates a *magnetic field* about the coil which *opposes* the increasing current flow. This slows down the rate of discharge of the capacitor.

(2) As the capacitor discharges and the negative plate loses its excess of electrons, the current first builds up to a maximum, and then would tend to die down and stop. However, a strong magnetic field has been built up in the meantime around the coil *L,* which *stores up the energy originally residing in the electric field of the capacitor. The energy in the magnetic field of the inductor now strongly opposes the dying down of the current, and continues to force an electron current through the circuit in the same direction.* Thus, the negative plate not only loses its excess electrons, but actually becomes deficient in electrons, and takes on a positive charge. The positive plate, on the other hand, now has an excess of electrons pushed on to it, and becomes negative; consequently, the capacitor is again charged, but now in the opposite direction, as shown in Fig. 4-35 (B).

(3) The capacitor now discharges again, but in the opposite direction, as shown in (B). The current flow in the reverse di-

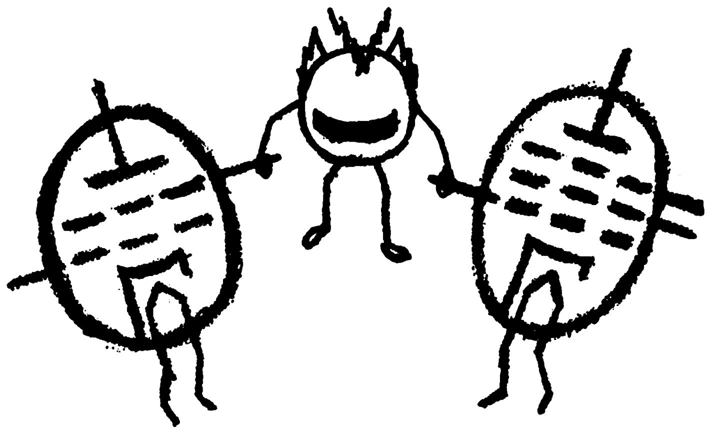
rection is again opposed by the magnetic field of the inductance $L$, and the entire process repeats itself in the opposite direction.

One cycle is completed when the plates of the capacitor are again charged up to their original polarity, as shown in (A). This sequence of charges and discharges continues, the to-and-fro motion of the electrons constituting an *oscillating current.* However, the see-saw of capacitor charge and discharge through the coil (which acts like a flywheel) does not continue indefinitely, since a certain amount of energy is lost during each cycle as the current encounters the resistance of the coil conductor. The amplitude of the oscillations, therefore, decreases gradually and oscillations soon die out.

If the amplitude of the electrical oscillations in the $L$-$C$ circuit is to be maintained at a constant level, sufficient energy must be fed into the circuit during each cycle to make up for losses occuring in the coil resistance. An elementary circuit for sustaining continuous oscillations, using a triode amplifier, is shown in Fig. 4-35 (C). It is known as a *tickler feedback oscillator,* because of the *tickler* coil $L'$, which feeds back sufficient energy from the plate circuit of the tube to the $L$-$C$ circuit to maintain continuous oscillations. The grid resistor, $R_g$, (bypassed through capacitor $C_g$) is used to automatically bias the tube at a negative value through the flow of grid current.

Oscillations in the circuit of Fig. 4-35 (C) commence spontaneously, since any small random voltage present in the grid-to-cathode circuit will be amplified by the tube and fed back to the grid circuit through $L'$ to start the process. Although the output voltage in the plate circuit of the tube is 180 degrees out-of-phase with the input voltage in the grid circuit, the feedback from coil $L'$ to inductance $L$ is in phase with the grid voltage, since a second 180-degree phase reversal takes place by the transformer action occuring betwen coils $L'$ and $L$. Consequently, any small voltage present in the grid circuit of the tube, will be amplified in the plate circuit and fed back in phase through the coupling of coil $L'$ to the grid circuit, so as to build up the oscillations in amplitude. The oscillations will reach such an amplitude that the energy fed back by the tube is just sufficient to overcome all losses in the grid circuit, effectively making its resistance equal to zero. Oscillations continue as long as the proper voltages are maintained at the tube electrodes to operate it as an amplifier.

You may wonder about the *frequency* of the oscillations taking place in the *L-C* grid circuit. This is determined by the values of the inductance *L* and the capacitor *C*. The *greater* the value of *L* and *C*, the *lower* is the frequency of oscillations; the *smaller* the values of *L* and *C*, the *higher* is the frequency. Generally, the capacitor is made variable, as indicated by the arrow in (C), in order to obtain a continuous variation of frequencies for the oscillations by *tuning* the capacitor through its range. A great variety of vacuum-tube oscillators exist with which you will undoubtedly become familiar as you make further studies in the field of electronics.



*Chapter 5*

# MULTIELECTRODE TUBES

In our considerations of vacuum tubes thus far we have dealt with the fundamental operations and principles of the diode and triode. During the early days of radio broadcasitng these were the only tubes available, and many receiver circuits were designed to compensate for their shortcomings. It was not until late in the 1920's that tube manufacturers introduced the *multielectrode* or *multielement* vacuum tubes that made possible the efficient receivers in use today.

Multielectrode or multielement tubes employ more than three electrodes (that is, more than one grid) to attain special desirable characteristics which enable them to function more efficiently than a triode. These tubes are also known as *multigrid* tubes. For example, a tube which utilizes two grids, or *four* electrodes in all is known as a *tetrode* ("tetra" means "four"), while a tube with three grids, or *five* electrodes altogether, is called a *pentode* ("penta" means "five").

Sometimes two or more tubes are placed within the same envelope to perform several separate functions and reduce the number of tubes in a radio receiver. An example are the duo-diodes we have discussed in Chapter 3. These later types of tubes, which perform more than one function and have many electrodes, are known as *multiunit* or *multipurpose* tubes. We shall give some additional examples of these later on. For the present, let us turn to the tetrodes.

## TETRODES

In Chapter 4 we have shown that the various electrodes of a triode act like the charged plates of a capacitor, and that there is a certain interelectrode capacitance between them. Although the interelectrode capacitances are small, their effect at high frequencies becomes important, since even very small capacitors present little opposition to the passage of high-frequency alternating currents. Especially the grid-to-plate capacitance, $C_{gp}$, becomes troublesome when it is attempted to attain large amplifications of weak radio-frequency signals. The grid-to-plate capacitance then has the effect of transferring a portion of the a-c output voltage in the plate circuit back to the grid circuit, thus destroying the efficiency and faithfulness of the amplification. If this *feedback action* from plate to grid becomes sufficiently great, instability and oscillations will result, in the same manner as was discussed in Chapter 4 in connection with oscillators. The frequency of these oscillations is independent of the incoming frequency, and may drown out the signal to be received. Although various *neutralization* circuits can overcome the effects of the grid-to-plate capacitance, their operation and adjustment is generally too critical to be satisfactory in a radio receiver.

The most effective answer to the feedback caused by the grid-to-plate capacitance is the tetrode tube, in which an additional grid—called the *screen grid*—has been placed between the control grid and the plate of the tube. The screen grid encloses the plate almost completely and hence acts as an effective *electrostatic shield* between grid and plate. Because of the presence of this screen grid, the tetrode is sometimes referred to as a *screen-grid* tube. In practice the screen grid stabilizes the tube and reduces the grid-to-plate capacitance from a value of about 2 to 5 micromicrofarads (or

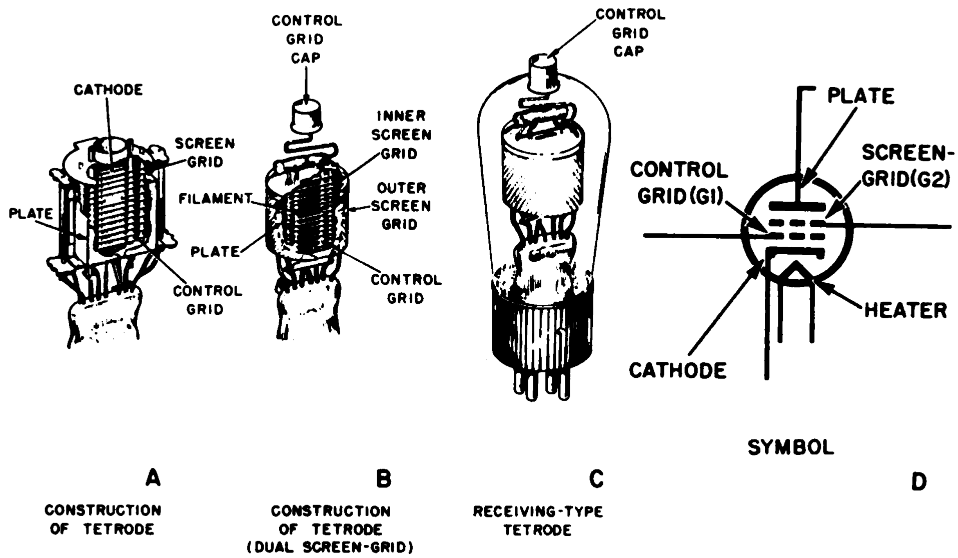



Fig. 5-1. Physical construction and schematic symbol of tetrode.

more) in triodes to as little as 0.01 micromicrofarad in a tetrode. This effectively cancels out the high-frequency feedback action between plate and grid. However, we might as well say it right now, the introduction of the screen grid also produces some undesirable distortions of the tube characteristics and other disadvantages, which have made the tetrode virtually obsolete in recent years. This is especially true, because the successor to the tetrode, the so-called *pentode,* retains the advantages of the screen grid in the tetrode without the attendent disadvantages. Nevertheless it is important to understand the basic action occuring in the tetrode, because the operation of the pentode is essentially the same.

## Construction

The tetrode contains all the electrodes of the triode (with the same functions), and in addition the screen grid, which is inserted between the control grid and plate. The physical arrangement of these four elements is illustrated in Fig. 5-1. The cathode, plate and control grid are not substantially different from those of a triode. The cathode may be either a filament or an indirectly heated type. The control grid is the usual spiral wire helix with closely spaced turns. The cylindrical plate is separated from the control grid either by a single wire screen on one side, or it may be completely enclosed by the screen grid. In (A) of Fig. 5-1, the screen grid is rectangular in shape and is located on one side of the plate, separating it from the control grid. The plate is fin-shaped for improved heat dissipation. In (B) of the figure, a tube is shown which uses a dual screen grid to completely enclose the plate of the tube. The outer screen grid, located between the plate and the glass envelope, is a perforated metal structure of circular shape. The inner screen grid is oval and is located between plate and control grid.

The plate, screen-grid, heater, and cathode connections are made through the conventional pins at the bottom of the tube base. The connection to the control grid, however, is made through the glass envelope by means of a cylindrical metal cap at the top of the tube. This helps to reduce the capacitance between the plate connections (at the bottom) and the control grid (at the top).

The external view of a typical receiving tetrode is shown in Fig. 5-1 (C). The cathode, heater, plate, and screen-grid connections are made to the base pins at the bottom, while the control-grid connection is made to the top cap. The schematic circuit symbol for a tetrode is shown in (D). The screen grid is shown as another dashed line, similar to the control grid, and placed nearer to the plate. To distinguish between the two grids in circuit schematics the symbol *G1* is used to identify the control grid, and *G2* is used to identify the screen grid. The lower number generally is used for the grid nearer to the cathode in multielectrode tubes.

### Basic Circuit

To illustrate the differences from the triode circuit, the basic tetrode circuit with all required operating voltages is shown in Fig. 5-2. This circuit may be used to develop the tetrode charac-

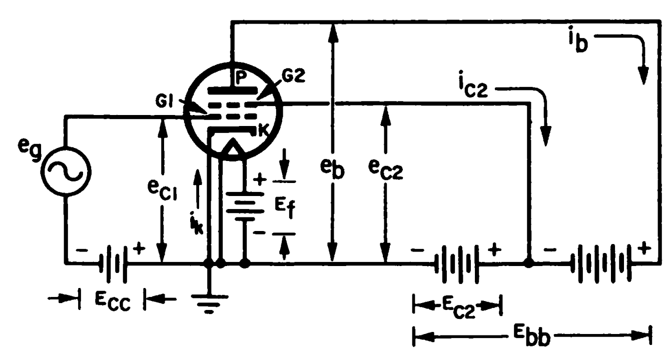



**Fig. 5-2. Basic tetrode circuit showing operating voltages and currents.**

teristic curves, provided the a-c signal, $e_g$, is shorted out and the various supply voltages are made variable. As is evident, in normal use the screen grid is made positive with respect to the cathode by receiving a part of the plate-supply voltage, $E_{cc}$, generally from a tap at the plate voltage supply. The d-c screen-grid voltage is usually appreciably less than the d-c plate voltage. Except for the d-c supply voltages, which are shown in capital letters, we have labeled the various currents and voltages in Fig. 5-2 with small letters to indicate *instantaneous* values for a-c conditions in the presence of an a-c input signal. We have previously identified the abbreviations $e_g$, $E_{cc}$, $E_{bb}$, $e_b$, and $i_b$. The meaning of the remaining symbols in Fig. 5-2 is as follows:

$E_f$ = filament or heater supply voltage (dc or ac)
$e_{c1}$ = same as $e_c$ in a triode; the instantaneous total voltage between grid and cathode ($e_{c1} = E_{cc} + e_g$)
$e_{c2}$ = instantaneous total screen-grid voltage (between screen grid and cathode)
$E_{c2}$ = screen-grid d-c supply voltage (part of $E_{bb}$)
$i_{c2}$ = instantaneous total screen-grid current
$i_k$ = instantaneous cathode current, or *total space current* (Both the plate current, $i_b$, and the screen-grid current, $i_{c2}$, flow through the cathode circuits, hence $i_k = i_b + i_{c2}$.)

**Basic Action of the Tetrode**

As we have seen, the screen grid (often called simply the *screen*) is located in the space between the control grid and plate, and hence it is in the path of the electrons flowing toward the plate. The positive voltage on the screen accelerates the electrons moving from the cathode toward screen and plate. Some of these electrons strike the positive screen and form the screen current, $i_{c2}$, which flows back to the cathode through the external circuit. This screen current generally serves no useful purpose and is much smaller than the plate current, but it cannot be avoided entirely. Most of the electrons emitted from the cathode pass through the openings in the screen-grid mesh and are collected by the plate. The screen thus reinforces the action of the plate in attracting electrons toward it. The sum of the plate and screen currents make up the total space current flowing though the tube and cathode (Fig. 5-3).

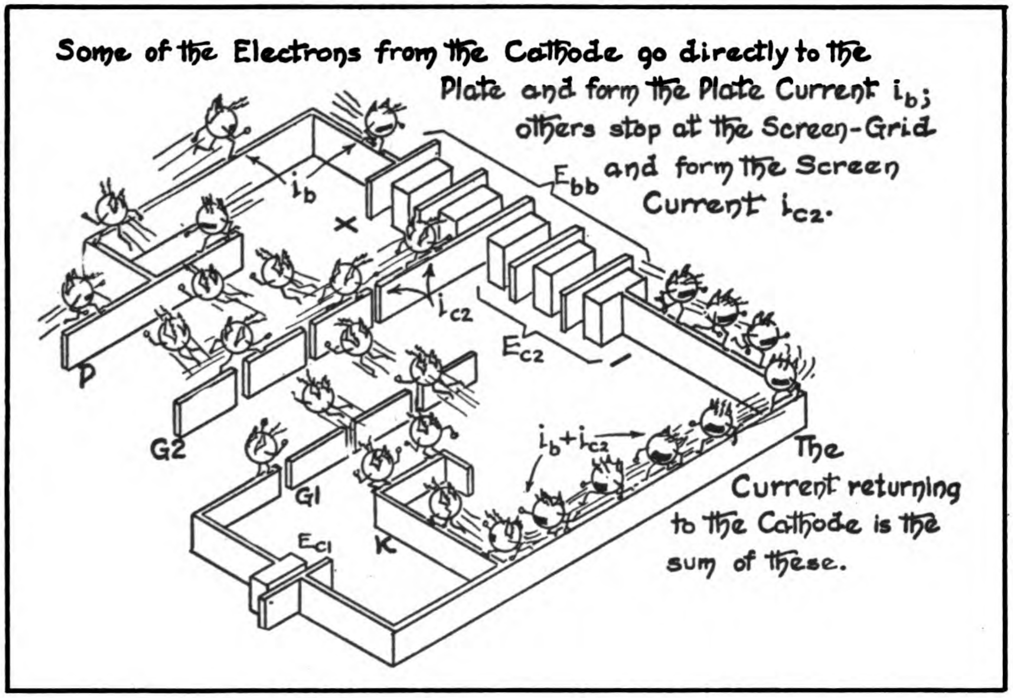



Fig. 5-3.

As we have previously pointed out, the main purpose of the screen grid is to reduce the grid-to-plate capacitance, which is the path for the undesirable feedback of energy in high-frequency amplifiers. The screen grid accomplishes this by acting as an electrostatic shield between the control grid and the plate, thus isolating the plate and avoiding the undesirable coupling to the grid. However, this shielding action of the screen grid has another very important effect. It practically *seals off the effect of the plate's electrostatic field on the space charge, and hence on the flow of plate current.* The shielding action of the screen, therefore, makes the *plate current practically independent of the plate voltage,* and variations in plate voltage have little effect on the plate current. The electrostatic field of the plate may be thought of as terminating on the *screen rather than on the space charge* (as in the case of the triode) and hence it cannot affect the flow of plate current to any great extent. The plate still functions as an effective *collector* of electrons, but the *control* of electron flow is transferred to the control grid and the screen grid.

You will recall, that we defined the amplification factor of a triode in Chapter 4 as the ratio of a required change in plate

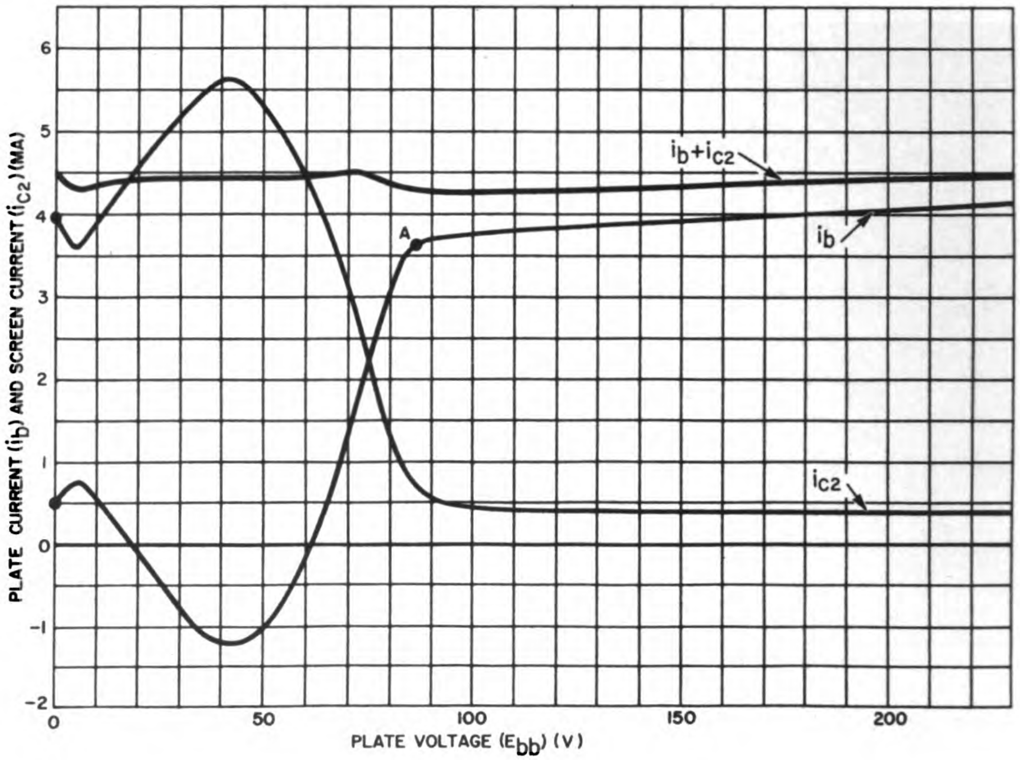



**Fig. 5-4. Plate-current plate-voltage characteristic curves for early tetrode, showing variations in plate and screen currents.**

voltage to the change in control grid voltage, for the same change in the plate current. Since we have just seen that the plate voltage has very little effect on the plate current in a tetrode, while the control grid retains its effectiveness, it is evident that a very large change in plate voltage is required to attain the same change in plate current as a small change in control-grid voltage. Consequently, the amplification factor of a tetrode is very high, generally from 20 to 50 times that of triodes. Furthermore, the a-c plate resistance which represents the ratio of the change in plate voltage required to produce a small change in plate current is also *extremely high,* because the plate voltage has little effect on the plate current. We shall see later on that while both the amplification factor and plate resistance of a tetrode are high, their ratio, which is the transconductance $(g_m = \frac{\mu}{r_p})$ is not significantly higher for a tetrode than for a triode.

**Plate-Current Plate-Voltage Characteristic Curves of Tetrodes**

The behavior of a tetrode under various operating conditions can be analyzed from its plate-current plate-voltage characteristic curves, just as was done in the case of the triode. The circuit for obtaining the curves shown in Figs. 5-4 and 5-5, is that illustrated in Fig. 5-2, with the signal voltage $e_g$ shorted out and the grid-supply voltage made variable. The tetrode used to obtain the curves of Fig. 5-4 was an early type which exhibits certain properties of fundamental interest which later types of tetrodes do not show. For illustrative purposes, the curves in Fig. 5-4 are shown for just one control-grid and screen-grid voltage setting. The control-grid voltage, $e_{c1}$ (or $E_{cc}$) was held constant at $-1.5$ volts and the screen-grid voltage was fixed at $+75$ volts in this particular case.

Referring to Fig. 5-4, the horizontal axis shows the variation of the plate voltage over a range from 0 to 230 volts, while the vertical axis is the scale for both the plate current ($i_b$) and the

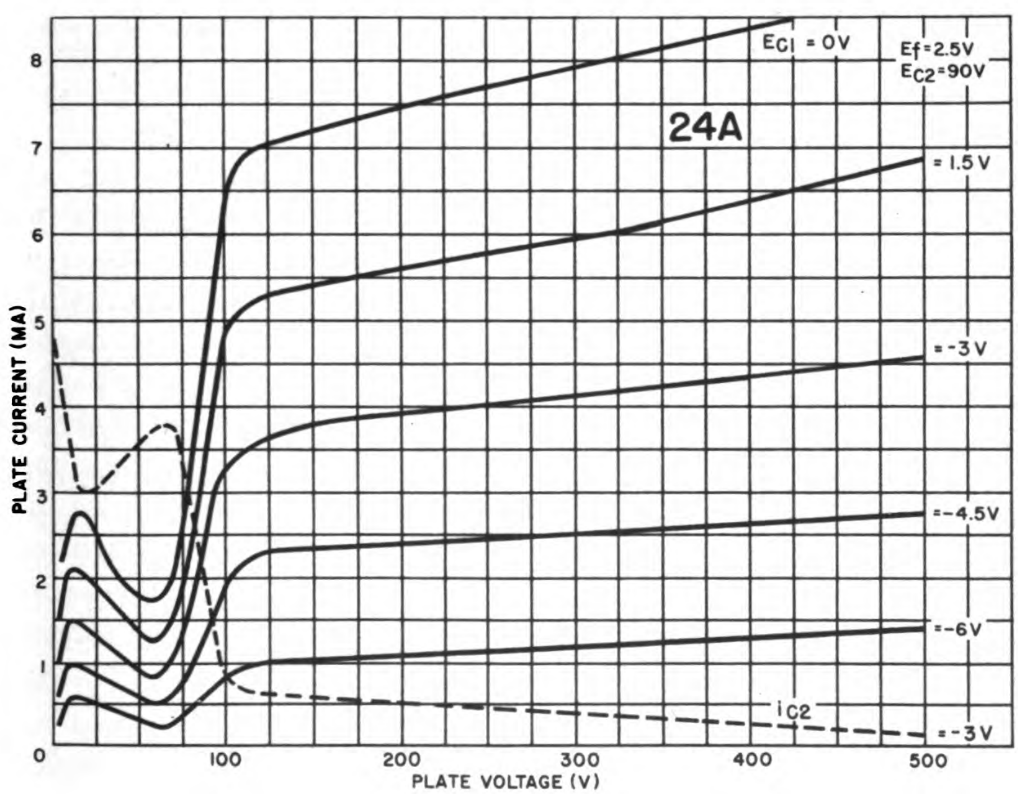



Fig. 5-5. Plate family of characteristic curves for type 24A tetrode.

screen current ($i_{c2}$). It is evident from the curves that great changes occur in the plate and screen currents for plate voltages below approximately 90 volts, while the curve for the total space current, $i_b + i_{c2}$, remains almost constant for the complete range of plate voltage. Since we have stated that the plate voltage has little effect on the plate current in a tetrode, what are the reasons for the erratic plate and screen current curves at low plate voltages? To obtain an answer to this important question, let us analyze the curves throughout their range.

With +75 volts applied to the screen, an electrostatic field exists between the screen and cathode, even when the plate voltage is zero. Consequently, the electrons are attracted toward the screen and there is a small screen current (about 4 ma) when the plate voltage is zero. A few of the electrons going to the screen have a sufficient amount of energy to pass through the screen openings and reach the plate, as shown by the tiny plate current (about 0.5 ma) at zero plate voltage. Raising the plate voltage to about 5 volts positive is seen to increase the plate current ($i_b$) slightly, while decreasing the screen current ($i_{c2}$) by about the same amount. The reason for this is apparent. With the screen at a fixed potential of +75 volts, and the plate screened off, the total space current ($i_b + i_{c2}$) remains approximately the same regardless of the value of the plate voltage. However, with the plate voltage becoming slightly positive, a few more of the high-energy electrons passing through the openings in the screen are diverted toward the plate. This increases the plate current somewhat, while decreasing the screen current proportionately. We would expect this process to go on as the plate voltage is increased, anticipating an increasing fraction of the total space current to be diverted toward the plate, with resulting increases in the plate current and decreases in the screen current. However, as you can see from the curves, just the opposite occurs. As the plate voltage is increased above 5 volts, the plate current suddenly decreases, while the screen current increases proportionately. In order to explain this sudden reversal in normal tube behavior, we must discuss the phenomenon of *secondary emission.*

*Secondary Emission.* With the screen voltage fixed, the velocity with which the electrons hit the plate increases with the plate voltage. When the plate voltage is increased above a few volts, the electrons acquire a sufficiently high velocity to strike the plate with such force as to dislodge other loosely held electrons in the plate material and knock them into the region between plate and screen grid. These additional electrons produced by the impact of the *primary* electrons (from the cathode) with the plate are called *secondary electrons,* and the phenomenon is known as *secondary emission.* Secondary emission also takes place in the triode, but since the plate is the only highly positive electrode in a triode, the secondary electrons are immediately recollected by the plate.

In the tetrode, however, the presence of the positively charged screen will attract some of the secondary electrons freed from the plate toward the screen. The more positive the screen is with respect to the plate, and the greater the number of secondary electrons that are available from the plate, the larger will be the flow of secondary electrons toward the screen and through the external circuit. It is evident that the flow of secondary electrons to the screen is in the opposite direction to the normal plate-current flow, and hence *subtracts from the current* entering the plate. *The net plate current is the number of primary electrons received from the cathode minus the number of scondary electrons lost to the screen grid.* When the plate voltage is considerably less than the screen voltage, as in the left-hand portion of Fig. 5-4, the screen grid attracts practically all the secondary electrons freed from the plate, with a consequent reduction in the effective plate current and a corresponding increase in the screen current. The total space current also increases very slightly.

As the plate voltage is increased from 5 to about 40 volts (in Fig. 5-4) the velocity of the primary electrons striking the plate continues to increase, and more and more secondary electrons are produced. Some of the secondary electrons may strike other atoms within the plate with sufficient force to free additional electrons, so that *several secondary electrons* may be produced *from a single primary electron arriving at the plate.* With the screen at a much higher positive potential than the plate, these additional electrons all flow to the screen, thus subtracting from the plate current and increasing the screen current. At about 20 volts plate potential, a curious thing happens; more secondary electrons are flowing to the screen than primary electrons arrive at the plate, so that the net plate current turns back on itself and becomes actually *negative.* This is caused by the fact that *each primary electron pro-*

*duces on the average more than one secondary electron,* so that the "backward" flow of secondary electrons to the screen exceeds the "forward" flow of primary electrons to the plate. The plate current remains negative up to about 63 volts plate voltage.

*Negative Resistance.* In Fig. 5-4, the plate current *decreases* as the plate voltage is *increased* from 5 to 40 volts (or vice versa, the current increases as the voltage is decreased). This is contrary to the usual behavior of practically all current-consuming electrical devices which —in accordance with Ohm's law—exhibit increasing current flow with increasing voltage across the device. A device—such as the tetrode for plate voltages lower than the screen voltage—which has a downward-sloping (negative) current characteristic for increasing voltage, is said to exhibit a *negative resistance,* and may be thought of a *source of power,* rather than a device that consumes power. We have seen in the last chapter, when discussing oscillators, that oscillations take place in a circuit when its resistive losses are overcome. Similarly, when a tetrode is operated in the negative-resistance portions of its characteristic, instability will occur and oscillations may take place in the circuit associated with the tube. Although this is generally to be avoided by operating the tube at high plate voltages, we shall see later an application of the tube as an oscillator, which makes use of this negative resistance characteristic.

*High Plate Voltage.* As the plate voltage in Fig. 5-4 is increased above 43 volts, the plate current is seen to increase again, and the screen current decreases. Although more and more secondary electrons are being freed, some of these are now attracted toward the increasingly positive plate. Since the secondary electrons are initially near the plate, the plate voltage does not need to be as great as the screen voltage to collect a substantial portion of the secondary electron flow. When the plate voltage is made equal to the screen voltage (+ 75 volts), practically all the secondary electrons are retained by the plate, and the plate current is seen to equal the screen current in this particular tube. As the plate voltage is increased above 85 volts (beyond point *A*) the plate retains all its electrons and in addition receives a small number of secondary electrons from the screen. The plate current now becomes stable at a high value almost equal to the total space current, while the screen current drops to a low, constant value. Further increases in plate voltage have little effect on the space charge, and the plate current becomes practically independent of the plate voltage at plate voltages considerably higher than the screen voltage. In order to avoid instability and distortion, the tetrode must be operated in the region of the characteristic to the right of point *A*. Moreover, when a load is present in the plate circuit, the plate-supply voltage, $E_{bb}$ must be made sufficiently high (or else the grid input signal must be limited) so that plate does not fall to a potential below the linear part of the characteristic (point *A* in Fig. 5-4) for the maximum positive grid voltage swing. This generally requires excessively high plate-supply voltages, or a very low grid input signal, both of which are disadvantages.

*Complete Plate Family.* A complete plate family of characteristics for the type 24A tetrode is shown in Fig. 5-5. Here the screen voltage is held constant at 90 volts, while the control-grid voltage is varied from 0 to −6 volts to obtain the characteristic curves. The curves still show a negative-resistance characteristic in the region below about 70 volts on the plate, but—as you will note—the plate current actually never reverses or becomes negative. This somewhat more stable behavior has been achieved by treating the plate of the 24A tetrode chemically, so as to reduce the production of secondary electrons by the impact of primary electrons. Thus, the secondary electron flow never exceeds the primary electron current.

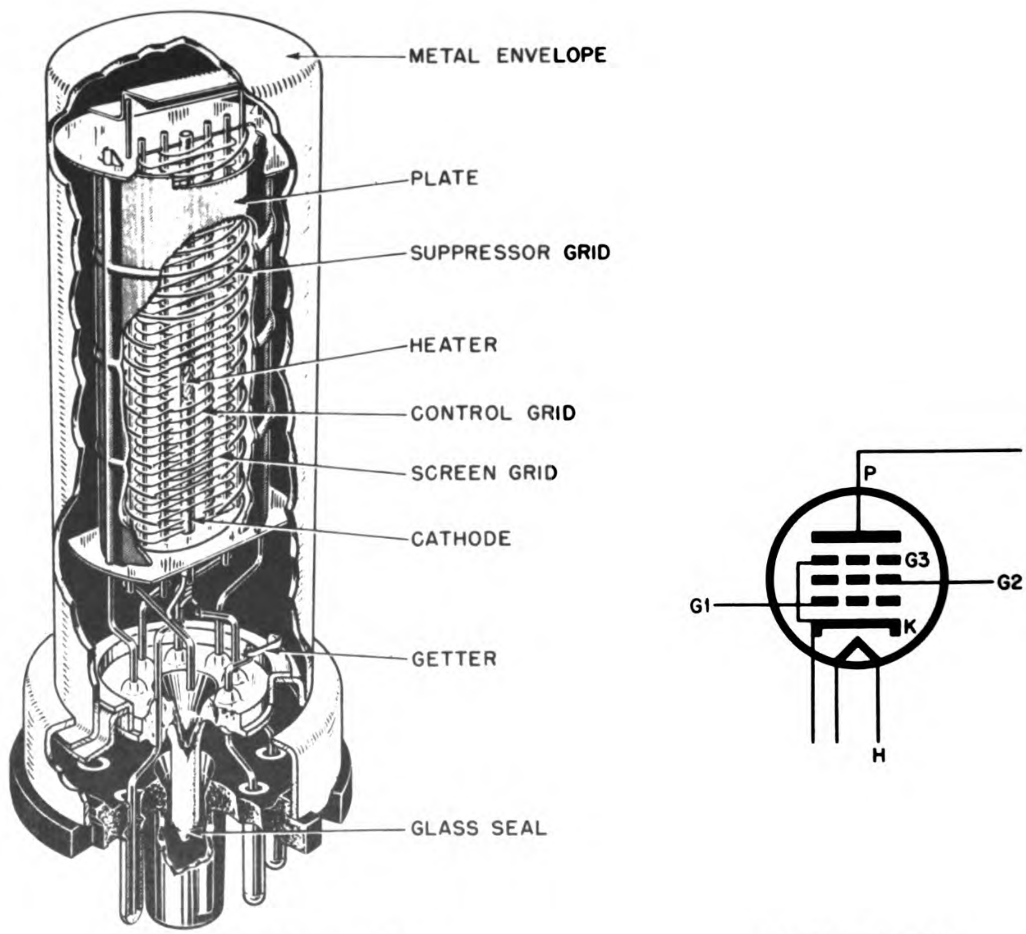
### Tetrode Tube Constants

As mentioned previously, the tetrode has the same basic tube constants as the triode and other vacuum tubes. We have seen that the relative independence of the plate current from the plate voltage leads to a very high a-c plate resistance and a high amplification factor for tetrodes. The a-c plate resistance $r_p$ of receiving tetrodes varies between about 70,000 and 500,000 ohms, in contrast to much lower values (around 10,000 ohms) usually found in triodes. The amplification factor ($\mu$) of tetrodes is rated at about 400 to 600, compared to values from 5 to 50 for most triode tubes.

Although the amplification factor and the plate resistance in tetrodes are both high, the transconductance—which is their ratio $\left(g_m = \frac{\mu}{r_p}\right)$ —is not very high in tetrodes. The transconductance of tetrodes averages about 1,000 to 1,500 micromhos, or about the same as for triodes. Special types of power tetrodes with $g_m$ values as high as 4,500 micromhos, are available, however.

## PENTODES

If a fifth element, called a *suppressor grid,* is added to the tetrode, we obtain a five-element tube, or *pentode.* The pentode functions essentially in the same way as the tetrode, but the additional grid serves to overcome the undesirable effects of secondary emission and eliminates the negative-resistance characteristic of tetrodes.




PENTODE CONSTRUCTION

**A**

PENTODE SYMBOL

**B**

**Fig. 5-6. Physical construction (metal-type) and schematic symbol of pentode.**

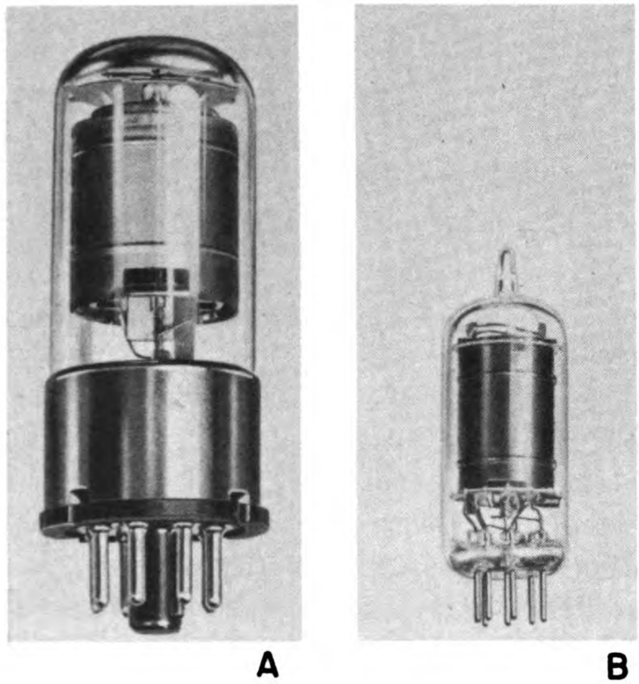



Fig. 5-7. Different types of receiving pentodes.

**Construction**

The pentode contains an emitter (cathode), three grids and a plate, or five electrodes altogether. The grid closest to the cathode, *G1,* is the control grid, next is the screen grid, *G2,* and the third grid, located between screen grid and plate, is the suppressor grid, *G3.* The physical construction of a metal-type pentode is shown in Fig. 5-6 (A), while the schematic circuit symbol of a pentode is illustrated in (B). In external appearance, many pentodes resemble the tetrode; some of the older types also have top grid caps. Two glass-envelope receiving-type pentodes are shown in Fig. 5-7. The miniature-type pentode tube shown in (B) is more popular than its larger glass or metal counterpart in newer equipment.

**Pentode Circuit**

The basic amplifier circuit of a pentode with an a-c input signal voltage ($e_g$) and a plate-load resistor ($R_L$) in the output, is illustrated in Fig. 5-8. The current and voltage notations are the same, as those shown in Fig. 5-2 for the tetrode.

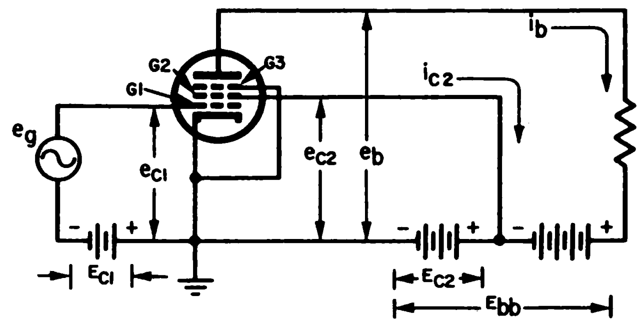



**Fig. 5-8. Basic pentode amplifier circuit.**

The connections and operating potentials for the pentode are practically the same as for the tetrode. The screen grid is maintained at a positive potential with respect to the cathode. In Fig. 5-8 the screen-supply voltage has been tapped off from part of the plate-supply voltage ($E_{bb}$), so that it is at a lower potential than the plate. However, inasmuch as the effects of secondary emission have been overcome in the pentode, the screen may be operated at the *same potential* as the plate, and this in fact is often done.

The suppressor grid is placed at cathode potential, either by an external wire connection, or in some types of pentodes, internally within the envelope of the tube. If separate external connections are provided, the tube can be connected to operate as a triode, as will be explained later on.

## Suppressor-Grid Action

The action of the suppressor grid, located between the plate and the screen grid, is designed—as its name implies—to suppress the effects of secondary emission from the plate and prevent it from reaching the screen grid. This is accomplished in the following manner: Primary electrons, emitted by the cathode, successively pass through the openings of the control grid, *G1,* the screen grid, *G2,* and the suppressor grid, *G3,* and finally strike the plate. The impact of the high-speed electrons on the plate result in the production of secondary emission, as in the case of the tetrode. But whereas these secondary electrons in the tetrode flow to the positive screen grid, they cannot do so in the pentode, because of the presence of the suppressor grid. Being connected to the cathode, the *suppressor grid is highly negative with respect to the plate and repels the secondary electrons back to the plate* (See Fig. 5-9). The reverse current between the plate and the screen is therefore avoided, even if the screen voltage momentarily exceeds the plate voltage. Although the suppressor grid is effective in preventing the passage of the low-speed secondary electrons from the plate to the screen, its openings are sufficiently large and its repelling effect is small enough to permit the flow of the primary high-speed electrons to the plate without much decrease in their velocity. Note, however, that the suppressor grid *does not* eliminate secondary emission from the plate, but prevents it from reaching the screen grid.

The presence of the suppressor grid further increases the shielding between the plate and the control grid, thus further reducing the grid-to-plate capacitance present in triodes. Also, for the same reasons as discussed for the tetrode, the increased shielding of the pentode results in a still higher amplification factor and higher plate resistance, as is the case for the tetrode.

### Pentode Plate Family of Characteristic Curves

The effect of the suppressor-grid action upon the characteristics of a typical pentode (type 6SJ7) is illustrated in Fig. 5-10. These

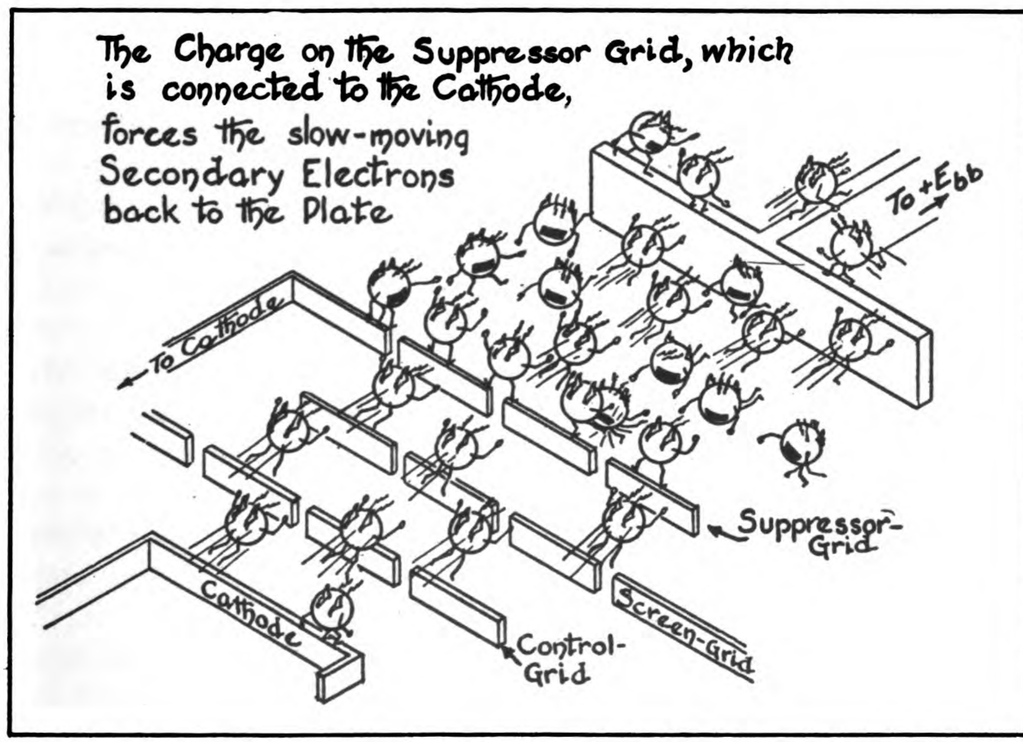



Fig. 5-9.

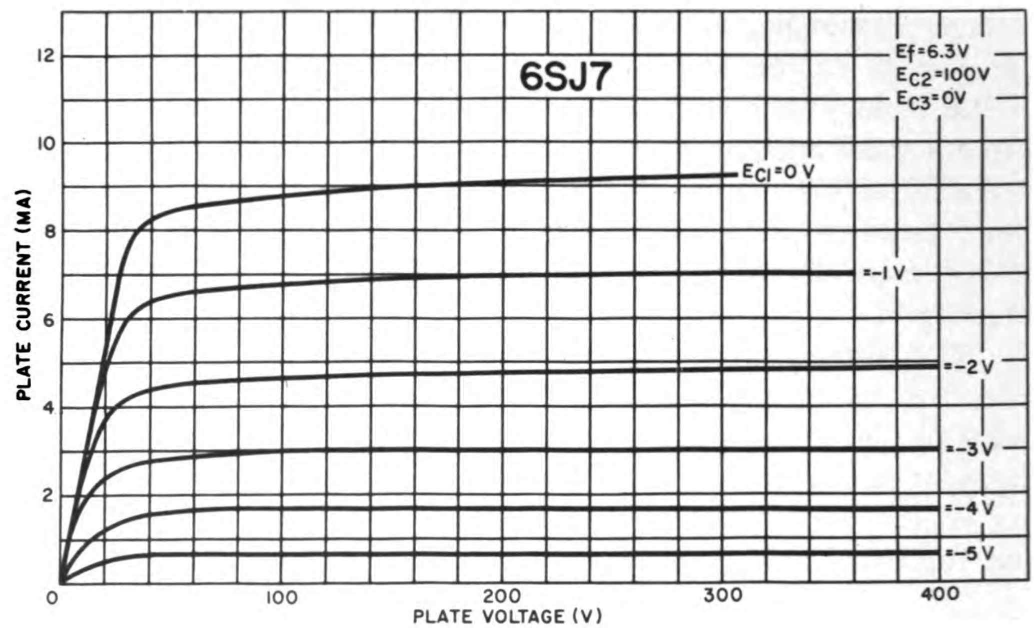



**Fig. 5-10. Plate family of characteristic curves for type 6SJ7 pentode.**

curves have been obtained by fixing the screen-grid voltage at 100 volts (suppressor voltage is zero), and varying the plate voltage over a range from 0 to 400 volts for diifferent control-grid voltages between 0 and –5 volts.

As can be seen, each of the curves rises quickly to its maximum current value, and there are no erratic dips and negative resistance regions present as in the case of the tetrode. The usable portion of each characteristic curve is to the right of the characteristic "knee". where the curves are flat, and the plate current is substantially independent of changes in the plate voltage.

At very low plate voltages (below 40 volts in Fig. 5-10), the electrostatic field produced by the plate is insufficient to draw off all the electrons arriving at the screen-side of the suppressor grid as rapidly as they arrive from the cathode. Consequently, an accumulation of electrons, or a space charge, forms in front of the suppressor grid, similar to the space charge surrounding the cathode. The effect of this space charge in front of the suppressor grid is the same as in a triode. It makes the plate-current flow dependent on the plate voltage, while changes in the control-grid voltage have little effect. In other words, at low plate voltages the current is *space-charge limited,* and depends on the plate voltage.

As the plate voltage approaches from 30 to 40 volts, the space charge in front of the suppressor is drawn off by the plate, and the plate current rapidly saturates at a value determined by the screen-grid and control-grid voltage (as well as the emission). Above about 50 volts on the plate, the plate current becomes practically constant for each curve, and is independent of the plate voltage. Because of the double shielding, the curves for a pentode are even flatter than those for the tetrode. In general, in a well-designed pentode, the plate current varies only slightly with increasing plate voltage, for all plate voltages greater than about 50 percent of the screen-grid voltage. The magnitude of the total space current ($i_b + i_{c2}$) is determined almost completely by the control-grid and screen-grid voltages.

You will observe in Fig. 5-10 that the spacing between adjacent plate-current curves is *unequal for equal changes in the grid voltage.* This means that the plate current does not change by the same amount for equal increments in the grid voltage, with the screen and plate voltage fixed.

For example, at a plate voltage of 300 volts, a change in the control-grid voltage from 0 to −1 volt, produces a change in the plate current from 9.3 to 7 ma, or a change of 2.3 ma. However, changing the grid voltage from −4 to −5 volts, for the same plate voltage (300 volts), reduces the plate current from 1.6 to 0.6 ma, or a change of only 1 ma. This indicates that changes in grid voltage caused by an incoming signal will result in unequal (or nonlinear) changes in the plate current, and hence in considerable distortion. As a matter of fact, distortion in pentode amplifiers is usually considerably higher than for triode amplifiers. By limiting the input signal to small values and choosing the proper operating point, distortion can be reduced to low levels. Because of its very high amplification, the pentode tube enjoys great popularity despite its somewhat higher distortion.

### Pentode Constants

Since the suppressor grid is usually fixed at cathode potential, no additional tube constants are needed to characterize the effect of the suppressor grid on the plate current in relation to other electrodes. Pentodes, therefore, have the conventional three tube constants, $\mu$, $r_p$ and $g_m$.

*Amplification Factor.* The fact that the characteristic curves of Fig. 5-10 are almost horizontal for plate voltages above 50 volts indicates that even very large changes in plate voltage produce but very small changes in plate current. On the other hand, the plate current is greatly influenced by the control-grid and screen-grid voltages. Since very large changes in plate voltage are required to produce the same effect on the plate current as results from a small change in control-grid voltage, it is evident that the amplification factor of a pentode must be very great. The amplification factor of the 6SJ7 (Fig. 5-10) is about 1,500 or about 100 times as great as for the average triode, and two to three times greater than that of tetrodes. The improvement over tetrodes results from the fact that the double-shielding action in pentodes make the plate current still more independent of the plate voltage.

*Plate Resistance.* The a-c plate resistance of a pentode is also extremely high for the same reasons as described for the amplification constant. For example, the 6SJ7 has a plate resistance of about 1 megohm, which is almost 150 times as great as the plate resistance of the average triode, and several times as great as that of a tetrode. An inspection of the characteristic curves reveals that the plate resistance increases as the value of the negative grid bias is made higher, just as in the case of triodes.

In *power pentodes* used in the output stages of receivers and amplifiers, the plate resistance is made somewhat lower (about 100,000 ohms) than for the usual type of pentode, but it is still many times greater than the plate resistance of triodes intended for similar service.

*Transconductance.* The transconductance of pentodes compares with that for triodes, and is sometimes even a little lower. The 6SJ7 pentode, for example, has a transconductance of about 1,650 micromhos, while the transconductance of the 6J5 triode is about 2,600 micromhos for similar conditions. With fixed suppressor-grid and plate voltages, the transconductance of a pentode increases in proportion as the screen-grid voltage is made higher and the negative grid bias is made lower (is made more positive). Increasing the voltage has only a slight effect on increasing the transconductance of a pentode.

### Pentode Load Lines

When a load resistor is inserted in the plate circuit of a pentode, the performance of the tube can be ascertained by drawing a load line on the static plate family of curves, in the same manner as was shown for triodes in Chapter 4. In Fig. 5-11 we have drawn four load lines, for 0 ohms (no load), 30,000 ohms, 50,000 ohms, and 100,000 ohms, on the static plate family of the 6SJ7 tube (previously shown in Fig. 5-10). The load lines were obtained for a plate-supply voltage of 300 volts, a screen voltage of 100 volts, and a suppressor grid voltage of 0 volts ($G3$ connected to cathode). Each load line is fixed by two points, as was explained for the triode. One terminating point is the value of the plate-supply voltage (300 volts) when the plate current is zero and the plate voltage equals the plate-supply voltage (no voltage drop across the load). The other extreme point of each load line is the condition where the load consumes the entire plate-supply voltage; in this case the plate voltage is zero and the plate current equals the value of $E_{bb}/R_L$. (In the present example: $E_{bb}=300$ v and $R_L$ is 0, 30,000, 50,000, and 100,000 ohms, respectively.)

*Amplification.* You may wonder why the load resistors selected have rather low values in relation to the a-c plate resistance of the tube, especially since we have discovered in the case of triodes that the voltage amplification increases directly with the value of the load resistance. It is true for pentodes, also, that the amplification increases with higher values of the load resistor, and as a matter of fact the voltage amplification, or again, is *approximately* given by the expression:

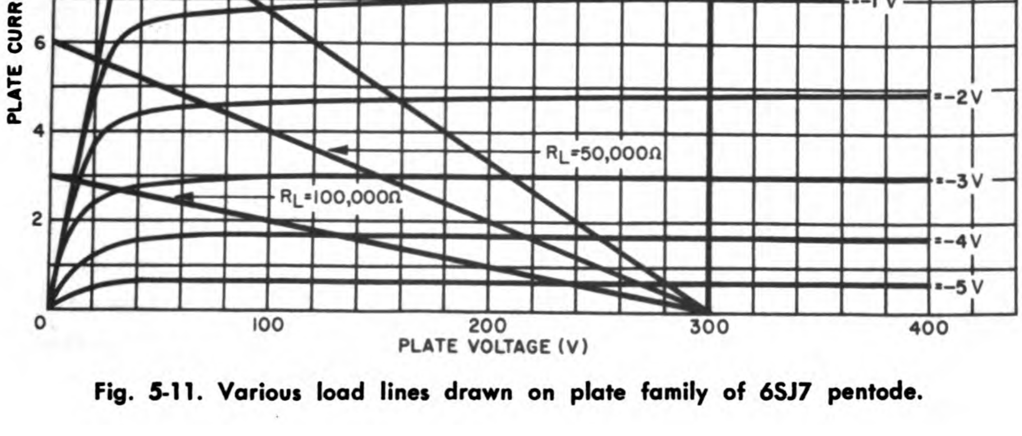



**Fig. 5-11. Various load lines drawn on plate family of 6SJ7 pentode.**

$$\text{voltage amplification} = g_m \times R_L$$

(This equation holds only when the load resistance, $R_L$, is very much less—about 1/10th or less—than the plate resistance, $r_p$, of the tube. This is generally the case, as we shall see presently.)

The reasons why the load resistance is generally made only a fraction of the a-c plate resistance of the tube are two-fold. First of all, if the load resistance would even approach the value of the plate resistance (1 to 2 megohms), the voltage drop across the load would become so great, as to leave very little voltage at the plate, unless the plate-supply voltage were made excessively high. With so little voltage at the plate, the tube could not operate properly, and the expected voltage amplification could not be realized.

The second reason for the relatively low values of the load resistance is evident from Fig. 5-11. You will note, that only the load lines for $R_L=0$ (that is, no load) and for $R_L=30{,}000$ ohms intersect the static plate-current curves *above the knee* of the zero-voltage control-grid ($E_{c1}=0$) curve, while the other two load lines (for 50,000 and 100,000 ohms, respectively) intersect the static curves *below the knee,* where the plate current changes very little or not at all with changes in the grid voltage. Operation in this portion of the characteristic is highly nonlinear, and results in excessive distortion of the ouput waveform. For this reason chiefly, a sufficiently *low* value of the load resistance must be chosen so that operation takes place at all times above the knee of the characteristic curves, even for the most positive swing of the grid input signal, which ordinarily drives the control-grid voltage to zero volts ($E_{c1}=0$).

### Pentode Dynamic Transfer Characteristic

The distortion occurring when a pentode is driven in the region below the knee of the static plate family of curves is illustrated graphically in Fig. 5-12 where the three load lines of Fig. 5-11 have been replotted onto the grid family of characteristics to obtain the *dynamic transfer characteristics* of the 6SJ7 pentode.

These curves were obtained by exactly the same method as described for triodes in Chapter 4. We pointed out then, that the straighter the dynamic transfer characteristic, the more linear is the tube's operation and the less distortion takes place in the output waveform. But while in the case of triodes, the transfer characteristics straightened out when the load resistance was increased, just the opposite takes place in the case of the pentode. The load lines for 50,000 and 100,000 ohms, which operate the tube in the knee of the plate characteristic for high signal voltages (low negative control-grid voltages), are completely nonlinear and flatten out badly as the control-grid voltage approaches zero. You will remember from the example of the overdriven amplifier in the last chapter that the flattening out of the transfer characteristic at low values of the negative control-grid voltage has the

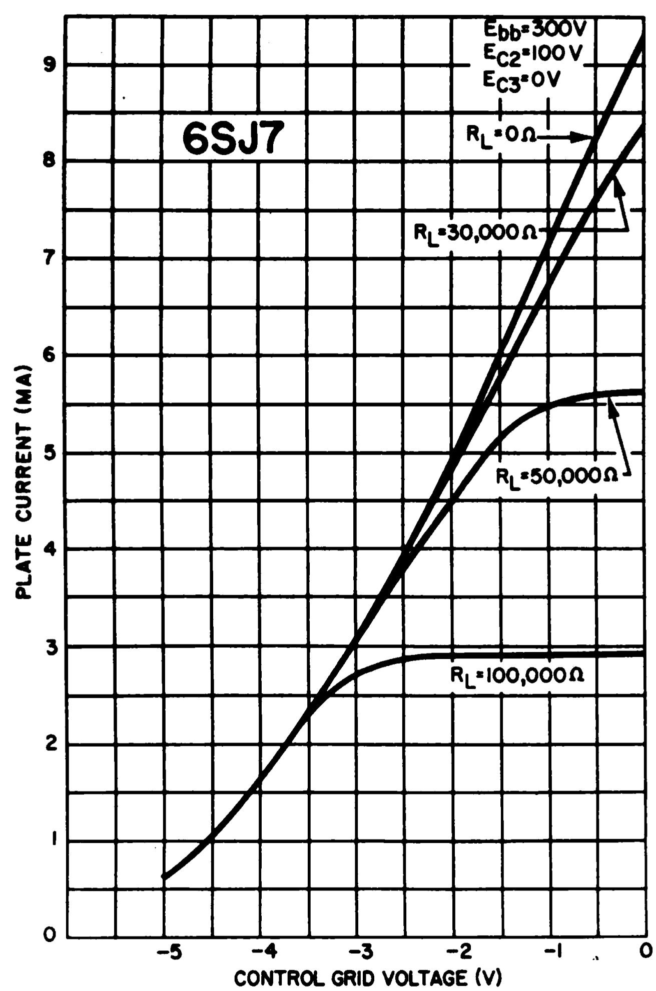



**Fig. 5-12. Dynamic transfer characteristic curves of 6SJ7 pentode.**

effect of clipping off the tops of the positive plate-current half-cycles, and results in severe distortion.

About the nearest approach to distortionless amplification is the transfer characteristic for a load resistance of 30,000 ohms, although even this curve is not linear throughout its length. Another solution to straightening out the dynamic transfer characteristic for high values of the load resistance is to *reduce the screen voltage* to a small fraction of the plate voltage, in practice about one-seventh or one-tenth of the plate voltage. This has the effect of increasing the slope of the plate-current rise for low plate voltages, and shifts the knee for each plate-current curve to a lower value of plate voltage. For example, in Fig. 5-11 the knee of the zero-volt control-grid voltage curve ($E_{c1} = 0$) is reached for a plate voltage of about 40 volts, with the screen voltage held constant at 100 volts. If the screen voltage is now reduced to 40 volts, the same point on the knee of the zero grid-voltage curve is reached with a plate voltage of only 16 volts. This substantially reduces the distortion occurring at low control-grid voltages and permits the use of a higher value of the load resistance. Of course, it also reduces the amount of plate-current flow, but this may be of little consequence.

The improvement in the dynamic transfer characteristics resulting from a reduction in the screen-grid voltage is illustrated in Fig. 5-13. Here the plate-supply voltage of the 6SJ7 has been held at 300 volts, as before, but the screen-grid voltage has been reduced to 40 volts. Dynamic transfer characteristics are shown for values of the load resistance of 0, 100,000 ohms, 200,000 ohms, 250,000 ohms, and 500,000 ohms. It is evident that a great improvement has taken place. Note especially that the characteristic for a 100,000-ohm load has been completely straightened out, permitting linear operation. As is seen from Fig. 5-13, values of the load resistance up to 200,000 ohms may now be used without excessive distortion taking place. Above 200,000 ohms, however, flattening is again evident and distortion becomes excessive.

### The Beam Power Tube

A type of tube which combines the advantages of the tetrode and pentode, and is capable of handling large electrical powers in the output stages of receivers and amplifiers, is known as a *beam power tube*. The tube is essentially a tetrode which operates like a

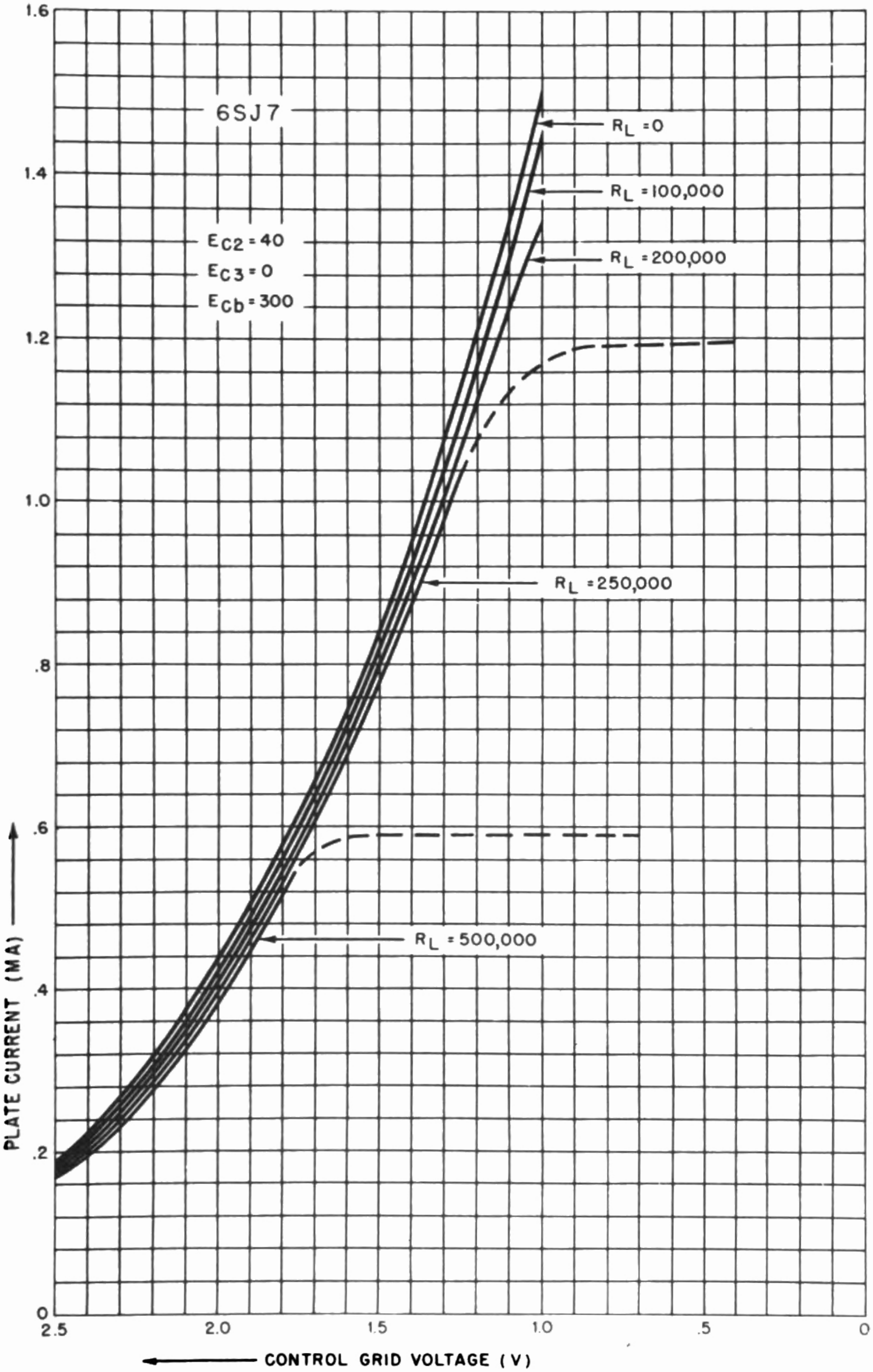



**Fig. 5-13. Dynamic transfer characteristic curves for 6SJ7 pentode when screen voltage is reduced to 40 volts.**

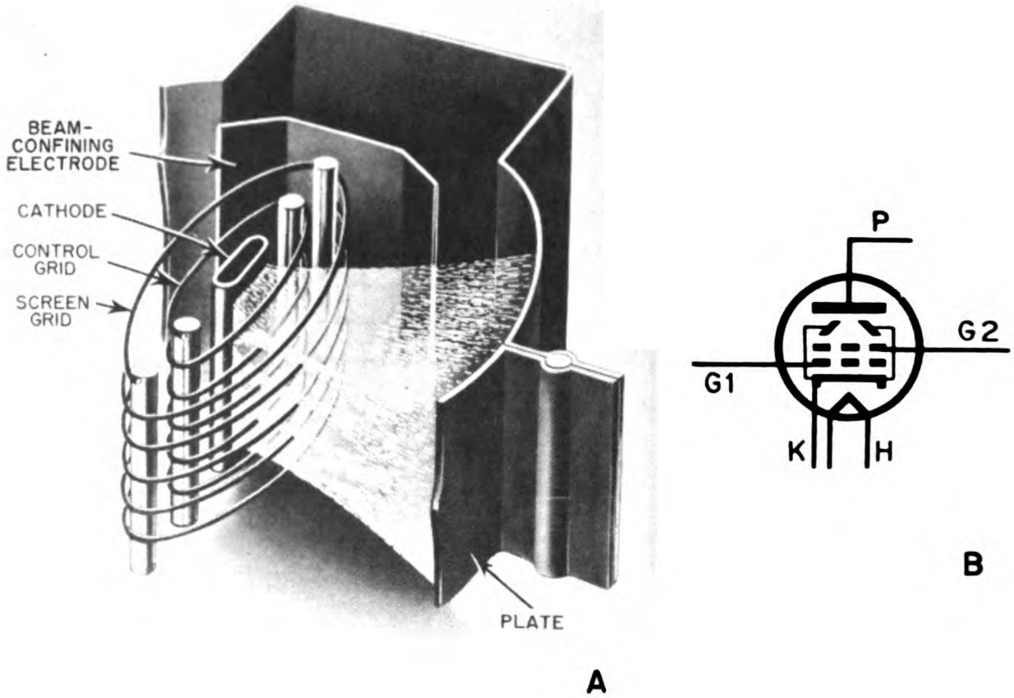



**Fig. 5-14. (A) Structure of beam power tube, showing electron beam formation. (B) Schematic symbol.**

pentode through specially designed electrodes, but it has additional advantages over the pentode because of lower distortion and greater power-handling capability. In external appearance, the beam power tube looks like an ordinary tetrode or pentode, although it is sometimes larger in its dimensions.

In a beam power tube, the control-grid and screen-grid wires are so aligned that the turns of the screen grid are of the same pitch as the control grid, and lie directly behind it in its "shadow." As a result, very few electrons are intercepted by the "shadowed" screen grid. Therefore, the screen current is low, the plate current is high, and the electron density in the space between screen and plate is higher than usual. Special *beam-confining electrodes,* connected to the cathode, assist in producing electron beams and further increase the electron density in the plate-screen region. The resulting bunching of the electrons in this region constitutes *a space charge which repels secondary electrons from the plate without the necessity of a suppressor grid.* As a matter of fact, the beam power tube does the job more efficiently than the suppressor grid of a pentode. The formation of the electrons into high-density sheets or beams is illustrated in Fig. 5-14. A similar beam (not shown) issues from the opposite side of the cathode. The tube shown is a type 6L6.

The high-density electron beam and effective suppressor action are combined with a large effective plate area for collecting electrons and a large cathode area, resulting in a tube with high power output for small input signals, and high efficiency. The lower distortion in a beam power tube, as compared to a tetrode or pentode, can be appreciated by a study of Fig. 5-15. The solid

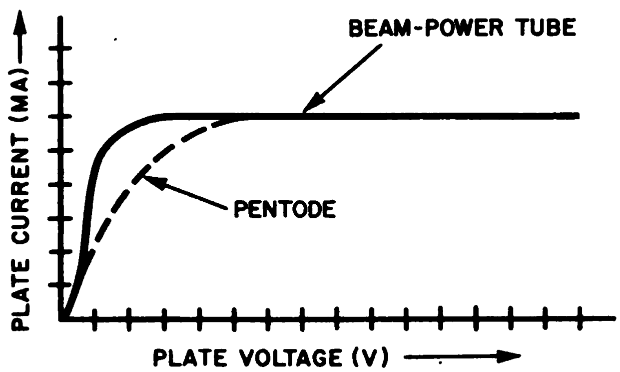



**Fig. 5-15. Beam power characteristic curve compared with pentode characteristic under the same conditions.**

curve for the beam power tube shows that the region of distortion, where the plate current is dependent on the plate voltage, is confined to a few volts in the beam power tube because of the sharp rise of the plate current. In contrast, the dashed curve for a pentode rises much more gradually, with resulting higher distortion for the same power output.

### Variable-Mu Tubes (Remote Cut-Off Tubes)

The amplification factor ($\mu$) is a function of the geometry of the tube, and depends also on the spacing between turns of the control-grid wire. In conventional vacuum tubes, the turns are *uniformly spaced* throughout the length of the control grid, with the result that the amplification factor remains approximately constant throughout the whole range of plate-current and grid-voltage values. Furthermore, as the grid bias is made more and more negative all parts of the control-grid structure begin to cut off the plate current at the same time, resulting in a so-called *sharp cut-off* characteristic.

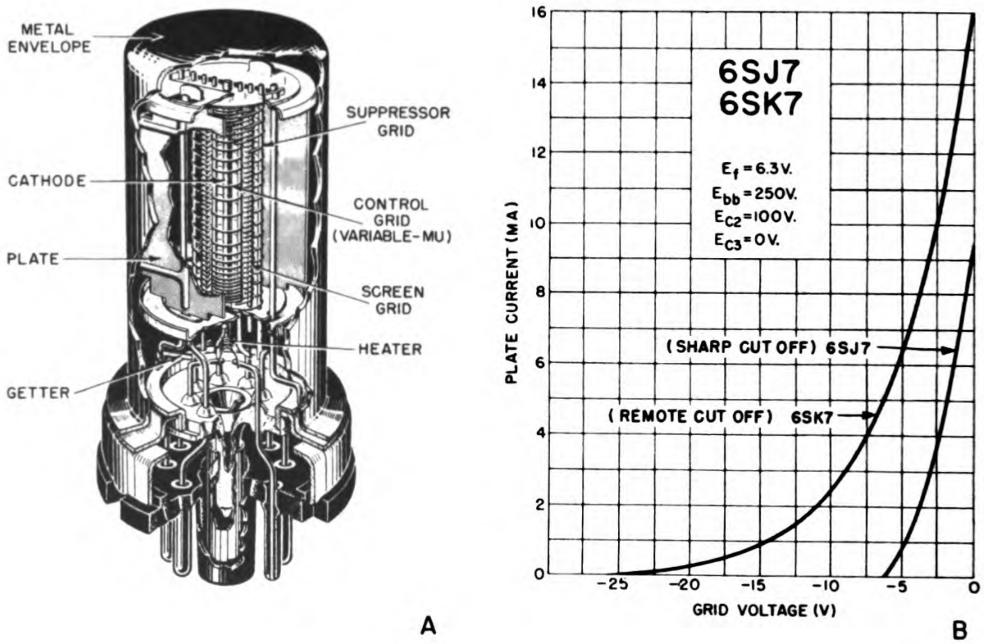



**Fig. 5-16. Construction of variable-$\mu$ pentode and comparison of its plate-current cut-off characteristic with 6SJ7 pentode.**

The sharp cut-off of conventional pentodes is not always an advantage, since many times in communication circuits large-amplitude signals must be accommodated without the distortion accompanying plate-current cutoff. Also, in *automatic volume control circuits* it is necessary to *vary the amplification of a tube* automatically *by changing the grid bias* which is derived from the signal amplitude. A tube which accomplishes both a gradual cut-off of the plate current and a changing $\mu$ with variations in the bias is the so-called *variable-mu or remote cut-off* pentode, illustrated in Fig. 5-16 (A). As is seen from the illustration, the spacing of the control-grid wires is *nonuniform* in this tube, the turns being closer together at the top and bottom of the winding and more widely spaced in the center of the winding.

At low values of the grid bias the tube operates in the normal manner. As the control grid is made more negative, however, the closely spaced (high-mu) regions of the grid at each end reach plate-current cut-off first, while the center, or low-mu portion of the grid still permits some plate current flow. With operation forced into the center portion of the grid, the amplification factor

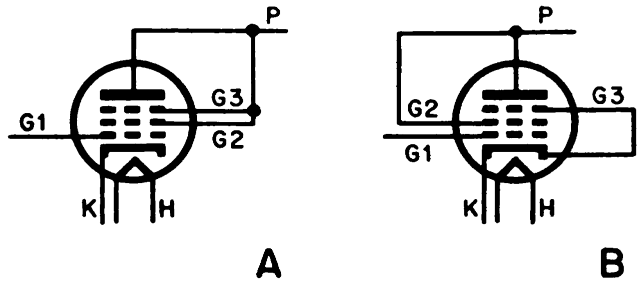



Fig. 5-17. Illustration shows two ways of connecting a pentode to function as a triode.

decreases markedly with high negative grid bias. Eventually, when the negative grid bias has been made sufficiently high, all parts of the control-grid winding reach plate-current cut-off. However, the grid voltage required to attain cut-off may be several times as high as for a conventional tube, and for this reason such tubes are identified as remote cut-off pentodes. Figure 5-16 (B) compares the sharp cut-off characteristic of a standard 6SJ7 pentode with the gradual or remote cut-off characteristic of the variable-mu 6SK7 pentode. Note that the cut-off bias for the 6SK7 is about four times as high as for the 6SJ7.

## Pentodes Connected as Triodes

Pentodes may be connected to function as triodes, and the tube manuals give information for triode operation of many pentodes. When a pentode tube is triode-connected, it loses its well known characteristics and assumes those of a triode, as described in Chapter 4. Triode connection should be attempted only for tubes which have all grid and plate connections at the base of the tube (that is, have no top cap). The connection may be made in two ways, as illustrated in Fig. 5-17. In (A) of the figure, both the screen grid (*G2*) and the suppressor grid (*G3*) are connected to the plate (*P*) at the base of the tube. This is the usual connection. Less frequently used is the connection in (B), where the suppres-

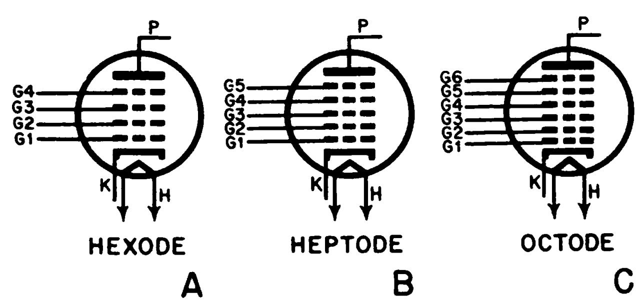



Fig. 5-18. Schematic circuit symbols of multigrid tubes.

sor grid ($G3$) is hooked to the cathode, and the screen grid ($G2$) is connected to the plate.

### Multigrid Tubes

Tubes which have more than three grids are commonly known as *multigrid* tubes. Figure 5-18 illustrates three types of multigrid tubes used in practice. Part (A) of the figure shows a tube with four grids, or six electrodes total, known as a *hexode*. This tube is chiefly used for experimental purposes sometimes to permit grid excitation from separate signals. A tube with five grids, or seven electrodes total, is shown in (B). The tube is called a *heptode* (seven electrodes) or a *pentagrid* (five grids) tube. The heptode is chiefly used in mixer and frequency converter circuits of superheterodyne receivers. In this application two voltages of different frequencies are impressed on separate grids of the tube to obtain frequency conversion.

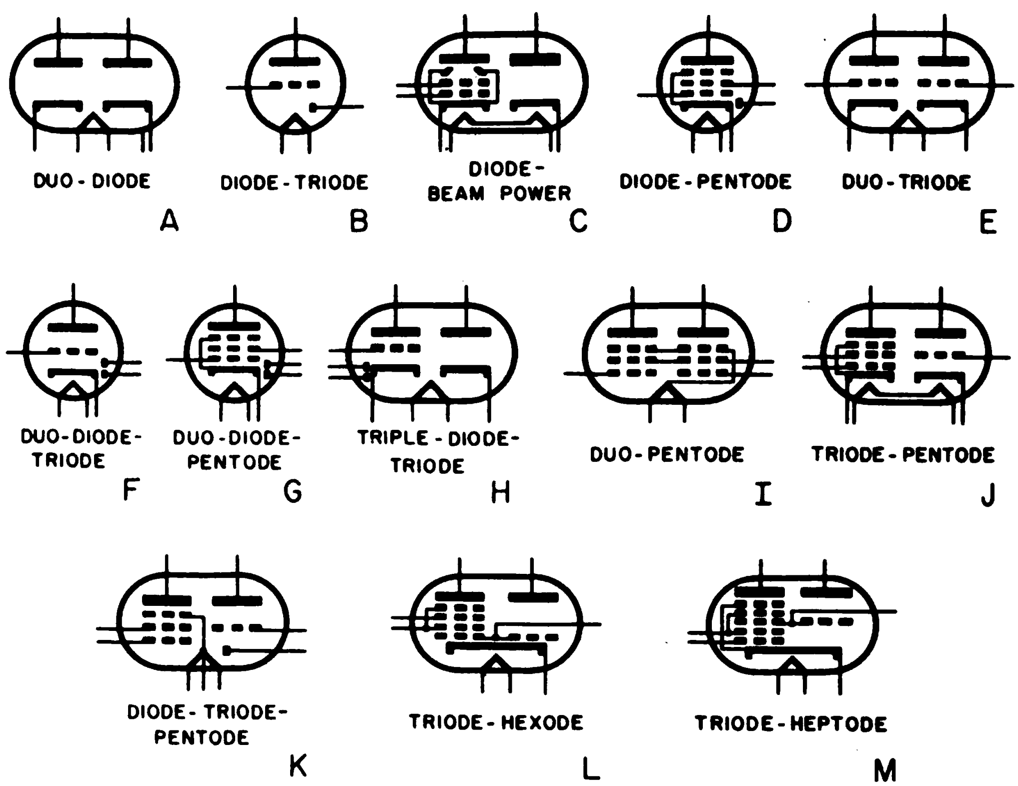



Fig. 5-19. Schematic circuit symbols for various multiunit tubes.

A tube with six grids, or eight electrodes total, and known as an *octode* is shown in (C) of Fig. 5-18. Like the heptode, the octode is most frequently used in mixer and frequency converter applications. In some receivers the tube is sometimes used for several functions at the same time, to reduce the total number of tubes in the set.

### Multiunit or Multipurpose Tubes

Two or more separate tube structures are frequently placed within a single envelope, either with a common cathode, or separate cathodes. By combining several functions in one tube, the total number of tubes is cut down, and compactness and economy—desirable in many mobile applications—is achieved. Figure 5-19 illustrates a number of multipurpose tubes encountered in practice. The most commonly used types are the duo-diodes shown in (A), (for rectifier and discriminator applications) and the duo-triodes, shown in (E) (for cascade or push-pull amplifier applications). The triode-hexode, in (L), and the triode-heptode, in (M), are used as mixer-oscillators in superheterodyne receivers. The diode-pentode, in (D), is used as a combined amplifier-detector, and the duo-diode-pentode, in (G), as a combined amplifier-detector and automatic volume control rectifier tube in superheterodyne receivers. The other types are employed in special applications.

## APPLICATIONS OF TETRODES AND PENTODES

As in previous chapters, we shall now attempt to give a quick bird's-eye-view of some of the major applications of the tube types we have discussed in this chapter. Since we have previously described most of the basic tube functions (they can all be performed by the triode) we shall now look into some of the special applications for which tetrodes and pentodes are most suited.

### Negative-Resistance Oscillator (Dynatron)

You will remember that a tetrode exhibits negative resistance when the plate voltage is made less than the screen-grid voltage, as indicated by the reversed slope of the plate-current plate-voltage characteristic curves (Figs. 5-4 and 5-5). As we have said before,

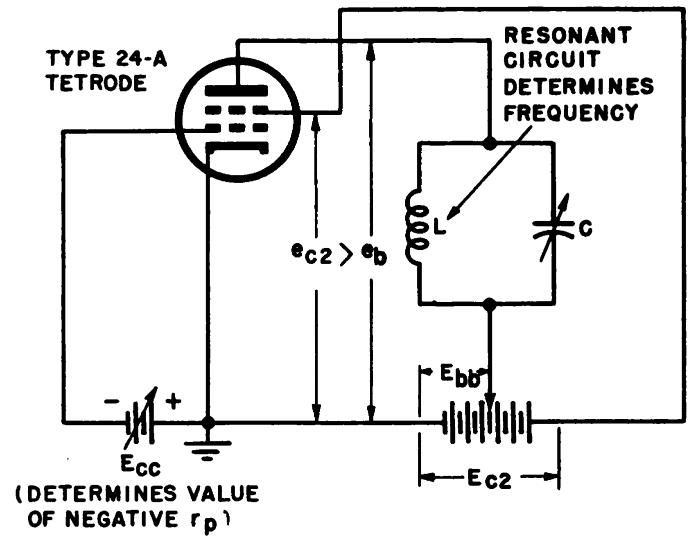



Fig. 5-20. Dynatron (negative-resistance) oscillator circuit.

this effect is caused by the secondary emission from the plate, which sets up a reverse current to the screen grid. The so-called *dynatron oscillator* illustrated in Fig. 5-20, makes use of this negative-resistance characteristic. It consists essentially of a tetrode (a type 24-A in this example) having appreciable secondary emission, and operated with the plate *less positive* than the screen grid. The value of the negative plate resistance can be varied by adjusting the control-grid potential. The plate voltage is tapped off from part of the screen-voltage supply, $E_{c2}$.

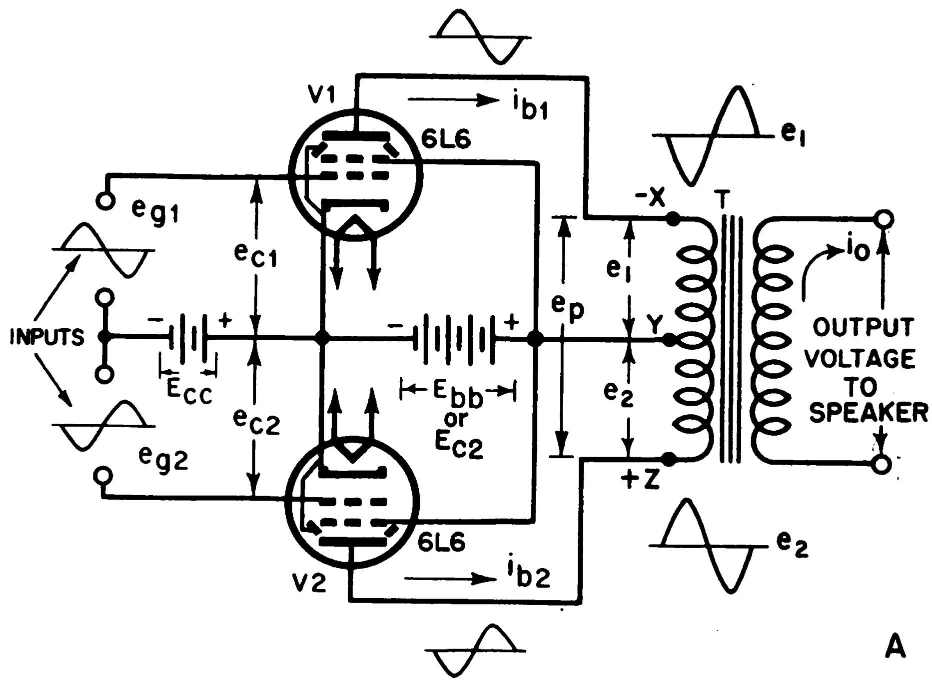
The *L-C* circuit in the plate lead of the tube is tuned to the desired frequency of oscillation by varying the capacitor. This tuned circuit represents the plate load resistance. Oscillations take place when the losses occuring due to the (positive) resistance in the *L-C* tuned circuit are overcome by the negative plate resistance of the tube, that is, as soon as the negative resistance is slightly greater in value than the positive resistance of the parallel-resonant *L-C* circuit. If the negative resistance of the tube is just barely sufficient to start oscillations, the frequency stability with respect to changes in tube voltages is very high, and the waveform of the oscillations is practically sinusoidal. This simple oscillator circuit can be operated over a wide range of frequencies, from low audio frequencies to as high as about 15 megacycles. It is very useful for low-power and laboratory applications.

### Push-Pull Power Amplifier

A very popular amplifier circuit, called the *push-pull amplifier,* is shown in Fig. 5-21. It is used in the output stages of radio receivers or amplifiers to deliver a high power output at low distortion to a loudspeaker. Basically, power amplification is no different from voltage amplification, as least the tube doesn't know any difference. In a power amplifier emphasis is placed on obtaining large plate currents, which together with high plate voltages will result in large output powers (E $\times$ I) rather than in high voltage gain. For this reason, tubes are desired which have a large transconductance and a low plate resistance, to obtain high plate currents even at the sacrifice of high amplification factors. In the present example, two type 6L6 beam power amplifier tubes have been employed, but pentodes with the suppressor grid connected to the cathode or triodes could have been used in the same basic circuit. The circuit provides more than twice the power of each tube used alone, and has considerably less distortion than a single output tube.

The symbol notations are the same as previously used, except that the numerical subscripts refer to tube 1 (*V1*) or tube 2 (*V2*) in this example. The circuit requires two input signal voltages, $e_{g1}$ and $e_{g2}$, which are equal in amplitude, but *180 degrees out-of-phase.* Two equal, out-of-phase voltages may be secured either from a phase inverter, such as that shown in the previous chapter, or from a center-tapped input transformer. The total a-c input voltage, $e_{g1} + e_{g2}$, is twice that required for operating a single tube. The bias, $E_{cc}$, is common to both tubes. The plate-supply voltage, $E_{bb}$, provides plate voltage as well as screen voltage to both tubes. In the case of pentodes or beam power tubes the screen may be operated at the same voltage as the plate, but for a tetrode, the screen voltage should be made somewhat lower than the plate voltage.

When no input signals are applied to the grids of the two tubes, each tube draws the same quiescent (d-c) plate current, and both the output voltage and output current ($i_o$) in the transformer secondary are zero, since a d-c current induces no voltage in a transformer. Furthermore, since the two d-c plate currents flow in opposite directions through the transformer primary, the resulting *magnetizing* current in the transformer is zero.



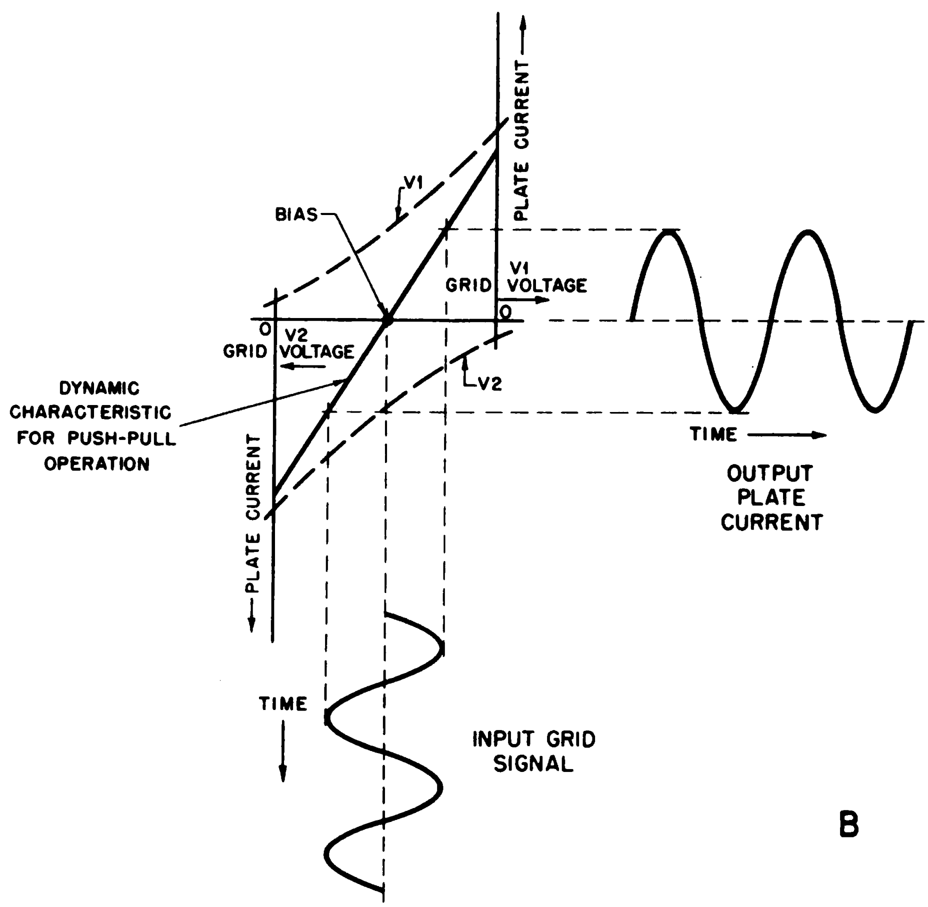




Fig. 5-21. Push-pull power amplifier circuit (A) and operation (B).

When two sinusoidal signal voltages, $e_{g1}$ and $e_{g2}$, are applied to the respective grids of the two tubes, sinusoidal plate currents, $i_{b1}$ and $i_{b2}$, flow in the plate circuits of *V1* and *V2*, respectively. Plate current $i_{b1}$ is 180 degrees out-of-phase with $i_{b2}$, since the two grid signals are 180 degrees out-of-phase with each other. During the positive grid swing of *V1*, plate current $i_{b1}$ of *V1* increases, resulting in an increased voltage drop across the upper half of the transformer primary ($e_1$). Consequently, a point X which is connected to the plate of *V1* becomes negative with respect to point *Y* (mid-point of the primary). (You will remember that the plate voltage drops when the plate current increases.) At the same time, the grid of V2 is being driven more negative, the plate current $i_{b2}$ of *V2* decreases, and hence the voltage drop across the lower half of the transformer primary ($e_2$) falls off. This, in turn, makes point *Z* connected to the plate of *V2* positive with respect to point *Y* by the same amount as point X was made negative. These two voltages add up to the a-c voltage across the primary, $e_p$, which is exactly twice of either $e_1$ or $e_2$. With an a-c voltage, $e_p$, present across the primary, an output voltage is induced in the the transformer secondary and the output current, $i_o$, flows through the load, which is usually a loudspeaker. A half-cycle later, all the input and output current and voltage polarities reverse, but the primary a-c voltage, $e_p$, is again equal to $e_1 + e_2$.

The dynamic transfer characteristic for push-pull operation, with the input and output waveforms plotted against it, is shown in Fig. 5-21 (B). The composite characteristic, obtained by adding the individual transfer characteristics of *V1* and *V2* together, is seen to be completely straight, and the waveform of the output plate current is, therefore, undistorted.

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