How Tubes Work:

Introduction to a short basic course on tubes:
Vacuum tubes were used not only in radio, TV's and broadcasting, but also in commercial radio equipment, telephone systems, two way repeater systems, test equipment, and in many types of industrial electronic equipment. Although transistors and now have taken over many of the jobs originally done by tubes, there are still applications where the vacuum tube is superior to the transistor. Even in those applications where the transistor is superior to the vacuum tube, there are many older pieces of electronic equipment still in use using vacuum tubes. There are other applications where a transistor could be used in place of a vacuum tube, but vacuum tubes are used because of the power involved or cost less in some situations, and particularly in the audio market where people prefer the quality and characteristics of the sound produced by tubes.

There are many different sizes and shapes of vacuum tubes. Some tubes are so small they are scarcely larger than a thumbnail; other tubes found in large radio and TV transmitters are several feet tall. Regardless of whether the tube is a miniature tube such as those found in hearing aids or a large tube such as those found in transmitters, they all work on the same basic principles.

ELECTRON EMISSION:
It is important to understand that basically electrons stay within the circuit wiring and flow only over a solid path. For example, when you connect a resistor across a terminal of a battery, the electrons are set in motion around the circuit. Electrons flow through the resistor, the wires and the battery, but they stay within the closed circuit. Electrons do not leave the wire connecting the resistor to the battery and travel off into space around the wire, nor do they leave the resistor and move into the space around it. In a tube, however, electrons are forced to fly off into the space surrounding one of the elements in the tube. This element is called the cathode. When an electron leaves the cathode we say it is "emitted" by the cathode; the giving up of electrons by the cathode is called **"emission"**.

All material is made up of atoms, and that one of the parts of the atom is the electron. The electrons in an atom are in a continuous state of motion. The speed and the amount of motion depend, for one thing, upon the temperature of the material. Normally the atomic force within the atom prevents electrons from escaping and flying off into space. This is true even in the case of the free electrons in a conductor that move through the conductor when current flows. However, if enough heat is supplied to a conductor, it is sometimes possible to overcome the force holding the electrons within the surface of the conductor. Under this condition some of the electrons can be driven off into the space surrounding it. This is what we mean by emission. This type of emission is often called **"thermionic"** emission; thermionic means emission by heat. Some materials give off electrons more readily and at lower temperatures than other materials. Often the cathodes of tubes are coated with these materials that will readily give off electrons at low temperatures.

There are four ways in which electrons can gain enough energy to escape from a material into the space around it. These are: (1) they can be evaporated or driven out by applying heat; (2) they can be driven off by bombardment by very small, high-speed particles such as other electrons; (3) they can be driven out of some materials by the energy in light rays; and (4) they can be jerked or pulled out by a very high positive potential placed on a nearby metallic object. All four of these methods are used in various types of electron tubes to provide the free electrons that all tubes depend upon for their operation. However, the first method, evaporation by heat, is by far the most important, and we will spend our time on this type of emission. We will also briefly discuss the second and third types of emission.

Thermionic Emission:
As we mentioned, when electrons are driven from a metal or metallic compound by means of heat, this type of emission is called thermionic emission. As mentioned, thermo means heat, ionic refers to electrons and hence the word thermionic is used to describe the type of emission where the electrons are driven from the cathode by heat.

In the operation of a vacuum tube it makes no difference where the heat comes from; if the cathode can be made hot enough it will emit electrons. However, the most convenient method of producing the heat needed is by means of a heater, or filament placed inside the vacuum tube. A voltage is applied to the heater or filament and this voltage causes a current to flow through the heater or filament and causes it to heat to at least a red heat, and sometimes to a white heat. The hot filament or cathode then gives off the electrons required to operate the tube. It is important to realize the heater/filament voltage applied to the tube for the purpose of heating the tube does not actually enter into the operation of the tube in any way except to provide the energy necessary to heat the cathode to a desired temperature to allow for the correct amount of electrons to be emitted. If instead of using electrical energy to heat the cathode we were able to heat the cathode with a gas flame, the heater/filament voltage could be removed entirely and the tube would perform just as well.

The terms heater, filament and cathode might be somewhat confusing at this time. A cathode is an electrode which gives off electrons. It is heated by means of an element called a heater. A **"filament"** is a combination heater and cathode. We will go into this in detail in the next section.

Secondary Emission.

When electrons are driven off a metal by bombarding the metal with high-speed particles such as other electrons, we refer to this type of emission as **"secondary emission"**. What happens in this type of emission is that a particle traveling at a very high speed strikes the metal object with such force that it is able to dislodge a number of electrons from the material. These dislodged electrons fly off the material into the space surrounding it. You will see later that this type of emission is not always desirable; and as a matter of fact, it creates a problem in some vacuum tubes.

Photoelectric Emission:

When electrons are driven out of the material by the energy in light rays, this type of emission is called photoelectric emission. Photoelectric tubes were used in the motion picture industry in connection with the sound track of a film. A sound track is put on the side of the film. Light passing through this sound track strikes a photoelectric tube. The density of the sound track varies as the speech or sound originally recorded on the film varies. This causes the amount of light striking the photoelectric tube to vary, which in turn varies the number of electrons emitted. Photo-emission is not often encountered much anymore as it once was in radio and TV but it is still found in vintage electronic equipment needing servicing.

We have provided only the first step in the process of understanding how tube work. I have left out many details in order to approach the subject gradually. So lets start by studying the simplest tube.

The Diode Tube:

The simplest tube has only two elements, one to give off the electrons and another to receive them. The element that gives off the electrons is called the cathode, and the element that receives the electrons is called the plate or anode. A simple tube having only two elements is called a diode. Other tubes have other elements in addition to these two. However, as we cover the diode, remember that tubes with more than two elements are really diodes with additional elements added.

TUBE CATHODES:

Tube cathodes can be divided into two types, those that are directly heated and those that are indirectly heated. Directly heated cathodes are called filament type cathodes or, more frequently, simply filaments. This type of cathode was used in all early vacuum tubes and was often used in tubes designed for battery operation, and in large transmitting tubes. Indirectly heated cathodes are simply called cathodes. Filament Type Cathodes.

The schematic symbol used to represent a filament type of cathode is shown in Fig. 1. The voltage used to heat the filament is applied directly between the two leads from the filament.

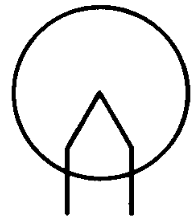


FIGURE #1: Filament type Cathode:

In large transmitting tubes the filament is made either of pure tungsten or of a mixture of tungsten and thorium. The very large transmitting tubes generally have a pure tungsten filament. Tungsten is a metal that can be operated at very high temperatures. Most electric light bulbs manufactured had a large percentage of tungsten in the filament that is heated to a very high temperature to give off light.

The filaments used in many of the smaller transmitting tubes are made of a mixture of thorium and tungsten and are called thoriated filaments. The addition of thorium to the tungsten provides a material that will give off electrons at a somewhat lower temperature than pure tungsten. Thus the amount of power required to heat the filament is lower than for a pure tungsten filament. Thoriated tungsten is not as suitable as pure tungsten in large transmitting tubes. The very high voltages used on these tubes can pull the thorium right out of the filament and thus destroy the tube. In smaller transmitting tubes the voltages used are not high enough to do this.

Filament type receiving tubes designed for operation in portable receivers were widely manufactured at one time. The filaments of these tubes were coated with oxides of certain metals. This type of filament is called an oxide coated filament. It has the characteristics of giving off electrons at a still lower temperature than a thoriated filament. Thus the filament power required by this type of tube is even less than that required by the thoriated filament.

Even though filament type receiving tubes operated on comparatively low voltages and required only a very small current, the fact that the heater power served no useful purpose untamedly led to the discontinuation of this type of tube. However, you may own, collect, or run across an older portable receiver that some set owner is particularly fond of and have to fix or supply tubes for such a receiver. Generally, filament type tubes were available for replacement purposes. Today some audio tubes are still produced this way like the 300B still made by some firms!

Oxide filaments were found in some small transmitting tubes used in mobile applications. However, if the voltage applied to the tube exceeds 500 volts by very much, the oxide on the filament may be pulled off by this voltage and therefore oxide-coated filaments were used only in small transmitting tubes.

The filaments of transmitting tubes that are made of either tungsten or thoriated tungsten can be operated on either ac or dc. However, the oxide-coated filament used in small tubes designed for use in battery-operated equipment are usually made very small and thin in order to keep the filament power required as low as possible. If these, filaments are operated from ac, a problem occurred. As the ac drops to zero and then rises to a maximum value twice during each cycle, the current flowing through the filament will vary, causing the temperature of the filament to vary. This will cause a variation in emission from the filament resulting in hum. Therefore the filament of small transmitting tubes and the older obsolete portable receiver types must be operated from dc.

The filament of a vacuum tube must be supported so it will stay in position. Typical filaments showing the type of support used are shown in Fig. 2. It is important that the filament be held tight so that it cannot sag and short to nearby elements in the tube. As a matter of fact, if the position of the filament changes, even though the filament may not touch any other elements in the tube, the characteristics of the tube will change because there are several tube characteristics that depend upon the spacing between the filament and the other elements in the tube.

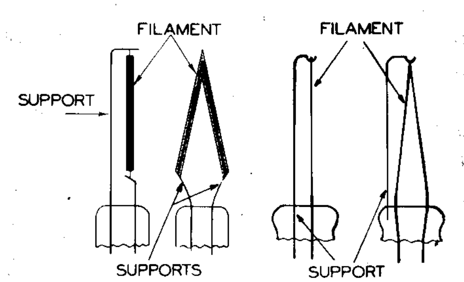


FIGURE #2: Filament Structures:

Indirectly-Heated Cathodes:

The schematic symbol used to represent an indirectly heated cath-ode is shown in Fig. 3. The indirectly heated cathode is simply called a cathode. Notice that in addition to the cathode we have another element drawn beneath the cathode in the schematic symbol. This is the Fig. 3. Schematic symbol used for a heater and indirectly heated cathode.

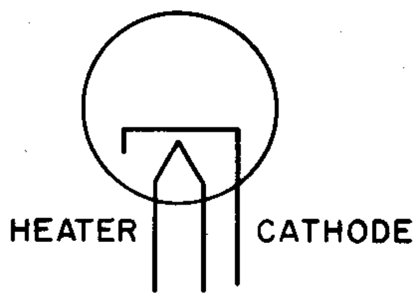


FIGURE #3: Indirectly heated cathode symbol:

HEATER CATHODE:

A heater, which is used to heat the cathode. Sometimes this is loosely called a filament because of its similarity to the filament we have just discussed and because the first tubes had directly heated cathodes. In fact the transformer winding used to supply heater voltage is still often called the filament winding.

The cathode is built in the form of a hollow cylinder like those shown in Fig. 4 on the next page.

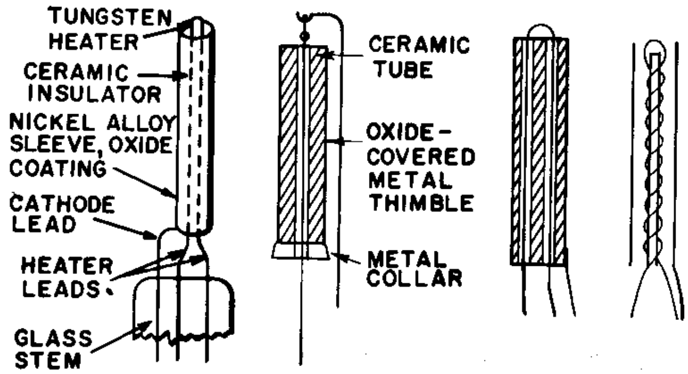


FIGURE #4: Cathode Structure:

The heater is placed inside of this hollow cylinder. Voltage is applied to the heater, and the heat produced by the heater is radiated and in turn heats the cathode.
The cathode is usually coated with oxide. This is done in order to provide an abundant supply of electrons at low operating temperatures. This type of cathode is used only in receiving tubes or small transmitting tubes where the applied voltage is not high enough to pull the oxide material off the cathode.

In many schematic diagrams of circuits in which an indirectly heated cathode type of tube is used, the heater is omitted. The heater actually serves no useful purpose as far as the operation of the tube is concerned, other than to heat the cathode. It does not enter into the characteristics of the tube and therefore the heater connections can be omitted to simplify the schematic diagram. The connections to the other elements in the tube are the ones that actually determine what the tube will do and how it will operate.

Operating Voltages:

The filament or the heater of a vacuum tube is designed to operate on a certain definite voltage. The first number used to identify receiving tubes gives an indication of the heater or filament voltage. For example, a 12 AU7 tube operates on a heater voltage of approximately 12 volts. The exact voltage is 12.6 volts. The number preceding the first letter indicates the heater voltage. A 35Z5 tube requires a heater voltage of 35 volts. A 6F6 tube requires a heater voltage of 6.3 volts, and a 2BN4 tube requires a heater voltage of 2.3 volts. Keep this in mind; it will be helpful to you when you start doing testing tubes. The first number or group of numbers preceding the letters in the tube designation is an indication of the filament or heater voltage for which the tube was designed. This system is followed only for modern receiving tubes. Older receiving tubes did not use this system, and transmitting and industrial tubes do not use it.

THE PLATE:

In the first vacuum tubes made, the anode that received electrons emitted by the cathode was simply a flat piece of metal, and hence was called a plate. In modern vacuum tubes the plate completely surrounds the filament or cathode. The shape of the platedepends to some extent on the type of cathode used. If the cathode is simply a round cylinder, then the chances are that the plate will also be a round cylinder. However, if a filament type of cathode is used, such as those shown in Fig. 2, the plate will usually be rectangular in shape. Typical plate structures are shown in Fig. 5.

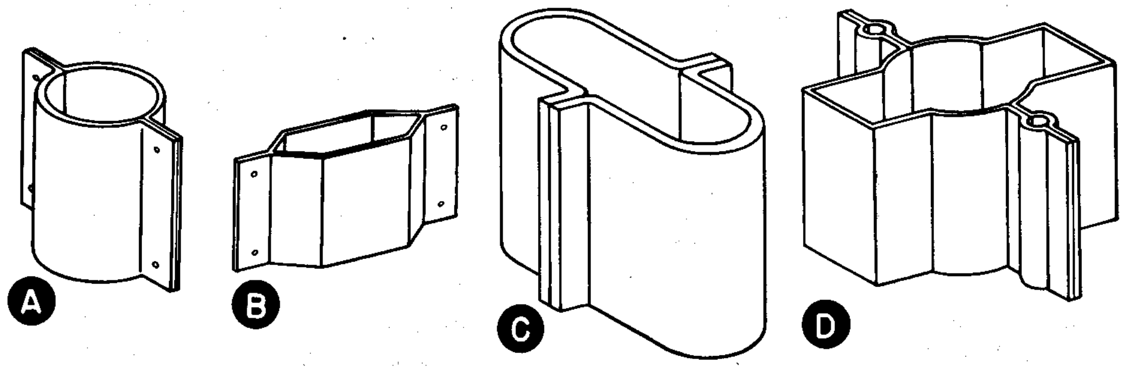


FIGURE #5: Plate Structures:

Vacuum tube plates may be made of any of several different materials, such as nickel, molybdenum, carbon, iron, tungsten, tantalum, and graphite. Zirconium is also sometimes applied as a coating on the plate. The plates of most receiving tubes and small transmitting tubes are made of nickel, which can easily be formed into the desired shape. The plate of a vacuum tube is subjected to a certain amount of heating. Part of this heat comes from the filament or cathode, and part of it is produced by the electrons striking the plate. These electrons striking the plate can cause considerable heating; as a matter of fact in some transmitting tubes they produce so much heat that the plate becomes a bright red color. The fact that the plate is heated results in a few additional problems. First, if the plate gets hot enough it will give off electrons, and if this happens the tube may not work properly because electrons may be able to travel both ways through it. The tube would simply act like a resistor. Therefore steps must be taken to keep the plate below the temperature where it will emit electrons. This is not too big a problem in small receiving tubes, but in the larger tubes it can be quite serious. The plate is often given a dull black finish because a black surface radiates heat readily (black body radiator) and therefore will be cooler than a polished surface. The plates of many transmitting tubes are fitted with fins to provide a larger surface to dissipate, the heat produced at the plate. Large transmitting tubes are often water cooled. Even if the plate is kept cool enough to prevent thermionic emission, the electrons traveling from the cathode of the tube over to the plate can pick up enough speed to strike the plate so hard that they will knock other electrons loose from the surface of the plate. Remember, this is one of the types of emission discussed before and is called secondary emission. The electrons that are knocked off the plate of the tube in this way leave the plate at a rather low speed. The plate normally has a positive voltage applied to it and the electron is negative, so in a diode tube, if the plate is positive, the electrons are simply attracted back to the plate. Secondary emission does not cause any difficulty in a diode. However, in tubes having additional elements, secondary emission can be a problem.

Another problem that is created when the plate of a tube becomes very hot is that almost all metals have a certain amount of gas trapped in the metal. When a metal plate becomes very hot, the gas trapped in it may be forced out of the metal and into the space surrounding the plate of the tube. Gas in a tube can destroy its usefulness. We will look at why it is important that the amount of gas in a tube be kept as low as possible.

GAS EVACUATION:

Tubes are called vacuum tubes because all the gases inside the tube including air are normally evacuated. There are two important reasons why these gases must be removed from inside the tube. First, if air is permitted in the tube, the filament or heater will oxidize; in other words, it will simply burn up when heated. Secondly, even if this problem could be overcome, there is another important reason why all gases must be removed from the tube. Gases are made up of molecules. Although these particles are extremely small, they are still many times the size of an electron. An electron traveling from the cathode of the tube to the plate moves at a fairly high speed. The chances are that the majority of electrons traveling from the cathode to the plate would strike one, or more gas molecules if there were a large amount of gas in the tube. If a high speed electron strikes a gas molecule the electron will be deflected from its path and it will knock electrons out of the gas molecule. Normally a gas molecule has no charge. However, if it is struck by an electron, which knocks other electrons out of the molecule, the molecule will be short of electrons, and then they will have a positive charge. Positively charged molecules are called **"ions "**. These ions are large and heavy in comparison to electrons and have a fairly high positive charge on them. Since the cathode of the tube is normally connected to a negative voltage source, it is negative, and will attract these positive ions. In fact, the positive ions will pick up a fair amount of speed traveling to the cathode and may bombard it with such force that small particles of the cathode material will be knocked loose.

Gas inside a vacuum tube is extremely undesirable. Therefore, in the manufacturing process, every effort is made to remove all the gases from inside the tube. However, some of the gas will remain in the tube and additional gas will boil out of the materials from which the tube is made the first time the tube is heated. To get rid of these gases left in the tubes a "getter " is placed inside the tube.

A getter is a small cup containing chemicals. During the manufacturing process, the tube is first evacuated by means of vacuum pumps. This will remove most of the gases from the tube. The tube is sealed and then it is heated. In the heating process gases are driven off the metals inside the tube such as the cathode and the plate. At the same time, the getter is heated and the chemicals in the getter combine with any gas molecules released, forming metal compounds, which are deposited on the glass envelope of the tube. The compounds in the getter hold onto the gas molecules and will not easily release them into the space inside the tube again. The silvery appearance that many tubes have near the base of the bulb and in other locations in the bulb is produced by these compounds forming on the glass envelope of the tube.

By using this procedure it is possible to obtain an excellent vacuum in tubes with a pure tungsten filament. The vacuum inside a tube with a thoriated tungsten filament is not quite as good, and the vacuum inside tubes with oxide coated filaments is still poorer yet. The reason for this is that you can heat a tube with a pure tungsten filament to a higher temperature than you can the other types and so the action of the getter is even more complete in these tubes than it is in the other types.

For this reason, tubes with thoriated tungsten filaments or oxide coated cathodes are limited to uses where the operating voltages are somewhat lower than those that can be applied to pure tungsten filament tubes.

The leads connected to the various elements inside the tube are brought through glass seals. The glass is heated to a high temperature and it flows around the leads, providing a **nearly perfect seal**. Thus once the tube is evacuated, it is <u>almost impossible</u> for air to leak back into the tube. We say almost impossible because there is no such thing as a perfect seal and air will gradually leak back into the tube. It may take several years for enough air to get into the tube to affect its performance, but if the tube is left around unused long enough, eventually enough gas will get into the tube so that its operation will be impaired, this is an issue to consider and to be sure to test for with all NOS tubes.

Tubes that have had all the gas removed from inside them are called hard tubes. Most tubes found in radio and TV receivers are hard tubes. However, there is another group of tubes into which certain types of gas have been deliberately introduced. Mercury is put inside some diode tubes. When these tubes are operated, the mercury will heat and vaporize, filling the inside of the tube with mercury vapor.

This type of tube is called a soft tube or a gaseous tube. Other gases are sometimes used, but mercury vapor is the gas you will be most likely to encounter. It is easy to identify a mercury vapor tube because mercury gives off a characteristic blue glow. Therefore, if you see a tube operating with a bright blue glow, the chances are it is a mercury vapor tube like the 83 tube used in most tube testers and in may old power supplies too!

If there is excessive gas inside a hard tube it also will have a blue glow. However, the blue glow is not as bright as it is in a mercury vapor tube. Mercury vapor tubes are almost always diode/rectifier tubes, although a special type called a thyratron has three elements and thus is a triode. These tubes are usually quite easy to pick out. If you discover a blue glow between the elements of a hard tube, the tube is gassy and should be replaced. Before leaving this subject there is one other point that should be brought out. Electrons emitted from the cathode of a hard tube frequently travel at a high speed and miss the plate of the tube and strike the glass envelope. When they do this there will often be a blue glow on the envelope of the tube. This does not indicate a defect in the tube. If a hard tube shows this blue glow on the envelope of the tube you can for get about it; it does not mean anything. However, if the blue glow appears between the elements of a hard tube, the tube is gassy.

CHARACTERISTIC CURVES:

Among the information published by vacuum tube manufacturers are the characteristic curves of their tubes. These curves make it possible for the engineer or technician to predict how the tube will perform under a given set of operating conditions. The characteristic curve of a diode tube shows how much current will flow when a given voltage is applied to the plate of the tube. A typical diode characteristic curve is shown in Fig. 6.

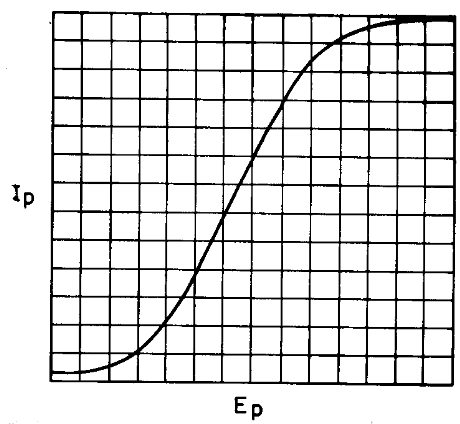


Figure. #6: Diode Characteristic Curve: The characteristic curve of a diode showing the relationship between plate current and plate voltage. Notice that there is a small plate current even when the plate voltage is zero. This is caused by a few electrons being emitted by the cathode at such a high speed that they travel over and strike the plate even when no voltage is applied to it.

Notice that this characteristic curve is not a straight line. It is bent on the two ends. Also notice that there is a very small current flow even when the plate voltage is zero. This is because a few of the electrons emitted by the cathode travel with sufficient velocity to reach the plate even without a positive voltage on the plate. As the plate voltage is slowly increased from zero to a high positive value the number of electrons flowing to the plate gradually increases. At first the increase is non-linear, but as the plate voltage is increased still further, eventually a point is reached where the characteristic curve becomes quite linear. By this we mean the curve is close a straight line which indicates that we will get an almost constant change in plate current for a given change in plate voltage.

For example, on a linear curve, if increasing the plate voltage from 25 to 50 volts causes an increase in current of 5 milliamperes, we can expect an increase in plate current of 5 more milliamperes when we increase the plate voltage from 50 volts to 75 volts. Again, if we increase the voltage from 75 volts to 100 volts and the curve is linear, we can expect another 5 milliampere plate current increase. Notice that the top of the curve begins to round out and become flat, this is called plate current saturation. Eventually a point is reached where all of the electrons emitted by the cathode are drawn immediately to the plate of the tube. In other words, the electrons do not form a space charge, or electron cloud around the cathode, but instead travel immediately from the cathode of the tube right over to the plate. When this point is reached, increasing the plate voltage still further will result in no further increase in the plate current flowing in the tube because the plate is pulling all the free electrons over to it and is gathering them up as fast as the cathode can emit them. As a matter of fact, if the plate voltage is increased beyond this point, there is the danger that some electrons will be emitted from the cathode by the process of jerking them out of the cathode by the high plate voltage. This may cause small particles of the cathode material to jerk/brake loose, and if this happens the cathode of the tube will soon disintegrate and the tube will no longer be usable.

SUMMARY:

There are a number of important things you should remember in this section. First, the cathode found in tubes can be divided into two types the directly heated cathode which is called a filament, and the indirectly heated cathode, which is simply called a cathode. Remember that the heater used to heat an indirectly heated cathode performs no useful purpose other than to heat the cathode of the tube. It does not enter into the 'electrical circuit and operation of the tube itself. Three types of cathode material are found in vacuum tubes : pure tungsten, thoriated tungsten, and oxide coatings.

Several different types of plates are used in vacuum tubes ; the exact shape of the plate is usually determined by the shape and type of cathode used in the tube. The plate of a vacuum tube will give off electrons by thermionic emission if it becomes too hot. However, some transmitting tube plates can operate at a red temperature without giving off electrons, the materials used in the manufacture of the plates of these tubes are selected because they give off electrons only at a very high temperature. The plate may also give off electrons due to secondary emission. In some tube types this can become a problem.

The inside of a vacuum tube is normally highly evacuated. A tube with a high vacuum is called a hard tube. Gas is deliberately introduced into some tubes, and these are called soft tubes.

The Triode Tube:

The development of the diode or two-element tube opened the door to the field of electronics. The diode tube has only limited applications. It can be used as a rectifier to change ac to dc, and in some other special circuits, but it cannot be used to amplify.

Early in the twentieth century, the triode tube was developed. This tube touched off the rapid development in electronics that has occurred since then. The development of the triode tube led to the development of other multi-element tubes which have made possible circuits previously undreamed of.

As mentioned the triode tube has three elements : a cathode, a grid, and a plate. The introduction of the grid between the cathode and the plate of the tube made it possible for a vacuum tube to amplify weak signals. You may already have a general idea of how the grid works, but in this section we will review this idea, expand it, and then learn more about tube characteristics. It is important for you to understand all the details of how a triode tube works, because the multi-element tubes that we will cover later are simply triodes with additional elements added. Fig. 7. Different ways of representing the grid on schematic diagrams.

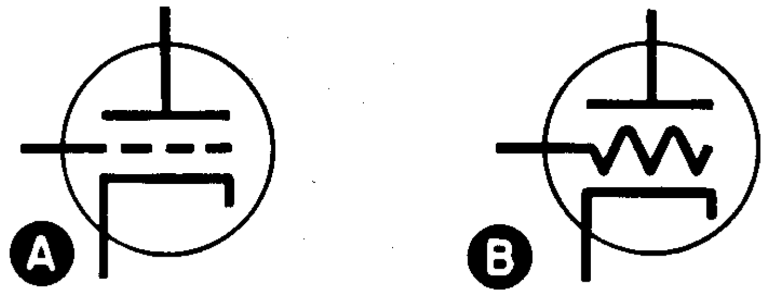


FIGURE #7: Typical Grid symbols:

HOW THE GRID WORKS:

The third element inside the vacuum tube is placed between the cathode and plate and is called the grid. As the name implies, the grid is of open construction. The schematic symbol used to represent a grid is shown in Fig. 7A. On some old diagrams you might find the symbol shown in 7B used, this symbol is obsolete.

Several different types of grid construction are shown in Fig. 8. Notice that in A the grid is made in the form of a spiral mesh, like a screen, whereas the grid shown in B is made up of a spiral-wound coil with the turns placed relatively close together. In C the same type of construction is used as in B, but the space between the turns is much greater. In D the grid is more or less rectangular in shape and is supported by the U-shaped elements at the end so that the grid is held in a very rigid position. The grid is supported by this frame and this type of construction is often referred to as a frame grid. It has an advantage over the other types: the grid wires can be placed very close together and very close to the cathode, which as we will cover later makes it possible to make a tube with a much higher gain than that of the other types of grids.

Before we review how the tube amplifies, we will consider the effect of the grid on the flow of plate current when different voltages are applied to it. The first case is where the grid is connected directly to the cathode so that the voltage applied to it is zero. Zero Grid Voltage.

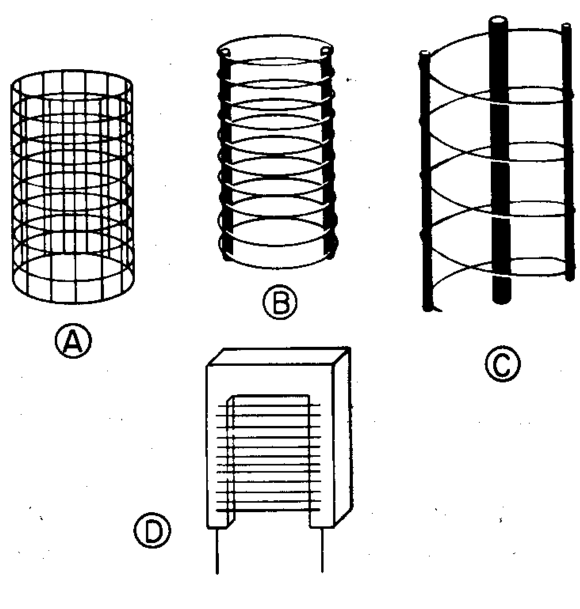


FIGURE #8: Typical Grid Structures:

When the grid is connected directly to the cathode we have the arrangement shown in Fig. 9.

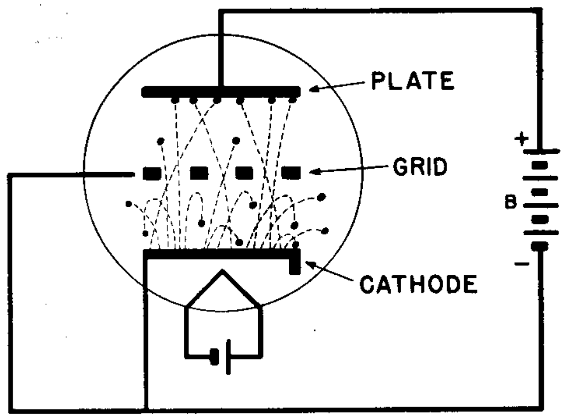


FIGURE #9: With no grid bias there will be some number of electrons that will flow to the plate while the rest will form a space charge between the cathode and the grid.

Here the plate is connected to the positive side of a B battery and the cathode is connected to the negative side of a battery. The grid is connected directly to the cathode, and a small battery is used to provide the heater voltage required to heat the heater, which in turn heats the cathode of the tube. When the cathode is heated, it will emit electrons and they will fly off into the space surrounding the cathode. These electrons will form a cloud of electrons around the cathode. This cloud of electrons is called a space charge. Some of the electrons in the space charge will fall back to the cathode, others will be attracted by the positive potential applied to the plate of the tube and they will be drawn through the grid wires to the plate. A few electrons in traveling from the cathode to the plate of the tube may accidentally strike the grid wires. These electrons will flow through the external circuit from the grid back to the cathode of the tube. As long as the grid is connected directly to the cathode, the tube acts very much like a diode and the grid has very little effect on the flow of plate current. The amount of plate current flowing will depend primarily upon the voltage applied between the plate and cathode of the tube and the spacing between the plate and cathode. Fig. 10. Fig.

Positive Grid Voltage:
Now if we modify the circuit shown in Fig. 9, by adding a small C battery in the grid circuit as shown in Fig. 10, we will have a positive voltage on the grid of the tube. This means that the grid will be slightly positive with respect to the cathode. The B battery used between the plate and cathode has a much higher voltage than the C battery, and therefore the plate will have a much higher positive potential than the grid.

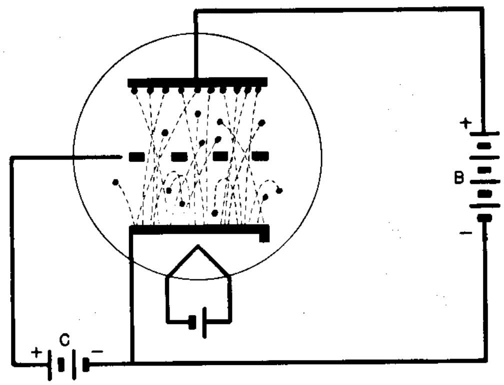


Figure. 10: Making the grid positive with respect to the cathode will greatly increase the flow of electrons to the plate:

With the C battery connected in the grid circuit, the positive voltage on the grid of the tube will attract electrons from the space charge around the cathode and start these electrons speeding toward the grid. By the time the electrons travel the short distance from the space charge to the grid most of them will be traveling at such a high speed that they will pass right through the grid wires and then come under the influence of the high positive voltage on the plate of the tube. Most of the electrons will continue traveling towards the plate until they eventually will reach and strike the plate.

The number of electrons reaching the plate will be much higher than in the preceding case where there was no voltage applied to the grid. The grid is able to increase the number of electrons flowing to the plate because the grid is placed very close to the cathode, and even though there is only a low positive voltage applied to the grid it is able to pull many electrons from the electron cloud and start them on their way to the plate.

Because the grid has a positive voltage applied to it, there will be more electrons striking the grid than there were in the preceding case when there was no voltage applied to the grid. However, even though a few electrons will be attracted to the grid, a small positive voltage applied to the grid will increase the flow of plate current. If the positive voltage is made higher, in other words if the grid is made more positive, it will start to attract more and more electrons.

Eventually a point will be reached where the grid will be taking many of the electrons that would normally flow over to the plate of the tube. Then, instead of causing the plate current to increase, the large number of electrons flowing to the grid of the tube will starve the plate so that the plate current will be less than it would be if the grid were operated at zero potential.

When the number of electrons striking the grid becomes high, the energy that these electrons give to the grid upon striking it may cause the grid to become very hot. As a matter of fact, if enough electrons strike the grid, the grid will become red hot. Keep this in mind. If you see a vacuum tube where one of the grids is glowing red heat, the number of electrons reaching the grid is too high--there is something wrong in the circuit.

Negative Grid Voltage.
If instead of putting a positive voltage on the tube grid, you put a negative voltage on it, you will have the circuit shown in Fig. 11. Now the negative potential on the grid of the tube repels the electrons coming from the space charge and drives them back to the space charge so that the number of electrons getting through the grid and reaching the plate of the tube is greatly reduced.

As a matter of fact, if the negative voltage applied to the grid of the tube is made high enough, all electron movement between the cathode and the plate will be stopped. There will be no flow of electrons from the cathode to the plate of the tube.

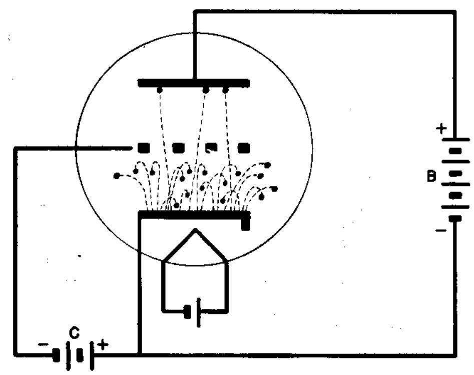


Figure. #11. When you make the grid negative you will reduce the flow of electrons to the plate:

Amplification Factor.
Current is actually a movement of electrons, and since the grid controls the electrons flowing from the cathode to the plate of the tube, the grid can control the current flowing from the cathode to the plate. The current flowing in the plate circuit is called the plate current. Changing the plate voltage on a triode tube will cause the plate current to change, but because the grid is closer to the cathode than the plate, it exerts a greater effect on plate current than the plate does. In fact, we may have to change the plate voltage on a tube as much as 100 volts to get the same change in plate current that can be obtained by changing the grid voltage only 1 volt. The exact ratio between the change in plate voltage and the change in grid voltage needed to get the same change in plate current is called the amplification factor. If we have to change the plate voltage 50 volts to get the same change in plate current we can get by changing the grid voltage 1 volt, the amplification factor is **50/1 = 50. A** triode tube may have an amplification factor somewhere between 5 and about 100. The amplification factor of a tube depends primarily upon the ratio of the plate to cathode spacing to the grid to cathode spacing.
The amplification factor of a triode tube is a very important characteristic of the tube. It is a good indication of how much voltage gain you can expect to obtain from an amplifier stage using the tube. The total amplified voltage produced by the tube is equal to the amplification factor times the signal voltage applied between the grid and the cathode of the tube. It is not possible to get all of this amplified voltage out of the tube, because the tube has internal resistance, and part of the voltage will be dropped across this resistance, but in general the higher the amplification factor of a tube, the greater the gain we can expect to obtain from the tube.

To provide a short form for expressing the amplification factor of a tube, the Greek letter, mu, which is pronounced "mew", and written μ, is used as a symbol to represent the amplification factor. The amplification factor is often referred to as the mu of the tube. Thus a high-mu tube is a tube with a high amplification factor.

HOW A TRIODE AMPLIFIES
You have already had a brief explanation of how a triode amplifies a signal, so this will be primarily a review. First, let's consider what type of signal we may want to amplify. For example, let's assume that we have a sine-wave signal that represents a certain sound. The amplitude of the signal is extremely weak.

In order to use the signal to produce sound, we must increase the strength of the signal. The usual procedure is to first build up the voltage of the signal.

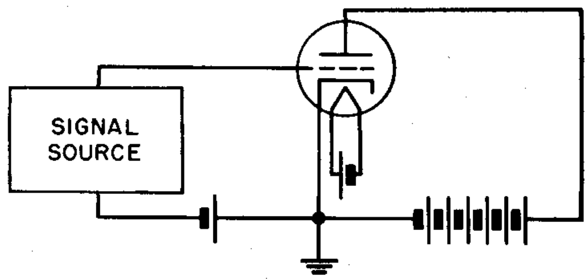


Figure. #12. When a AC signal is applied between the grid and the cathode the result in an AC plate current.

An amplifier stage used for this purpose is called a voltage amplifier. If we apply the signal between the grid and the cathode of a vacuum tube connected as shown in Fig. 12, we know the ac signal in the grid circuit will produce variations in the plate current. We know this is true because the voltage applied to the grid has a pronounced effect on the flow of current to the plate. Thus the varying signal applied between the grid and the cathode of the tube will cause the plate current to vary. However, we are interested in a varying output voltage. If we feed a weak signal voltage into the grid of a tube to amplify it, what we want is an amplified voltage in the output. The desired result can be obtained with a circuit like the one shown in Fig. 13. Now let's stop and consider what happens in this circuit first when the signal voltage is zero.

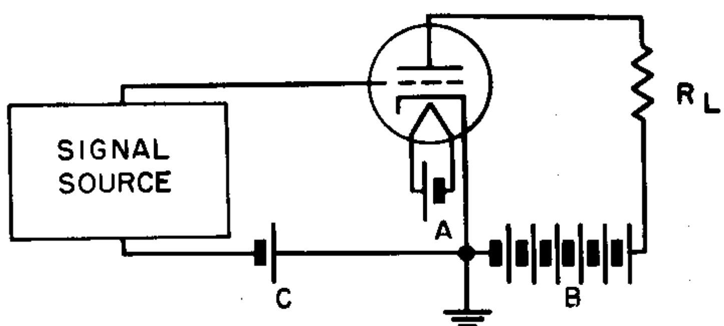


Figure. #13. With a signal applied to the grid input you will develop a output signal across the plate load resistance from the plate current flow.

When there is no ac signal applied to the input, a steady plate current will flow from the cathode of the tube to the plate of the tube. The exact amount of current is relatively unimportant, but it will depend upon the grid bias voltage supplied by the C battery, the plate voltage supplied by the B battery, the characteristics of the tube itself, and the size of the plate load resistor marked R_L. The plate current flowing through the tube will flow from the negative side of the battery to the cathode of the tube. The heated cathode will give off electrons, which will flow through the space between the cathode and the grid of the tube over to the plate of the tube. The electrons will then flow from the plate of the tube through the plate load resistor R_L to the positive side of the battery, through the battery, back to the negative battery terminal. It sounds as though the electrons start from the negative terminal and then gradually flow around the circuit. Actually, the movement of electrons in the circuit is instantaneous. The electrons start moving in all parts of the circuit at the instant the tube is heated and power applied.

When current flows through the load resistor R_L , there will be a voltage drop produced across the resistor. The exact value will depend upon the current flow and the size of the resistor. We know this is true from Ohm 's Law which states that E =IxR. If there is a voltage drop across the dropping resistor, this means that the plate voltage, which is the voltage between the plate and the cathode of the tube, will be less than the B supply voltage by an amount equal to the voltage drop across the plate load resistor. Again, we know this is true because the sum of the voltage drops in a series circuit must be equal to the source voltage. In this series circuit we have the plate-cathode circuit of the tube in series with the load resistor. Therefore, the voltage across the tube equals the B supply voltage minus the voltage drop across the load resistor.

Before a signal is applied between the grid and the cathode of the tube the plate current will reach what is called a steady state. The voltage between the plate of the tube and the cathode will be some constant value.
Now let us consider what happens when a signal voltage like the sine-wave shown in Fig. 14A is applied between the grid and the cathode of the tube. Notice the first half cycle, which is numbered 1-2-3 on the in-put signal at A. This signal swings in a positive direction.

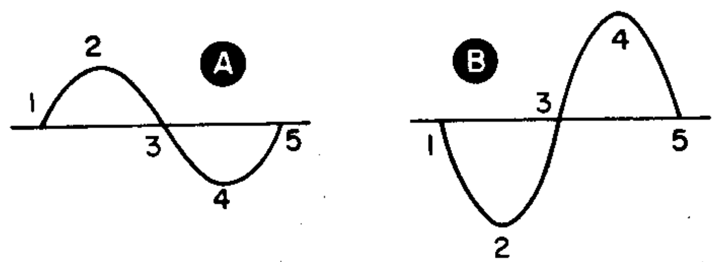


Figure. #14A & #14B. Figure “A” displays the sign wave signal voltage, while “B” repesents the output signal voltage.

When the ac input voltage swings positive, its polarity will be such that it will subtract from the grid bias voltage. This will make the grid voltage less negative. If we make the grid voltage less negative, we are moving it in a positive direction. When the grid becomes less negative it will allow more electrons to flow from the cathode of the tube to the plate. If the number of electrons moving in this part of the series circuit increases, then the total number of electrons in motion in all parts of the series circuit must increase. The number of electrons flowing through the plate load resistor R_L increases. When this happens, the voltage drop across the plate load resistor increases, and there will be less of the B supply voltage between the plate and cathode of the tube. This means that the plate voltage will decrease.

The plate voltage will continue to decrease as the input signal moves from point 1 to point 2. The plate voltage will look like the wave shape shown in Fig. 14B and as the input moves from point 1 to point 2 on curve A, the output will move from point 1 to point 2 on curve B.
If the input signal begins to decrease from its peak point 2 back to zero voltage at point 3, the plate voltage between the plate and cathode of the tube will start to increase, because as the input signal moves from point 2 to point 3, the negative grid voltage on the tube will be increased. This means that there will be fewer electrons flowing from the cathode to the plate of the tube, and thus fewer electrons will be flowing through the load resistor. When the number of electrons flowing through this resistor decreases, the voltage drop across it decreases. Since the sum of the voltage drop across the load resistor and the voltage between the plate and cathode is always equal to the B supply voltage, the voltage between the plate and cathode of the tube must increase.

During the second half of the input cycle, when the input signal swings from point 3 to point 4, the signal is swinging in a negative direction, so it adds to the grid bias voltage applied to the tube by the C battery. This makes the grid even more negative, and reduces further the number of electrons moving from the cathode to the plate of the tube. This reduction in electrons flowing in the series circuit means that there will be an even smaller voltage drop across the plate load resistor R_L and even more voltage between the plate and the cathode of the tube. As the input signal moves from point 3 to point 4 and then on to point 5, the output signal between the plate and cathode of the tube will follow the shape shown from point 3 to point 4 and then to point 5. This variation in the voltage between the plate and cathode of the tube will be several times the amplitude of the input signal.

Before going ahead let's take a look at what we have in the plate circuit of the tube. Examine the waveform shown in Fig. 14B. Notice that a single ac cycle has been produced and the amplitude, frequency, and wave shape of the signal depend upon the signal applied between the grid and the cathode. This signal is an amplified version of the signal applied between the grid and the cathode of the tube. The total signal applied between the grid and the cathode of the tube actually consists of a dc voltage applied by the C battery plus an ac voltage which is superimposed or added to it. The voltage between the cathode and grid will be the algebraic sum of the two voltages. When the signal voltage tends to swing the grid positive it will actually be subtracting from the C battery voltage so that the net negative voltage applied to the grid will be reduced. When the signal source tends to swing the grid in a negative direction, it will add to the C battery voltage so that the grid will be made more negative with respect to the cathode and will reduce the current flow through the tube.

The voltage in the plate circuit actually consists of a dc voltage applied to the tube with an ac voltage superimposed on it. Notice, however, that the ac voltage at the plate is inverted when compared to the input signal. In other words, when the input signal swings in a positive direction, the output signal swings in a negative direction, and when the input signal swings in a negative direction, the output signal swings in a positive direction. We say that the two signals are 180 out of phase.

Notice that the cathode of the tube in the circuit shown in Fig. 13 is grounded. This type of circuit is called a "grounded-cathode" amplifier. One of the characteristics of the grounded-cathode amplifier is that there is a 180° phase-shift between the input and output signals.
The signal voltage applied in series with the C bias voltage between the grid and cathode causes the plate current flowing from the cathode to the plate of the tube to vary. Actually, the current looks like a dc current with an ac current superimposed on it. Therefore, when we refer to the ac current in a tube, we mean the signal current or the variation in dc current caused by a signal applied between the grid and cathode. Remember that the current through a tube always flows from cathode to plate; it never reverses in direction. However, the variation in current through the tube due to the signal variations produces the same effect as we would have with a dc current with an ac current superimposed on it.

Remember that when you studied the amplification factor we pointed out that the amplification factor is based on a change in plate voltage and a change in grid voltage. Another way of expressing the same idea is in terms of ac voltages. We can say that it is the ratio of ac plate voltage to the amount of ac grid voltage required to produce the same ac plate current. As we mentioned previously, we are speaking of an ac current ' superimposed on a dc current.

SUMMARY
This section is extremely important. Rather than doing a summary on this material I think it is better that you go back and read over the entire section again to be sure you understand it thoroughly. Grasping clearly the idea of how a tube amplifies is extremely important. If you master this idea now, the remaining material should be comparatively simple.

Tube Characteristics
Tube characteristics are important both to the engineer and to the technician. They are important to the engineer because he uses them in designing circuits. He must know the characteristics of the tube in order to select the correct value of parts to use along with the tube to get the best possible performance out of the circuit. They are important to the technician because often he will have to service equipment in which detailed service information is not available. By identifying the tube types used in the equipment and referring to a tube manual which describes the characteristics of the tubes used, he can obtain a great deal of useful information on how the equipment should work. A great deal of information about tubes is given in the form of characteristic curves. The most important of these curves is the Eg-Ip (grid voltage-plate current) curve.

THE Eg-Ip CURVE
A tube is able to reproduce a signal only as long as a given change in grid voltage will produce a constant change in the plate current. Let's assume we have a tube with a voltage of 2 volts between the grid and cathode, and that the grid is 2 volts negative with respect to the cathode. If we increase this voltage from 2 volts to 2 -1/2 volts, we know that the plate current will decrease. We could actually measure this change in plate current. Now, if we increase the voltage still further from 2-1/2 volts to 3 volts, we should get the same change in the plate current that we got when we changed the voltage from 2 volts to 2-1/2 volts. It is quite likely that we would get the same change, but eventually a point will be reached where changing the grid voltage ½ a volt will not produce this same change in plate current. When we reach this situation, we say that this tube becomes non-linear. This characteristic of a tube limits the amount of signal that can be applied between the grid and cathode of the tube.
The change in plate current that can be expected for a given change in grid voltage is shown on a curve called the Eg-Ip curve. A typical Eg-Ip curve is shown in Fig. 15. Notice how the plate current will be different for different values of grid voltage. Also notice that part of this curve is relatively straight, but the two ends of the curve are quite bent. In the middle of the curve, we have a straight section that is called the linear range. This simply means that as long as the tube is operated within these limits a given change in grid voltage will produce the same change in plate current. As long as this change in plate current for a given change in the grid voltage remains constant, the output will be a faithful reproduction of the input signal. However, once the change becomes non-linear, the output will be distorted. This means the output signal will not be a faithful reproduction of the input signal.

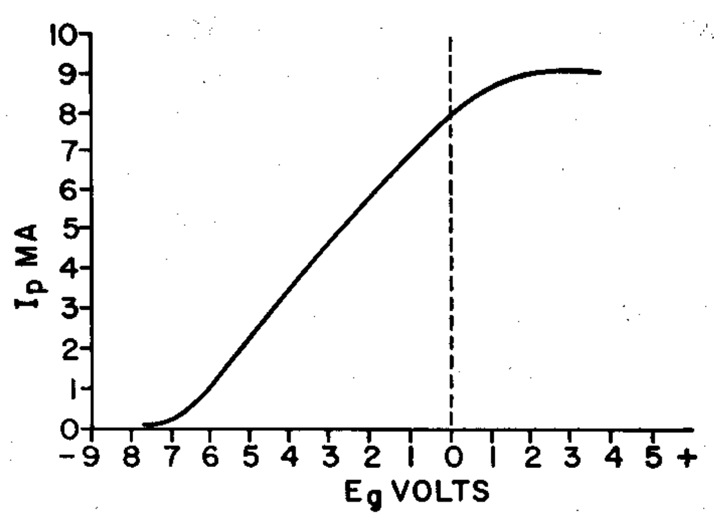


Figure. #15. Typical Eg - Ip Characteristic curve:

Grid Bias:
The voltage applied by the C battery that is connected between the grid and cathode of a tube is called the grid bias voltage. To bias something means to fix or adjust it. The grid bias voltage fixes, or adjusts the tube to operate under the most favorable conditions. The idea of a grid bias voltage is to apply a voltage to the grid that will place the tube operation on the desired portion of its characteristic curve. In the case of the amplifier we have been considering, we bias the tube to operate at the center of the linear, or straight part of the characteristic curve. If you look at Fig. 15 you can see that the characteristic curve is comparatively straight between zero grid voltage and the grid voltage at -6 volts. Slightly to the right of zero grid voltage the curve becomes distorted, and to the left of -6 volts it also becomes distorted. Therefore, to get the tube operating on the linear part of the curve, we would apply a grid bias of -3 volts. With a grid bias of -3 volts, if the input signal drives the grid voltage 3 volts in a positive direction, we can expect the same change in plate current as we will get when the input voltage swings 3 volts in a negative direction. When the input voltage swings 3 volts in the positive direction, it will subtract from the grid bias, so the net voltage applied to the grid of the tube will be zero, and when it swings 3 volts in the negative direction, it will add to the grid bias so that the net voltage applied between the grid and the cathode of the tube will be -6 volts. Changing the grid voltage between these limits produces linear or constant changes in plate current.

On the other hand, if instead of a grid bias of -3 volts we had a grid bias of -5 volts and a 3-volt input signal, when the grid swings in the positive direction we will get a total voltage of -2 volts on the grid. This will produce a change in plate current. However, when the grid swings 3 volts in the opposite direction, due to the signal, we will get a total grid voltage of -8 volts. This will produce a change in plate current, but it will not be the same as the change produced when the signal went in the opposite direction. In fact, you can see from the curve that once the signal is past -7 volts little, or no change in plate current will occur. Under these circumstances, a plate current change that is different when the signal swings in one direction is different from the plate current change when the signal swings in the opposite direction and we get distortion. This means that the signal is not reproduced faithfully. For an input signal like the one shown in Fig. 16A we would get an output signal like the one shown in Fig. 16B. Notice that in the first half cycle when the input signal swings in a positive direction the output signal swings in the opposite direction. However, the output signal is a faithful reproduction of the input signal.

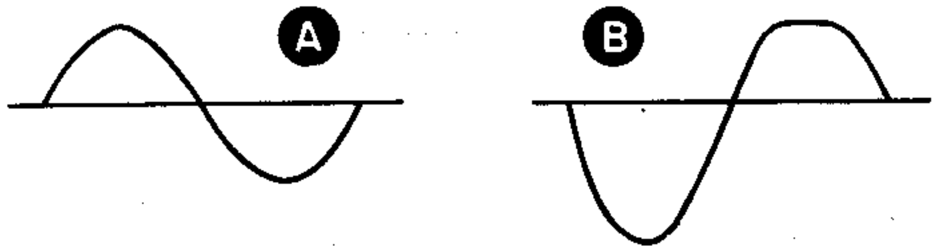


Figure. #16 A/B: Input voltage = “A” and output voltage = “B” The flattened top on the right side of the “B” waveform is distortion from access bias:

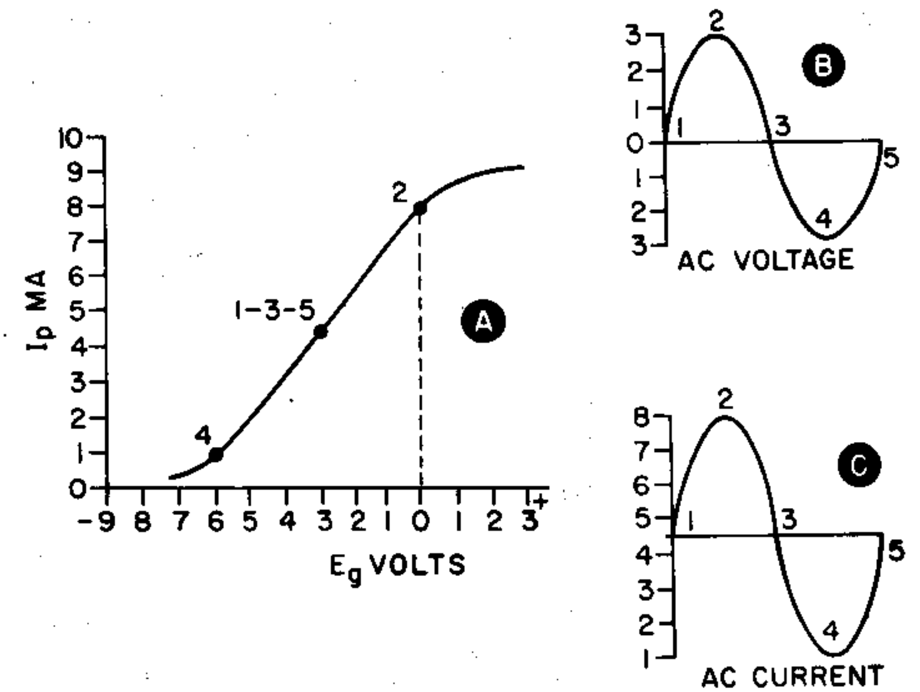


Figure. #17A & B & C. Figure "A" Is a typical characteristic curve, showing how the grid voltage "B" and the plate current "C" vary on it.

During the second half cycle, when the input signal swings in a negative direction, the output signal swings in a positive direction, but is flattened off at the top. The amplified signal is not a faithful reproduction of the input signal. As mentioned, this is called distortion, and this particular case of distortion is called amplitude distortion because the amplitude of one half of the cycle is compressed.

Now let us see how different values of grid bias affect the way in which a tube amplifies a signal. As you know, the grid voltage is made up of a fixed bias voltage, and the ac signal is superimposed on it. Assume we have a tube with the E g-Ip curve shown in Fig. 17A. The center of the linear part of the curve is at -3 volts. Now suppose we have a bias voltage of -3 volts, and the signal voltage shown in Fig. 17B, Eg VOLTS which varies from 0 to 3 volts, is superimposed on it. When the ac signal is at the start of its cycle, point 1, it will be zero, so the total grid voltage will be -3, point 1 on the curve in 17A. When it increases to point 2, the total voltage will then be zero, point 2 on the curve. At point 3 the total voltage will be -3 volts again. At point 4 the total voltage will be -6, and at point 5 the total voltage will again be -3.

Now let's draw a picture showing what is happening to the plate current at each of these points. At point 1 the current is 4.5 ma ; at point 2 it is 8 ma ; at point 3 it is again 4.5 ma; at point 4 it is 1 ma; and at point 5 it is 4.5 ma again. This is shown in Fig. 17C As you can see, this is a faithful reproduction of the applied signal.

We often show these things all on one chart as shown in Fig. 18 on the next page. Notice how we have drawn the signal voltage. By drawing it in this position, we can follow up to the point it represents on the characteristic curve, and then show the curve for the corresponding plate current.

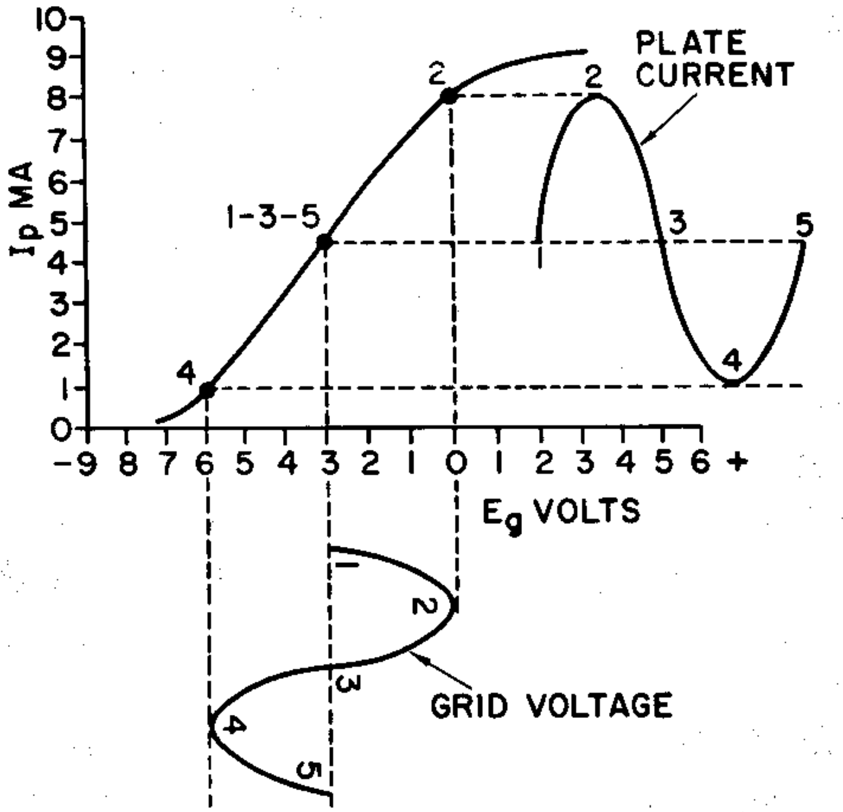
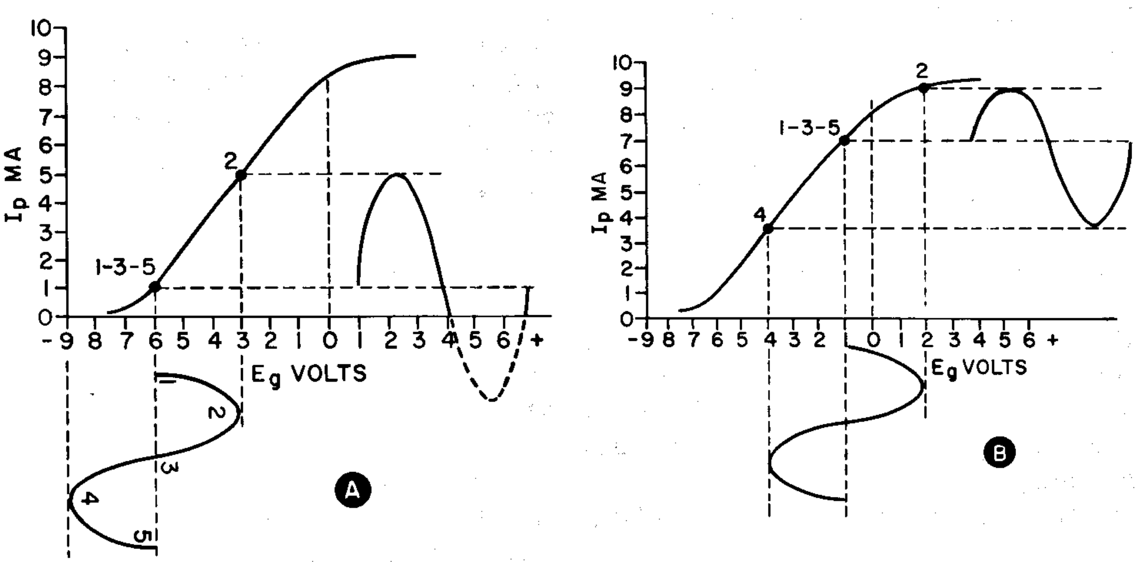


Figure. #18. We often show the information of Figure. #17. all on one diagram like this.



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gure. #19A and #19B: Figure "A" displays too much bias and "B" represents too little bias.

In Fig. 19 we have shown what happens when the operating bias is too high or too low. In Fig. 19A the operating bias is too high (too negative) and the result is that the grid is driven beyond the cut-off voltage on the negative half of each cycle. This means that the plate current drops to zero and flattens off on the negative half of each cycle.

In Fig. 19B the operating voltage is not high enough, so during part of each cycle the grid becomes positive. When this happens the grid will start to take some of the electrons that would normally flow to the plate of the tube with the result that the top of the plate current curve is somewhat distorted. The variations in plate current for a given input signal are not linear when the bias is too low.

THE Ep-Ip CURVE:

The characteristic curves shown in a tube manual are usually Ep-Ip (plate voltage-plate current) curves such as those shown in Fig. 20. Each curve is for a particular value of grid voltage. As you can see, when the plate voltage is higher it takes a higher grid bias voltage to cut off the flow of plate current. You can also get a good idea of how a change in grid voltage affects the plate current. Find the vertical line representing a plate voltage of 200 volts. Follow this line up until you see where it cuts the curve representing zero grid volts. It cuts this line just above the horizontal line representing a plate current of 6 ma. The -1 volt grid curve cuts the 200 volt line at about 3.5 ma. Thus, changing the grid voltage from zero to -1 volt will change the plate current from above 6 ma to 3.5 ma, or about 2.5 ma. Notice how much more effective the grid is in controlling plate current than the plate is. We saw that a change in grid voltage of 1 volt caused a plate current change of 2.5 ma. The -1 volt grid curve cuts the 200 volt line at 3.5 ma. If we increase the plate voltage to 250 volts and keep the grid bias at -1 volt, the plate current will be 5 ma, which is a change of only 1.5 ma from the 200 volt point. Thus the change in plate voltage of 50 volts has less effect on the plate current than a change of grid voltage of only 1 volt.

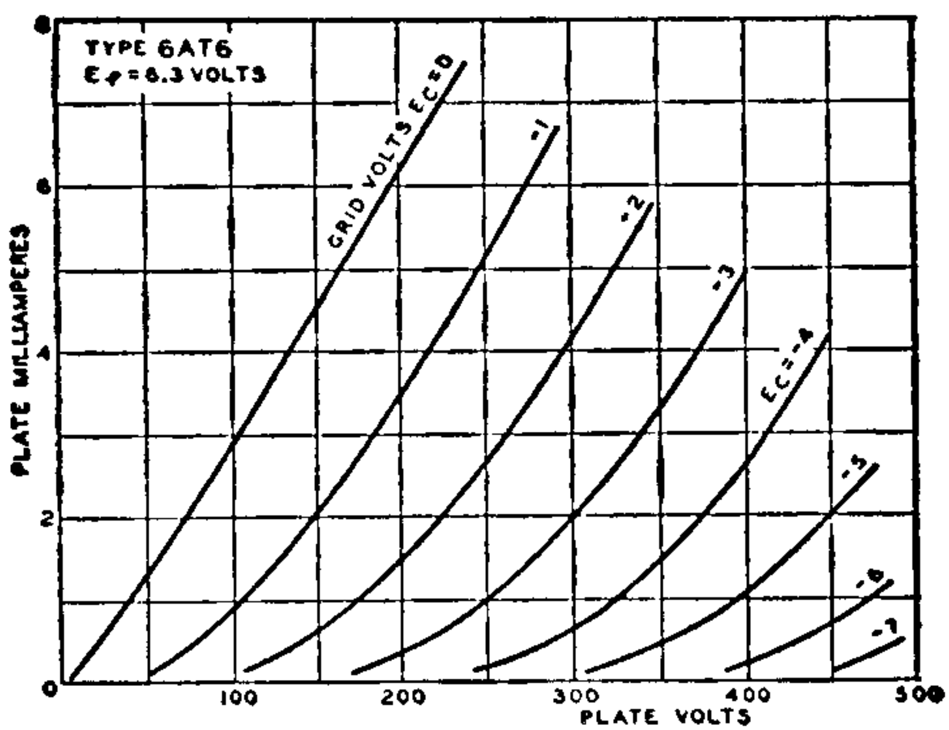

Figure. #20. **EP-IP curves of " a 6AT6 tube.**

PLATE RESISTANCE

As we mentioned previously, a tube has internal resistance. The tube, in amplifying a signal, acts very much like a generator with an internal resistance. This internal resistance of the tube is called the ac plate resistance. Because the tube has this internal plate resistance, the gain that can be obtained from a tube is never quite equal to the amplification factor of the tube.

The ac plate resistance is defined as the ratio of the change in plate volts to the change in plate current that it produces. The symbol rp is usually used to represent the ac plate resistance of the tube. The symbol ep is used to represent the change in plate voltage and the symbol ip is used to represent the change in plate current. Thus the plate resistance of a tube in ohms is: rp = ep/ip

The ac plate resistance is one of the characteristics listed in manufacturers' tube manuals. When the tube manual gives a plate resistance, it is for a certain value of plate and grid voltage. The ac plate resistance of a tube is affected by the dc voltage applied to the plate and by the dc voltage applied to the grid. Therefore, if the tube is operated at voltages other than those listed, the plate resistance will not be the same as the values shown. In some engineering type tube manuals the plate resistance is given in the form of a curve so that the plate resistance can be determined with different values of plate and/or grid voltages.

So far we have been talking about the ac plate resistance of a tube. However, a tube also has a dc resistance. In a circuit such as the one previously shown in Fig. 13, with no input signal applied to the grid, a certain value of plate current will flow. This plate current produces a voltage drop across the tube and a voltage across the load resistor. You know from Ohm's Law that the resistance is equal to the voltage divided by the current, thus the dc resistance of the tube is equal to the dc plate voltage, which is the voltage between the plate and cathode of the tube divided by the dc plate current. Notice that both of these values are dc values and there-fore we get a dc plate resistance for the tube.

This particular characteristic is not usually of importance and when we refer to the plate resistance of the tube we will always mean the ac plate resistance unless we specifically say that we are referring to the dc plate resistance.

MUTUAL CONDUCTANCE

Another important tube characteristic is mutual conductance. The mutual conductance of the tube is usually represented by the symbol gm or Gm. It is equal to the change in plate current divided by the change in grid voltage required to produce the change in plate current. The unit of mutual conductance is the mho. Notice that mho is simply ohm written backwards.

The formula for the mutual conductance of a tube is : Gm = ip/eg where gm is the mutual conductance, ip is the change in plate current and eg is the change in grid voltage.

Since the change in plate current is usually in milliamperes, and the change in grid volts is in volts, the mutual conductance of the tube turns out to be a fraction of a mho. For example, if a change in grid voltage of 1 volt produces a change in plate current of 1 milliampere, the mutual conductance is: gm = .001/1 = .001 mho.   To eliminate the fraction we usually express the mutual conductance of a tube in micromhos. A micro-mho is a millionth of a mho. Thus .001 mho equals 1000 micromhos.

RELATIONSHIP BETWEEN TUBE CHARACTERISTICS

So far we have discussed three important tube characteristics. They are the amplification factor, the plate resistance, and the mutual conductance.
They can be represented by symbols as follows :

Amplification factor = u = ep/eg
Plate resistance = rp = ep/ip
Mutual Conductance = gm = ip/eg

Now let us look at how these characteristics are interrelated. If we multiply the plate resistance by the mutual conductance we get: rp x gm = ep/ip x ip/eg

If you look at the second expression you will see that you have ip both above and below the line so these two can be cancelled and we get: ep/eg

We already know that ep over eg equals p., which is the amplification factor. Thus the amplification factor is equal to the plate resistance times the mutual conductance or:
u = rp x gm

EQUIVALENT CIRCUITS

It is sometimes difficult to visualize exactly what is happening inside a tube and in the circuit associated with the tube. However, by means of what is called an equivalent circuit we can analyze the performance of a tube more easily. A typical triode amplifier is shown in Fig. 21A and the equivalent circuit for this stage is shown in Fig. 21B.Notice that the tube is represented by a generator with a resistance connected in series with it. The voltage developed by the tube is equal to the amplification factor of the tube times the grid voltage which is written p .eg. We know, however, that the output voltage will be 180 degrees out of phase with the input, and we therefore put the minus sign in front of "ueg" and indicate that the generator voltage is "-ueg". This indicates that the generator voltage, which is the amplified voltage produced by the tube, is 180 degrees out of phase with the grid voltage. In other words, at the instant the grid voltage swings positive, the generator will swing negative and then when the grid voltage swings negative, the generator voltage swings positive.

The ac plate resistance of the tube is represented by the resistor rp. The voltage dropped across this resistance is lost as far as obtaining useful output is concerned.
Now let us see just exactly how much gain we can obtain from the circuit shown in Fig. 21A on the next page. We could **find the** plate resistance of the tube and the amplification factor by looking them up in a tube manual. Let's assume that the amplification factor of the tube used in the circuit is 100, and the plate resistance of the tube is 50,000 ohms. The load resistance R_L is 100K ohms as shown on each diagram.

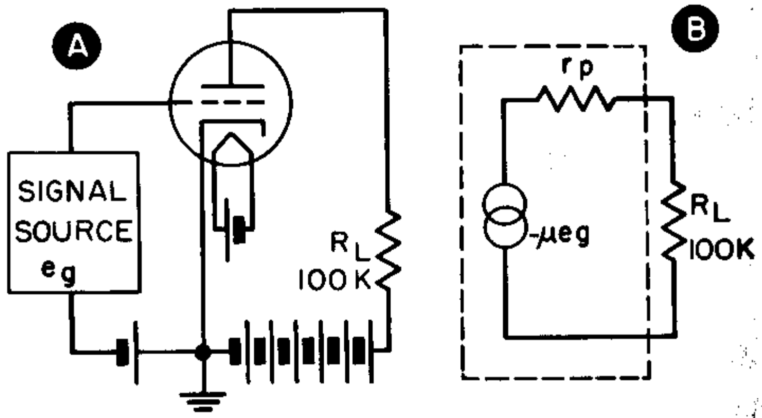

Figure. #21. Simple amplifier circuit shown in figure " A" , and the equivalent circuit in "B".

If the input signal eg had an amplitude of 1 volt, then the generator output voltage ueg = 100 x 1 = 100 volts. The 100 volts produced by the generator divides between the 50,000-ohm plate resistance rp and the 100,000 ohm load resistance, R_L . Thus, since the load resistance is twice the size of the plate resistance, the voltage across the load resistance will be twice the voltage across the plate resistance. This means that one third of the 100 volts at the generator will appear across the plate resistance, and two thirds, or approximately 66 volts, will appear across the load resistance. From this we can see that for an input voltage of 1 volt, the useful output voltage across the load resistor is 66 volts. The gain of the stage is equal to the output voltage divided by the input voltage, which in this case is 66 /1 = 66. Therefore in this circuit using a tube with an amplification factor of 100, we obtained a gain of 66.

Consider what would happen if instead of using a 100,000 ohm plate load resistor we used a 200,000 ohm plate load resistor. Now the plate load resistor is four times the plate resistance and therefore there will be four times as much voltage across the load resistor as across the plate resistance. This means that one fifth of the voltage, or 20 volts, will appear across the plate resistance, and four fifths, or 80 volts, will appear across the load resistor. Therefore, the output voltage in this case would be 80 volts and the gain of the stage would be 80.
From this you might think that all we have to do is make the plate load resistor very large and we would get even more gain. This is true up to a point, but remember that the current flowing in the plate-cathode circuit of the tube must also flow through the plate load resistor. The current through the plate load resistor produces a voltage drop across the load resistor. The higher the resistance of the resistor the greater the voltage drop across it. Since the voltage available between the plate and the cathode of the tube is equal to the B supply voltage minus the voltage drop across the plate load resistor there will be very little voltage available between the plate and cathode of the tube if we make the plate load resistor too large. Eventually a point is reached where the plate-cathode voltage is so low that the amplification factor of the tube begins to fall off. When this point is reached, increasing the size of the plate load resistor results in no further increase in the gain of the stage. A way to calculate the gain of a triode stage is by the equation :
Stage gain $= u \times R_L / R_L + rp$

This equation shows that the larger the value of R_L with respect to rp, the greater the gain of the stage. However, as we pointed out there are practical limits to this because the plate voltage does drop too low if R_L is made too large.

SUMMARY:
I hope we have at this point greatly expanded your knowledge of tubes. There is a great deal of information in the section, and you should not expect to master and retain all the ideas presented with one reading. Be sure to go back and review this section as often as you need.

Characteristic curves are important because they give you an indication of how the plate current of a tube is going to change with changes in grid voltage. You can also see how large a signal a tube can handle without distortion. We do not expect you to remember what the characteristic curves we show look like, but you should remember that they are curved on both ends and this curvature in the characteristic curve limits the amount of signal that can be handled without distortion. The three characteristics of tubes that you should remember are the plate resistance, the amplification factor, and the mutual conductance. Remember what they are :
Plate resistance = r_P = ep/ip
Amplification factor = u = ep/eg
Mutual conductance = gm = ip/eg

You should also remember that the amplification factor of a tube is equal to the plate resistance times the mutual conductance also remember what the equivalent circuit of the simple triode amplifier looks like. We consider the tube as a generator with a resistance in series with it. The output voltage of the generator is equal to -peg. The resistance in series with the generator is equal to rp, the plate resistance of the tube.

Remember that the equivalent tube circuit applies only to the ac signal amplifying operation of the tube. We did not discuss the dc operating voltages when we discussed the equivalent circuit. Later you will see that the equivalent circuit is very valuable in analyzing and understanding the operation of amplifier stages. It will be particularly useful when we study how amplifiers amplify signals of different frequencies.

Multi-Element Tubes
From the preceding section you can see that the triode tube is a very useful device. However, the triode has some definite limitations, and these limitations can be overcome by adding additional elements to the tubes. First, before studying the multi-element tubes, let's consider one of the big disadvantages of the triode in order to be able to understand the advantages of multi-element tubes better.

PLATE-TO-GRID CAPACITY
Here you will need to have some understanding of what a capacitor is and how it works. <u>I will assume that you have this understanding, but if I am wrong you can find it on the internet!</u>

A capacitor consists of two metal plates placed close to each other. In capacitors the metal plates are deliberately placed near each other in order to have capacity. However, when two pieces of metal that are insulated from each other are brought near each other, we will have a capacitor whether we want it or not; for example, the plate and grid of a vacuum tube. The plate, as you know, consists of a cylindrically shaped piece of metal. The grid is a spiral wire or mesh. The grid and plate, since they are placed near and are insulated from each other, actually form the two plates of a capacitor. Because the grid wire is small and there is a reasonable amount of space between the plate and grid, the capacity is small, but in some circuits, particularly where fairly high frequencies are involved, there is a high enough capacity to introduce a number of undesired effects.

A high frequency even a small capacitor has a fairly low reactance. Therefore if a triode tube is used to amplify a high frequency signal, the amplified signal present in the plate circuit of the tube can be fed back into the grid circuit through the plate-to-grid capacity.

Under certain circumstances this signal fed from the plate back to the grid can be in phase with the signal applied to the grid of the tube so it will add to the input signal. This increase in the amplitude of the input signal in turn produces a still greater signal in the output.
The increased signal in the output in turn increases the signal fed back into the grid circuit which makes the grid signal still stronger. This increases the output signal still more. This action goes on and on until eventually a point is reached where the signal in the plate circuit takes control in the grid and the tube begins to generate its own signal voltage. This is called oscillation. The signal fed from the plate of the tube back to the grid is called a feedback signal. When the feed-back signal, or more simply the feedback, is of the correct phase so that it adds to the grid signal, the tube will oscillate, which means generate its own signal, and hence will not work as an amplifier.

Not all triode amplifier stages will oscillate. It is possible to overcome this problem by means of appropriate circuitry. However, in most applications it is easier and more practical to overcome the problem in the tube itself. This is accomplished by the addition of another grid inside the tube. The second grid is placed between the plate and the first grid to shield, or screen the grid from the plate and is called the screen grid, or simply the screen. The screen is also called the number two grid.

THE SCREEN-GRID TUBE
The screen grid tube is a four element tube usually called a tet-rode. The four elements are the cathode, the grid, the screen grid, and the plate. A top view of a screen-grid tube showing the four elements is shown in Fig. 22A, and the schematic symbol for the screen-grid tube is shown in Fig. 22B.

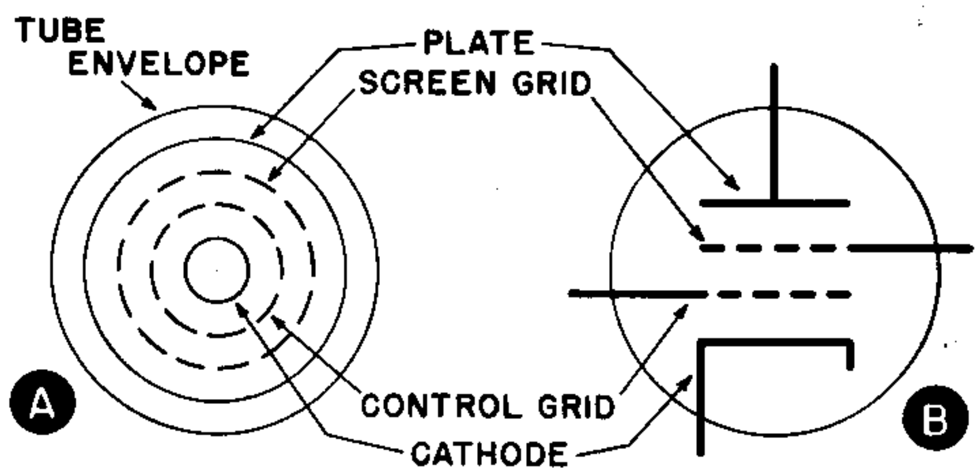

Figure. #22. Figure "A" is of a Screen-grid tube cross section showing the arrangement of the elements; while figure "B", represents the schematic symbol.

The screen grid is usually made just like a spiral wound coil. The screen grid wires are placed directly behind the grid wires so they are completely hidden from the electrons by the grid wire. A cutaway view of the tube would look something like Fig. 23. Notice that the screen grid wires are immediately behind the control grid wires.
The effect of the screen grid is to break the capacity between the plate and the control grid into two separate capacitors. In other words, there is a small capacity between the plate of the tube and the screen, and another capacity between the screen of the tube and the grid. These two capacitors are connected in series so that the net plate to grid capacity is much smaller than it is in the triode. In Fig. 23. There is a cutaway view of a screen-grid tube.

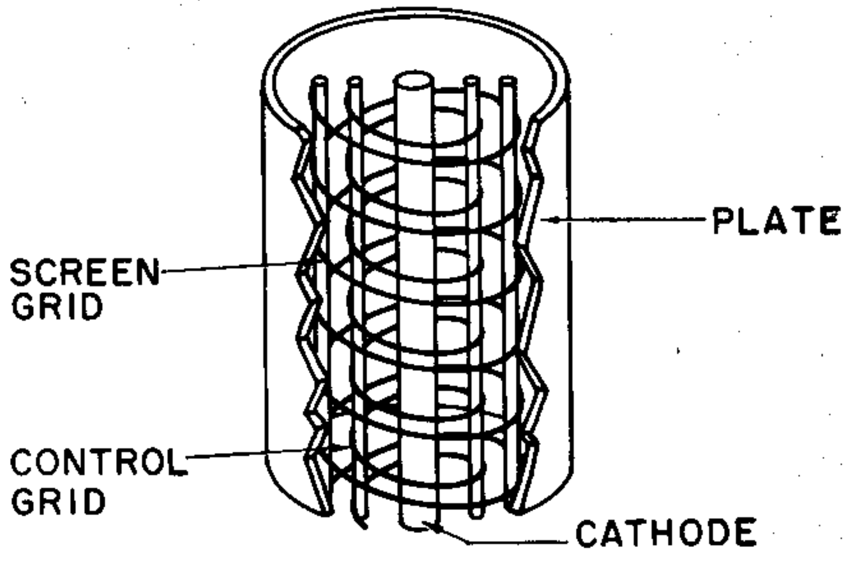

Figure. #23 Cross section of Screen grid tube.

In addition, the screen grid of a tube is normally operated at signal ground potential. Therefore any energy fed from the plate of the tube back towards the grid is fed to ground at the screen. This practically eliminates the feedback from the plate to the grid of the tube.
The dc potential applied to the screen is always positive with respect to the cathode. Usually the voltage placed on the screen grid is about half the voltage applied to the plate of the tube, but in some tubes the screen grid voltage may be as high as the plate voltage. This may appear to be a contradiction because we said that the screen grid is operated at the signal ground potential.

Actually, it is possible to have a tube element at signal ground potential and still have a positive or negative dc voltage applied to it. As a capacitor can offer a low reactance to the flow of ac through it. Therefore we can ground the screen of a tube so far as the signal is concerned by putting a capacitor between the screen of the tube and ground. If the capacitor is large enough, its reactance to the signal is so low that the screen is practically at signal ground potential. At the same time, since a capacitor does not permit the flow of dc through it. So you can connect it to a dc voltage source and apply a positive voltage to the screen.

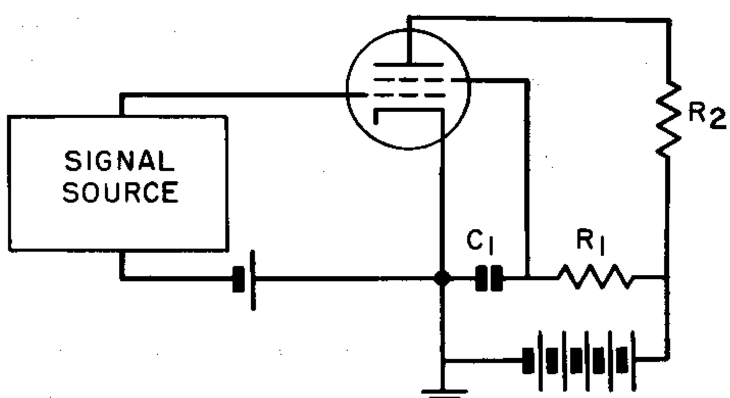

Figure. #24. Schematic of a screen grid amplifier circuit:

In the Fig. 24 on the prior page, RI is used to reduce the B supply voltage for the screen, and is called the screen voltage dropping resistor, or simply the screen dropping resistor. Cl is the screen bypass capacitor. R2 is the plate load resistor. The heater of the tube has been omitted to simplify the diagram.

The schematic diagram of a typical screen grid amplifier circuit is shown in Fig. 24. Here the input signal is fed between the grid and the cathode of the tube as in the case of the triode. Electrons flow from the cathode of the tube to the plate of the tube as in the triode. However, in the tetrode tube the number of elec-trons flowing will depend upon the plate voltage, the grid voltage and the screen-grid voltage. In fact, the number of electrons flowing from the cathode towards the plate will depend much more on the screen and grid voltages than on the plate voltage. As in the triode tube, small changes in grid voltage produced by the ac signal applied to the input will produce comparatively large changes in plate current.

These changes in plate current will cause the voltage between the plate and cathode of the tube to vary, and this voltage will be the amplified output signal. A few of the electrons flowing from the cathode of the tube towards the plate of the tube will strike the screen. Thus there will be a small current flowing from the cathode of the tube, to the screen grid, through the power supply and back to the cathode. Because the plate voltage has much less effect on the plate current in a screen grid tube than in a triode tube, screen grid tubes have a much higher amplification factor than triodes. In addition they have a much higher plate resistance.

Disadvantages.
Although the tetrode is a great improvement over the triode, it does have certain disadvantages. One of these disadvantages, which led to the development of the pentode or five-element tube, occurs because of secondary emission. As we have previously mentioned, electrons travelling from the cathode of the tube to the plate reach a fairly high speed, and when they strike the plate they may knock other electrons off the plate. In a diode and a triode the plate is the only positive element in the vicinity of these loose electrons, and therefore they are attracted back to the plate. However, in a tetrode we have, in addition to the plate, the screen grid with a positive voltage applied to it. If the plate voltage is substantially higher than the screen voltage, the electrons will be attracted back to the plate, but if the screen voltage is almost equal to, or even higher than the plate voltage, then the electrons knocked off the plate of the tube will be attracted to the screen instead of to the plate. Thus, for every electron reaching the plate from the cathode there may be two or three electrons emitted by the plate. This means that if the grid swings in a positive direction more electrons will strike the plate, knocking still more electrons off the plate. The net result can be that the plate current decreases when the grid swings positive. To prevent this undesirable action a third grid called a suppressor grid was added to develop the pentode tube.

PENTODE TUBES
The pentode tube is a tube with five elements. It is simply a refinement of the screen grid tube, which is made by adding an additional grid between the screen grid and the plate of the tube. Thus, the pentode has three grids. The third grid, or suppressor grid, gets its name because it is put in the tube to suppress, or eliminate the undesirable effects of secondary emission occurring at the plate of the tetrode tube. Because it is also the third grid it is sometimes called the number three grid.

The suppressor is usually connected directly to the cathode of the tube, but sometimes it is connected directly to ground. It has very little effect upon the electrons travelling from the cathode of the tube towards the plate. These electrons are attracted from the cathode by the positive potential on the screen of the tube. They are accelerated by this voltage, but as they approach the screen, instead of stopping at the screen they pass right through the screen wires. Once they get through these wires they are attracted to the plate by its positive voltage, which is usually higher than the voltage on the screen. In the pentode tube, after the electrons have passed the screen they are moving at a fairly high velocity, and they travel right on through the sup-pressor grid to the plate.

The suppressor does not have any appreciable effect on the progress of the electron as it moves from the cathode toward the plate. When the electrons strike the plate they knock other electrons off the plate, as in the case of the screen grid tube. However, these electrons are traveling at a comparatively low speed when they are knocked off the plate. The suppressor, which is connected to the cathode, or to ground, or may be operated with a low negative voltage applied to it, repels the electrons emitted from the plate by secondary emission, and these electrons move back to the plate of the tube. Thus, the addition of the suppressor grid eliminates the undesirable current flow from the plate of the tube to the screen grid, which we found could occur in the tetrode tube.

Because the pentode tube has a screen grid, it has the low plate-to-grid capacity that we found in the tetrode tube. In addition, the pentode has the advantage that it does not suffer from the adverse effects of secondary emission.

We should point out that the plate voltage on a tetrode or a pentode tube has very little effect on the plate current. The voltage on these tubes can be varied over wide limits without appreciably changing the plate current that will flow in the tube. For a given grid voltage, the plate current will depend primarily upon the screen voltage. The screen is the electrode that starts the electrons moving from the cathode to the plate and has more effect on the number of electrons that will flow from the cathode to the plate than the plate voltage does.

One of the characteristics of vacuum tubes is the amplification factor. The amplification factor is the ratio of the plate voltage required to produce a given change in plate current to the grid voltage required to produce the same change in plate current.

Remember that the formula is $u = ep/eg$

Since the plate voltage has very little effect on the plate current in a tetrode, or pentode tube, it takes a very large change in plate voltage to produce the same change in plate current that can be produced by a small change in grid voltage. Thus, the amplification factor of a tetrode or a pentode tube is very high. We mentioned that the amplification factor of a triode may be somewhere between about 5 and 100. A triode with an amplification factor of 100 is called a high-mu triode because it has a high amplification factor for a triode. However, pentodes with amplification factors of over 1000 are common.

BEAM POWER TUBES

Another tube that solves the problem of secondary emission in screen-grid tubes is the beam power tube. The beam power tube, like the screen-grid tube, is a tetrode or four-element tube in which this problem has been overcome. A sketch of a beam power tube is shown in Fig. 25.

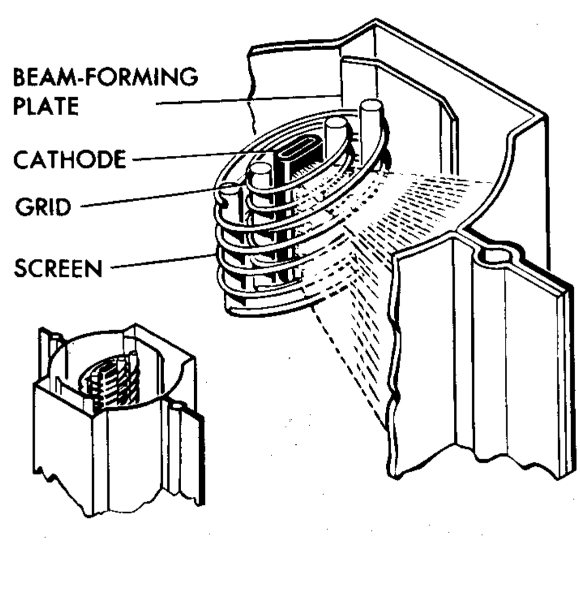

Figure. #25. A beam-power tube structure:

Notice the shape of the cathode of the tube. It has two flat surfaces. The construction of the cathode is such that most of the electrons will be emitted by the flat surfaces and hence there is a tendency for the electrons to form into two beams, one on each side of the cathode. Only one of these beams is shown in the drawing. Notice the two small additional plates between the screen grid and the plate of the tube. These plates are called the beam confining or beam-forming plates. The beam forming plates are connected internally to the cathode of the tube and repel electrons. These plates act to keep the electrons concentrated into the two beams that are formed at the cathode. The electrons flowing from the cathode of the tube towards the plate are bunched together in these beams. Remember that an electron has a negative charge and will repel other electrons. Therefore, if an electron traveling at a high speed from the cathode of the tube to the plate knocks additional electrons off the plate, these loose electrons, which will be travelling at a low speed, will be repelled back to the plate by the negative charge on the electron beam.
The beam power tube has proven superior to the pentode in applications where large amounts of power must be handled.

OTHER TUBE TYPES:
The diode, triode, tetrode, and pentode are the basic tube types. However, there are many special tubes that have been manufactured for special applications. In addition, there are tubes that are simply combinations of several tubes in the same envelope. An example of a tube where several types have been combined in one envelope is the tube with a triode and two diodes in it. A schematic of this type of tube is shown in Fig. 26. This tube is called a duo-diode-triode. As this name indicates, it has two diodes and a triode in one envelope.

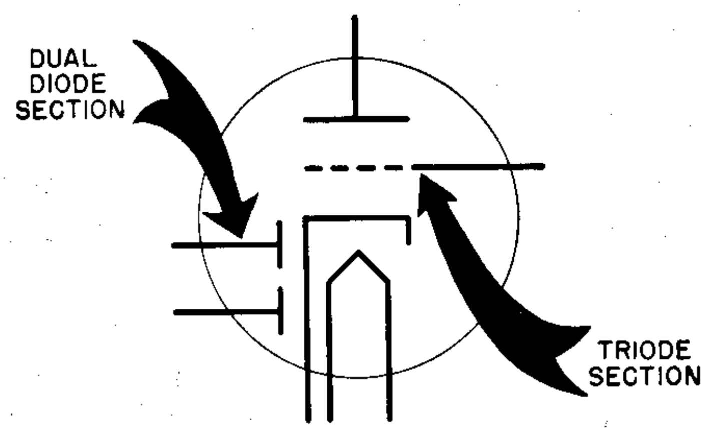

Figure. #26. A combination tube containing two diodes and a triode. This is called a duo-diode triode.

Other typical tubes types consist of two triodes in one envelope such as shown in Fig. 27. On the next page. In the schematic shown at A, a common cathode is used for the two triode sections ; in the one shown at B, each triode section has its own separate cathode.

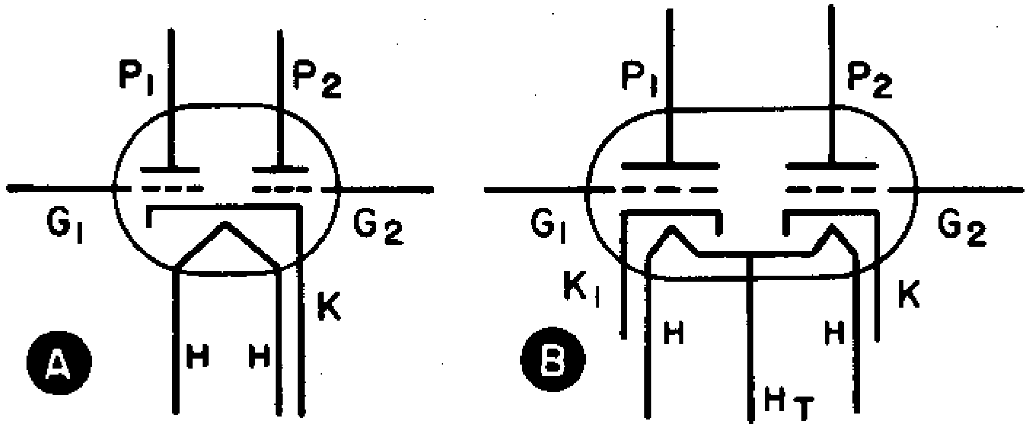

Figure. #27. Dual triode tubes. The tube at “A” has a common cathode. The tube at “B” has two separate cathodes. Notice this tube has a single heater with a center tap. Not all tubes of this type have tapped heaters.

Another combination type is the pentode-triode shown in Fig. 28.

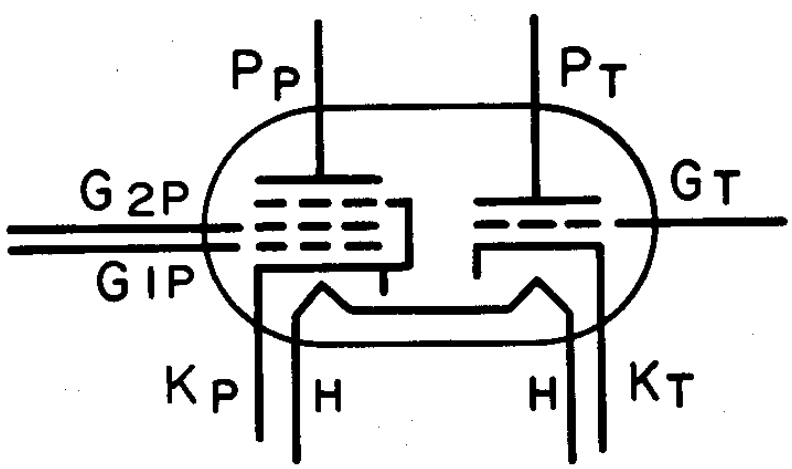

Figure. #28. A pentode-triode combination.

Compactrons offer an advantage over tubes in separate envelopes in--asmuch as they are somewhat less expensive to manufacture than sepa-rate tubes, and also it is possible to make more compact equipment because the space occupied by the multi-function tube is considerably smaller than the space that would be required for separate tubes.

The characteristic curves for beam power tubes are quite similar to those for pentode tubes. We have not shown curves for screen-grid tubes, because the screen-grid tube has been replaced by the pentode and beam power tubes.

SUMMARY

In this section we covered some multi-element tubes. Remember that the screen-grid tube was developed to eliminate the undesirable effects produced by the high plate-to-grid capacity found in triode tubes. A screen grid tube is a tube with a high amplification factor and low plate-to-grid capacity. However, because the screen is operated with a positive voltage, the electrons emitted from the plate by secondary emission were, attracted both to the plate and to the screen of the tube. Some of the electrons would flow to the screen and introduce a number of undesirable effects.

To overcome the problem created by secondary emission in the screen grid tube, the pentode or five-element tube was developed. The pentode contains three grids : a control grid, a screen grid, and a suppressor grid. These grids are often referred to as grids 1, 2, and 3 respectively.

The undesirable effects of secondary emission can also be overcome by constructing a flat type of cathode and using beam forming plates. This led to the development of the beam power tube. The beam power tube is a tetrode tube, but it differs substantially in performance and construction from the old screen grid tube.

In addition to the screen grid, pentode, and beam power tubes, there are a number of special tubes. These tubes may actually be tubes designed for one specific application such as the pentagrid converter type tube, or may simply be two or three different tubes combined in the one envelope. Tubes of this type consist of twin triodes, triode-pentode combinations, and duo-diode-triodes.

Special Tube Types

There are a number of special purpose tubes that have been designed for particular applications. Many of these tubes were designed for use in transmitting and industrial electronic equipment, but some of these tubes will also be found in equipment you may be using even today. In most cases with the fundamental understanding of tubes as presented here it should not be particularly difficult to understand how these tubes operate.

This concludes our short course on how tubes work! It was not my intention to provide a detailed course on tubes, but only a primer, if you will on how they fundamentally operate and to cover the basic tube types. I hope you found this information useful.