AM 5-209

BASIC ELECTRONICS
VACUUM TUBES

December 2012

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PREFACE

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References

Allied Communications Publications (ACP):

1. ACP - 121 - Communications Instruction, General
2. ACP - 124 - Radiotelegraph Procedures
3. ACP - 125 - Radiotelephone Procedures
4. ACP - 126 - Communications Instructions - Radio Teletypewriter
5. ACP - 131 - Communications Instructions Operating Signals

DOD Instructions

1. DOD Instruction 4650.2.

US Army Documents

US Army Regulations

1. AR 25-6 - Military Auxiliary Radio System (MARS) and Amateur Radio Program

US Army FM/TM Manuals

1. FM 6-02.52 - Tactical Radio Operations
2. TM 5-811-3 - Electrical Design, Lightning and Static Electricity Protection

US Army MARS

1. AM 2-200 - US Army MARS Net Plan

Commercial References

1. Basic Electronics, Components, Devices and Circuits; ISBN 0-02-81860-X, By William P Hand and Gerald Williams

Contributors

This document has been produced by the Army MARS Technical Writing Team under the authority of Army MARS HQ, Ft Huachuca, AZ. The following individuals are subject matter experts who made significant contributions to this document.

- William P Hand

Acronyms and Abbreviations:

Abbreviations	Definition
E_G	Grid Voltage
E_q	grid bias voltage
E_p	Plate Voltage
E_{piv}	Peak Inverse Voltage
gm	transconductance
I_{MAX}	Maximum Plate Current
I_p	Plate Current
R_p	Plate Resistance
μ	amplification factor

1 INTRODUCTION

When metals are heated to a high enough temperature, electrons are boiled off. This is called the Edison Effect or Thermionic Emission (Figure 1-1). The electrons given off by a heated wire filament form what is called a space charge, a cloud of electrons around the filament.

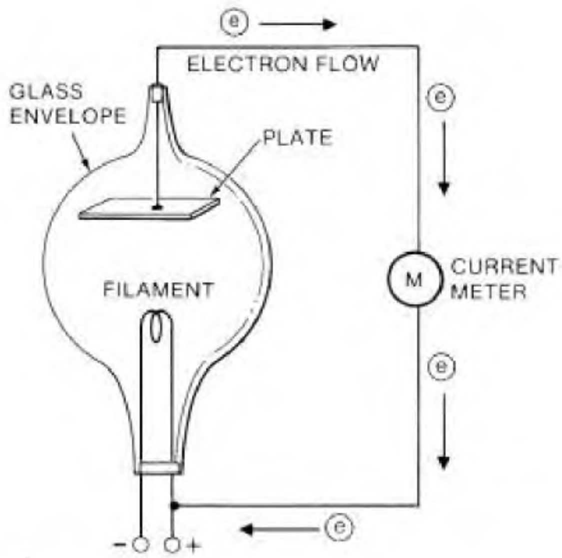


Figure 1-1
The Edison Effect

Electrons emitted by the heated filament are attracted to the positive plate. When the electrons reach the positive plate they flow through the wire, through the meter, and back to the positive side of the power source, reference Figure 1-2.

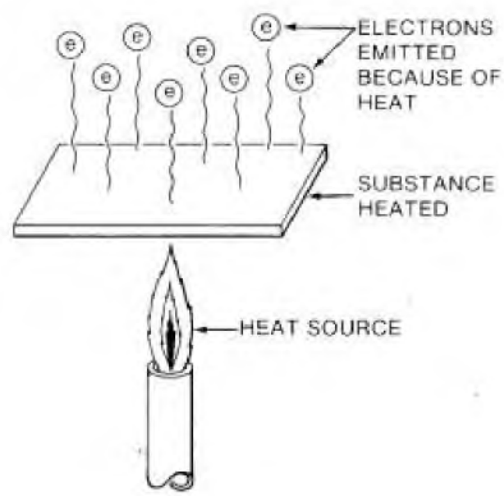
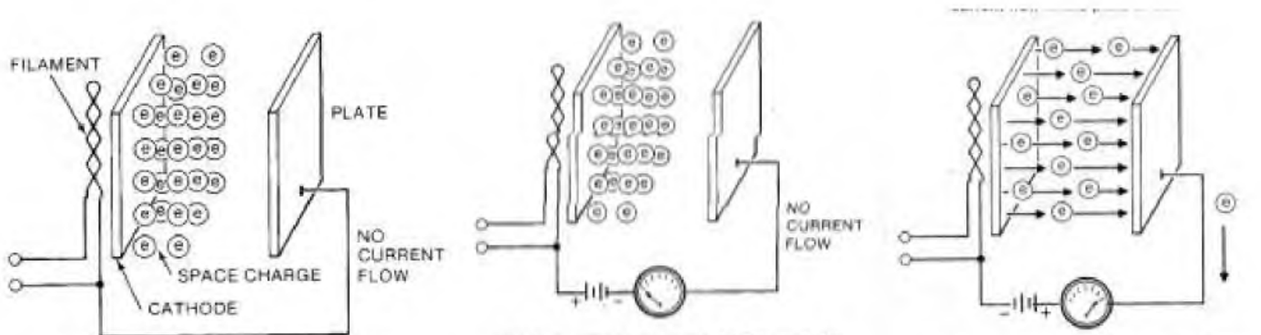


Figure 1-2
Thermionic Emission

In order to be consistent, we will use electron flow in this text in any discussion of current unless otherwise stated.

In Figure 1-3 one battery supplies power to heat the filament and a second supplies power between the filament and plate. This second power source is commonly known as the plate supply, or B+. As long as the filament is heated and B+ is applied to the plate, there is current flow in the plate circuit. Now, if the plate supply voltage is reversed in its polarity then there is a negative charge on the plate that repels electrons, and there will be no current flow from the filament to the negatively charged plate.



(A) Plate and filament at the same voltage. No current flowing in the plate circuit.

(B) Plate negative with respect to filament. No current flow in the plate circuit.

(C) Plate positive with respect to the filament. Current flow in the plate circuit.

Figure 1-3
Current due to Edison Effect

Note in Figure 1-3 that there are three possible combinations of plate voltage polarity with respect to the filament polarity.

2 THE DIODE

The Fleming valve, shown in Figure 2-1, was the forerunner of the modern diode (two electrodes) tube.

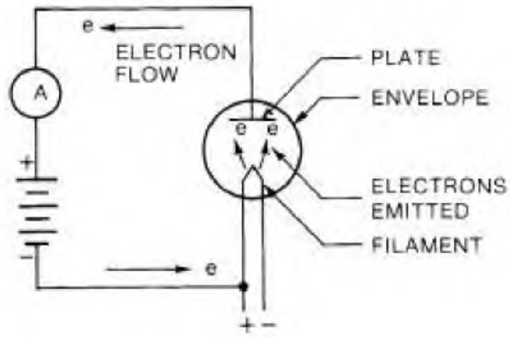


Figure 2-1
Fleming Valve

Figure 2-2 gives the schematic diagram symbols for the two basic types of diodes, the directly heated and the indirectly heated cathode types.

In the directly heated tube the filament .also serves as the cathode, whereas in the in directly heated version, they are separate elements. Figure 2-3 shows the separation of cathode and filament.

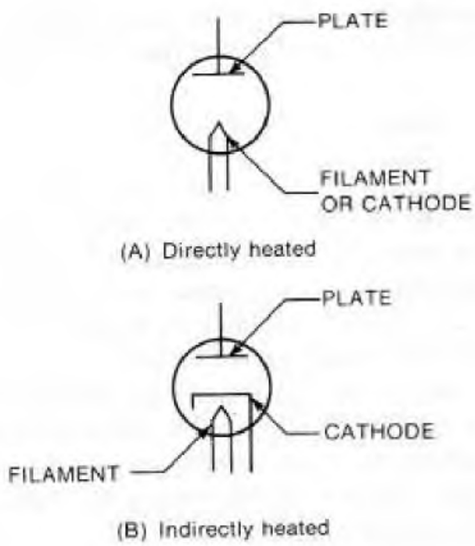


Figure 2-2
Diode Tube Schematic Diagrams

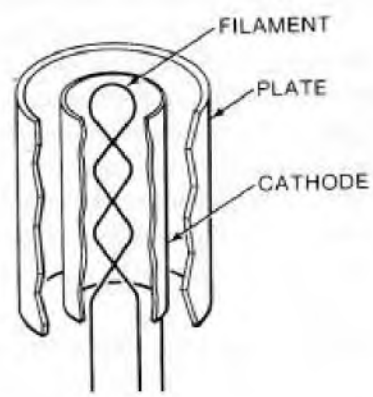


Figure 2-3
Cutaway of Diode Tube

When the indirectly heated cathode is raised to its correct temperature by the filament, it emits electrons just as the filament does. However, it is electrically insulated from the filament and this insulation allows us to place high voltages on a cathode when the circuit requires it.

If we take a diode tube and supply a variable plate voltage, as shown in Figure 2-4, we can plot the characteristic curve shown in Figure 2-5.

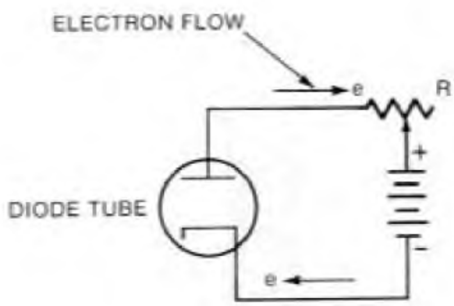


Figure 2-4
Diode Tube Circuit

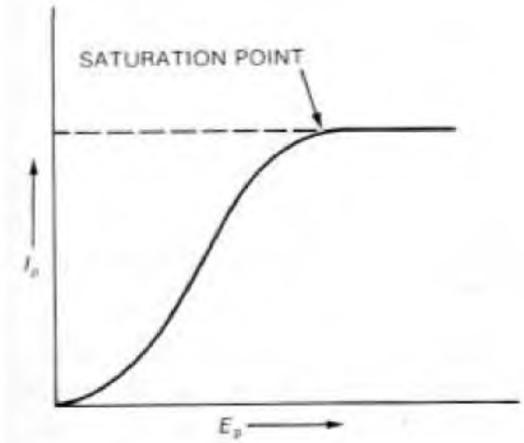


Figure 2-5
Diode Tube Characteristic Curve

Figure 2-5 has the characteristic plate current (I_p) on the vertical axis and plate voltage (E_p) on the horizontal axis. It can be seen that I_p is slow to increase at very low voltages, but at higher voltages I_p starts to increase rapidly at almost a linear rate up to a point where further increases in E_p will cause no further increases in current. This point is known as the tube's saturation point.

The diode tube acts as a switch, without moving mechanical parts that allows current to flow only in one direction. If we replace the plate voltage battery in Figure 2-4 with an AC source, as in Figure 2-6, the plate voltage will be first positive, then negative. Reference Figure 2-7.

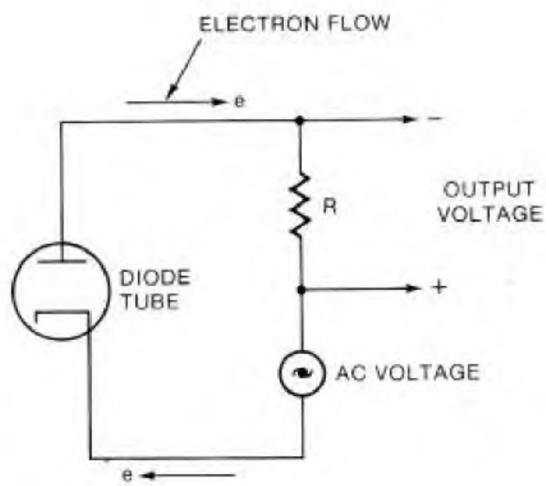


Figure 2-6
AC Applied to a Diode Tube

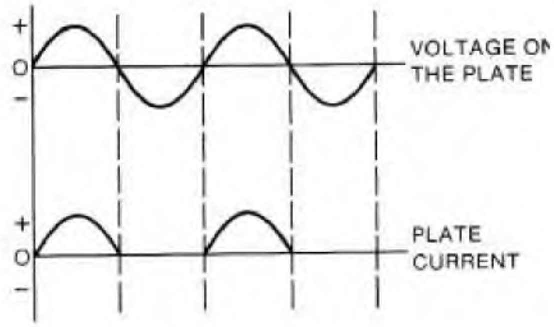


Figure 2-7
Graph of Voltage and Current in Plate of a Diode Tube

When current flows only during half of the input wave, the action is called half- wave rectification. This rectifying action can be visualized by plotting the input and output waveforms on the tube's characteristic curve, as shown in Figure 2-8.

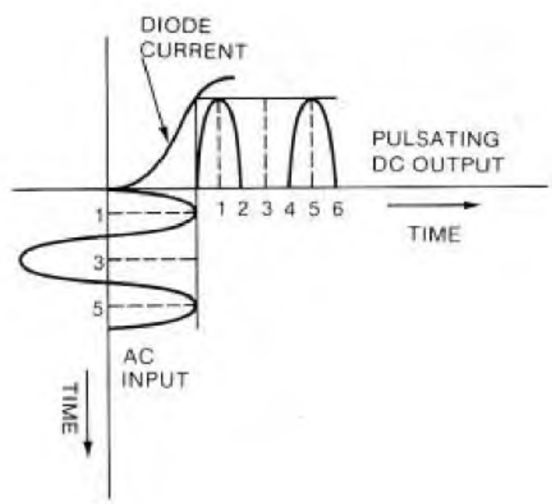


Figure 2-8
Graph of Rectifying Action

The characteristics of a given diode can be described by four important ratings:

1. **Maximum Plate Current (I_{max})**: The maximum current that can flow in the tube without damage.
2. **Plate Dissipation**: The power loss to heat, because of the electron bombardment of the plate,
3. **Peak Inverse Voltage (E_{piv})**: The maximum voltage that can be applied between elements of the tube in the off condition without damage.
4. **Plate resistance (R_p)**: The internal path resistance of the current within the tube itself. It is found by applying Ohm's law using I_p and E_p, as follows:

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

3 COMMON MULTIELEMENT TUBES

There are many tubes with more elements than the diode. For example, the *triode*, developed in 1907 when the. American inventor Lee DeForest inserted a third electrode between the cathode and the plate of a diode.

3.1 TRIODE TUBE:

Figure 3-1 shows the elements of a triode tube. Note that the *grid*, as the third element is called, is simply a wire wound in a spiral around the cathode with spacers to keep it at a specified distance.

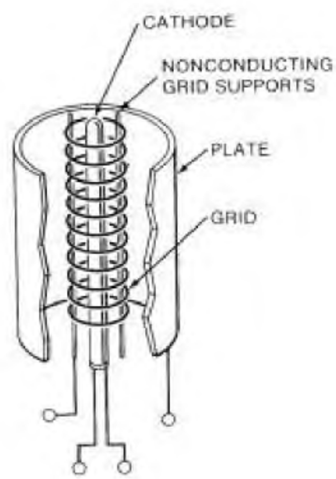


Figure 3-1
Elements of a Triode Tube

In the triode the flow of electrons is from the cathode to the plate, as it is in the diode. In the triode this current flow passes through the grid. This grid potential can be varied to control the amount of current through the tube. Figure 3-2 illustrates the three possible polarity states that the grid can have.

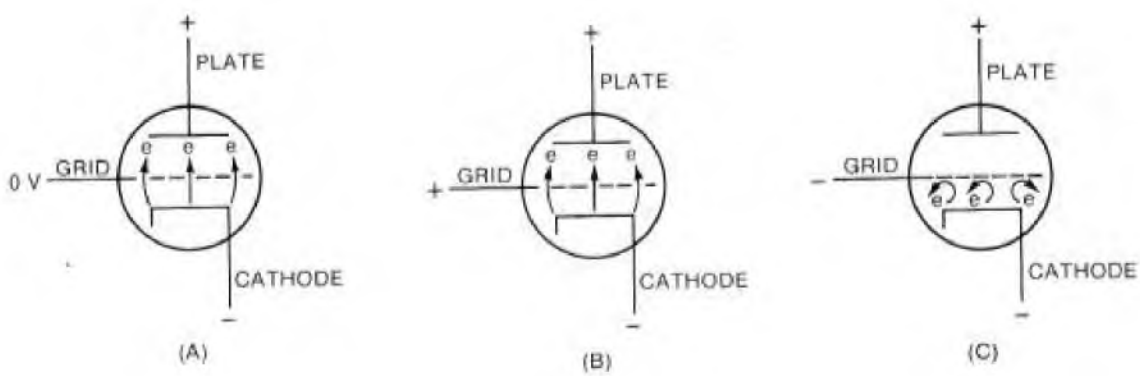


Figure 3-2
Grid Action in a Triode Tube

In part A of Figure 3-2 where the grid has 0 volts, or no charge, the grid has little effect on the current flow in the tube. In part B, the grid's positive voltage has an acceleration effect on the electrons flowing toward the plate. This causes an increase in IP. A positive EG that is too high may cause the plate to overheat.

In part C of Figure 3-2, where there is a negative grid voltage, electrons that would normally flow toward the plate are repelled back toward the cathode. If this grid voltage is negative enough, it causes the tube current to cease and the tube is said to be cut off.

The polarity of the grid voltage is always taken with respect to the cathode. Thus if the cathode is at a + 150 volts potential, then a voltage of + 145 on the grid would be a 5 volt negative grid voltage.

This grid voltage is often called the grid bias voltage and is designated by E_c or E_g. (The two terms are used interchangeably in this and most other texts.)

In the triode tube there are three basic quantities of particular interest to us. These are the grid voltage, or bias; the plate voltage (between plate and cathode); and the plate current. If these three values are known we can see how the tube works by plotting the values on a graph described as the set of the tube's characteristic curves.

Figure 3-3 is such a set of curves for a typical triode tube. Our example is the type 6SN7-GT tube. The curve designated "grid volts E_o = 0" is the curve for the tube connected to act as a diode. Looking back at Figure 2-5, note the resemblance between it and Figure 3-3.

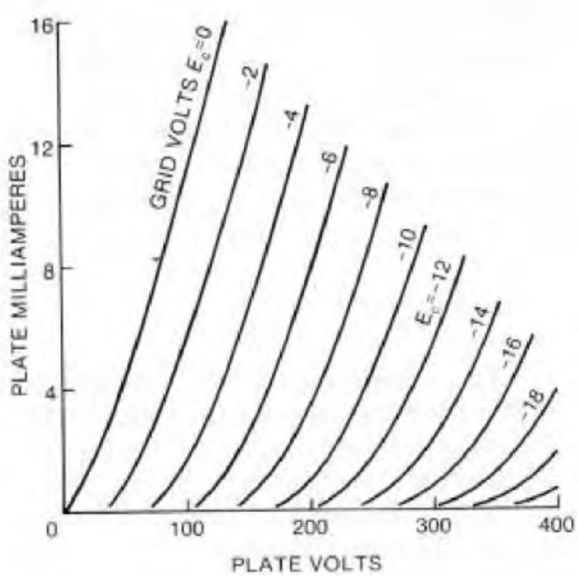


Figure 3-3
6SN7GT Average Plate Characteristics

In Figure 3-3 each curve was plotted with a different grid bias voltage. Notice that as the negative bias is increased, the plate voltage must be increased in order to obtain the same plate current. For example, if 4 mA of tube current is flowing with -2 volts of grid bias, the plate voltage is approximately 75 volts. However, if the grid bias is increased to -14 volts, a plate voltage of approximately 325 volts is needed to yield a plate current of 4 mA.

Let us examine the curves of Figure 3-3 a little further. Looking at the -2 volt bias curve at a plate voltage of 100 volts, we see that the plate current is 5.4 mA. Now if we increase the plate voltage to 125 volts and maintain the -2 volt bias, the plate current becomes 8.4 mA, an increase of 3 mA. If we maintain the plate voltage and change bias the plate current also increases, but here a much smaller voltage change is needed for the same amount of plate current increase. For example, assume the plate voltage is 200 volts and the bias is changed from -8 to -6 volts, an increase of +2 volts.

This will cause the plate current to increase from 3.4 mA to 7.6 mA, a plate current increase of only a +2 volt change in grid bias. This ratio of the change in plate voltage to grid voltage change, if the plate current change in each case is the same, is known as the tube's amplification factor, represented by the Greek letter μ. Thus a tube's μ is

$$\mu = \frac{\Delta E_p}{\Delta E_c}$$

The amplification factor describes the effect of the grid bias on the plate current. The value is generally determined by the way in which the tube is constructed. The nearer the grid is to the cathode, the larger its effect will be on the plate current.

Another important factor to consider is the elements in a tube act like the plates of a capacitor (vacuum dielectric). Thus by bringing the grid closer to the cathode, the interelectrode capacitance is increased. This capacitance is normally a very undesirable thing, as we will see later in our study.

The small change in grid bias causes a change in plate current is known as transconductance (gm). Transconductance is also known as mutual conductance. It can be determined by the equation:

$$gm = \frac{\Delta I_b}{\Delta e_c}$$

Transconductance of a tube is measured in micromhos. The micromho is 0.00000 I of a mho. As an example, a tube that has a 2 mA change (Δ) in P_l for 1 volt of change in grid bias, has a transconductance of 2,000 micromhos.

The three basic parameters are: grid bias, plate voltage, plate current. The relationship between the three basic parameters of a tube can be expressed as follows:

$$\mu = (gm)\ (r_p)$$

where gm is transconductance, r_p is plate resistance, and μ is the amplification factor.

Example 3-1

Problem: What is the amplification factor of a tube with a plate resistance of 1,500 ohms with a 5 mA change in plate current for a 2 volt change in bias?

Solution:

$$gm = \frac{5\ mA}{2\ volts} = 2.5 \times 10\text{-}3 \text{ or } 0.0025 \text{ mho.} = 2{,}500 \text{ micromhos}$$

$$\mu = (2{,}500)\ (7{,}500)$$

This is 0.0025 X 7500 to produce 18.75

$$\mu = 18.75$$

3.2 TETRODE TUBE:

Let us return for a moment to the interelectrode capacitance of a tube. If we allow the capacitance to become very large, any change in plate current will be fed back to the grid by this capacitive coupling. The capacitive coupling can be reduced by the use of an additional electrode placed between the grid and the plate, as shown in Figure 3-4. This tube with an extra grid (screen grid) is known as a tetrode.

A screen grid has the undesirable characteristic of collecting the electrons knocked off the plate (secondary emission). The collecting of these electrons will cause a dip in the plate current characteristic curve, as shown in Figure 7-18..

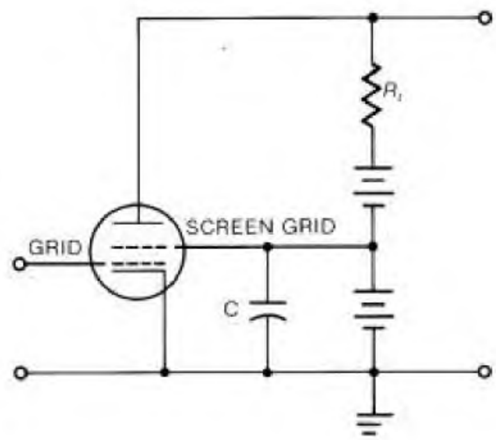


Figure 3-4
Tetrode Circuit

3.3 PENTODE TUBE:

This dip can be eliminated by the addition of still another grid called the suppressor grid. A tube with a suppressor grid (called a pentode) is diagrammed in Figure 3-5. It is inserted between the screen grid and the plate. The suppressor grid is usually connected to the cathode and thus is normally negative with respect to the plate. The suppressor grid is able to repel the secondary emission electrons back to the plate and so prevent a dip in the I_p E_p curve.

In a pentode the amplification factor can have a very high value, often in the order of 1,400 micromhos or greater. The r p is also very high, in the order of 1.5 megohms. The transconductance (gm) of the pentode is normally lower than that of a tetrode, but some do have gm in the order of 8,000 or 9,000.

There are many tubes that have more than three grids, but only the heptode (five grids), known as the pentagrid mixer or converter, is at all common in tube equipment.

The schematic symbol for this tube is shown in Figure 7-21.

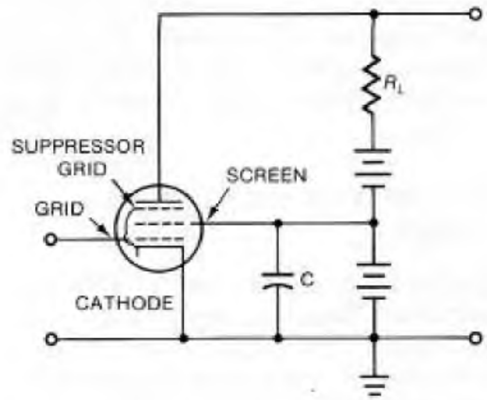


Figure 7-21
Pentagrid Tube

It is common in tube equipment to have several tubes within one envelope. An example is the 12AX7, which has two triode sections within one envelope.

As a general rule for most tubes, the first digit or two in the type number indicates the filament voltage. For example, the 6BA6 has a 6.3 volt filament and the 12AX7 has a 12.6 volt filament. The final digit is the number of elements contained in the envelope. The 12AX7, for- example, has seven elements-two plates, two grids, two cathodes, and one filament. A particular tube is often available with a variety of filament voltages; for example, a 6CD6 and a 12CD6 would be identical except for the filament voltage.

4 VHF AND MICROWAVE TUBES

Special tubes are used in VHF and microwave frequency spectrum that take advantage of the special qualities of cavity resonators or electron transit time resonance. In Figure 4-1 are examples of some VHF and microwave tubes that are still in use in some older microwave equipment.

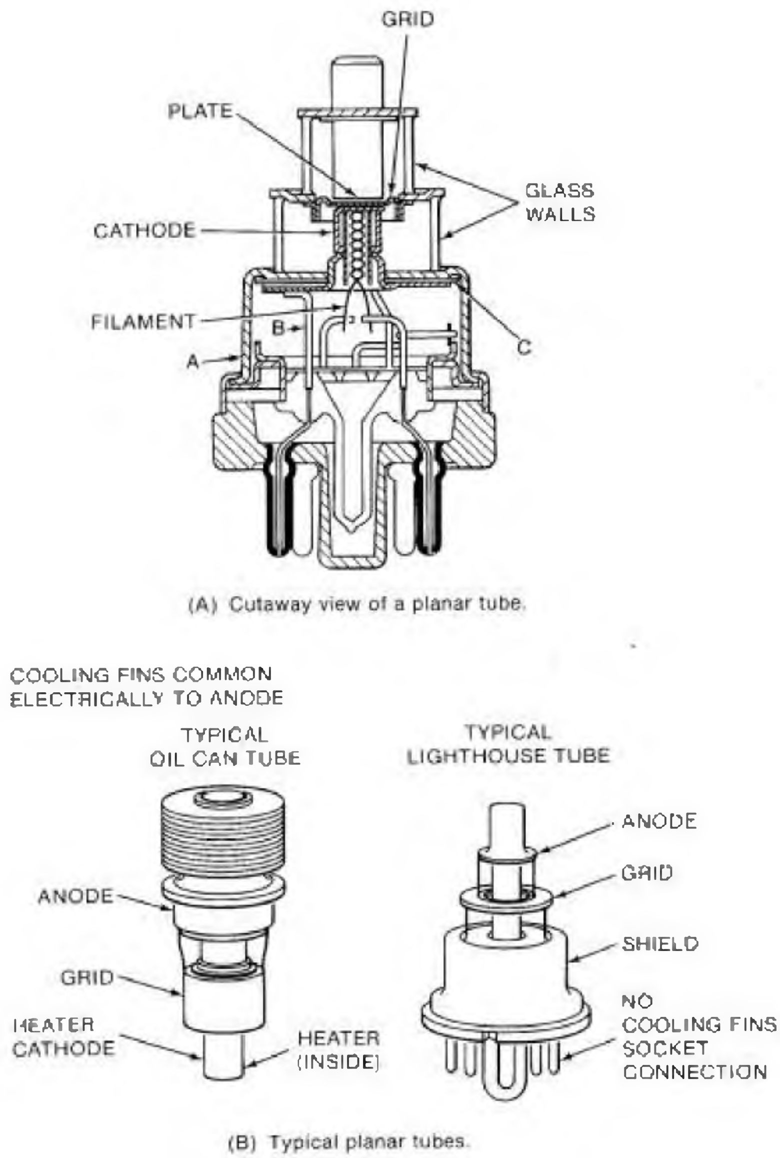


Figure 4-1
Typical VHF Tubes

A planar or lighthouse tube is a common VHF or microwave oscillator amplifier used in VHF equipment. It is not often used in new designs because existing technology has provided better devices for the purpose.

Figure 4-1A shows a cutaway drawing of a typical planar triode tube. Note tube elements are arranged in parallel planes rather than in concentric cylinders used in construction of most other tubes.

Figure 4-1B shows two examples of planar tubes in use today.

4.1 THE KLYSTRON:

One of the most common microwave tubes still in use is a klystron. Figure 4-2 is a picture of a small tunable klystron, this one is about 4 feet tall and used in a HITAB Command transmitter.

A basic klystron tube consists of four parts: a beam or electron source, a velocity modulating unit called a buncher, a drift tube where the velocity-modulated beam travels, and a catcher that removes energy from the velocity modulated beam. These basic sections are detailed in Figure 4-3.

The beam source is an electron gun similar to cathode ray tubes. The electron beam is emitted from a heated cathode, and flows along converging paths. It looks like a tetrode tube without a plate. The control grid, as usual, controls the number of electrons allowed to move toward the catcher while the accelerating grid speeds up any electrons passed by the control grid. The electron velocity is adjusted by varying voltage on the accelerating grid. (Reference Figure 4-4A)

Figure 4-2
Klystron Tube

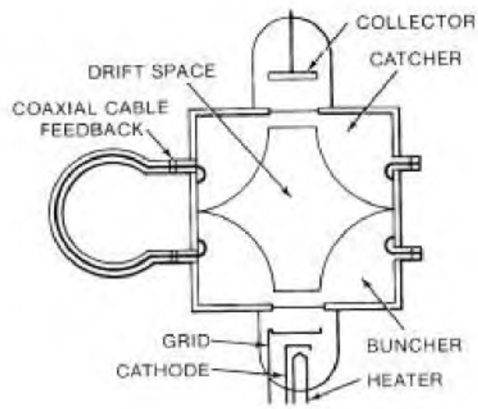


Figure 4-3
Cutaway of Klystron Tube

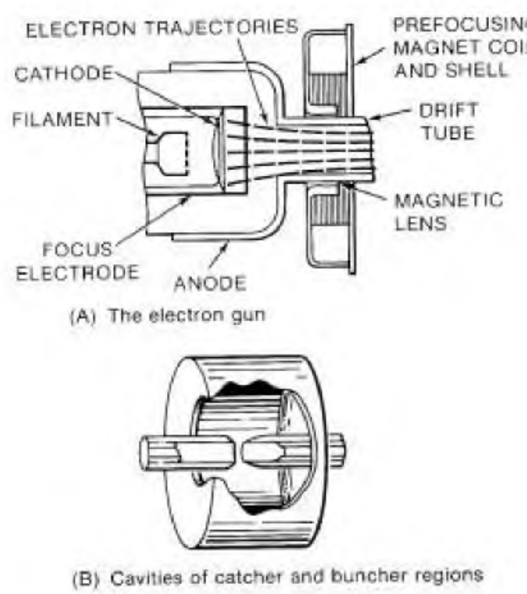


Figure 4-4
Klystron Electron Gun

A buncher, or cavity, and drift space region is made up of the drift tube and two to four resonant cavities surrounding the tube at preset intervals. The drift tube itself is an axial-interrupted tube where electrons are neither accelerated nor decelerated. The drift tube's length to diameter ratio is about 20: 1. Each of the interruption points along the tube has an associated buncher cavity constructed so that the drift tube tips in the cavity to become the capacitive loading elements of the cavity. Thus, very large RF voltages are impressed across them. The cylindrical structure of the cavity forms the inductive element of the cavity.

The final element in a klystron is the collector, or catcher. The catcher simply gathers the electrons after their function has been completed and returns them to the beam power supply. The collector must dissipate the large energy content of the spent electron beam; therefore, the collector must be cooled to transfer this energy from the tube. In high power klystrons, the tube is liquid-cooled to dissipate heat.

In high power amplifier type klystrons a very strong axial magnetic field is used to direct and maintain the electron beam in the drift tube. There is one magnetic coil per cavity. A typical high power klystron is shown in Figure 4-5.

When the electron beam leaves the electron gun, it is in one continuous stream and will not produce radio frequency power as it flows through the klystron. As a result, the beam must be varied to be useful. This is accomplished by the drift tube cavity group, which changes the relative velocity of the electrons in the beam.

A special type of klystron, known as the reflex klystron, is shown in cutaway form in Figure 4-6. This klystron has only one cavity, but its principle of operation is the same as other klystrons.

Klystron operation itself is simple. The beam of electrons is fed to the buncher cavities. They are velocity modulated by feeding energy to the cavity. This energy causes the beam electrons to either slow or accelerate, and this causes them to gather in groups or bunches as they progress down the drift tube. When the tube is correctly adjusted, this bunching occurs at the microwave frequency. The bunched electrons pass through the catcher grids at the microwave frequency. The bunching acts like an ac current between the catcher grids and will excite the catcher. Thus the klystron acts as an amplifier, taking in energy at a low level at the buncher cavity and providing a high level output at the catcher cavity.

If some of the output is fed back to the input, the tube will oscillate.

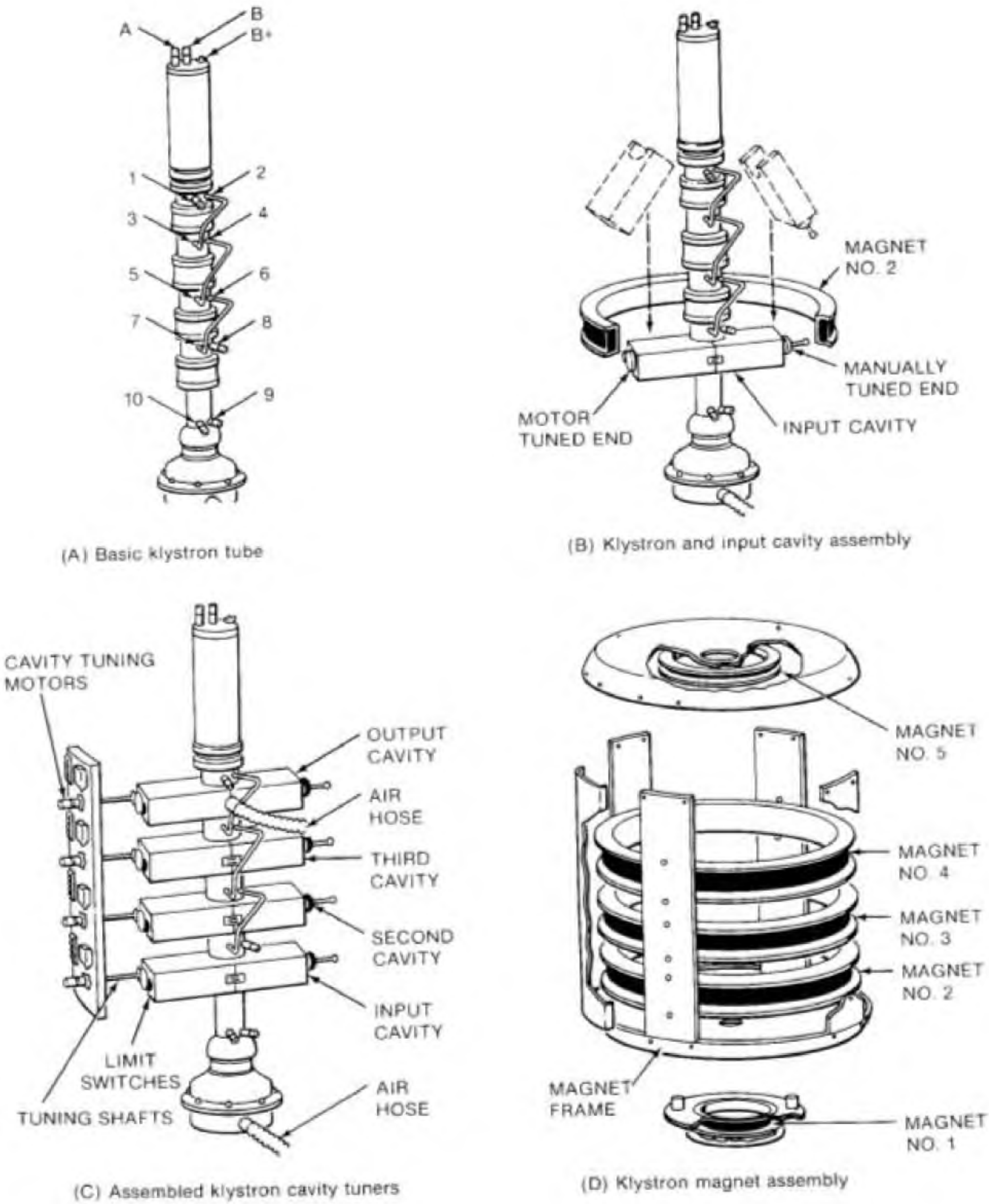


Figure 4-5
High Power Klystron Breakdown

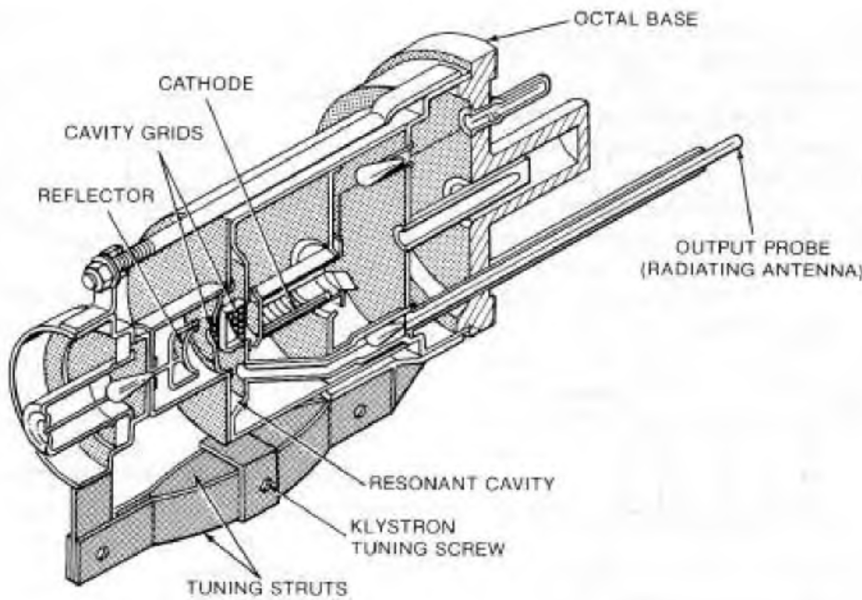


Figure 4-6
Reflex Klystron Cutaway

4.2 MAGNETRON TUBE:

Except for the klystron, the magnetron is the most common microwave tube. The magnetron is a device that depends upon resonant cavities within its structure to operate.

Before we proceed with how the magnetron operates, we will take a brief look at how it is built. In Figure 4-7, we see a picture of a small 5 KW magnetron used in tracking radar. Note the large magnets attached to the central body. These magnets can be rated well in excess of 15,000 gauss.

Figure 4-7
Small Magnetron

Figure 4-8 illustrates the anode of the magnetron showing the hole and slot system of resonant cavities in a simple magnetron. Part A of the figure is a view on the axis of the cylinder that shows only the main outline of the anode. Each of the cavities consists of a cylindrical hole joined to the central space by a small slot. Although six cavities are shown, magnetrons with other numbers of cavities are not uncommon. Part B is a sectional view of the anode in perspective. There are no cavity grids in a magnetron. Instead, the electric field generated in the resonant cavity is what modulates the circular electron beam. This field is illustrated in Figure 4-9.

The cathode generating the electron beam is normally placed along the axis of the anode, as shown in Figure 4-10.

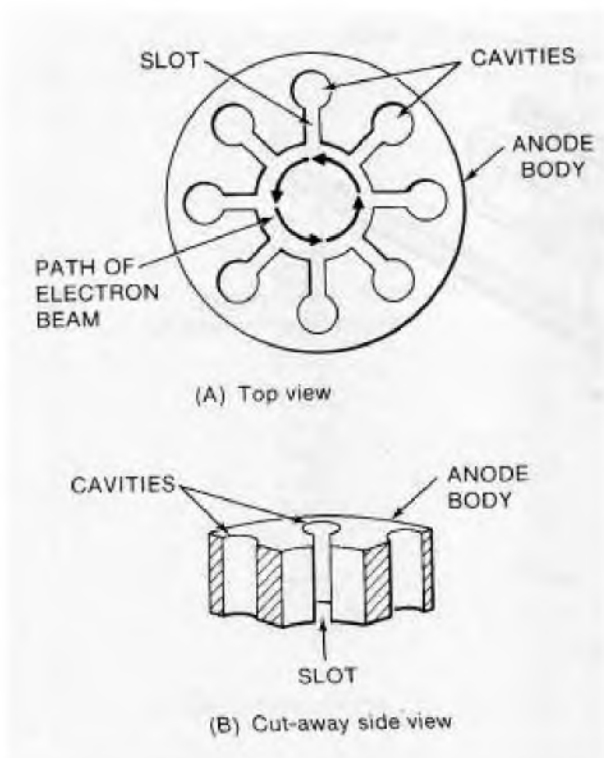


Figure 4-8
Hole and Slot Resonate Cavity

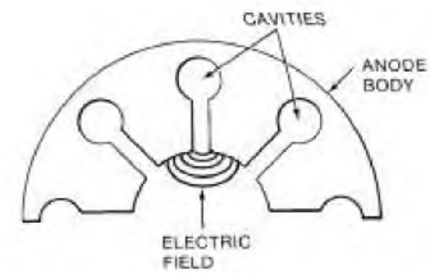


Figure 4-9
Electric Field in the Slot

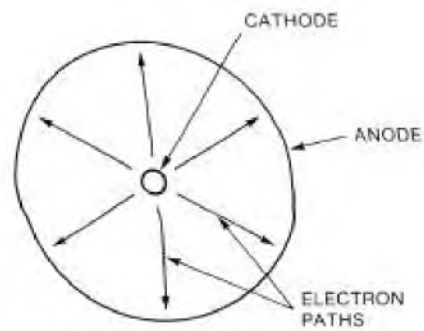


Figure 4-10
Electron Paths in a Magnetron Without a Magnetic Field

Except for the cavities in the anode, a magnetron is a simple diode tube. If there were no magnetic field, the tube would act like any other diode tube. The electrons would travel radically outward from the cathode to the anode, as shown in Figure 4-11.

In Figure 4-12 we can see how the electron path is affected if a magnetic field is applied to the axis of the anode. In part A we see a very low magnetic field strength and the electron paths are curved slightly. A stronger magnetic field or a lower voltage between cathode and anode will lead to the more sharply curved paths shown in part B. When the correct relation exists between the magnetic field strength and the cathode-anode voltage, the electron paths are like those shown in Figure 4-13A. This is a rather idealized picture, since it neglects all interaction between the electrons and also neglects the effect of the cavities. In practice, collisions between the electrons disrupt the simple path that runs from cathode to anode and back again. The actual path spirals outward so that the electrons ultimately are captured by the anode, as shown in part B.

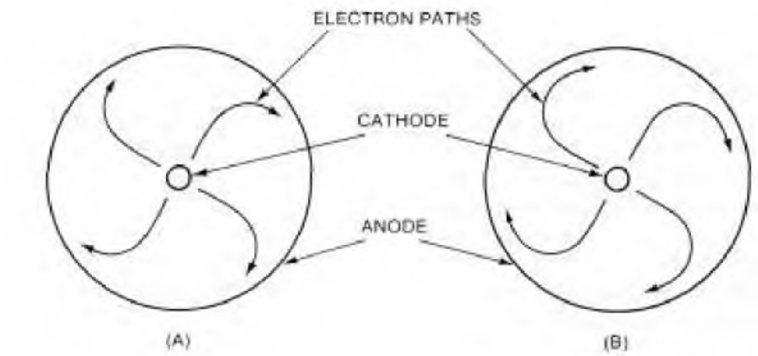


Figure 4-12
Electron Paths affected by a Magnetic Field

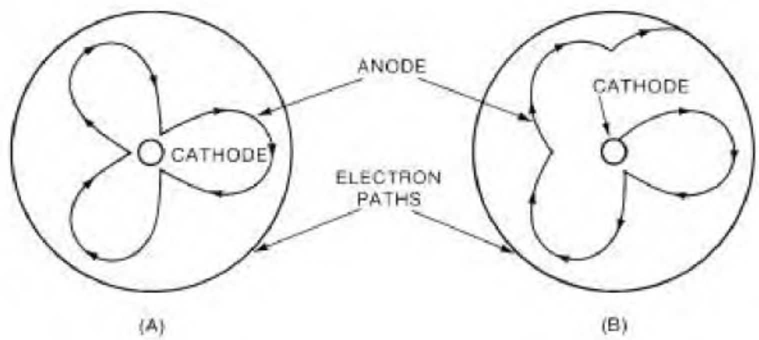


Figure 4-13
Electron Paths with a Correct

Correct electron paths can be obtained with almost any anode voltage if the correct magnetic field is used. If the correct voltage is applied to the anode, the possibility of oscillation (transfer of energy from the electrons to the cavities) depends on the relations between electron velocities, and spacing between the various anode cavities, and the resonant frequency of those various cavities. Because of this interaction, the magnetron will oscillate only over a very narrow range of magnetic field strengths arid anode voltages.

The basic operation of the magnetron is not as involved as it may sound. The magnetic field causes the electrons to pass energy to the cavities as they go by them. The anode removes the electrons from the system as they slow up.

Because of the nature of a magnetron, it can be affected by changes in the output impedance. A change in load will vary not only the power output, but also the frequency. Therefore care must be taken in a magnetron's operation to prevent these changes, which are known as pulling, from occurring. .

Magnetrons are available in many sizes, up to 10 kilowatts output for pulse work. In pulse service a duty cycle of 1/ 1000 is common. That is, an output for only about 1/1000 (on for I microsecond, and off for 1000 microseconds). There are magnetrons available for high duty cycles and even continuous duty operation, but these are normally lower powered types. In general, as the frequency of the operation is increased, the physical structure of the magnetron is smaller because of the smaller size needed in the resonant cavities. A magnetron is normally about 35 percent efficient. Thus a small physical size will limit the power output because of heat dissipation limitations.

5 CATHODE RAY TUBES:

The cathode ray tube, or CRT as it is commonly known, is a special type of tube where the electrons emitted by the cathode are concentrated into a small narrow beam. This beam of electrons is accelerated to a very high velocity before striking a specially treated phosphor screen which, when struck by the electron beam, it glows.

In the previous section we saw how an electron beam can be affected by a magnetic field or an electrostatic field. This control of an electron beam can be used to focus it into one spot, and by an additional set of electrostatic or magnetic deflection controls, a beam can be directed to any point on the CR T screen.

In Figure 5-1 we see an example of an electrostatic focusing system for a CRT using magnetic fields to accomplish the focusing. Figure 5-2 is the optical equivalent of Figure 5-1. However, operating the basic principle of all CR Ts is the same.

Deflection of the electron beam in a CRT is accomplished by either an electric field on deflection plates or by electromagnets called deflection coils mounted outside of the tube. There are several different kinds of phosphors used, varying in chemical structure and thus in persistence (glow time) and color (among other things). Most oscilloscope CRT faceplates are coated with a green-emitting phosphor, because green phosphors are most efficient.

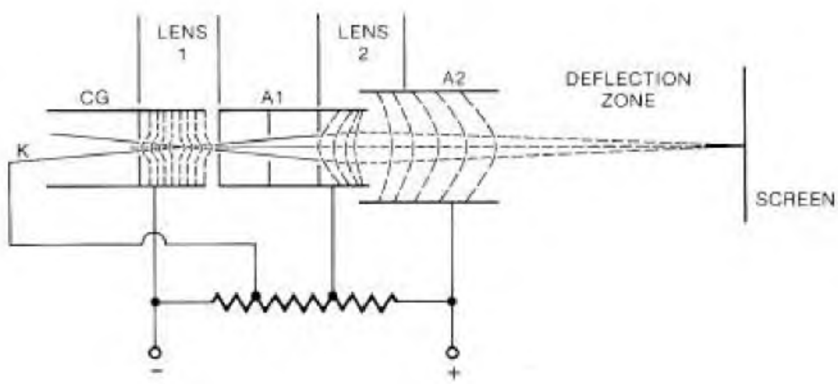


Figure 5-1
Cathode Ray Tube

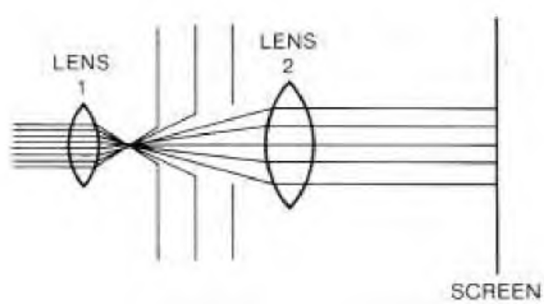


Figure 5-2
Optical Equivalent of a CRT