CHAPTER FOUR

# Vacuum-Tube Principles

In the previous chapters we have seen the manner in which an electric current flows through a metallic conductor as a result of an electron drift. This drift, which takes place when there is a difference in potential between the ends of the metallic conductor, is in addition to the normal random electron motion between the molecules of the conductor.

The electron may be considered as a minute negatively charged particle, having a mass of $9 \times 10^{-28}$ gram, and a charge of $1.59 \times 10^{-19}$ coulomb. Electrons are always identical, regardless of the source from which they are obtained.

An electric current can be caused to flow through other media than a metallic conductor. One such medium is an ionized solution, such as the sulfuric acid electrolyte in a storage battery. This type of current flow is called *electrolytic conduction*. Further, it was shown at about the turn of the century that an electric current can be carried by a stream of free electrons in an evacuated chamber. The flow of a current in such a manner is said to take place by *electronic conduction*. The study of electron tubes (also called vacuum tubes, or valves) is actually the study of the control and use of electronic currents within an evacuated or partially evacuated chamber.

Since the current flow in an electron tube takes place in an evacuated chamber, there must be located within the enclosure both a source of electrons and a collector for the electrons which have been emitted. The electron source is called the *cathode*, and the electron collector is usually called the *anode*. Some external source of energy must be applied to the cathode in order to impart sufficient velocity to the electrons within the cathode material to enable them to overcome the surface forces and thus escape into the surrounding medium. In the usual types of electron tubes the cathode energy is applied in the form of heat; electron emission from a heated cathode is called *thermionic emission*. In another common type of electron tube, the photoelectric cell, energy in the form of light is applied to the cathode to cause *photoelectric emission*.

## 4-1 Thermionic Emission

**Electron Emission** Emission of electrons from the cathode of a thermionic electron tube takes place when the cathode of the tube is heated to a temperature sufficiently high that the free electrons in the emitter have sufficient velocity to overcome the restraining forces at the surface of the material. These surface forces vary greatly with different materials. Hence different types of cathodes must be raised to different temperatures to obtain adequate quantities of electron emission. The several types of emitters found in common types of transmitting and receiving tubes will be described in the following paragraphs.

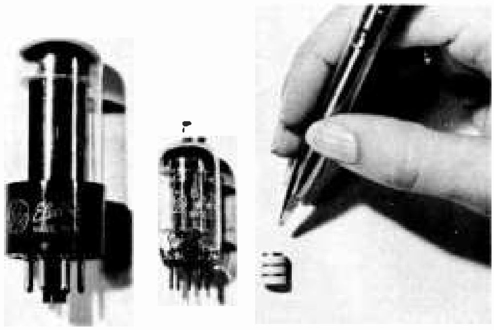


**Figure 1**

**ELECTRON-TUBE TYPES**

***The General Electric ceramic triode (6BY4) is shown alongside a conventional miniature tube (6265) and an octal-based receiving tube (25L6). The ceramic tube is designed for rugged service and features extremely low lead inductance.***

**Cathode Types** The emitters or cathodes as used in present-day thermionic electron tubes may be classified into two groups; the directly heated or *filament type* and the indirectly heated or *heater-cathode type*. Directly heated emitters may be further subdivided into three important groups, all of which are commonly used in modern vacuum tubes. These classifications are: the pure-tungsten filament, the thoriated-tungsten filament, and the oxide-coated filament.

**The Pure-Tungsten Filament** Pure-tungsten wire was used as the filament in nearly all the earlier transmitting and receiving tubes. However, the thermionic efficiency of tungsten wire as an emitter (the number of milliamperes emission per watt of filament-heating power) is quite low; the filaments become fragile after use; their life is rather short, and they are susceptible to burnout at any time. Pure-tungsten filaments must be run at bright white heat (about 2500° Kelvin). For these reasons, tungsten filaments have been replaced in all applications where another type of filament could be used. They are, however, still often employed in large water-cooled tubes and in certain large, high-power air-cooled triodes where another filament type would be unsuitable. Tungsten filaments are the most satisfactory for high-power, high-voltage tubes where the emitter is subjected to positive ion bombardment caused by the residual gas content of the tubes. Tungsten is not adversely affected by such bombardment.

**The Thoriated-Tungsten Filament** In the course of experiments made upon tungsten emitters, it was found that filaments made from tungsten having a small amount of thoria (thorium oxide) as an impurity had much greater emission than those made from the pure metal. Subsequent development has resulted in the highly efficient carburized thoriated-tungsten filament as used in many medium-power transmitting tubes today.

Thoriated-tungsten emitters consist of a tungsten wire containing from 1% to 2% thoria. The activation process varies between different manufacturers of vacuum tubes, but it is essentially as follows: (1) the tube is evacuated; (2) the filament is burned for a short period at about 2800° Kelvin to clean the surface and reduce some of the thoria within the filament to metallic thorium; (3) the filament is burned for a longer period at about 2100° Kelvin to form a layer of thorium on the surface of the tungsten; (4) the temperature is reduced to about 1600° Kelvin and some pure hydrocarbon gas is admitted to form a layer of tungsten carbide on the surface of the tungsten. This layer of tungsten carbide reduces the rate of thorium evaporation from the surface at the normal operating temperature of the filament and thus increases the operating life of the vacuum tube. Thorium evaporation from the surface is a natu-


**Figure 2**

**VHF and UHF TUBE TYPES**

***At the left is an 8058 nuvistor tetrode, representative of the family of small vhf types useful in receivers and low power transmitters. The second type is an 6816 planar tetrode rated at 180 watts input to 1215 MHz. The third tube from the left is a 3CX100A5 planar triode, an improved and ruggedized version of the 2C39A, and rated at 100 watts input to 2900 MHz. The fourth tube from the left is the X-843 (Eimac) planar triode designed to deliver over 100 watts at 2100 MHz. The tube is used in a grounded-grid cavity configuration. The tube to the right is a 7213 planar tetrode, rated at 2500 watts input to 1215 MHz. All of these vhf/uhf negative-grid tubes make use of ceramic insulation for lowest envelope loss at the higher frequencies and the larger ones have coaxial bases for use in resonant cavities.***

ral consequence of the operation of the thoriated-tungsten filament. The carburized layer on the tungsten wire plays another role in acting as a reducing agent to produce new thorium from the thoria to replace that lost by evaporation. This new thorium continually diffuses to the surface during the normal operation of the filament.

The last process, (5), in the activation of a thoriated tungsten filament consists of re-evacuating the envelope and then burning or aging the new filament for a considerable period of time at the normal operating temperature of approximately 1900° K.

One thing to remember about any type of filament, particularly the thoriated type, is that the emitter deteriorates practically as fast when "standing by" (no plate current) as it does with any normal amount of emission load. Also, a thoriated filament may be either temporarily or permanently damaged by a heavy overload which may strip the surface layer of thorium from the filament.

**Reactivating Thoriated-Tungsten Filaments** Thoriated-tungsten filaments (and *only* thoriated-tungsten filaments) which have lost emission as a result of insufficient filament voltage, a severe temporary overload, a less severe extended overload, or even normal operation may quite frequently be reactivated to their original characteristics by a process similar to that of the original activation. However, only filaments which have not approached too close to the end of their useful life may be successfully reactivated.

The actual process of reactivation is relatively simple. The tube which has gone "flat" is placed in a socket to which only the two filament wires have been connected. The filament is then "flashed" for about 20 to 40 seconds at about 1½ times normal rated voltage. The filament will become extremely bright during this time and, if there is still some thoria left in the tungsten and if the tube did not originally fail as a result of an air leak, some of this thoria will be reduced to metallic thorium. The filament is then burned at 15 to 25 percent overvoltage for from 30 minutes to 3 to 4 hours to bring this new thorium to the surface.

The tube should then be tested to see if it shows signs of renewed life. If it does, but is still weak, the burning process should be continued at about 10 to 15 percent overvoltage for a few more hours. This should bring it back almost to normal. If the tube checks still very low after the first attempt at reactivation, the complete process can be repeated as a last effort.

**The Oxide-Coated Filament** The most efficient of all modern filaments is the oxide-coated type which consists of a mixture of barium and strontium oxides coated on a nickel alloy wire or strip. This type of filament operates at a dull-red to orange-red temperature (1050° to 1170° K) at which temperature it will emit large quantities of electrons. The oxide-coated filament is somewhat more efficient than the thoriated-tungsten type in small sizes and it is considerably less expensive to manufacture. For this reason all receiving tubes and quite a number of the low-powered transmitting tubes use the oxide-coated filament. Another advantage of the oxide-coated emitter is its extremely long life — the average tube can be expected to run from 3000 to 5000 hours, and when loaded very lightly, tubes of this type have been known to give 50,000 hours of life before their characteristics changed to any great extent.

Oxide filaments are unsatisfactory for use at very high plate voltage because: (1) their activity is seriously impaired by the high temperature necessary to de-gas the high-voltage tubes and, (2) the positive ion bombardment which takes place even in the best evacuated high-voltage tube causes destruction of the oxide layer on the surface of the filament.

Oxide-coated emitters have been found capable of emitting an enormously large current pulse with a high applied voltage for a very short period of time without damage. This characteristic has proved to be of great value in radar work. For example, the relatively small cathode in a microwave magnetron may be called on to deliver 25 to 50 amperes at an applied voltage of perhaps 25,000 volts for a period in the order of one microsecond. After this large current pulse has been passed, plate voltage normally will be removed for 1000 microseconds or more so that the cathode surface may recover in time for the next pulse of current. If the cathode were to be subjected to a continuous current drain of this magnitude, it would be destroyed in an exceedingly short period of time.

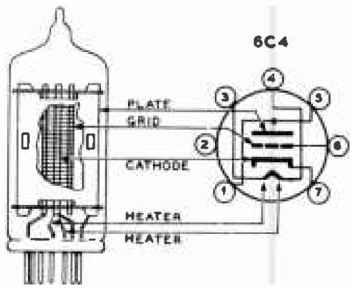



Figure 3

**CUTAWAY DRAWING OF A 6C4 TRIODE**

The activation of oxide-coated filaments also varies with tube manufacturers but consists essentially in heating the wire which has been coated with a mixture of barium and strontium carbonates to a temperature of about 1500° Kelvin for a time and then applying a potential of 100 to 200 volts through a protective resistor align limit the emission current. This process thermally reduces the carbonates to oxides, cleans the filament surface of foreign materials, and activates the cathode surface.

Reactivation of oxide-coated filaments is not possible since there is always more than sufficient reduction of the oxides and diffusion of the metals to the surface of the filament to meet the emission needs of the cathode.

**The Heater Cathode** The heater-type cathode was developed as a result of the requirement for a type of emitter which could be operated from alternating current and yet would not introduce a-c ripple modulation even when used in low-level stages. It consists essentially of a small nickel-alloy cylinder with a coating of strontium and barium oxides on its surface similar to the coating used on the oxide-coated filament. Inside the cylinder is an insulated heater element consisting usually of a double spiral of tungsten wire. The heater may operate on any voltage from 2 to 117 volts, although 6.3 is the most common value. The heater is operated at quite a high temperature so that the cathode itself usually may be brought to operating temperature in a matter of 15 to 30 seconds. Heat-coupling between the heater and the cathode is mainly by radiation, although there is some thermal conduction through the insulating coating on the heater wire, since this coating is also in contact with the cathode thimble.

Indirectly heated cathodes are employed in all a-c operated tubes which are designed to operate at a low level either for r-f or a-f use. However, some receiver power tubes use heater cathodes (6L6, 6V6, 6F6, and 6K6-GT) as do some of the low-power transmitter tubes (802, 807, 815, 3E29, 2E26, 5763, 6146, etc.). Heater cathodes are employed almost exclusively when a number of tubes are to be operated in series as in an a-c/d-c receiver. A heater cathode is often called a *unipotential cathode* because there is no voltage drop along its length as there is in the directly heated or filament cathode.

**The Bombardment Cathode** A special bombardment cathode is employed in many of the high-powered television transmitting klystrons (Eimac 3K 20,000 LA). The cathode takes the form of a tantalum diode, heated to operating temperature by the bombardment of electrons from a directly heated filament. The cathode operates at a positive potential of 2000 volts with respect to the filament, and a d-c bombardment current of 0.66 ampere flows between filament and cathode. The filament is designed to operate under space-charge limited conditions. Cathode temperature is varied by changing the bombardment potential between the filament and the cathode.

**The Emission Equation** The emission of electrons from a heated cathode is quite similar to the evaporation of molecules from the surface of a liquid. The molecules which leave the surface are those having sufficient kinetic (heat) energy to overcome the forces at the surface of the liquid. As the temperature of the liquid is raised, the average velocity of the molecules is increased, and a greater number of molecules will acquire sufficient energy to be evaporated. The evaporation of electrons from the surface of a thermionic emitter is similarly a function of average electron velocity, and hence is a function of the temperature of the emitter.

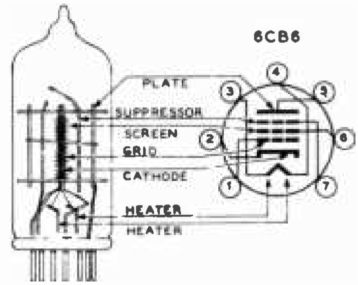



**Figure 4**

**CUTAWAY DRAWING OF A 6CB6 PENTODE**

Electron emission per unit area of emitting surface is a function of the temperature ($T$) in degrees Kelvin, the work function of emitting surface $b$ (which is a measure of the surface forces of the material and hence of the energy required of the electron before it may escape), and of the constant ($A$) which also varies with the emitting surface. The relationship between emission current in amperes per square centimeter ($I$) and the above quantities can be expressed as:

$$I = AT^2 \varepsilon^{-b/T}$$

**Secondary Emission** The bombarding of most metals and a few insulators by electrons will result in the emission of other electrons by a process called *secondary emission.* The secondary electrons are literally knocked from the surface layers of the bombarded material by the primary electrons which strike the material. The number of secondary electrons emitted per primary electron varies from a very small percentage to as high as 5 to 10 secondary electrons per primary.

The phenomena of secondary emission is undesirable for most thermionic electron tubes. However, the process is used to advantage in certain types of electron tubes such as the *image orthicon* (TV camera tube) and the *electron-multiplier* type of photoelectric cell. In types of electron tubes which make use of secondary emission, such as the type 931 photocell, the secondary-electron emitting surfaces are specially treated to provide a high ratio of secondary to primary electrons. Thus a high degree of current amplification in the electron-multiplier section of the tube is obtained.

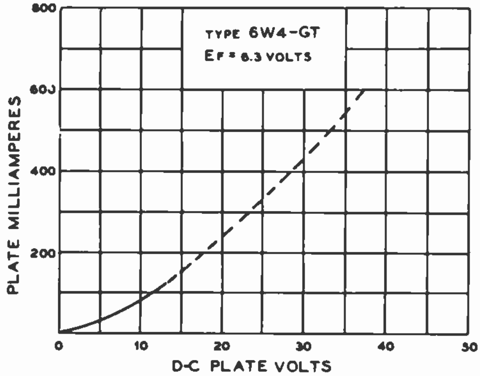



**Figure 5**

**AVERAGE PLATE CHARACTERISTICS OF A POWER DIODE**

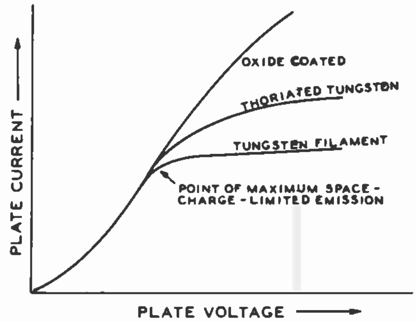



**Figure 6**

**MAXIMUM SPACE-CHARGE-LIMITED EMISSION FOR DIFFERENT TYPES OF EMITTERS**

**The Space-Charge Effect** As a cathode is heated so that it begins to emit, those electrons which have been discharged into the surrounding space form a negatively charged cloud in the immediate vicinity of the cathode. This cloud of electrons around the cathode is called the *space charge.* The electrons comprising the charge are continuously changing, since those electrons making up the original charge fall back into the cathode and are replaced by others emitted by it.

## 4-2 The Diode

If a cathode capable of being heated either indirectly or directly is placed in an evacuated envelope along with a plate, such a two-element vacuum tube is called a *diode.* The diode is the simplest of all vacuum tubes and is the fundamental type from which all the others are derived.

**Characteristics of the Diode** When the cathode within a diode is heated, it will be found that a few of the electrons leaving the cathode will leave with sufficient velocity to reach the plate. If the plate is electrically connected back to the cathode, the electrons which have had sufficient velocity to arrive at the plate will flow back to the cathode through the external circuit. This small amount of initial plate current is an effect found in all two-element vacuum tubes.

If a battery or other source of d-c voltage is placed in the external circuit between the plate and cathode so that it places a positive potential on the plate, the flow of current from the cathode to plate will be increased. This is due to the strong attraction offered by the positively charged plate for any negatively charged particles (figure 5).

**The Three-Halves Power Law** At moderate values of plate voltage the current flow from cathode to anode is limited by the space charge of electrons around the cathode. Increased values of plate voltage will tend to neutralize a greater portion of the cathode space charge and hence will cause a greater current to flow.

Under these conditions, with plate current limited by the cathode space charge, the plate current is not linear with plate voltage. In fact it may be stated in general that the plate-current flow in electron tubes does not obey Ohm's Law. Rather, plate current increases as the three-halves power of the plate voltage. The relationship between plate voltage, ($E$) and plate current, ($I$) can be expressed as:

$$I = K E^{3/2}$$

where,

$K$ is a constant determined by the geometry of the element structure within the electron tube.

**Plate-Current Saturation** As plate voltage is raised to the potential where the cathode space charge is neutralized, all the electrons that the cathode is capable of emitting are being attracted to the plate. The electron tube is said then to have reached *saturation* plate current. Further increase in plate voltage will cause only a relatively small increase in plate current. The initial point of plate-current saturation is sometimes called the point of *Maximum Space-Charge-Limited Emission* (MSCLE).

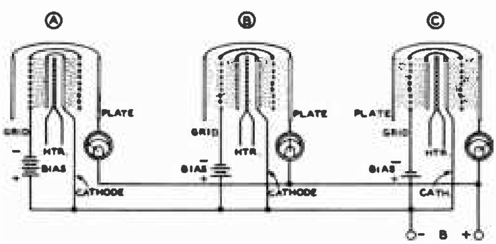



**Figure 7**

**ACTION OF THE GRID IN A TRIODE**

***(A) shows the triode tube with cutoff bias on the grid. Note that all the electrons emitted by the cathode remain inside the grid mesh. (B) shows the same tube with an intermediate value of bias on the grid. Note the medium value of plate current and the fact that there is a reserve of electrons remaining within the grid mesh. (C) shows the operation with a relatively small amount of bias which with certain tube types will allow substantially all the electrons emitted by the cathode to reach the plate. Emission is said to be saturated in this case. In a majority of tube types a high value of positive grid voltage is required before plate-current saturation takes place.***

The degree of flattening in the plate-voltage plate-current curve after the MSCLE point will vary with different types of cathodes. This effect is shown in figure 6. The flattening is quite sharp with a pure tungsten emitter. With thoriated tungsten the flattening is smoothed somewhat, while with an oxide-coated cathode the flattening is quite gradual. The gradual saturation in emission with an oxide-coated emitter is generally considered to result from a lowering of the surface work function by the field at the cathode resulting from the plate potential.

**Electron Energy Dissipation** The current flowing in the plate-cathode space of a conducting electron tube represents the energy required to accelerate electrons from the zero potential of the cathode space charge to the potential of the anode. Then, when these accelerated electrons strike the anode, the energy associated with their velocity is immediately released to the anode structure. In normal electron tubes this energy release appears as heating of the plate or anode structure.

## 4-3 The Triode

If an element consisting of a mesh or spiral of wire is inserted concentric with the plate and between the plate and the cathode, such an element will be able to control by electrostatic action the cathode-to-plate current of the tube. The new element is called a *grid*, and a vacuum tube containing a cathode, grid, and plate is commonly called a *triode*.

**Action of the Grid** If this new element through which the electrons must pass in their course from cathode to plate is made negative with respect to the cathode, the negative charge on this grid will effectively repel the negatively charged electrons (like charges repel; unlike charges attract) back into the space charge surrounding the cathode. Hence, the number of electrons which are able to pass through the grid mesh and reach the plate will be reduced, and the plate current will be reduced accordingly. If the charge on the grid is made sufficiently negative, all the electrons leaving the cathode will be repelled back to it and the plate current will be reduced to zero. Any d-c voltage placed on a grid is called a *bias* (especially so when speaking of a control grid). The smallest negative voltage which will cause cutoff of plate current at a particular plate voltage is called the value of *cutoff bias* (figure 7).

**Amplification Factor** The amount of plate current in a triode is a result of the net field at the cathode from interaction between the field caused by the grid bias and that caused by the plate voltage. Hence, both grid bias and plate voltage affect the plate current. In all normal tubes

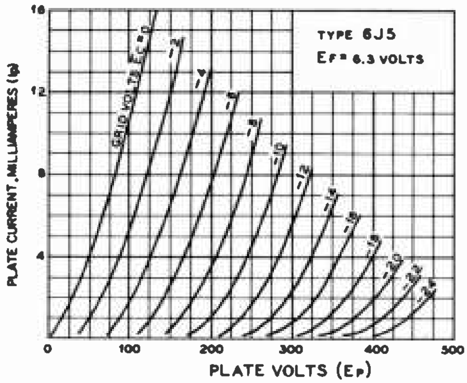



**Figure 8**

**NEGATIVE-GRID CHARACTERISTICS ($I_p$ VS. $E_p$ CURVES) OF A TYPICAL TRIODE**

***Average plate characteristics of this form are most commonly used in determining the class-A operating characteristics of a triode amplifier stage.***

a small change in grid bias has a considerably greater effect than a similar change in plate voltage. The ratio between the change in grid bias and the change in plate current which will cause the same small change in plate current is called the *amplification factor* or $\mu$ of the electron tube. Expressed as an equation:

$$\mu = -\frac{\Delta E_p}{\Delta E_g}$$

with $i_p$ constant ($\Delta$ represents a small increment).

The $\mu$ can be determined experimentally by making a small change in grid bias, thus slightly changing the plate current. The plate current is then returned to the original value by making a change in the plate voltage. The ratio of the change in plate voltage to the change in grid voltage is the $\mu$ of the tube under the operating conditions chosen for the test.

**Current Flow in a Triode** In a diode it was shown that the electrostatic field at the cathode was proportional to the plate potential ($E_p$) and that the total cathode current was proportional to the three-halves power of the plate voltage. Similiarly, in a triode it can be shown that the field at the cathode space charge is proportional to the equivalent voltage ($E_g + E_p/\mu$), where the amplification factor, $\mu$, actually represents the relative effectiveness of grid potential and plate potential in producing a field at the cathode.

It would then be expected that the cathode current in a triode would be proportional to the three-halves power of ($E_g + E_p/\mu$). The cathode current of a triode can be represented with fair accuracy by the expression:

$$\text{cathode current} = K\left(E_g + \frac{E_p}{\mu}\right)^{3/2}$$

where,

$K$ is a constant determined by element geometry within the triode.

**Plate Resistance** The *plate resistance* of a vacuum tube is the ratio of a change in plate voltage to the change in plate current which the change in plate voltage produces. To be accurate, the changes should be very small with respect to the operating values. Expressed as an equation:

$$R_p = \frac{\Delta E_p}{\Delta I_p}$$

where,

$E_g$ is held constant,

$\Delta$ equals small increment.

The plate resistance can also be determined by the experiment mentioned above. By noting the change in plate current as it occurs when the plate voltage is changed (grid voltage held constant), and by dividing the latter by the former, the plate resistance can be determined. Plate resistance is expressed in ohms.

**Transconductance** The *mutual conductance,* also referred to as *transconductance,* is the ratio of a change in the plate current to the change in grid voltage which brought about the plate-current change, the plate voltage being held constant. Expressed as an equation:

$$g_m = \frac{\Delta I_p}{\Delta E_g}$$

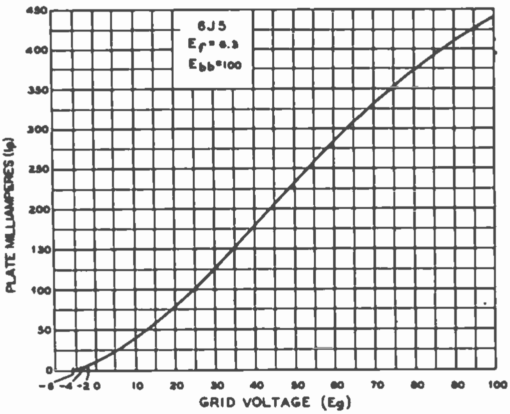



Figure 9

**POSITIVE-GRID CHARACTERISTICS ($I_p$ vs. $E_g$) OF A TYPICAL TRIODE**

***Plate characteristics of this type are most commonly used in determining the pulse-signal operating characteristics of a triode amplifier stage. Note the large emission capability of the oxide-coated heater cathode in tubes of the general type of the 6J5.***

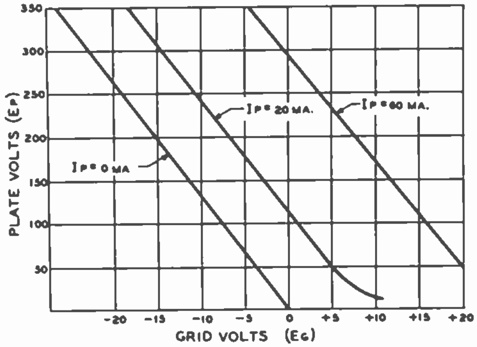



Figure 10

**CONSTANT CURRENT ($E_p$ vs. $E_g$) CHARACTERISTICS OF A TYPICAL TRIODE TUBE**

***This type of graphical representation is used for class-C amplifier calculations since the operating characteristic of a class-C amplifier is a straight line when drawn on a constant current graph.***

where,

$E_p$ is held constant,
$\Delta$ equals small increment.

The transconductance is also numerically equal to the amplification factor divided by the plate resistance. $g_m = \mu / R_p$.

Transconductance is most commonly expressed in microreciprocal-ohms or *micromhos*. However, since transconductance expresses change in plate current as a function of a change in grid voltage, a tube is often said to have a transconductance of so many milliamperes per volt. If the transconductance in milliamperes per volt is multiplied by 1000 it will then be expressed in micromhos. Thus the transconductance of a 6A3 could be called either 5.25 ma/volt or 5250 micromhos.

**Characteristic Curves of a Triode Tube** The operating characteristics of a triode tube may be summarized in three sets of curves: The $I_p$ vs. $E_p$ curve (figure 8), the $I_p$ vs. $E_g$ curve (figure 9) and the $E_p$ vs. $E_g$ curve (figure 10). The *plate resistance* ($R_p$) of the tube may be observed from the $I_p$ vs. $E_p$ curve, the *transconductance* ($g_m$) may be observed from the $I_p$ vs. $E_g$ curve, and the *amplification factor* ($\mu$) may be determined from the $E_p$ vs. $E_g$ curve.

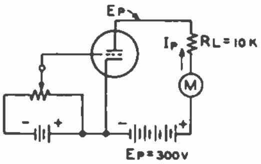
**The Load Line** A *load line* is a graphical representation of the voltage on the plate of a vacuum tube and the current passing through the plate circuit of the tube for various values of plate load resistance and plate supply voltage. Figure 11 illustrates a triode tube with a resistive plate load, and a supply voltage of 300 volts. The voltage at the plate of the tube ($e_p$) may be expressed as:

$$e_p = E_p - \left( i_p \times R_L \right)$$

where,

$E_p$ is the plate supply voltage,
$i_p$ is the plate current,
$R_L$ is the load resistance in ohms.

Assuming various values of $i_p$ flowing in the circuit, controlled by the internal resistance of the tube, (a function of the grid bias) values of plate voltage may be plotted as shown for each value of plate current ($i_p$). The line connecting these points is called the *load line* for the particular value of plate load resistance used. The *slope* of the load line is equal to the ratio of the lengths of the vertical and horizontal projections of any segment of the load line.




| IP (MA) | EP |
|---|---|
| 0 | 300 |
| 5 | 250 |
| 10 | 200 |
| 15 | 150 |
| 20 | 100 |
| 25 | 50 |
| 30 | 0 |

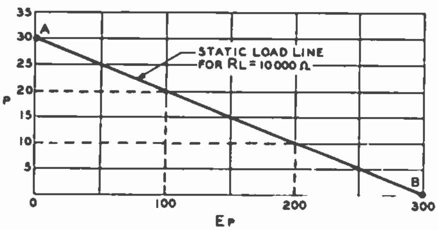



**Figure 11**

***The static load line for a typical triode tube with a plate load resistance of 10,000 ohms.***

For this example it is:

$$\text{slope} = -\left(\frac{.01 - .02}{100 - 200}\right)$$

$$= -.0001 = -\frac{1}{10{,}000}$$

The slope of the load line is equal to $-1/R_L$. At point A on the load line, the voltage across the tube is zero. This would be true for a perfect tube with zero internal voltage drop, or if the tube is short-circuited from cathode to plate. Point B on the load line corresponds to the cutoff point of the tube, where no plate current is flowing. The operating range of the tube lies between these two extremes. For additional information regarding *dynamic* load lines, the reader is referred to the *Radiotron Designer's Handbook* distributed by Radio Corporation of America.

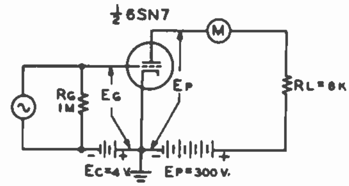



**Figure 12**

**TRIODE TUBE CONNECTED FOR DETERMINATION OF PLATE-CIRCUIT LOAD LINE AND OPERATING PARAMETERS OF THE CIRCUIT**

**Application of Tube Characteristics** As an example of the application of tube characteristics, the constants of the triode amplifier circuit shown in figure 12 may be considered. The plate supply is 300 volts, and the plate load is 8000 ohms.

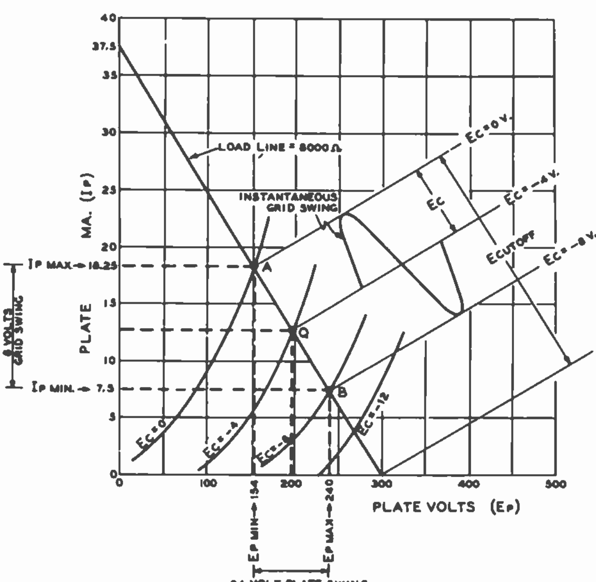



**Figure 13**

**APPLICATION OF $I_p$ vs. $E_p$ CHARACTERISTICS OF A VACUUM TUBE**

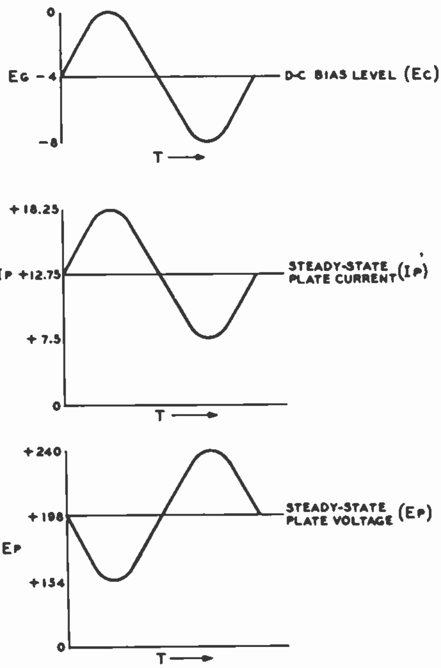



**Figure 14**

**POLARITY REVERSAL BETWEEN GRID AND PLATE VOLTAGES**

If the tube is considered to be an open circuit no plate current will flow, and there is no voltage drop across the plate load resistor ($R_L$). The plate voltage on the tube is therefore 300 volts. If, on the other hand, the tube is considered to be a short circuit, maximum possible plate current flows and the full 300 volt drop appears across $R_L$. The plate voltage is zero, and the plate current is 300/1000, or 37.5 milliamperes. These two extreme conditions define the ends of the load line on the $I_p$ vs. $E_p$ characteristic curve, figure 13.

For this application the grid of the tube is returned to a steady biasing voltage of $-4$ volts. The steady or quiescent operation of the tube is determined by the intersection of the load line with the $-4$-volt curve at point Q. By projection from point Q through the plate-current axis it is found that the value of plate current with no signal applied to the grid is 12.75 milliamperes. By projection from point Q through the plate-voltage axis it is found that the quiescent plate voltage is 198 volts. This leaves

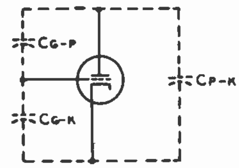



**Figure 15**

**SCHEMATIC REPRESENTATION OF INTERELECTRODE CAPACITANCE**

a drop of 102 volts across $R_L$ which is borne out by the relation $0.01275 \times 8000 = 102$ volts.

An alternating voltage of 4 volts maximum swing about the normal bias value of $-4$ volts is applied now to the grid of the triode amplifier. This signal swings the grid in a positive direction to 0 volts, and in a negative direction to $-8$ volts, and establishes the *operating region* of the tube along the load line between points A and B. Thus the maxima and minima of the plate voltage and plate current are established. By projection from points A and B through the plate-current axis the maximum instantaneous plate current is found to be 18.25 milliamperes and the minimum is 7.5 milliamperes. By projections from points A and B through the plate-voltage axis the minimum instantaneous plate-voltage swing is found to be 154 volts and the maximum is 240 volts.

By this graphical application of the $I_p$ vs. $E_p$ characteristic of the 6SN7 triode the operation of the circuit illustrated in figure 12 becomes apparent. A voltage variation of 8 volts (peak to peak) on the grid produces a variation of 84 volts at the plate.

**Polarity Inversion** When the signal voltage applied to the grid has its maximum positive instantaneous value the plate current is also maximum. Reference to figure 12 shows that this maximum plate current flows through plate-load resistor $R_L$, producing a maximum voltage drop across it. The lower end of $R_L$ is connected to the plate supply, and is therefore held at a constant potential of 300 volts. With maximum voltage drop across the load resistor, the upper end of $R_L$ is at a minimum instantaneous voltage. The plate of the tube is connected to this end of $R_L$ and is there-

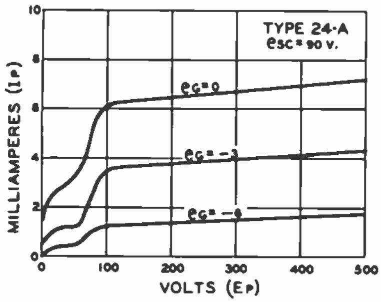



Figure 16

TYPICAL $I_p$ vs. $E_p$ TETRODE CHARACTERISTIC CURVES

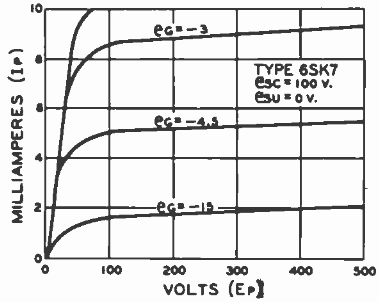



Figure 17

TYPICAL $I_p$ vs. $E_p$ PENTODE CHARACTERISTIC CURVES

fore at the same minimum instantaneous potential.

This polarity reversal between instantaneous grid and plate voltages is further clarified by a consideration of Kirchhoff's law as it applies to series resistance. The sum of the *IR* drops around the plate circuit must at all times equal the supply voltage of 300 volts. Thus when the instantaneous voltage drop across $R_L$ is maximum, the voltage drop across the tube is minimum, and their sum must equal 300 volts. The variations of grid voltage, plate current and plate voltage about their steady-state values is illustrated in figure 14.

**Interelectrode Capacitance** Capacitance always exists between any two pieces of metal separated by a dielectric. The exact amount of capacitance depends on the size of the metal pieces, the dielectric between them, and the type of dielectric. The electrodes of a vacuum tube have a similar characteristic known as *interelectrode capacitance*, illustrated in figure 15. These direct capacitances in a triode are: grid-to-cathode capacitance, grid-to-plate capacitance, and plate-to-cathode capacitance. The interelectrode capacitance, though very small, has a coupling effect, and often can cause unbalance in a particular circuit. At very-high frequencies (vhf), interelectrode capacitances become very objectionable and prevent the use of conventional tubes at these frequencies. Special vhf tubes must be used which are characterized by very small electrodes and close internal spacing of the elements of the tube.

## 4-4 Tetrode or Screen-Grid Tubes

Many desirable characteristics can be obtained in a vacuum tube by the use of more than one grid. The most common multielement tube is the tetrode (four electrodes). Other tubes containing as many as eight electrodes are available for special applications.

**The Tetrode** The quest for a simple and easily usable method of eliminating the effects of the grid-to-plate capacitance of the triode led to the development of the *screen-grid* tube, or *tetrode*. When another grid is added between the grid and plate of a vacuum tube the tube is called a tetrode, and because the new grid is called a *screen*, as a result of its screening or shielding action, the tube is often called a screen-grid tube. The interposed screen grid acts as an electrostatic shield between the grid and plate, with the consequence that the grid-to-plate capacitance is reduced. Although the screen grid is maintained at a positive voltage with respect to the cathode of the tube, it is maintained at ground potential with respect to r.f. by means of a bypass capacitor of very low reactance at the frequency of operation.

In addition to the shielding effect, the screen grid serves another very useful purpose. Since the screen is maintained at a positive potential, it serves to increase or accelerate the flow of electrons to the plate. There being large openings in the screen mesh, most of the electrons pass through it and on to the plate. Due also to the screen, the plate current is largely independent of plate voltage, thus making for high amplification. When the screen voltage is held at a constant value, it is possible to make large changes in plate voltage without appreciably affecting the plate current, (figure 16).

When the electrons from the cathode approach the plate with sufficient velocity, they dislodge electrons on striking the plate. This effect of *bombarding* the plate with high-velocity electrons, with the consequent dislodgement of other electrons from the plate, gives rise to the condition of secondary emission which has been discussed in a previous paragraph. This effect can cause no particular difficulty in a triode because the secondary electrons so emitted are eventually attracted back to the plate. In the screen-grid tube, however, the screen is close to the plate and is maintained at a positive potential. Thus, the screen will attract these electrons which have been knocked from the plate, particularly when the plate voltage falls to a lower value than the screen voltage, with the result that the plate current is lowered and the amplification is decreased.

In the application of tetrodes, it is necessary to operate the plate at a high voltage in relation to the screen in order to overcome these effects of *secondary emission.*

**The Pentode** The undesirable effects of secondary emission from the plate can be greatly reduced if yet another element is added between the screen and plate. This additional element is called a *suppressor*, and tubes in which it is used are called *pentodes*. The suppressor grid is sometimes connected to the cathode within the tube; sometimes it is brought out to a connecting pin on the tube base, but in any case it is established negative with respect to the minimum plate voltage. The secondary electrons that would travel to the screen if there were no suppressor are diverted back to the plate. The plate current is, therefore, not reduced and the amplification possibilities are increased (figure 17).

Pentodes for audio applications are designed so that the suppressor increases the limits to which the plate voltage may swing; therefore the consequent power output and gain can be very great. Pentodes for radio-frequency service function in such a manner that the suppressor allows high voltage gain, at the same time permitting fairly high gain at low plate voltage. This holds true even if the plate voltage is the same or slightly lower than the screen voltage.

**Remote-Cutoff Tubes** *Remote-cutoff* tubes (variable-$\mu$) are screen grid tubes in which the control grid structure has been physically modified so as to cause the plate current of the tube to drop off gradually, rather than to have a well-defined cutoff point (figure 18). A non-uniform control-grid structure is used, so that the amplification factor is different for different parts of the control grid.

Remote-cutoff tubes are used in circuits where it is desired to control the amplification by varying the control-grid bias. The characteristic curve of an ordinary screen-grid tube has considerable curvature near the plate-current cutoff point, while the curve of a remote-cutoff tube is much more linear (figure 19). The remote-cutoff tube minimizes cross-talk interference that would otherwise be produced. Examples of remote cutoff tubes are: 6BD6, 6BA6, 6SG7 and 6SK7.

**Beam-Power Tubes** A *beam-power* tube makes use of another method of suppressing secondary emission. In this tube there are four electrodes: a cathode, a grid, a screen, and a plate, so spaced and placed that secondary emission from the plate is suppressed without actual power loss. Because of the manner in which the electrodes are spaced, the electrons which travel to the plate are slowed down when the plate voltage is low, almost to zero velocity in a certain region between screen and plate. For this reason the electrons form a stationary cloud, or *space charge*. The effect of this space charge is to repel secondary electrons emitted from the plate and thus cause them to return to the plate. In this way, secondary emission is suppressed.

Another feature of the beam-power tube is the low current drawn by the screen. The screen and the grid are spiral wires wound so that each turn in the screen is shaded from the cathode by a grid turn. This alignment of the screen and the grid causes the electrons to travel in sheets between the turns of the screen so that very few of them

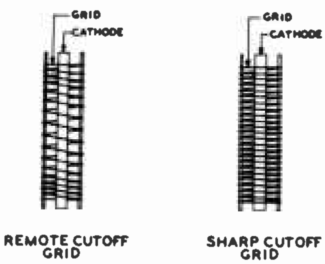



**Figure 18**

**REMOTE-CUTOFF GRID STRUCTURE**

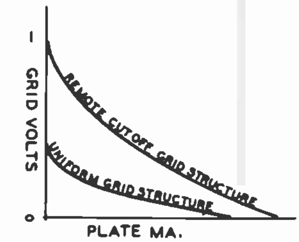



**Figure 19**

**ACTION OF A REMOTE-CUTOFF GRID STRUCTURE**

strike the screen itself. This formation of the electron stream into sheets or beams increases the charge density in the screen-plate region and assists in the creation of the space charge in this region.

Because of the effective suppressor action provided by the space charge, and because of the low current drawn by the screen, the beam-power tube has the advantages of high power output, high power sensitivity, and high efficiency. The 6AQ5 is such a beam-power tube, designed for use in the power-amplifier stages of receivers and speech amplifiers or modulators. Larger tubes employing the beam-power principle are being made by various manufacturers for use in the radio-frequency stages of transmitters. These tubes feature extremely high power sensitivity (a very small amount of driving power is required for a large output), good plate efficiency, and low grid-to-plate capacitance. Examples of these tubes are 813, 4-250A, 4CX250B, etc.

**Grid-Screen Mu Factor** The *grid-screen μ factor* ($\mu_{sg}$) is analogous to the amplification factor in a triode, except that the screen of a pentode or tetrode is substituted for the plate of a triode. $\mu_{sg}$ denotes the ratio of a change in grid voltage to a change in screen voltage, each of which will produce the same change in screen current. Expressed as an equation:

$$\mu_{sg} = \frac{\Delta E_{sg}}{\Delta E_g}$$

where,
$I_{sg}$ is held constant,
Δ equals small increment.

The grid-screen μ factor is important in determining the operating bias of a tetrode or pentode tube. The relationship between control-grid potential and screen potential determines the plate current of the tube as well as the screen current since the plate current is essentially independent of the plate voltage in tubes of this type. In other words, when the tube is operated at cutoff bias as determined by the screen voltage and the grid-screen μ factor (determined in the same way as with a triode, by dividing the operating voltage by the μ factor) the plate current will be substantially at cutoff, as will be the screen current. The grid-screen μ factor is numerically equal to the amplification factor of the same tetrode or pentode tube when it is triode connected.

**Current Flow in Tetrodes and Pentodes** The following equation is the expression for total cathode current in a triode tube. The expression for the total cathode current of a tetrode and a pentode tube is the same, except that the screen-grid voltage and the grid-screen μ factor are used in place of the plate voltage and μ of the triode.

$$\text{cathode current} = K\left(E_g + \frac{E_{sg}}{\mu_{sg}}\right)^{3/2}$$

Cathode current, of course, is the sum of the screen and plate currents plus control-grid current in the event that the control grid is positive with respect to the cathode. It will be noted that total *cathode* current is independent of plate voltage in a tetrode or pentode. Also, in the usual tetrode or pentode the *plate* current is substantially independent of plate voltage over the usual operating range—which means simply that the effective plate resistance of such tubes is relatively high. However, when the plate voltage falls below the normal operating range, the plate current falls sharply, while the screen current rises to such a value that the total cathode current remains substantially constant. Hence, the screen grid in a tetrode or pentode will almost invariably be damaged by excessive dissipation if the plate voltage is removed while the screen voltage is still being applied from a low-impedance source.

**The Effect of Grid Current** The current equations show how the total cathode current in triodes, tetrodes, and pentodes is a function of the potentials applied to the various electrodes. If only one electrode is positive with respect to the cathode (such as would be the case in a triode acting as a class-A amplifier) all the cathode current goes to the plate. But when both screen and plate are positive in a tetrode or pentode, the cathode current divides between the two elements. Hence the screen current is taken from the total cathode current, while the balance goes to the plate. Further, if the control grid in a tetrode or pentode is operated at a positive potential the total cathode current is divided between all three elements which have a positive potential. In a tube which is receiving a large excitation voltage, it may be said that the control grid robs electrons from the output electrode during the period that the grid is positive, making it always necessary to limit the peak-positive excursion of the control grid.

**Coefficients of Tetrodes and Pentodes** In general it may be stated that the amplification factor of tetrode and pentode tubes is a coefficient which is not of much use to the designer. In fact the amplification factor is seldom given on the design-data sheets of such tubes. Its value is usually very high, due to the relatively high plate resistance of such tubes, but bears little relationship to the stage gain which actually will be obtained with such tubes.

On the other hand, the *grid-plate transconductance* is the most important coefficient of pentode and tetrode tubes. Gain per stage can be computed directly when the $g_m$ is known. The grid-plate transconductance of a tetrode or pentode tube can be calculated through use of the expression:

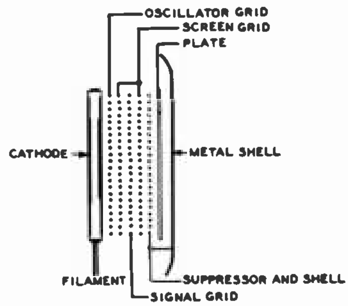



**Figure 20**

**GRID STRUCTURE OF 6SA7 CONVERTER TUBE**

$$g_m = \frac{\Delta I_p}{\Delta E_g}$$

with $E_{sg}$ and $E_p$ constant.

The plate resistance of such tubes is of less importance than in the case of triodes, though it is often of value in determining the amount of damping a tube will exert on the impedance in its plate circuit. Plate resistance is calculated from:

$$R_p = \frac{\Delta E_p}{\Delta I_p}$$

with $E_g$ and $E_{sg}$ constant.

## 4-5 Mixer and Converter Tubes

The superheterodyne receiver always includes at least one stage for changing the frequency of the incoming signal to the fixed frequency of the main intermediate-frequency amplifier in the receiver. This frequency-changing process is accomplished by selecting the beat-note difference frequency between a locally generated oscillation and the incoming signal frequency. If the oscillator signal is supplied by a separate tube, the frequency changing tube is called a *mixer*. Alternatively, the oscillation may be generated by additional elements within the frequency-changer tube. In this case the frequency changer is commonly called a *converter* tube.

**Conversion Conductance** The *conversion conductance* ($g_c$) is a coefficient of interest in the case of mixer or converter tubes, or of conventional triodes, tetrodes, or pentodes operating as frequency changers. The conversion conductance is the ratio of a change in the signal-grid voltage at the input frequency to a change in the output current at the converted frequency. Hence $g_c$ in a mixer is essentially the same as transconductance in an amplifier, with the exception that the input signal and the output current are on different frequencies. The value of $g_c$ in conventional mixer tubes is from 300 to 3000 micromhos. The value of $g_c$ in an amplifier tube operated as a mixer is approximately 0.3 the $g_m$ of the tube operated as an amplifier. The voltage gain of a mixer stage is equal to $g_c Z_L$ where $Z_L$ is the impedance of the plate load into which the mixer tube operates.

**The Diode Mixer** The simplest mixer tube is the diode. The noise figure, or figure of merit, for a mixer of this type is not as good as that obtained with other more complex mixers; however, the diode is useful as a mixer in uhf and vhf equipment where low interelectrode capacities are vital to circuit operation. Since the diode impedance is low, the local oscillator must furnish considerable power to the diode mixer. A good diode mixer has an over-all gain of about 0.5.

**The Triode Mixer** A triode mixer has better gain and a better noise figure than the diode mixer. At low frequencies, the gain and noise figure of a triode mixer closely approaches those figures obtained when the tube is used as an amplifier. In the uhf and vhf range, the efficiency of the triode mixer deteriorates rapidly. The optimum local-oscillator voltage for a triode mixer is about 0.7 as large as the cutoff bias of the triode. Very little local-oscillator power is required by a triode mixer.

**Pentode Mixers and Converter Tubes** A common multigrid converter tube for broadcast or shortwave use is the *pentagrid converter*, typified by the 6BE6, 6BA7, and 6SA7 tubes (figure 20). Operation of these converter tubes and pentode mixers will be covered in the Receiver Fundamentals Chapter.

## 4-6 Electron Tubes at Very-High Frequencies

As the frequency of operation of the usual type of electron tube is increased above about 20 MHz, certain assumptions which are valid for operation at lower frequencies must be re-examined. First, we find that lead inductances from the socket connections to the actual elements within the envelope no longer are negligible. Second, we find that electron transit time no longer may be ignored; an appreciable fraction of a cycle of input signal may be required for an electron to leave the cathode space charge, pass through the grid wires, and travel through the space between grid and plate.

**Effects of Lead Inductance** The effect of lead inductance is twofold. First, as shown in figure 21, the combination of grid-lead inductance, grid-cathode capacitance, and cathode-lead inductance tends to reduce the effective grid-cathode signal voltage for a constant voltage at the tube terminals as the frequency is increased. Second, cathode-lead inductance tends to introduce undesired coupling between the various elements within the tube.

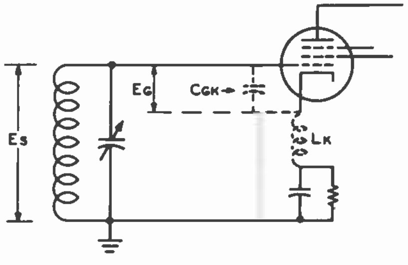



Figure 21

SHOWING THE EFFECT OF CATHODE LEAD INDUCTANCE

*The degenerative action of cathode-lead inductance tends to reduce the effective grid-to-cathode voltage with respect to the voltage available across the input tuned circuit. Cathode-lead inductance also introduces undesirable coupling between the input and the output circuits.*

Tubes especially designed for vhf and uhf use have had their lead inductances minimized. The usual procedures for reducing lead inductance are: (1) using heavy lead conductors or several leads in parallel (examples are the 6J4 and 6AK5), (2) scaling down the tube in all dimensions to reduce both lead inductances and interelectrode capacitances (examples are the 6CW4, 6F4, and other nuvistor and miniature tubes), and (3) the use of very low-inductance extensions of the elements themselves as external connections (examples are lighthouse tubes such as the 2C40, planar tubes such as the 2C29, and many types of vhf transmitting tubes).

**Effect of Transit Time** When an electron tube is operated at a frequency high enough that electron transit time between cathode and plate is an appreciable fraction of a cycle at the input frequency, several undesirable effects take place. First, the grid takes power from the input signal even though the grid is negative at all times. This comes about since the grid will have changed its potential during the time required for an electron to pass from cathode to plate. Due to interaction, and a resulting phase difference between the field associated with the grid and that associated with a moving electron, the grid presents a resistance to an input signal in addition to its normal "cold" capacitance. Further, as a result of this action, plate current no longer is in phase with grid voltage.

An amplifier stage operating at a frequency high enough that *transit time* is appreciable:

(a) Is difficult to excite as a result of grid loss from the equivalent input grid resistance,

(b) Is capable of less output since transconductance is reduced and plate current is not in phase with grid voltage.

The effects of transit time increase with the square of the operating frequency, and they increase rapidly as frequency is increased above the value where they become just appreciable. These effects may be reduced by scaling down tube dimensions; a procedure which also reduces lead inductance. Further, transit-time effects may be reduced by the obvious procedure of increasing electrode potentials so that electron velocity will be increased. However, due to the law of electron motion in an electric field, transit time is increased only as the square root of the ratio of operating potential increase; therefore this expedient is of limited value due to other limitations on operating voltages of small electron tubes.

## 4-7 Special Microwave Electron Tubes

Due primarily to the limitation imposed by transit time, conventional negative-grid electron tubes are capable of affording worthwhile amplification and power output only up to a definite upper frequency. This upper frequency limit varies from perhaps 100 MHz for conventional tube types to about 4000 MHz for specialized types such as the lighthouse tube. Above the limiting frequency, the conventional negative-grid tube no longer is practicable and recourse must be taken to totally different types of electron tubes in which electron transit time is not a limitation to operation. Three of the most important of such microwave tube types are the *klystron*, the *magnetron*, and the *traveling-wave tube*.

**The Power Klystron** The klystron is a type of electron tube in which electron transit time is used to advantage. Such tubes comprise, as shown in figure 22, a cathode, a focusing electrode, a resonator connected to a pair of grids which afford *velocity modulation* of the electron beam (called the "buncher"), a *drift space*, and another resonator connected to a pair of grids (called the "catcher"). A *collector* for the expended electrons may be included at the end of the tube, or the catcher may also perform the function of electron collection.

The tube operates in the following manner: The cathode emits a stream of electrons which is focused into a beam by the focusing electrode. The stream passes through the buncher where it is acted upon by any field existing between the two grids of the buncher cavity. When the potential between the two grids is zero, the stream passes through without change in velocity. But when the potential between the two grids of the buncher is increasingly positive in the

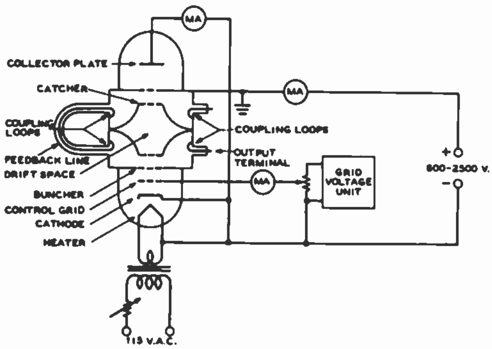



**Figure 22**

**TWO-CAVITY KLYSTRON OSCILLATOR**

***A conventional two-cavity klystron is shown with a feedback loop connected between the two cavities so that the tube may be used as an oscillator.***

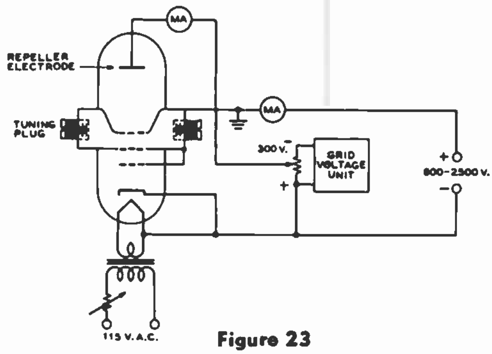



**Figure 23**

**REFLEX KLYSTRON OSCILLATOR**

***A conventional reflex klystron oscillator of the type commonly used as a local oscillator in superheterodyne receivers operating above about 2000 MHz is shown above. Frequency modulation of the output frequency of the oscillator, or afc operation in a receiver, may be obtained by varying the negative voltage on the repeller electrode.***

direction of electron motion, the velocity of the electrons in the beam is increased. Conversely, when the field becomes increasingly negative in the direction of the beam (corresponding to the other half-cycle of the exciting voltage from that which produced electron acceleration) the velocity of the electrons in the beam is decreased.

When the velocity-modulated electron beam reaches the drift space where there is no field, those electrons which have been sped up on one half-cycle overtake those immediately ahead which were slowed down on the other half-cycle. In this way, the beam electrons become bunched together. As the bunched groups pass through the two grids of the catcher cavity, they impart pulses of energy to these grids. The catcher-grid space is charged to different voltage levels by the passing electron bunches, and a corresponding oscillating field is set up in the catcher cavity. The catcher is designed to resonate at the frequency of the velocity-modulated beam, or at a harmonic of this frequency.

In the klystron amplifier, energy delivered by the buncher to the catcher grids is greater than that applied to the buncher cavity by the input signal. In the klystron oscillator a feedback loop connects the two cavities. Coupling to either buncher or catcher is provided by small loops which enter the cavities by way of concentric lines.

The klystron is an electron-coupled device. When used as an oscillator, its output voltage is rich in harmonics Klystron oscillators of various types afford power outputs ranging from less than 1 watt to many thousand watts. Operating efficiency varies between 5 and 50 percent. Frequency may be shifted to some extent by varying the beam voltage. Tuning is carried on mechanically in some klystrons by altering (by means of knob settings) the shape of the resonant cavity.

**The Reflex Klystron** The multicavity klystron as described in the preceding paragraphs is primarily used as a transmitting device since quite reasonable amounts of power are made available in its output circuit. However, for applications where a much smaller amount of power is required — power levels in the milliwatt range — for low-power transmitters, receiver local oscillators, etc., another type of klystron having only a single cavity is more frequently used.

The theory of operation of the single-cavity klystron is essential the same as the multicavity type with the exception that the velocity-modulated electron beam, after having left the buncher cavity is reflected back into the area of the buncher again by a repeller electrode as illustrated in figure 23. The potentials on the various electrodes are adjusted to a value such that proper bunching of the electron beam will take

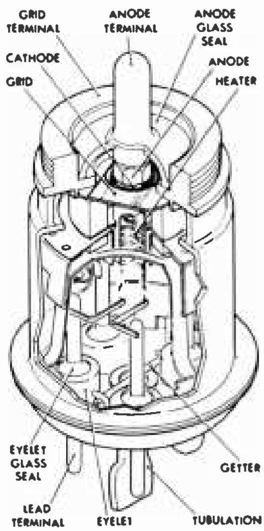



**Figure 24**

**CUTAWAY VIEW OF WESTERN ELECTRIC 416-B/6280 VHF PLANAR TRIODE TUBE**

***The 416-B, designed by the Bell Telephone Laboratories is intended for amplifier or frequency multiplier service in the 4000 MHz region. Employing grid wires having a diameter equal to fifteen wavelengths of light, the 416-B has a transconductance of 50,000. Spacing between grid and cathode is .0005", to reduce transit-time effects. Entire tube is gold plated.***

place just as a particular portion of the velocity-modulated beam re-enters the area of the resonant cavity. Since this type of klystron has only one circuit it can be used only as an oscillator and not as an amplifier. Effective modulation of the frequency of a single-cavity klystron for f-m work can be obtained by modulating the repeller electrode voltage.

**The Magnetron** The *magnetron* is an *uhf* oscillator tube normally employed where very-high values of peak power or moderate amounts of average power are required in the range from perhaps 700 MHz to 30,000 MHz. Special magnetrons were developed for wartime use in radar equipment which had peak power capabilities of several million watts (megawatts) output at frequencies in the vicinity of 3000 MHz. The normal duty cycle of operation of these radar units was approximately 1/10 of one percent (the tube operated about 1/1000 of the time and rested for the balance of the operating period) so that the average power output of these magnetrons was in the vicinity of 1000 watts.

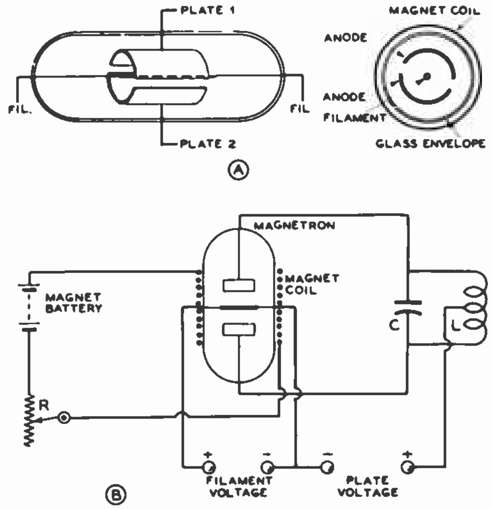



**Figure 25**

**SIMPLE MAGNETRON OSCILLATOR**

***An external tank circuit is used with this type of magnetron oscillator for operation in the lower uhf range.***

In its simplest form the magnetron tube is a filament-type diode with two half-cylindrical plates or anodes situated coaxially with respect to the filament. The construction is illustrated in figure 25A. The anodes of the magnetron are connected to a resonant circuit as illustrated in figure 25B. The tube is surrounded by an electromagnet coil which, in turn, is connected to a low-voltage d-c energizing source through a rheostat (R) for controlling the strength of the magnetic field. The field coil is oriented so that the lines of magnetic force it sets up are parallel to the axis of the electrodes.

Under the influence of the strong magnetic field, electrons leaving the filament are deflected from their normal paths and move in circular orbits within the anode cylinder. This effect results in a negative resistance which sustains oscillations. The oscillation frequency is very nearly the value determined by *L* and *C*. In other magnetron circuits, the frequency may be governed by

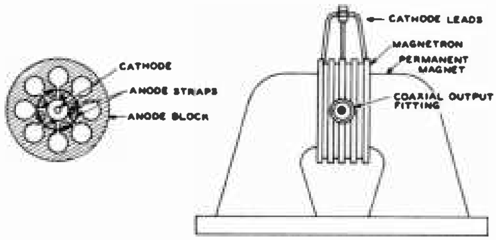



**Figure 26**

**MODERN MULTICAVITY MAGNETRON**

***Illustrated is an external-anode strapped magnetron of the type commonly used in radar equipment for the 10-cm. range. An integral permanent magnet is shown in the righthand portion of the drawing, with the magnetron in place between the pole pieces of the magnet.***

the electron rotation, no external tuned circuits being employed. Wavelengths of less than 1 centimeter have been produced with such circuits.

More complex magnetron tubes employ no external tuned circuit, but utilize instead one or more resonant cavities which are integral with the anode structure. Figure 26 shows a magnetron of this type having a multicellular anode of eight cavities. It will be noted, also, that alternate cavities (which would operate at the same polarity when the tube is oscillating) are strapped together. Strapping was found to improve the efficiency and stability of high-power radar magnetrons. In most radar applications of magnetron oscillators, a powerful permanent magnet of controlled characteristics is employed to supply the magnetic field, rather than the use of an electromagnet.

**The Traveling-Wave Tube** The *Traveling-Wave Tube* (figure 27) consists of a helix located within an evacuated envelope. Input and output terminations are affixed to each end of the helix. An electron beam passes through the helix and interacts with a wave traveling along the helix to produce broadband amplification at microwave frequencies.

When the input signal is applied to the gun end of the helix, it travels along the helix wire at approximately the speed of light. However, the signal velocity measured along the axis of the helix is considerably

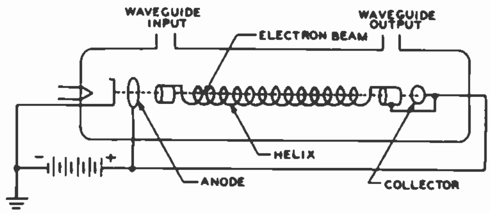



**Figure 27**

**THE TRAVELING-WAVE TUBE**

***Operation of this tube is the result of interaction between the electron beam and wave traveling along the helix.***

lower. The electrons emitted by the cathode gun pass axially through the helix to the collector, located at the output end of the helix. The average velocity of the electrons depends on the potential of the collector with respect to the cathode. When the average velocity of the electrons is greater than the velocity of the helix wave, the eletrons become crowded together in the various regions of retarded field, where they impart energy to the helix wave. A power gain of 100 or more may be produced by this tube.

## 4-8 The Cathode-Ray Tube

**The Cathode-Ray Tube** The *cathode-ray tube* is a special type of electron tube which permits the visual observation of electrical signals. It may be incorporated into an oscilloscope for use as a test instrument or it may be the display device for radar equipment or television.

**Operation of the CRT** A cathode-ray tube always includes an *electron gun* for producing a stream of electrons, a *grid* for controlling the intensity of the electron beam, and a *luminescent screen* for converting the impinging electron beam into visible light. Such a tube always operates in conjunction with either a built-in or an external means for focusing the electron stream into a narrow beam, and a means for deflecting the electron beam in accordance with an electrical signal.

The main electrical difference between types of cathode-ray tubes lies in the means employed for focusing and deflecting the electron beam. The beam may be focused

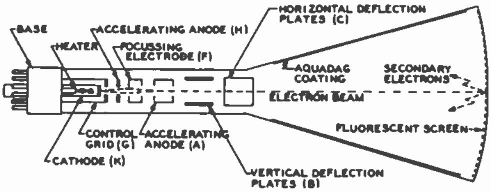



**Figure 28**

**TYPICAL ELECTROSTATIC CATHODE-RAY TUBE**

and/or deflected either electrostatically or magnetically, since a stream of electrons can be acted on either by an electrostatic or a magnetic field. In an electrostatic field the electron beam tends to be deflected toward the positive termination of the field (figure 28). In a magnetic field the stream tends to be deflected at right angles to the field. Further, an electron beam tends to be deflected so that it is normal (perpendicular) to the equipotential lines of an electrostatic field—and it tends to be deflected so that it is parallel to the lines of force in a magnetic field.

Large cathode-ray tubes used as *kinescopes* in television receivers usually are both focused and deflected magnetically. On the other hand, the medium-size CR tubes used in oscilloscopes and small television receivers usually are both focused and deflected electrostatically. Cathode-ray tubes for special applications may be focused magnetically and deflected electrostatically or vice versa.

There are advantages and disadvantages to both types of focusing and deflection. However, it may be stated that electrostatic deflection is much better than magnetic deflection when high-frequency waves are to be displayed on the screen; hence the almost universal use of this type of deflection for oscillographic work. When a tube is operated at a high value of accelerating potential so as to obtain a bright display on the face of the tube as for television or radar work, the use of magnetic deflection becomes desirable since it is relatively easier to deflect a high-velocity electron beam magnetically than electrostatically. An *ion trap* is required with magnetic deflection since the heavy negative ions emitted by the cathode are not materially deflected by the magnetic field and would burn an *ion spot* in the center of the luminescent screen. With electrostatic deflection the heavy ions are deflected equally as well as the electrons in the beam so that an ion spot is not formed.

**Construction of Electrostatic CRT** The construction of a typical electrostatic-focus, electrostatic-deflection cathode-ray tube is illustrated in the pictorial diagram of figure 28. The *indirectly heated cathode* (K) releases free electrons when heated by the enclosed filament. The cathode is surrounded by a cylinder (G) which has a small hole in its front for the passage of the electron steam. Although this element is not a wire mesh as is the usual grid, it is known by the same name because its action is similar: it controls the electron stream when its negative potential is varied.

Next in order, is found the first *accelerating anode* (H) which resembles another disk or cylinder with a small hole in its center. This electrode is run at a high or moderately high positive voltage, to accelerate the electrons toward the far end of the tube.

The *focusing electrode* (F) is a sleeve which usually contains two small disks, each with a small hole.

After leaving the focusing electrode, the electrons pass through another *accelerating anode* (A) which is operated at a high positive potential. In some tubes this electrode is operated at a higher potential than the first accelerating electrode (H) while in other tubes both accelerating electrodes are operated at the same potential.

The electrodes which have been described up to this point constitute the *electron gun,* which produces the free electrons and focuses them into a slender, concentrated, rapidly traveling stream for projecting onto the viewing screen.

**Electrostatic Deflection** To make the tube useful, means must be provided for deflecting the electron beam along two axes at right angles to each other. The more common tubes employ *electrostatic deflection plates*, one pair to exert a force on the beam in the vertical plane and one pair to exert a force in the horizontal plane. These plates are designated as B and C in figure 28.

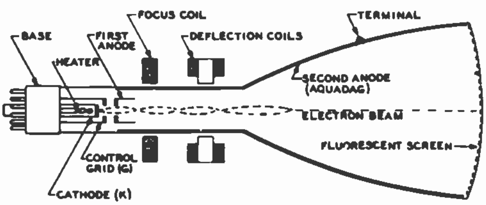



**Figure 29**

**TYPICAL ELECTROMAGNETIC CATHODE-RAY TUBE**

Standard oscilloscope practice with small cathode-ray tubes calls for connecting one of the B plates and one of the C plates together and to the high-voltage accelerating anode. With the newer three-inch tubes and with five-inch tubes and larger, all four deflection plates are commonly used for deflection. The *positive* high voltage is grounded, instead of the negative as is common practice in amplifiers, etc., in order to permit operation of the deflecting plates at a d-c potential at or near ground.

An *Aquadag* coating is applied to the inside of the envelope to attract any secondary electrons emitted by the fluorescent screen.

In the average electrostatic-deflection CR tube the spot will be fairly well centered if all four deflection plates are returned to the potential of the second anode (ground). However, for accurate centering and to permit moving the entire trace either horizontally or vertically to permit display of a particular waveform, horizontal- and vertical-centering controls usually are provided on the front of the oscilloscope.

After the spot is once centered, it is necessary only to apply a positive or negative voltage (with respect to ground) to one of the ungrounded or "free" deflector plates in order to move the spot. If the voltage is positive with respect to ground, the beam will be attracted toward that deflector plate, If it is negative, the beam and spot will be repulsed. The amount of deflection is directly proportional to the voltage (with respect to ground) that is applied to the free electrode.

With the larger-screen higher-voltage tubes it becomes necessary to place deflecting voltage on both horizontal and both vertical plates. This is done for two reasons: First, the amount of deflection voltage required by the high-voltage tubes is so great that a transmitting tube operating from a high-voltage supply would be required to attain this voltage without distortion. By using push-pull deflection with two tubes feeding the deflection plates, the necessary plate-supply voltage for the deflection amplifier is halved. Second, a certain amount of defocusing of the electron stream is always present on the extreme excursions in deflection voltage when this voltage is applied only to one deflecting plate. When the deflecting voltage is fed in push-pull to both deflecting plates in each plane, there is no defocusing because the *average* voltage acting on the electron stream is zero, even though the *net* voltage (which causes the deflection) acting on the stream is twice that on either plate.

The fact that the beam is deflected by a magnetic field is important even in an oscilloscope which employs a tube using electrostatic deflection, because it means that precautions must be taken to protect the tube from the transformer fields and sometimes even the earth's magnetic field. This normally is done by incorporating a magnetic shield around the tube and by placing any transformers as far from the tube as possible, oriented to the position which produces minimum effect on the electron stream.

**Construction of Electromagnetic CRT** The electromagnetic cathode-ray tube allows greater definition than does the electrostatic tube. Also, electromagnetic definition has a number of advantages when a rotating radial sweep is required to give polar indications.

The production of the electron beam in an electromagnetic tube is essentially the same as in the electrostatic tube. The grid structure is similar, and controls the electron beam in an identical manner. The elements of a typical electromagnetic tube are shown in figure 29. The *focus coil* is wound on an iron core which may be moved along the neck of the tube to focus the electron beam. For final adjustment, the current flowing in the coil may be varied. A second pair of coils, the *deflection coils*, are mounted at right angles to each other around the neck of the tube. In some cases, these coils can rotate around the axis of the tube.

Two *anodes* are used for accelerating the electrons from the cathode to the screen. The second anode is a graphite coating (*Aquadag*) on the inside of the glass envelope. The function of this coating is to attract any secondary electrons emitted by the fluorescent screen, and also to shield the electron beam.

In some types of electromagnetic tubes, a first, or *accelerating anode* is also used in addition to the *Aquadag*.

**Electromagnetic Deflection** A magnetic field will deflect an electron beam in a direction which is at right angles to both the direction of the field and the direction of motion of the beam.

In the general case, two pairs of deflection coils are used (figure 30). One pair is for horizontal deflection, and the other pair is for vertical deflection. The two coils in a pair are connected in series and are wound in such directions that the magnetic field flows from one coil, through the electron beam to the other coil. The force exerted on the beam by the field moves it to any point on the screen by application of the proper currents to these coils.

**The Trace** The human eye retains an image for about one-sixteenth second after viewing. In a CRT, the spot can be moved so quickly that a series of adjacent spots can be made to appear as a line, if the beam is swept over the path fast enough. As long as the electron beam strikes in a given place at least sixteen times a second, the spot will appear to the human eye as a source of continuous light with very little flicker.

**Screen Materials— "Phosphors"** At least five types of luminescent screen materials are commonly available on the various types of CR tubes commercially available. These screen materials are called *phosphors;* each of the five phosphors is best suited to a particular type of application. The P-1 phosphor, which has a green fluorescence with medium persistence, is almost invariably used for oscilloscope tubes for visual observation. The P-4 phosphor, with white fluorescence and medium

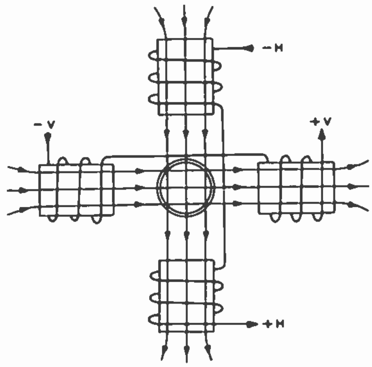



**Figure 30**

***Two pairs of coils arranged for electromagnetic deflection in two directions.***

persistence, is used on television viewing tubes (*Kinescopes*). The P-5 and P-11 phosphors, with blue fluorescence and very short persistence, are used primarily in oscilloscopes where photographic recording of the trace is to be obtained. The P-7 phosphor, which has a blue flash and a long-persistence greenish-yellow persistence, is used primarily for radar displays where retention of the image for several seconds after the initial signal display is required.

## 4-9 Gas Tubes

The space charge of electrons in the vicinity of the cathode in a diode causes the plate-to-cathode voltage drop to be a function of the current being carried between the cathode and the plate. This voltage drop can be rather high when large currents are being passed, causing a considerable amount of energy loss which shows up as plate dissipation.

**Action of Positive Ions** The negative space charge can be neutralized by the presence of the proper density of positive ions in the space between the cathode and anode. The positive ions may be obtained by the introduction of the proper amount of gas or a small amount of mercury into the envelope of the tube. When the voltage drop across the tube reaches the ionization potential of the gas or mercury vapor, the gas molecules will become ionized to form positive ions. The positive ions then tend to neutralize the space charge in the vicinity of the cathode. The voltage drop across the tube then remains constant at the ionization potential of the gas, up to a current drain equal to the maximum emission capability of the cathode. The voltage drop varies between 10 and 20 volts, depending on the particular gas employed, up to the maximum current rating of the tube.

**Mercury-Vapor Tubes** Mercury-vapor tubes, although very widely used, have the disadvantage that they must be operated within a specific temperature range (25° to 70° C) in order that the mercury-vapor pressure within the tube shall be within the proper range. If the temperature is too low, the drop across the tube becomes too high causing immediate overheating and possible damage to the elements. If the temperature is too high, the vapor pressure is too high, and the voltage at which the tube will "flash back" is lowered to the point where destruction of the tube may take place. Since the ambient temperature range specified above is within the normal room temperature range, no trouble will be encountered under normal operating conditions. However, by the substitution of xenon gas for mercury it is possible to produce a rectifier with characteristics comparable to those of the mercury-vapor tube except that the tube is capable of operating over the range from approximately −70° to +90° C. The 3B25 rectifier is an example of this type of tube.

**Thyratron Tubes** If a grid is inserted between the cathode and plate of a mercury-vapor gaseous-conduction rectifier, a negative potential placed on the added element will increase the plate-to-cathode voltage drop required before the tube will ionize or "fire." The potential on the control grid will have no effect on the plate-to-cathode drop after the tube has ionized. However, the grid voltage may be adjusted to such a value that conduction will take place only over the desired portion of the cycle of the a-c voltage being impressed on the plate of the rectifier.

**Voltage-Regulator Tubes** In a glow-discharge gas tube the voltage drop across the electrodes remains constant over a wide range of current passing through the tube. This property exists because the degree of ionization of the gas in the tube varies with the amount of current passing through the tube. When a large current is passed, the gas is highly ionized and the internal impedance of the tube is low. When a small current is passed, the gas is lightly ionized and the internal impedance of the tube is high. Over the operating range of the tube, the product ($IR$) of the current through the tube and the internal impedance of the tube is very nearly constant. Examples of this type of tube are the OB2, OC2, and VR-150.

**Vacuum-Tube Classification** Vacuum tubes are grouped into three major classifications: commercial, ruggedized, and premium (or reliable). Any one of these three groups may also be further classified for military duty (MIL spec. or JAN classification). To qualify for MIL classification, sample lots of the particular tube must have passed special qualification tests at the factory. It should not be construed that a MIL-type tube is better than a commercial tube, since some commercial tests and specifications are more rigid than the corresponding MIL specifications. The MIL stamped tube has merely been accepted under a certain set of conditions for military service.

**Ruggedized or Premium Tubes** Radio tubes are being used in increasing numbers for industrial applications, such as computing and control machinery, and in aviation and marine equipment. When a tube fails in a home radio receiver, it is merely inconvenient, but a tube failure in industrial applications may bring about stoppage of some vital process, resulting in financial loss, or even danger to life.

To meet the demands of these industrial applications, a series of tubes was evolved incorporating many special features designed to ensure a long and predetermined operating life, and uniform characteristics among similar tubes. Such tubes are known as *ruggedized* or *premium* tubes. Early attempts to select reliable specimens of tubes from ordinary stock tubes proved that in the long run the selected tubes were no better than tubes picked at random. Long life and ruggedness had to be built into the tubes by means of

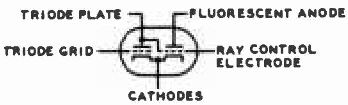



**Figure 31**

**SCHEMATIC REPRESENTATION OF "MAGIC EYE" TUBE**

proper choice and 100% inspection of all materials used in the tube, by critical processing inspection and assembling, and by conservative ratings of the tube.

Pure tungsten wire is used for heaters in preference to alloys of lower tensile strength. Nickel tubing is employed around the heater wires at the junction to the stem wires to reduce breakage at this point. Element structures are given extra supports and bracing. Finally, all tubes are given a 50-hour test run under full operating conditions to eliminate early failures. When operated within their ratings, ruggedized or premium tubes should provide a life well in excess of 10,000 hours.

Ruggedized tubes will withstand severe impact shocks for short periods, and will operate under conditions of vibration for many hours. The tubes may be identified in many cases by the fact that their nomenclature includes a "W" in the type number, as in 807W, 5U4W, etc. Some ruggedized tubes are included in the "5000" series nomenclature. The 5654 is a ruggedized version of the 6AK5, the 5692 is a ruggedized version of the 6SN7, etc.

## 4-10 Miscellaneous Tube Types

**Electron-Ray Tubes** The electron-ray tube or *magic eye* contains two sets of elements, one of which is a triode amplifier and the other a cathode-ray indicator. The plate of the triode section is internally connected to the ray-control electrode (figure 31), so that as the plate voltage varies in accordance with the applied signal the voltage on the ray-control electrode also varies. The ray-control electrode is a metal cylinder so placed relative to the cathode that it deflects some of the electrons emitted from the cathode. The electrons which strike the anode cause it to fluoresce,

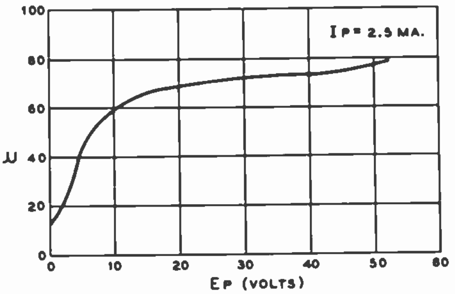



**Figure 32**

**AMPLIFICATION FACTOR OF TYPICAL STANDARD TUBE DROPS RAPIDLY AS PLATE VOLTAGE IS DECREASED BELOW 20 VOLTS**

or give off light, so that the deflection caused by the ray-control electrode, which prevents electrons from striking part of the anode, produces a wedge-shaped electrical shadow on the fluorescent anode. The size of this shadow is determined by the voltage on the ray electrode. When this electrode is at the same potential as the fluorescent anode, the shadow disappears; if the ray electrode is less positive than the anode, a shadow appears the width of which is proportional to the voltage on the ray electrode.

**Controlled Warmup Tubes** Series heater strings are employed in a-c/d-c radio receivers and television sets to reduce the cost, size, and weight of the equipment. Voltage surges of great magnitude occur in series-operated filaments because of variations in the rate of warm-up of the various tubes. As the tubes warm up, the heater resistance changes. This change is not the same between tubes of various types, or even between tubes of the same type made by different manufacturers. Some 6-volt tubes show an initial surge as high as 9 volts during warm-up, while slow-heating tubes such as the 25BQ6 are underheated during the voltage surge on the 6-volt tubes.

Standardization of heater characteristics in a new group of tubes designed for series heater strings has eliminated this trouble. The new tubes have either 600 ma or 400 ma heaters, with a controlled warm-up time of approximately 11 seconds. The 5U8, 6CG7, and 12BH7-A are examples.