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Chapter

3

Vacuum Tube Principles

3.1 Introduction

A power grid tube is a device using the flow of free electrons in a vacuum to produce useful work [1]. It has an emitting surface (the cathode), one or more grids that control the flow of electrons, and an element that collects the electrons (the anode). Power tubes can be separated into groups according to the number of electrodes (grids) they contain. The physical shape and location of the grids relative to the plate and cathode are the main factors that determine the *amplification factor* (μ) and other parameters of the device (see Section 3.2.5). The physical size and types of material used to construct the individual elements determine the power capability of the tube. A wide variety of tube designs are available to commercial and industrial users. By far the most common are triodes and tetrodes.

3.2 Characteristics of Electrons

Electrons are minute, negatively charged particles that are constituents of all matter. They have a mass of 9×10^{-28} g (1/1840 that of a hydrogen atom) and a charge of 1.59×10^{-19} coulomb. Electrons are always identical, irrespective of their source. Atoms are composed of one or more such electrons associated with a much heavier nucleus, which has a positive charge equal to the number of the negatively charged electrons contained in the atom; an atom with a full quota of electrons is electrically neutral. The differences in chemical elements arise from differences in the nucleus and in the number of associated electrons.

Free electrons can be produced in a number of ways. *Thermonic emission* is the method normally employed in vacuum tubes (discussed in Section 3.2.2). The principle of thermonic emission states that if a solid body is heated sufficiently, some of the electrons that it contains will escape from the surface into the surrounding space. Electrons also are ejected from solid materials as a result of the impact of rapidly moving electrons or ions. This phenomenon is referred to as *secondary electron emission*, because it is necessary to have a primary source of electrons (or ions) before the secondary emission can be obtained (Section 3.2.3). Finally, it is possible to pull electrons directly out of solid substances by an intense electrostatic field at the surface of the material.

Positive ions represent atoms or molecules that have lost one or more electrons and so have become charged bodies having the weight of the atom or molecule concerned, and a positive charge equal to the negative charge of the lost electrons. Unlike electrons, positive ions are not all alike and may differ in charge or weight, or both. They are much heavier than electrons and resemble the molecule or atom from which they are derived. Ions are designated according to their origin, such as mercury ions or hydrogen ions.

3.2.1 Electron Optics

Electrons and ions are charged particles and, as such, have forces exerted upon them by an electrostatic field in the same way as other charged bodies. Electrons, being negatively charged, tend to travel toward the positive or anode electrode, while the positively charged ions travel in the opposite direction (toward the negative or cathode electrode). The force F exerted upon a charged particle by an electrostatic field is proportional to the product of the charge e of the particle and the voltage gradient G of the electrostatic field [1]:

$$F = G \times e \times 10^{7} \tag{3.1}$$

Where:
F = force in dynes
G = voltage gradient in volts per centimeter
e = charge in coulombs

This force upon the ion or electron is exerted in the direction of the electrostatic flux lines at the point where the charge is located. The force acts toward or away from the positive terminal, depending upon whether a negative or positive charge, respectively, is involved.

The force that the field exerts on the charged particle causes an acceleration in the direction of the field at a rate that can be calculated by the laws of mechanics where the velocity does not approach that of light:

$$A = \frac{F}{M} \tag{3.2}$$

Where:
A = acceleration in centimeters per second per second
F = force in dynes
m = mass in grams

The velocity an electron or ion acquires in being acted upon by an electrostatic field can be expressed in terms of the voltage through which the electron (or ion) has fallen in acquiring the velocity. For velocities well below the speed of light, the relationship between velocity and the acceleration voltage is:

$$v = \sqrt{\frac{2 \times V \times e \times 10^7}{m}} \tag{3.3}$$

Where:
v = velocity in centimeters per second corresponding to V
V = accelerating voltage
e = charge in coulombs
m = mass in grams

Electrons and ions move at great velocities in even moderate-strength fields. For example, an electron dropping through a potential difference of 2500 V will achieve a velocity of approximately one-tenth the speed of light.

Electron optics, as discussed in this section, relies on the principles of classical physics. While modern tube design uses computer simulation almost exclusively, the preceding information is still valid and provides a basis for the understanding of electron motion within a vacuum tube device.

Magnetic Field Effects

An electron in motion represents an electric current of magnitude ev, where e is the magnitude of the charge on the electron and v is its velocity. A magnetic field accordingly exerts a force on a moving electron exactly as it exerts a force on an electric current in a wire. The magnitude of the force is proportional to the product of the equivalent current ev represented by the moving electron and the strength of the component of the magnetic field in a direction at right angles to the motion of the electron. The resulting force is, then, in a direction at right angles both to the direction of motion of the electron and to the component of the magnetic field that is producing the force. As a result, an electron entering a magnetic field with a high velocity will follow a curved path. Because the acceleration of the electron that the force of the magnetic field produces is always at right angles to the direction in which the electron is traveling, an electron moving in a uniform magnetic field will follow a circular path. The radius of this circle is determined by the strength of the magnetic field and the speed of the electron moving through the field.

When an electron is subjected to the simultaneous action of both electric and magnetic fields, the resulting force acting on the electron is the vector sum of the force resulting from the electric field and the force resulting from the magnetic field, each considered separately.

Magnetic fields are not used for conventional power grid tubes. Microwave power tubes, on the other hand, use magnetic fields to confine and focus the electron stream.

3.2.2 Thermal Emission From Metals

Thermonic emission is the phenomenon of an electric current leaving the surface of a material as the result of thermal activation. Electrons with sufficient thermal energy to overcome the surface-potential barrier escape from the surface of the material. This thermally emitted electron current increases with temperature because more electrons have sufficient energy to leave the material.

The number of electrons released per unit area of an emitting surface is related to the absolute temperature of the emitting material and a quantity b that is a measure of the work an electron must perform in escaping through the surface, according to the equation [1]:

$$I = A T^{2} \varepsilon^{-b/T} \tag{3.4}$$

Where:
T = absolute temperature of the emitting material
b = the work an electron must perform in escaping the emitter surface
I = electron current in amperes per square centimeter
A = a constant (value varies with type of emitter)

The exponential term in the equation accounts for most of the variation in emission with temperature. The temperature at which the electron current becomes appreciable is accordingly determined almost solely by the quantity b. Figure 3.1 plots the emission resulting from a cathode operated at various temperatures.

Thermal electron emission can be increased by applying an electric field to the cathode. This field lowers the surface-potential barrier, enabling more electrons to escape. This field-assisted emission is known as the *Schottky effect*.

Figure 3.2 illustrates common heater-cathode structures for power tubes.

3.2.3 Secondary Emission

Almost all metals and some insulators will emit low-energy electrons (secondary electrons) when bombarded by other energetic electrons. The number of secondary electrons emitted per primary electron is determined by the velocity of the primary bombarding electrons and the nature and condition of the material composing the surface being bombarded. Figure 3.3 illustrates a typical relationship for two types of surfaces. As shown in the figure, no secondary electrons are produced when the primary velocity is low. However, with increasing potential (and consequently higher velocity), the ratio of secondary to primary electrons increases, reaching a maximum and then decreasing. With pure metal surfaces, the maximum ratio of secondary to primary electrons ranges from less than 1 to approximately 3. Some complex surfaces based on alkali metal compounds yield ratios of secondary to primary electrons as high as 5 to 10.

The majority of secondary electrons emitted from a conductive surface have relatively low velocity. However, a few secondary electrons usually are emitted with a velocity nearly equal to the velocity of the bombarding primary electrons.

For insulators, the ratio of secondary to primary electrons as a function of primary electron potential follows along the same lines as for metals. The net potential of the insulating surface being bombarded is affected by the bombardment. If the ratio of secondary to primary current is less than unity, the insulator acquires a net negative charge

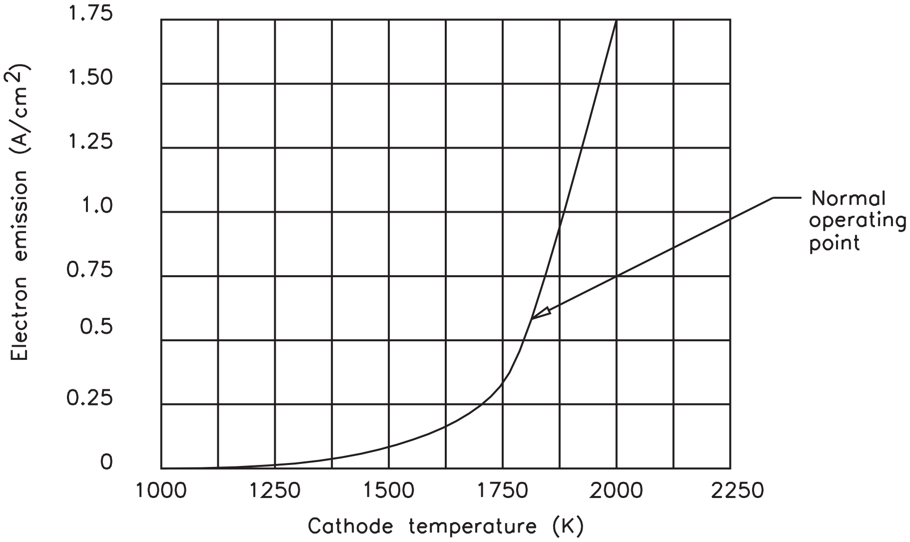


Figure 3.1 Variation of electron emission as a function of absolute temperature for a thoriated-tungsten emitter.

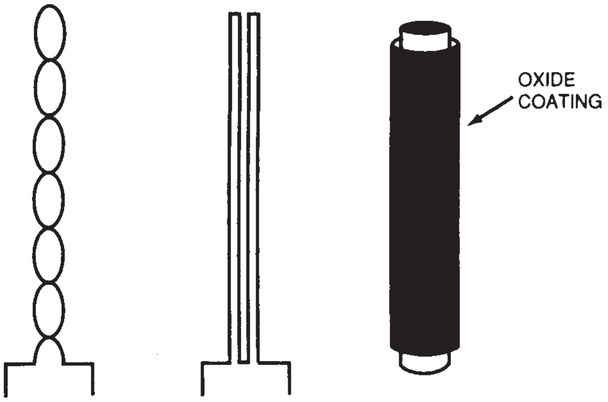


Figure 3.2 Common types of heater and cathode structures. (*From* [2]. *Used with permission.*)

because more electrons arrive than depart. This causes the insulator to become more negative and, finally, to repel most of the primary electrons, resulting in a blocking action. In the opposite extreme, when the ratio of secondary to primary electrons exceeds unity, the insulating surface loses electrons through secondary emission faster than

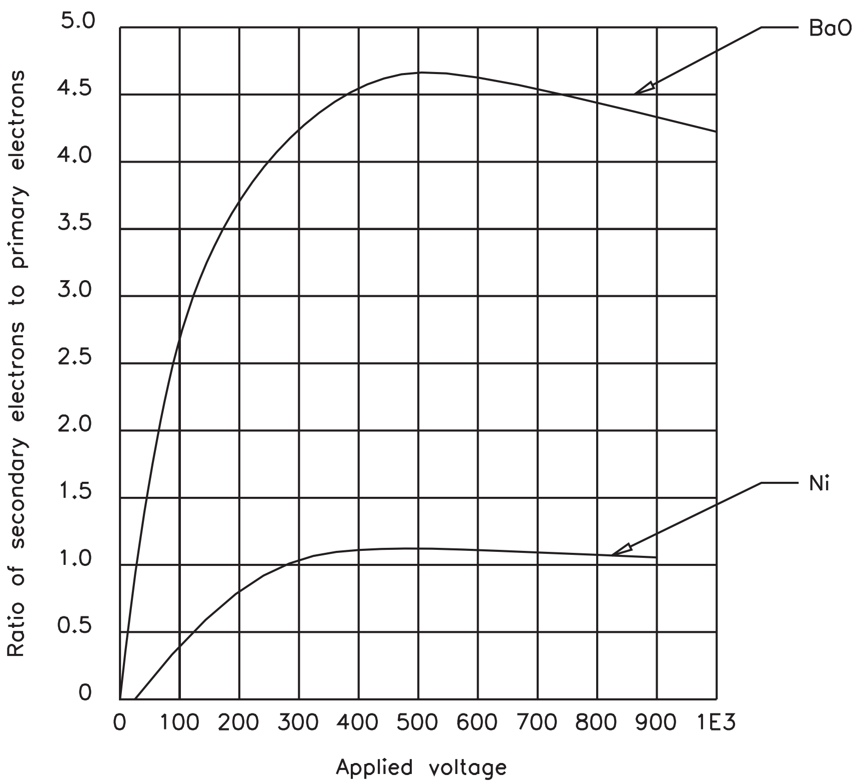


Figure 3.3 Ratio of secondary emission current to primary current as a function of primary electron velocity.

they arrive; the surface becomes increasingly positive. This action continues until the surface is sufficiently positive that the ratio of secondary to primary electrons decreases to unity as a result of the increase in the velocity of the bombarding electrons, or until the surface is sufficiently positive that it attracts back into itself a significant number of secondary electrons. This process makes the number of electrons gained from all sources equal to the number of secondary electrons emitted.

3.2.4 Diode

A diode is a two-electrode vacuum tube containing a cathode, which emits electrons by thermonic emission, surrounded by an anode (or plate). (See Figure 3.4) Such a tube is inherently a rectifier because when the anode is positive, it attracts electrons; current, therefore, passes through the tube. When the anode is negative, it repels the electrons and no current flows.

The typical relationship between anode voltage and current flowing to the positive anode is shown in Figure 3.5. When the anode voltage is sufficiently high, electrons are

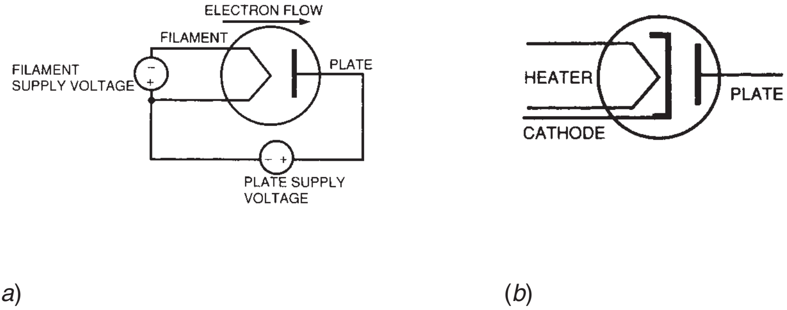


Figure 3.4 Vacuum diode: (*a*) directly heated cathode, (*b*) indirectly heated cathode. (*From* [2]. *Used with permission.*)

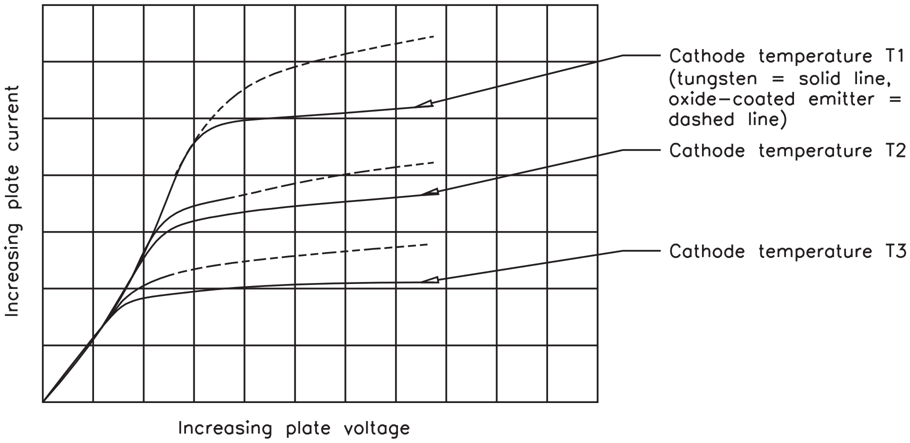


Figure 3.5 Anode current as a function of anode voltage in a two-electrode tube for three cathode temperatures.

drawn from the cathode as rapidly as they are emitted. The anode current is then limited by the electron emission of the cathode and, therefore, depends upon cathode temperature rather than anode voltage.

At low anode voltages, however, plate current is less than the emission of which the cathode is capable. This occurs because the number of electrons in transit between the cathode and plate at any instant cannot exceed the number that will produce a negative *space charge*, which completely neutralizes the attraction of the positive plate upon the electrons just leaving the cathode. All electrons in excess of the number necessary to neutralize the effects of the plate voltage are repelled into the cathode by the negative space charge of the electrons in transit; this situation applies irrespective of how many excess electrons the cathode emits. When the plate current is limited in this way by space charge, plate current is determined by plate potential and is substantially independent of the electron emission of the cathode.

Detailed examination of the space-charge situation will reveal that the negative charge of the electrons in transit between the cathode and the plate is sufficient to give the space in the immediate vicinity of the cathode a slight negative potential with respect to the cathode. The electrons emitted from the cathode are projected out into this field with varying emission velocities. The negative field next to the cathode causes the emitted electrons to slow as they move away from the cathode, and those having a low velocity of emission are driven back into the cathode. Only those electrons having the highest velocities of emission will penetrate the negative field near the cathode and reach the region where they are drawn toward the positive plate. The remainder (those electrons having low emission velocities) will be brought to a stop by the negative field adjacent to the cathode and will fall back into the cathode.

The energy that is delivered to the tube by the source of anode voltage is first expended in accelerating the electrons traveling from the cathode to the anode; it is converted into kinetic energy. When these swiftly moving electrons strike the anode, this kinetic energy is then transformed into heat as a result of the impact and appears at the anode in the form of heat that must be radiated to the walls of the tube.

The basic function of a vacuum tube diode—to rectify an ac voltage—has been superseded by solid-state devices. An understanding of how the diode operates, however, is important in understanding the operation of triodes, tetrodes, and pentodes.

3.2.5 Triode

The power triode is a three-element device commonly used in a wide variety of RF generators. Triodes have three internal elements: the cathode, control grid, and plate. Most tubes are cylindrically symmetrical. The filament or cathode structure, the grid, and the anode all are cylindrical in shape and are mounted with the axis of each cylinder along the center line of the tube, as illustrated in Figure 3.6.

The grid normally is operated at a negative potential with respect to the cathode, and so attracts no electrons. However, the extent to which it is negative affects the electrostatic field in the vicinity of the cathode and, therefore, controls the number of electrons that pass between the grid and the plate. The grid, in effect, functions as an imperfect electrostatic shield. It allows some, but not all, of the electrostatic flux from the anode to leak between its wires. The number of electrons that reach the anode in a triode tube under space-charge-limited conditions is determined almost solely by the electrostatic field near the cathode; the field in the rest of the interelectrode space has little effect. This phenomenon results because the electrons near the cathode are moving slowly compared with the electrons that have traveled some distance toward the plate. The result of this condition is that the volume density of electrons in proportion to the rate of flow is large near the cathode and low in the remainder of the interelectrode space. The total space charge of the electrons in transit toward the plate, therefore, consists almost

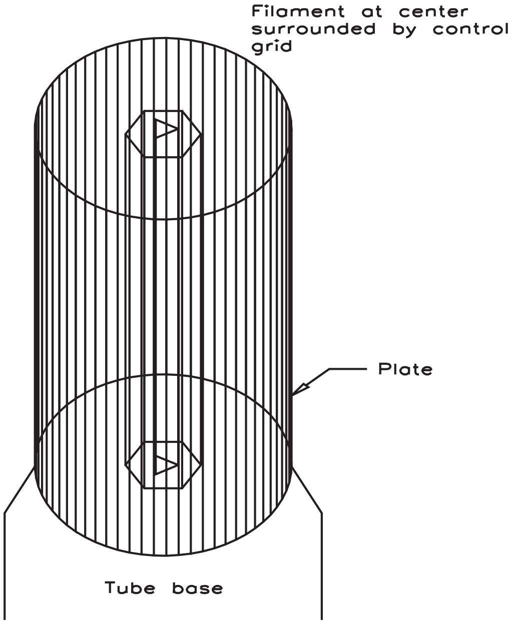


Figure 3.6 Mechanical configuration of a power triode.

solely of the electrons in the immediate vicinity of the cathode. After an electron has traveled beyond this region, it reaches the plate so quickly as to contribute to the space charge for only a brief additional time interval. The result is that the space current in a three-electrode vacuum tube is, for all practical purposes, determined by the electrostatic field that the combined action of the grid and plate potentials produces near the cathode.

When the grid structure is symmetrical, the field E at the surface of the cathode is proportional to the quantity:

$$\frac{E_c + E_b}{\mu} \tag{3.5}$$

Where:
E_c = control grid voltage (with respect to cathode)
E_b = anode voltage (with respect to cathode)
μ = a constant determined by the geometry of the tube

The constant μ, the amplification factor, is independent of the grid and plate voltages. It is a measure of the relative effectiveness of grid and plate voltages in producing electrostatic fields at the surfaces of the cathode. Placement of the control grid relative to the cathode and plate determines the amplification factor. The μ values of triodes generally range from 5 to 200. Key mathematical relationships include the following:

$$\mu = \frac{\Delta E_b}{\Delta E_{c1}} \tag{3.6}$$

$$R_p = \frac{\Delta E_b}{\Delta I_b} \tag{3.7}$$

$$S_m = \frac{\Delta I_b}{\Delta E_{c1}} \tag{3.8}$$

Where:
μ = amplification factor (with plate current held constant)
R_p = dynamic plate resistance
S_m = transconductance (also may be denoted G_m)
E_b = total instantaneous plate voltage
E_{c1} = total instantaneous control grid voltage
I_b = total instantaneous plate current

The total cathode current of an ideal triode can be determined from the equation:

$$I_k = \left\{ E_c + \frac{E_b}{\mu} \right\}^{3/2} \tag{3.9}$$

Where:
I_k = cathode current
K = a constant determined by tube dimensions
E_c = grid voltage
E_b = plate voltage
μ = amplification factor

Figure 3.7 plots plate and grid current as a function of plate voltage at various grid voltages for a triode with a μ of 12. The tube, a 304TL, is a classic design and, while not used in new equipment, provides a common example of the relationship between the parameters plotted. Figure 3.8 plots the same parameters for a tube with a μ of 20. Observe how much more plate current at a given plate voltage can be obtained from the 304TL (μ = 12) without driving the grid into the positive grid region. Note also how much more bias voltage is required for the 304TL to cut the plate current off at some given plate voltage. With this increased bias, there is a corresponding increase in grid voltage swing to drive up the zero grid voltage point on the curve. Low-μ tubes have lower voltage gain by definition. This fact can be seen by comparing Figures 3.7 and 3.8.

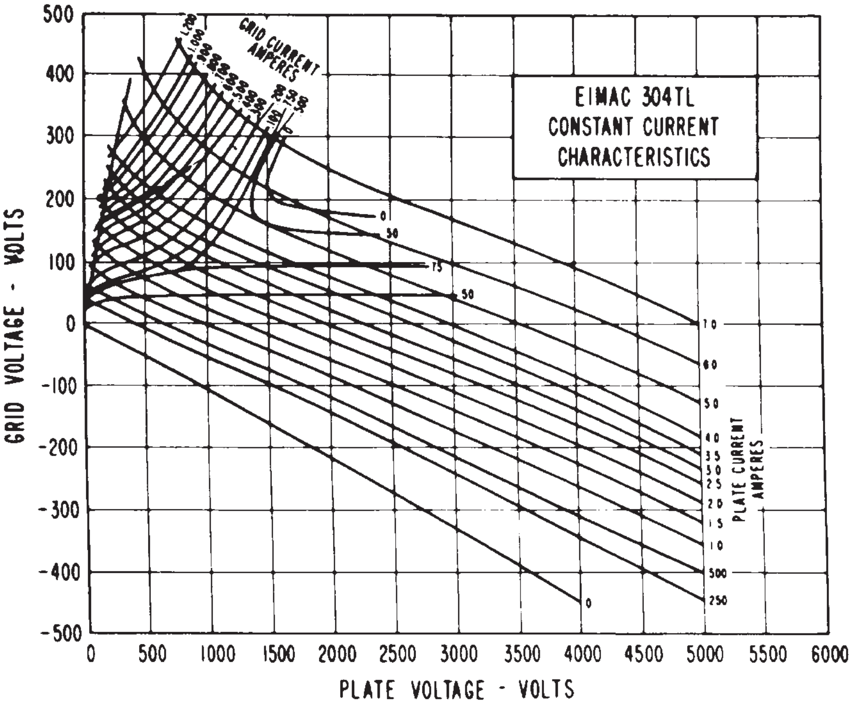


Figure 3.7 Constant-current characteristics for a triode with a μ of 12.

Triodes with a μ of 20 to 50 generally are used in conventional RF amplifiers and oscillators. High-μ triodes (200 or more) may be designed so that the operating bias is zero, as depicted in Figure 3.9. These *zero-bias triodes* are available with plate dissipation ratings of 400 W to 10 kW or more. The zero-bias triode commonly is used in grounded-grid amplification. The tube offers good power gain and circuit simplicity. No bias power source is required. Furthermore, no protection circuits for loss of bias or drive are needed. Despite these attributes, present-day use of the zero-bias triode is limited.

Low- and medium-μ devices usually are preferred for induction heating applications because of the wide variations in load that an induction or dielectric heating oscillator normally works into. Such tubes exhibit lower grid-current variation with a changing load. The grid current of a triode with a μ of 20 will rise substantially less under a light- or no-load condition than a triode with a μ of 40. High-μ triode oscillators can be designed for heating applications, but extra considerations must be given to current rise under no-load conditions.

Vacuum tubes specifically designed for induction heating are available, intended for operation under adverse conditions. The grid structure is ruggedized with ample dissi-

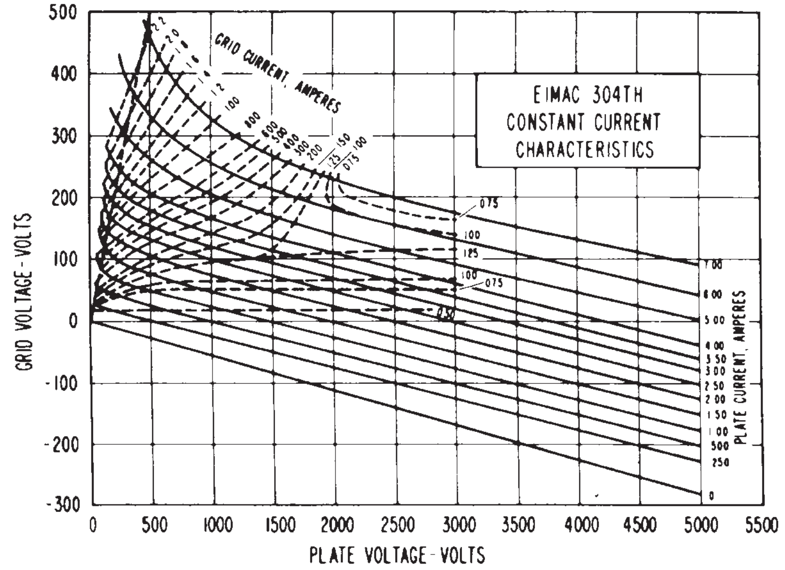


Figure 3.8 Constant-current characteristics for a triode with a μ of 20.

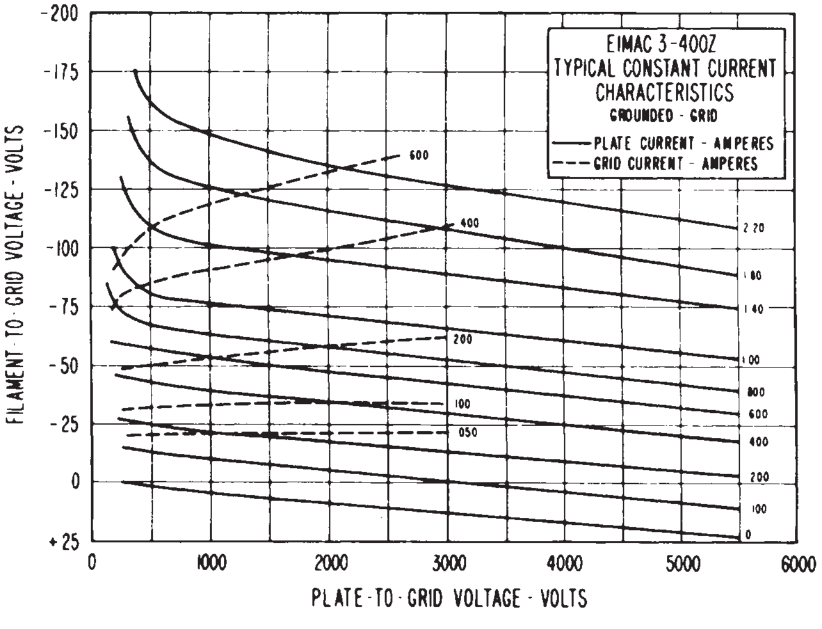


Figure 3.9 Grounded-grid constant-current characteristics for a zero-bias triode with a μ of 200.

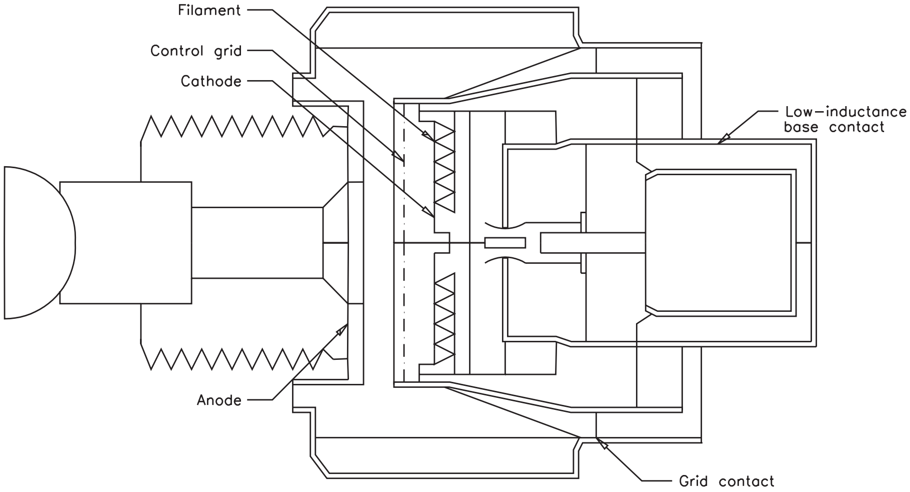


Figure 3.10 Internal configuration of a planar triode.

pation capability to deal with wide variations in load. As the load decreases, grid dissipation increases.

Triodes also are manufactured with the cathode, grid, and anode in the shape of a flat surface, as shown in Figure 3.10. Tubes so constructed are called *planar triodes*. This construction technique permits operation at high frequencies. The close spacing reduces electron *transit time*, allowing the tube to be used at high frequencies (up to 3 GHz or so). The physical construction of planar triodes results in short lead lengths, which reduces lead inductance. Planar triodes are used in both *continuous wave* (CW) and pulsed modes. The contacting surfaces of the planar triode are arranged for easy integration into coaxial and waveguide resonators.

3.2.6 Tetrode

The tetrode is a four-element tube with two grids. The control grid serves the same purpose as the grid in a triode, while a second (*screen*) grid with the same number of vertical elements (bars) as the control grid is mounted between the control grid and the anode. The grid bars of the screen grid are mounted directly behind the control-grid bars, as observed from the cathode surface, and serve as a shield or screen between the input circuit and the output circuit of the tetrode. The principal advantages of a tetrode over a triode include:

- Lower internal plate-to-grid feedback.

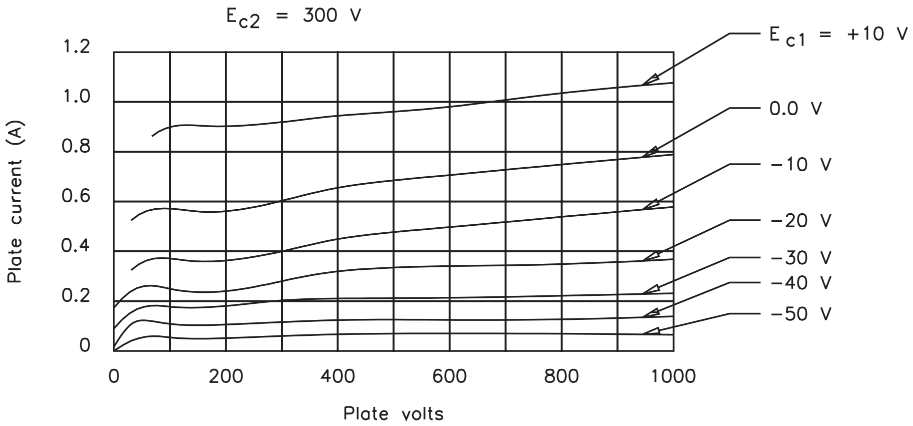


Figure 3.11 Tetrode plate current characteristics. Plate current is plotted as a function of plate voltage, with grid voltages as shown.

- Lower drive power requirements. In most cases, the driving circuit need supply only 1 percent of the output power.
- More efficient operation. Tetrodes allow the design of compact, simple, flexible equipment with little spurious radiation and low intermodulation distortion.

Plate current is almost independent of plate voltage in a tetrode. Figure 3.11 plots plate current as a function of plate voltage at a fixed screen voltage and various grid voltages. In an ideal tetrode, a change in plate current does not cause a change in plate voltage. The tetrode, therefore, can be considered a *constant-current device*. The voltages on the screen and control grids determine the amount of plate current.

The total cathode current of an ideal tetrode is determined by the equation:

$$I_k = K\left\{E_{c1} + \frac{E_{c2}}{\mu_s} + \frac{E_b}{\mu_p}\right\}^{3/2} \tag{3.10}$$

Where:
I_k = cathode current
K = a constant determined by tube dimensions
E_{c1} = control grid voltage
E_{c2} = screen grid voltage
μ_s = screen amplification factor
μ_p = plate amplification factor
E_b = plate voltage

Figure 3.12 Radial beam power tetrode (4CX15000A).

The arithmetic value of the screen μ generally is not used in the design of an RF amplifier. In most tetrode applications, the screen amplification factor is useful to categorize roughly the performance to be expected.

Application Example

Figure 3.12 shows a radial beam power tetrode (4CX15000A) designed for class AB_1 or class C power amplification. The device is particularly well suited for RF linear power amplifier service. The tube has a directly heated thoriated-tungsten mesh filament for mechanical ruggedness and high efficiency. The maximum rated plate dissipation of the tube is 15 kW using air cooling.

The tube must be protected from damage that may result from an internal arc occurring at high plate voltage. A protective resistance typically is inserted in series with the tube anode to help absorb stored power supply energy in case an internal arc occurs.

The maximum control grid dissipation is 200 W, determined (approximately) by the product of the dc grid current and the peak positive grid voltage.

Screen grid maximum dissipation is 450 W. With no ac applied to the screen grid, dissipation is the product of dc screen voltage and dc screen current. Plate voltage, plate loading, and/or bias voltage must never be removed while filament and screen voltages are present.

The 4CX15000A must be mounted vertically, base up or down. The tube requires forced-air cooling in all applications. The tube socket is mounted in a pressurized compartment where cooling air passes through the socket and is guided to the anode cooling fins by an air chimney. Adequate movement of cooling air around the base of the tube

Table 3.1 Minimum Cooling Airflow Requirements for the 4CX15000A Power Tetrode at Sea Level

Plate Dissipation (W)	Airflow (CFM)	Pressure Drop (inches of water)
7500	230	0.7
12,500	490	2.7
15,000	645	4.6

keeps the base and socket contact fingers at a safe operating temperature. Although the maximum temperature rating for seals and the anode is 250°C, good engineering practice dictates that a safety factor be provided. Table 3.1 lists cooling parameters for the tube with the cooling air at 50°C and a maximum anode temperature of 225°C. The figures given in the table apply to designs in which air passes in the base-to-anode direction. Pressure drop values shown are approximate and apply to the tube/socket/chimney combination.

At altitudes significantly above sea level, the flow rate must be increased for equivalent cooling. At 5000 ft above sea level, both the flow rate and the pressure drop is increased by a factor of 1.20; at 10,000 ft, both flow rate and pressure drop are increased by 1.46.

Anode and base cooling is applied before or simultaneously with filament voltage turn-on, and normally should continue for a brief period after shutdown to allow the tube to cool properly.

An outline of the principal tube dimensions is given in Figure 3.13. General specifications are listed in Table 3.2.

3.2.7 Pentode

The pentode is a five-electrode tube incorporating three grids. The control and screen grids perform the same function as in a tetrode. The third grid, the *suppressor grid*, is mounted in the region between the screen grid and the anode. The suppressor grid produces a *potential minimum*, which prevents secondary electrons from being interchanged between the screen and plate. The pentode's main advantages over the tetrode include:

- Reduced secondary emission effects.
- Good linearity.
- Ability to let plate voltage swing below the screen voltage without excessive screen dissipation. This allows slightly higher power output for a given operating plate voltage.

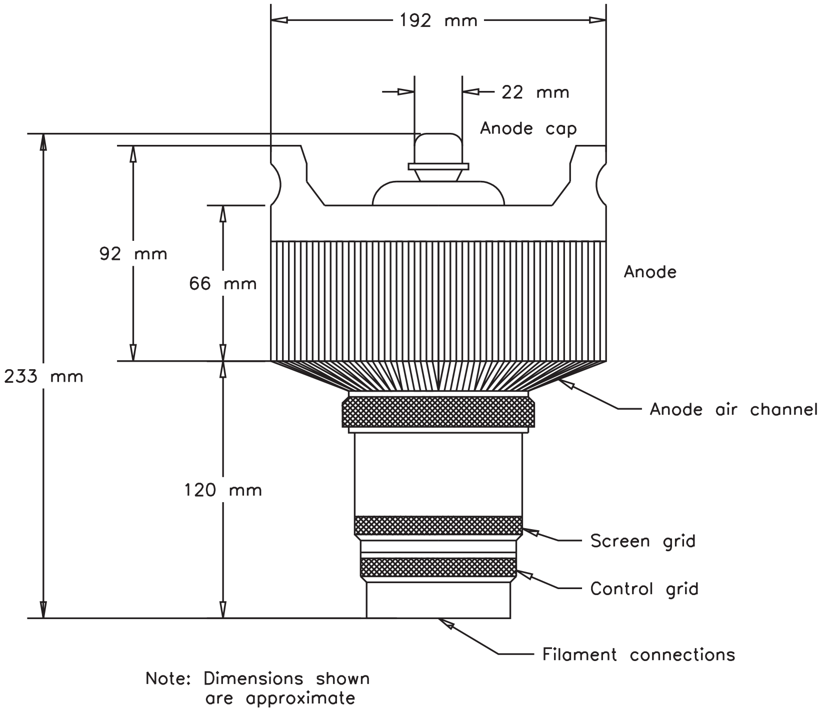


Figure 3.13 Principal dimensions of 4CX15000A tetrode.

Because of the design of the pentode, plate voltage has even less effect on plate current than in the tetrode. The same total space-current equation applies to the pentode as with the tetrode:

$$I_k = K \left\{ E_{c1} + \frac{E_{c2}}{\mu_s} + \frac{E_b}{\mu_p} \right\}^{3/2} \tag{3.11}$$

Where:
I_k = cathode current
K = a constant determined by tube dimensions
E_{c1} = control grid voltage
E_{c2} = screen grid voltage
μ_s = screen amplification factor
μ_p = plate amplification factor
E_b = plate voltage

The suppressor grid may be operated negative or positive with respect to the cathode. It also may be operated at cathode potential. It is possible to control plate current

Table 3.2 General Characteristics of the 4CX15000A Power Tetrode (*Courtesy of Svetlana Electron Devices*.)

Electrical Characteristics		
Filament type		Thoriated-tungsten mesh
Filament voltage		6.3 ± 0.3 V
Filament current		164 A (at 6.3 V)
Amplification factor (average), grid to screen		4.5
Direct interelectrode capacitance (grounded cathode)	C_{in}	158 pF
	C_{out}	25.8 pF
	C_{pk}	1.3 pF
Direct interelectrode capacitance (grounded grid)	C_{in}	67 pF
	C_{out}	25.6 pF
	C_{gk}	0.21 pF
Maximum frequency for full ratings (CW)		110 MHz
Mechanical Characteristics:		
Length		238 mm (9.38 in)
Diameter		193 mm (7.58 in)
Net weight		5.8 kg (12.8 lb)
Operating position		Axis vertical, base up or down
Maximum operating temperature (seals/envelope)		250°C
Cooling method		Forced air
Base type		Coaxial
Radio Frequency Power Amplifier (class C FM) (absolute maximum ratings)		
DC plate voltage		10,000 V
DC screen voltage		2000 V
DC grid voltage		–750 V
DC plate current		5.0 A
Plate dissipation		15 kW
Screen dissipation		450 W
Grid dissipation		200 W
Typical Operation (frequencies up to 110 MHz)		
DC plate voltage	7.5 kV dc	10.0 kV dc
DC screen voltage	750 V dc	750 V dc
DC grid voltage	–510 V dc	–550 V dc
DC plate current	4.65 A dc	4.55 A dc
DC screen current	0.59 A dc	0.54 A dc
DC grid current	0.30 A dc	0.27 A dc
Peak RF grid voltage	730 V	790 V
Calculated driving power	220 W	220 W
Plate dissipation	8.1	9.0 kW
Plate output power	26.7	36.5 kW

Figure 3.14 5CX1500B power pentode device.

by varying the potential on the suppressor grid. Because of this ability, a modulating voltage can be applied to the suppressor to achieve amplitude modulation. The required modulating power is low because of the low electron interception of the suppressor.

Application Example

The 5CX1500B is a ceramic/metal power pentode designed for use as a class AB_1 linear amplifier or FM VHF amplifying device. The exterior of the device is shown in Figure 3.14. Basic specifications for the tube are given in Table 3.3.

The filament of the 5CX1500B is rated for 5.0 V. Filament voltage, measured at the socket, is maintained to ±5 percent of the rated value for maximum tube life.

The rated dissipation of the control grid is 25 W. This value is approximately the product of dc grid current and peak positive grid voltage. Operation at bias and drive levels near those listed in Table 3.3 will ensure safe operation.

The power dissipated by the screen grid must not exceed 75 W. Screen dissipation, in cases where there is no ac applied to the screen, is the simple product of screen voltage and screen current. If the screen voltage is modulated, screen dissipation will depend on the rms screen current and voltage. Screen dissipation is likely to rise to excessive levels if the plate voltage, bias voltage, or plate load are removed with filament and screen voltages applied. Suitable protective means must be provided to limit screen dissipation to 75 W in the event of a circuit failure.

The rated dissipation of the suppressor grid is 25 W. Suppressor current is zero or nearly zero for all typical operating conditions specified in Table 3.3. The 5CX1500B

Table 3.3 General Characteristics of the 5CX1500B Power Pentode (*Courtesy of Svetlana Electron Devices*.)

Electrical Characteristics		
Filament type		Thoriated-tungsten mesh
Filament voltage		5.0 ± 0.25 V
Filament current		38.5 A (at 5.0 V)
Transconductance (avg.), I_b = 1.0 A dc, E_{c2} = 500 V dc		24,000 μmhos
Amplification factor (average), grid to screen		5.5
Direct interelectrode capacitance (grounded cathode)	Input	75 pF
	Output	17.8 pF
	Feedback	0.20 pF
Frequency (maximum) CW		110 MHz
Mechanical Characteristics		
Cooling method		Forced air
Base		Ring and breechblock
Recommended air system socket		SK-840 series
Recommended (air) chimney		SK-806
Operating position		Axis vertical, base down or up
Maximum operating temperature		250°C
Maximum dimensions	Length	130 mm (5.2 in)
	Diameter	85.6 mm (3.37 in)
Net weight		850 gm (30 oz)
Radio Frequency Linear Amplifier (class C, CW conditions) Maximum Ratings		
Plate voltage		5000 V
Screen voltage		750 V
Plate dissipation		1500 W
Suppressor dissipation		25 W
Screen dissipation		75 W
Grid dissipation		25 W
Typical Operation (frequencies to 30 MHz)		
Plate voltage	3000 V dc	4500 V dc
Suppressor voltage	0	0
Screen voltage	500 V dc	500 V dc
Grid voltage	–200 V dc	–200 V dc
Plate current	900 mA dc	900 mA dc
Screen current	94 mA dc	88 mA dc
Grid current	35 mA dc	34 mA dc
Peak RF grid voltage	255 V	255 V
Calculated driving power	9.0 W	9.0 W
Plate input power	2700 W	4050 W
Plate dissipation	720 W	870 W
Plate output power	1980 W	3180 W

Table 3.4 Minimum Cooling Airflow Requirements for the 5CX1500B Power Tetrode

Plate Dissipation (W)		Airflow (CFM)	Pressure Drop (inches of water)
At sea level	1000	27	0.33
	1550	47	0.76
At 6000 ft	1000	33	0.40
	1550	58	0.95

has been designed for zero voltage operation of the suppressor grid for most applications.

The plate dissipation rating of the 5CX1500B is 1500 W. The tube and associated circuitry should be protected against surge current in the event of an arc inside the tube. A current-limiting resistance of 10 to 25 Ωbetween the power supply and plate is sufficient. The resistor should be capable of withstanding the surge currents that may develop; it should not be used as a fuse.

Cooling requirements for the 5CX1500B follow along the same lines as for the 4CX15000A discussed in the previous section. Table 3.4 lists the airflow requirements for the pentode. Note that the power dissipated by the device is equal to the power dissipated by the plate, heater, and grids (control, screen, and suppressor) combined. In the case of the 5CX1500B, the heater and three grids account for approximately 350 W dissipation.

Mechanical dimensions for the 5CX1500B are given in Figure 3.15.

3.2.8 High-Frequency Operating Limits

As with most active devices, performance of a given vacuum tube deteriorates as the operating frequency is increased beyond its designed limit. Electron *transit time* is a significant factor in the upper-frequency limitation of electron tubes. A finite time is taken by electrons to traverse the space from the cathode, through the grid, and travel on to the plate. As the operating frequency increases, a point is reached at which the electron transit-time effects become significant. This point is a function of the accelerating voltages at the grid and anode and their respective spacings. Tubes with reduced spacing in the grid-to-cathode region exhibit reduced transit-time effects.

A power limitation also is interrelated with the high-frequency limit of a device. As the operating frequency is increased, closer spacing and smaller-sized electrodes must be used. This reduces the power-handling capability of the tube. Figure 3.16 illustrates the relationship.

Gridded tubes at all power levels for frequencies up to about 1 GHz are invariably cylindrical in form. At higher frequencies, planar construction is almost universal. As the operating frequency is increased beyond design limits, output power and efficiency both decrease. Figure 3.17 illustrates the relationship.

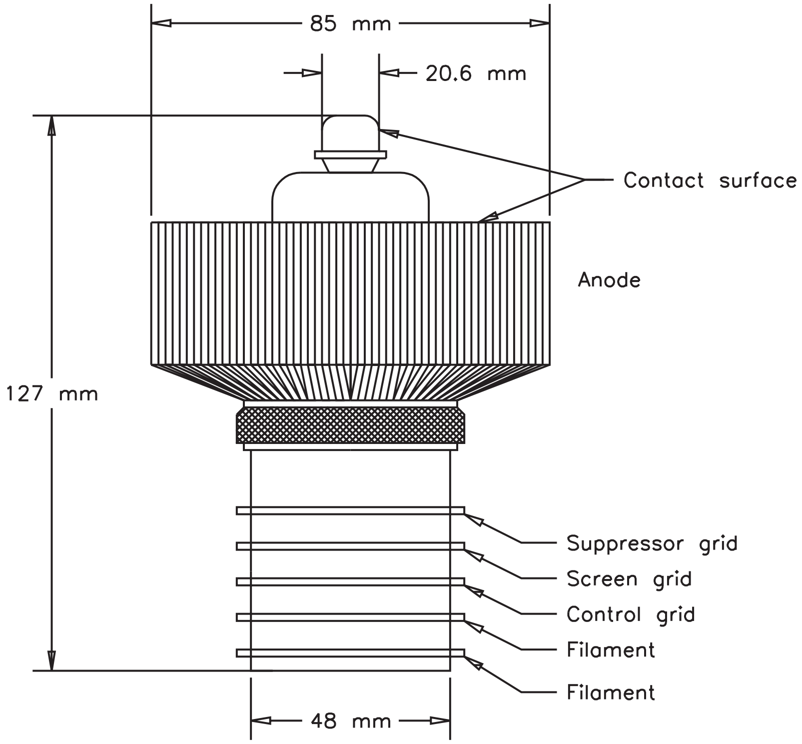


Figure 3.15 Principal dimensions of 5CX1500B pentode.

Transit time typically is not a problem for power grid tubes operating below 30 MHz. Depending on the application, power grid tubes can be used at 100 MHz and above without serious consideration of transit time effects. Klystrons and other microwave tubes actually take advantage of transit time, as discussed in Chapter 6.

Transit-Time Effects

When class C, class B, or similar amplifier operations are carried out at frequencies sufficiently high that the transit time of the electrons is not a negligible fraction of the waveform cycle, the following complications are observed in grid-based vacuum tubes:

- *Back-heating* of the cathode
- Loading of the control grid circuit as a result of energy transferred to electrons that do not necessarily reach the grid to produce a dc grid current
- Debunching of plate current pulses

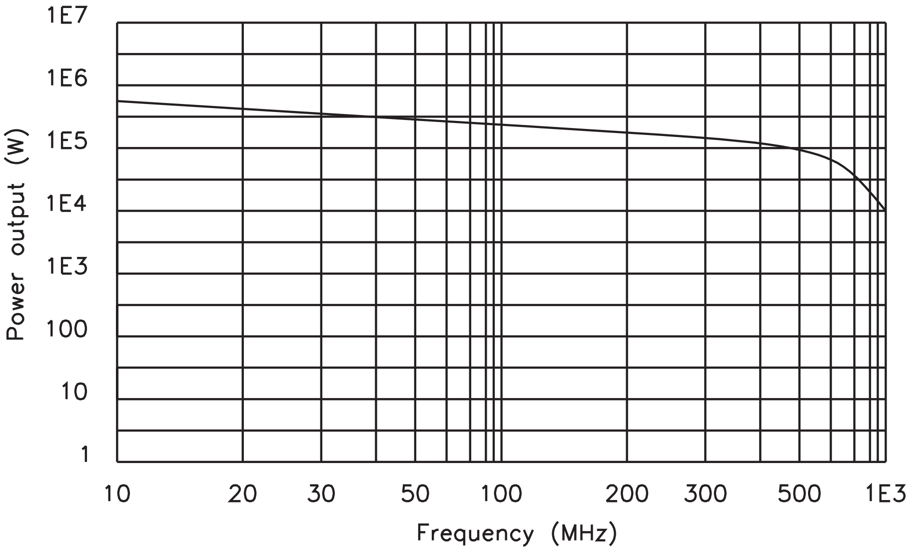


Figure 3.16 Continuous wave output power capability of a gridded vacuum tube.

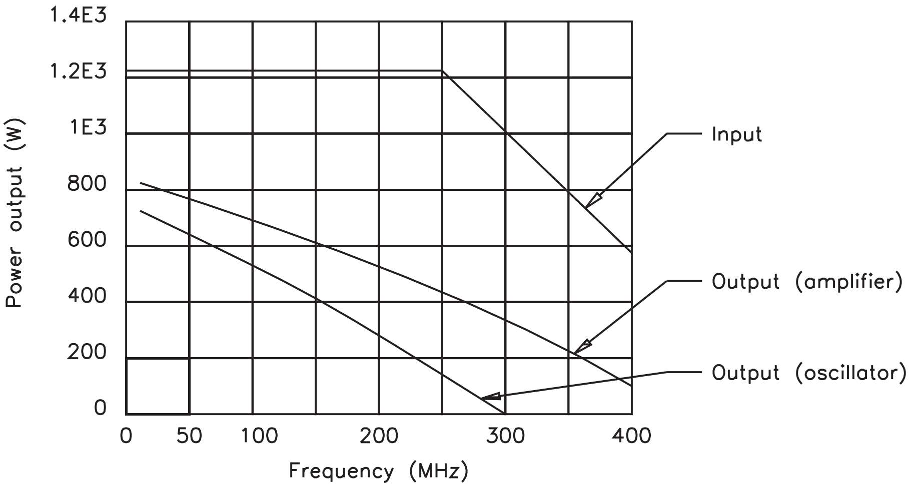


Figure 3.17 Performance of a class C amplifier as the operating frequency is increased beyond the design limits of the vacuum tube.

- Phase differences between the plate current and the exciting voltage applied to the control grid

Back-heating of the cathode occurs when the transit time in the grid-cathode space is sufficiently great to cause an appreciable number of electrons to be in transit at the instant the plate current pulse would be cut off in the case of low-frequency operation. A considerable fraction of the electrons thus trapped in the interelectrode space are returned to the cathode by the negative field existing in the grid-cathode space during the cutoff portion of the cycle. These returning electrons act to heat the cathode. At very high frequencies, this back-heating is sufficient to supply a considerable fraction of the total cathode heating required for normal operation. Back-heating may reduce the life of the cathode as a result of electron bombardment of the emitting surface. It also causes the required filament current to depend upon the conditions of operation within the tube.

Energy absorbed by the control grid as a result of input loading is transferred directly to the electron stream in the tube. Part of this stream acts to produce back-heating of the cathode. The remainder affects the velocity of the electrons as they arrive at the anode of the tube. This portion of the energy is not necessarily all wasted. In fact, a considerable percentage of it may, under favorable conditions, appear as useful output in the tube. To the extent that this is the case, the energy supplied by the exciting voltage to the electron stream is simply transferred directly from the control grid to the output circuits of the tube without amplification.

An examination of the total time required by electrons to travel from the cathode to the anode in a triode, tetrode, or pentode operated as a class C amplifier reveals that the resulting transit times for electrons at the beginning, middle, and end of the current pulse will differ as the operating frequency is increased. In general, electrons traversing the distance during the first segment of the pulse will have the shortest transit time, while those near the middle and end of the pulse will have the longest transit times, as illustrated in Figure 3.18. The first electrons in the pulse have a short transit time because they approach the plate before the plate potential is at its minimum value. Electrons near the middle of the pulse approach the plate with the instantaneous plate potential at or near minimum and, consequently, travel less rapidly in the grid-plate space. Finally, those electrons that leave the cathode late in the current pulse (those just able to escape being trapped in the control grid-cathode space and returned toward the cathode) will be slowed as they approach the grid, and so have a large transit time. The net effect is to cause the pulse of plate current to be longer than it would be in operation at a low frequency. This causes the efficiency of the amplifier to drop at high frequencies, because a longer plate current pulse increases plate losses.

3.3 Vacuum Tube Design

Any particular power vacuum tube may be designed to meet a number of operating parameters, the most important usually being high operating efficiency and high gain/bandwidth properties. Above all, the tube must be reliable and provide long operating life. The design of a new power tube is a lengthy process that involves com-

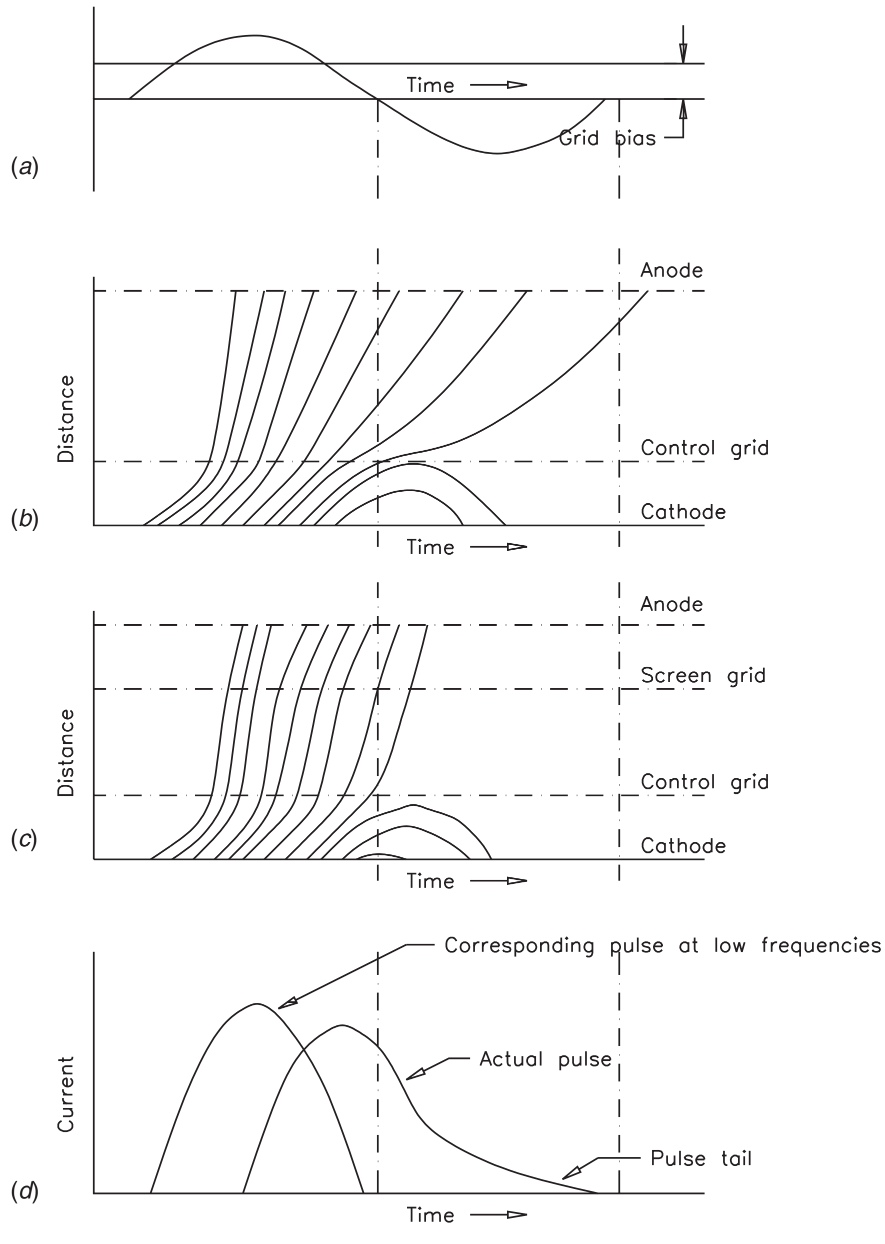


Figure 3.18 Transit-time effects in a class C amplifier: (*a*) control grid voltage, (*b*) electron position as a function of time (triode case), (*c*) electron position as a function of time (tetrode case), (*d*) plate current (triode case).

puter-aided calculations and modeling. The design engineers must examine a laundry list of items, including:

- **Cooling**: how the tube will dissipate heat generated during normal operation. A high-performance tube is of little value if it will not provide long life in typical applications. Design questions include whether the tube will be air-cooled or water-cooled, the number of fins the device will have, and the thickness and spacing of the fins.
- **Electro-optics**: how the internal elements line up to achieve the desired performance. A careful analysis must be made of what happens to the electrons in their paths from the cathode to the anode, including the expected power gain of the tube.
- **Operational parameters**: what the typical interelectrode capacitances will be, and the manufacturing tolerances that can be expected. This analysis includes: spacing variations among elements within the tube, the types of materials used in construction, the long-term stability of the internal elements, and the effects of thermal cycling.

3.3.1 Device Cooling

The main factor that separates tube types is the method of cooling used: air, water, or vapor. Air-cooled tubes are common at power levels below 50 kW. A water cooling system, although more complicated, is more effective than air cooling—by a factor of 5 to 10 or more—in transferring heat from the device. Air cooling at the 100 kW level is virtually impossible because it is difficult to physically move enough air through the device (if the tube is to be of reasonable size) to keep the anode sufficiently cool. Vapor cooling provides an even more efficient method of cooling a power amplifier (PA) tube than water cooling, for a given water flow and a given power dissipation. Naturally, the complexity of the external blowers, fans, ducts, plumbing, heat exchangers, and other hardware must be taken into consideration in the selection of a cooling method. Figure 3.19 shows how the choice of cooling method is related to anode dissipation.

Air Cooling

A typical air cooling system for a transmitter is shown in Figure 3.20. Cooling system performance for an air-cooled device is not necessarily related to airflow volume. The cooling capability of air is a function of its mass, not its volume. An appropriate airflow rate within the equipment is established by the manufacturer, resulting in a given resistance to air movement.

The altitude of operation is also a consideration in cooling system design. As altitude increases, the density (and cooling capability) of air decreases. To maintain the same cooling effectiveness, increased airflow must be provided. (Air cooling systems are discussed in detail in Section 8.2.1.)

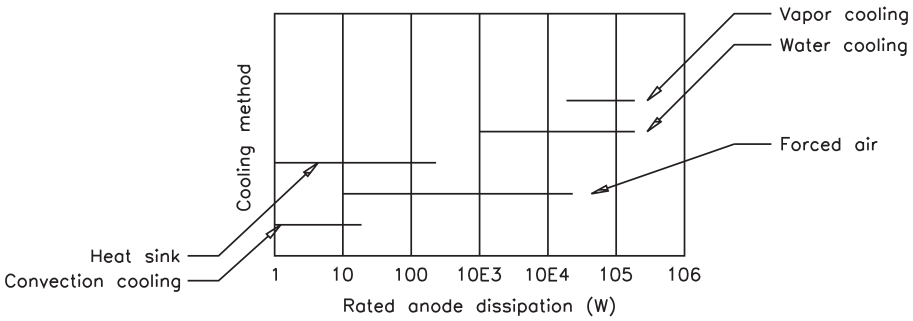


Figure 3.19 The relationship between anode dissipation and cooling method.

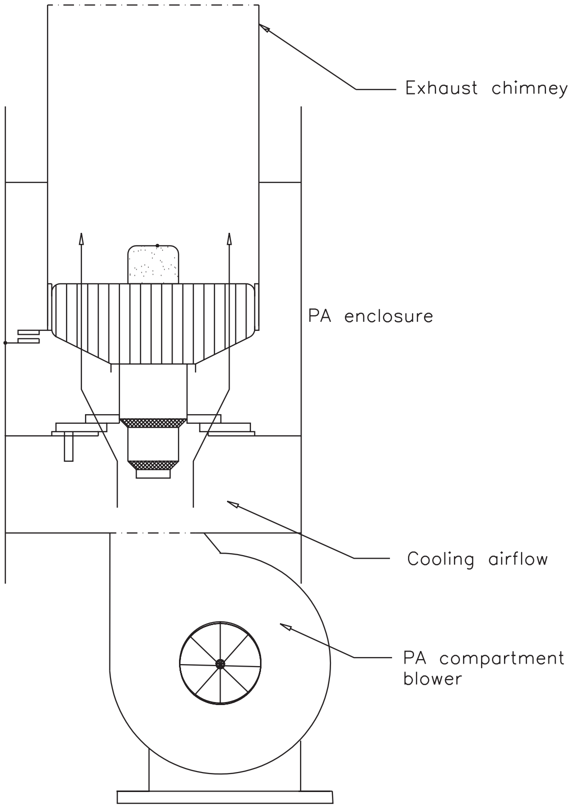


Figure 3.20 A typical transmitter PA stage cooling system.

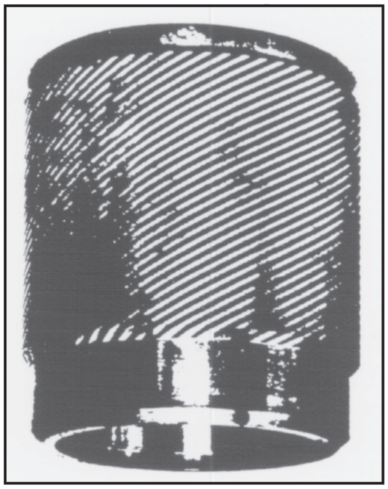


Figure 3.21 Water-cooled anode with grooves for controlled water flow.

Water Cooling

Water cooling usually is preferred over air cooling for power outputs above about 50 kW. Multiple grooves on the outside of the anode, in conjunction with a cylindrical jacket, force the cooling water to flow over the surface of the anode, as illustrated in Figure 3.21.

Because the water is in contact with the outer surface of the anode, a high degree of purity must be maintained. A resistivity of 1 mΩ-cm (at 25°C) typically is specified by tube manufacturers. Circulating water can remove about 1 kW/cm_2 of effective internal anode area. In practice, the temperature of water leaving the tube must be limited to 70°C to prevent the possibility of spot boiling.

After leaving the anode, the heated water is passed through a heat exchanger where it is cooled to 30 to 40°C before being pumped back to the tube.

In typical modern water-cooled tubes, the dissipation ranges from 500 W to 1 kW per square centimeter. Water-cooled anodes have deen designed that can operate at 10 kW per square centimeter and above. However, with the exception of "big science" applications, dissipations this high are seldom required. (Water cooling systems are discussed in detail in Section 8.2.2.)

Vapor-Phase Cooling

Vapor cooling allows the permissible output temperature of the water to rise to the boiling point, giving higher cooling efficiency compared with water cooling. The benefits of vapor-phase cooling are the result of the physics of boiling water. Increasing the temperature of one gram of water from 40 to 70°C requires 30 calories of energy. However, transforming 1 g of water at 100°C into steam vapor requires 540 calories. Thus, a vapor-phase cooling system permits essentially the same cooling capacity as water cooling, but with greatly reduced water flow. Viewed from another

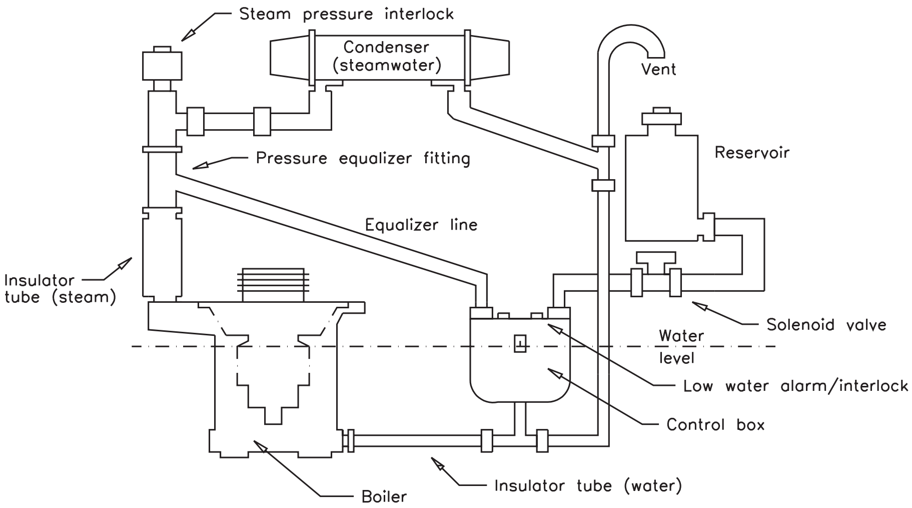


Figure 3.22 Typical vapor-phase cooling system.

perspective, for the same water flow, the dissipation of the tube may be increased significantly (all other considerations being the same).

A typical vapor-phase cooling system is shown in Figure 3.22. A tube incorporating a specially designed anode is immersed in a boiler filled with distilled water. When power is applied to the tube, anode dissipation heats the water to the boiling point, converting the water to steam vapor. The vapor passes to a condenser, where it gives up its energy and reverts to a liquid state. The condensate then is returned to the boiler, completing the cycle. Electric valves and interlocks are included in the system to provide for operating safety and maintenance. A vapor-phase cooling system for a transmitter with multiple PA tubes is shown in Figure 3.23. (Vapor-phase cooling systems are discussed in detail in Section 8.2.3.)

Special Applications

Power devices used for research applications must be designed for transient overloading, requiring special considerations with regard to cooling. Oil, heat pipes, refrigerants (such as Freon), and, where high-voltage hold-off is a problem, gases (such as sulfahexafluoride) are sometimes used to cool the anode of a power tube.

3.3.2 Cathode Assembly

The ultimate performance of any vacuum tube is determined by the accuracy of design and construction of the internal elements. The requirements for a successful tube

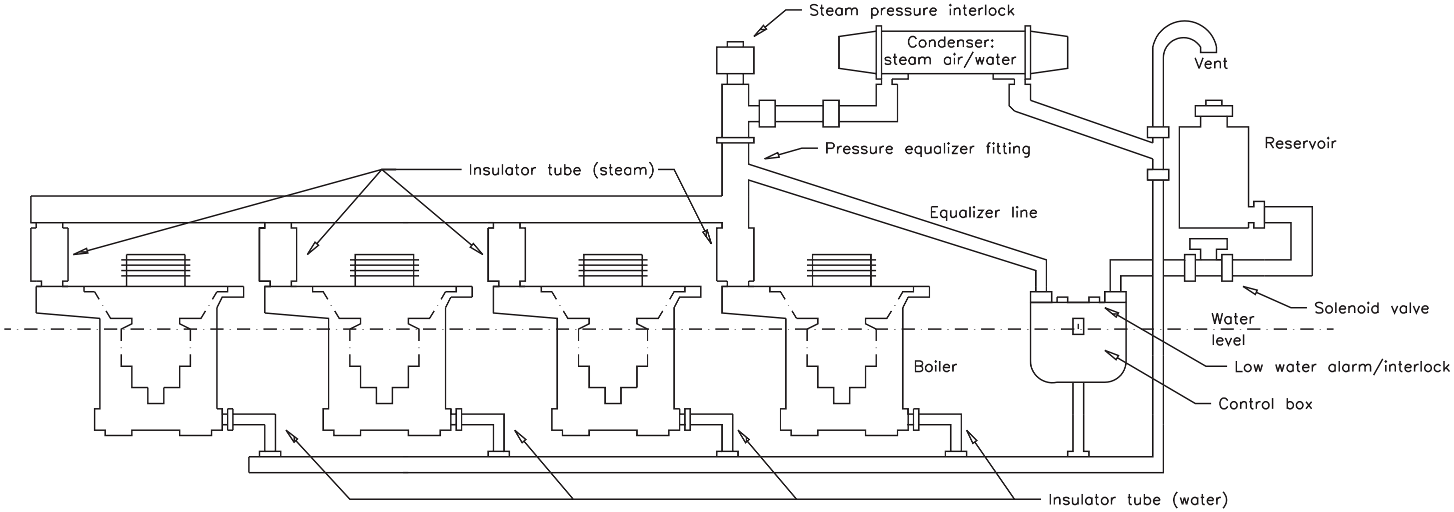


Figure 3.23 Vapor-phase cooling system for a 4-tube transmitter using a common water supply.

Table 3.5 Characteristics of Common Thermonic Emitters

Emitter	Heading Method[1]	Operating Temp. (°C)	Emission Density (A/cm^2)	
			Average	Peak
Oxide	Direct and indirect	700 to 820	0.10 to 0.50	0.10 to 20
Thoriated tungsten	Direct	1600 to 1800	0.04 to 0.43	0.04 to 10
Impregnated tungsten	Direct and indirect	900 to 1175	0.5 to 8.0	0.5 to 12

[1] Directly heated refers to a filament-type cathode.

include the ability to operate at high temperatures and withstand physical shock. Each element is critical to this objective.

The cathode used in a power tube obtains the energy required for electron emission from heat. The cathode may be directly heated (filament type) or indirectly heated. The three types of emitting surfaces most commonly used are:

- Thoriated-tungsten
- Alkaline-earth oxides
- Tungsten-barium-aluminate-impregnated emitters

The thoriated-tungsten and tungsten-impregnated cathodes are preferred in power tube applications because they are more tolerant to *ion bombardment*. The characteristics of the three emitting surfaces are summarized in Table 3.5.

A variety of materials may be used as a source of electrons in a vacuum tube. Certain combinations of materials are preferred, however, for reasons of performance and economics.

Oxide Cathode

The conventional production-type oxide cathode consists of a coating of barium and strontium oxides on a base metal such as nickel. Nickel alloys, in general, are stronger, tougher, and harder than most nonferrous alloys and many steels. The most important property of nickel alloys is their ability to retain strength and toughness at elevated temperatures. The oxide layer is formed by first coating a nickel structure (a can or disk) with a mixture of barium and strontium carbonates, suspended in a binder material. The mixture is approximately 60 percent barium carbonate and 40 percent strontium carbonate.

During vacuum processing of the tube, these elements are *baked* at high temperatures. As the binder is burned away, the carbonates subsequently are reduced to oxides. The cathode is then said to be *activated* and will emit electrons.

An oxide cathode operates CW at 700 to 820°C and is capable of an average emission density of 100 to 500 mA/cm^2. High emission current capability is one of the main

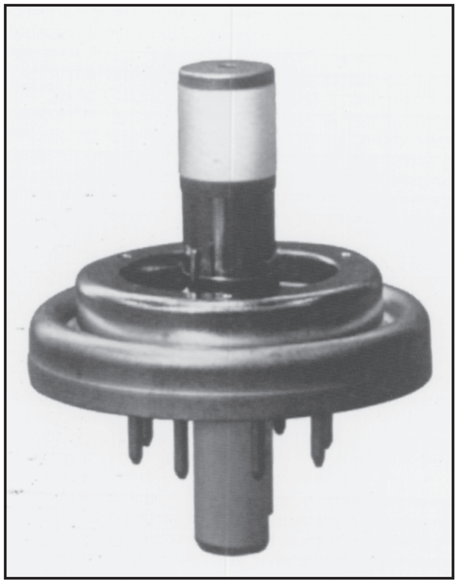


Figure 3.24 Photo of a typical oxide cathode. (*Courtesy of Varian.*)

advantages of the oxide cathode. Other advantages include high peak emission for short pulses and low operating temperature. As shown in Table 3.5, peak emission of up to 20 A/cm^2 is possible from an oxide cathode. A typical device is shown in Figure 3.24.

Although oxide-coated emitters provide more peak emission per watt of heating power than any other type, they are not without their drawbacks. Oxide emitters are more easily damaged or "poisoned" than other emitters and also deteriorate more rapidly when subjected to bombardment from high-energy particles.

The oxide cathode material will evaporate during the life of the tube, causing free barium to migrate to other areas within the device. This evaporation can be minimized in the design stage by means of a high-efficiency cathode that runs as cool as possible but still is not emission-limited at the desired heater voltage. In the field, the heater voltage must not exceed the design value. An oxide cathode that is overheated produces little, if any, additional emission. The life of the tube under such operation, however, is shortened significantly.

Thoriated-Tungsten Cathode

The thoriated-tungsten filament is another form of atomic-film emitter commonly used in power grid tubes. Tungsten is stronger than any other common metal at temperatures of more than 3500°F. The melting point of tungsten is 6170°F, higher than that of any other metal. The electrical conductivity of tungsten is approximately one-third that of copper, but much better than the conductivity of nickel, platinum, or iron-based alloys. The resistivity of tungsten in wire form is exploited in filament applications. The thoriated-tungsten filament (or cathode) is created in a high-temperature gaseous atmosphere to produce a layer of *ditungsten carbide* on the surface of the cathode element(s). Thorium is added to tungsten in the process of making tungsten wire. The thorium concentration is typically about 1.5 percent, in the form of thoria. By proper processing during vacuum pumping of the tube envelope, the metallic thorium is brought to the surface of the filament wire. The result is an increase in emission of approximately 1000 times over a conventional cathode.

At a typical operating temperature of 1600 to 1800°C, a thoriated-tungsten filament will produce an average emission of 40 to 430 mA/cm^2. Peak current ranges up to 10 A/cm^2 or more.

One of the advantages of a thoriated-tungsten cathode over an oxide cathode is the ability to operate the plate at higher voltages. Because oxide cathodes are susceptible to deterioration caused by ion bombardment, plate voltage must be limited. A thoriated-tungsten cathode is more tolerant of ion bombardment, so higher plate voltages can be safely applied.

The end of useful life for a thoriated-tungsten tube occurs when most of the carbon has evaporated or has combined with residual gas, depleting the carbide surface layer. Theoretically, a 3 percent increase in filament voltage will result in a 20 degree Kelvin (K) increase in cathode temperature, a 20 percent increase in peak emission, and a 50 percent decrease in tube life because of carbon loss. This cycle works in reverse, too. For a small decrease in temperature and peak emission, the life of the carbide layer—hence, the tube—may be increased.

Tungsten-Impregnated Cathode

The tungsten-impregnated cathode typically operates at 900 to 1175°C and provides the highest average emission density of the three types of cathodes discussed in this section (500 mA/cm^2 to 8 A/cm^2). Peak power performance ranges up to 12 A/cm^2.

Tungsten, as an element, is better able than other emitters to withstand bombardment by high-energy positive ions without suffering emission impairment. These positive ions are always present in small numbers in vacuum tubes as a result of ionization by collision with the residual gas.

Cathode Construction

Power tube filaments can be assembled in several different configurations. Figure 3.25 shows a spiral-type filament, and Figure 3.26 shows a bar-type design. The spiral filament is used extensively in low-power tubes. As the size of the tube increases, mechanical considerations dictate a bar-type filament with spring loading to compensate for thermal expansion. A mesh filament can be used for both small and large tubes. It is more rugged than other designs and less subject to damage from shock and vibration. The rigidity of a cylindrical mesh cathode is determined by the following parameters:

- The diameter of the cathode
- The number, thickness, and length of the wires forming the cathode
- The ratio of welded to total wire crossings

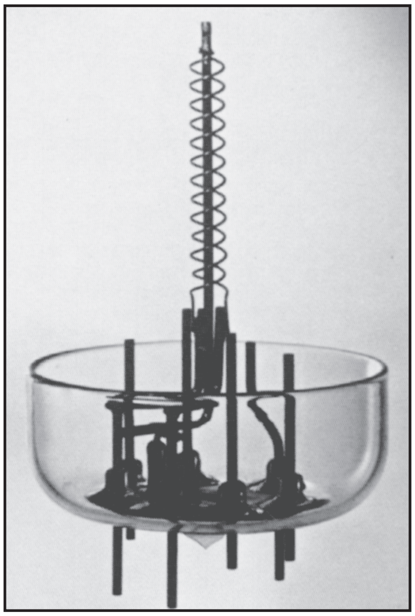


Figure 3.25 Spiral-type tungsten filament. (*Courtesy of Varian.*)

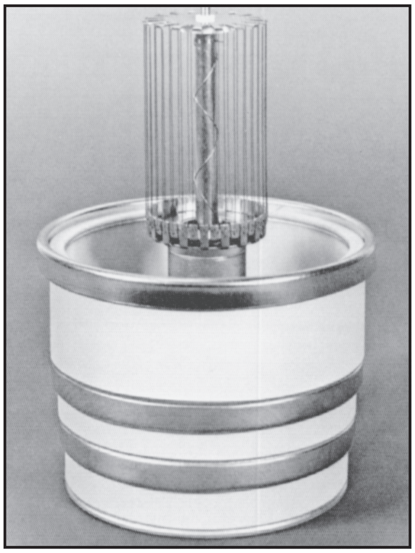


Figure 3.26 Bar-type tungsten filament. (*Courtesy of Varian.*)

A mesh cathode is shown in Figure 3.27.

Most power grid tubes are designed as a series of electron gun structures arranged in a cylinder around a centerline. This construction allows large amounts of plate current to flow and to be controlled with a minimum of grid interception. With reduced grid in-

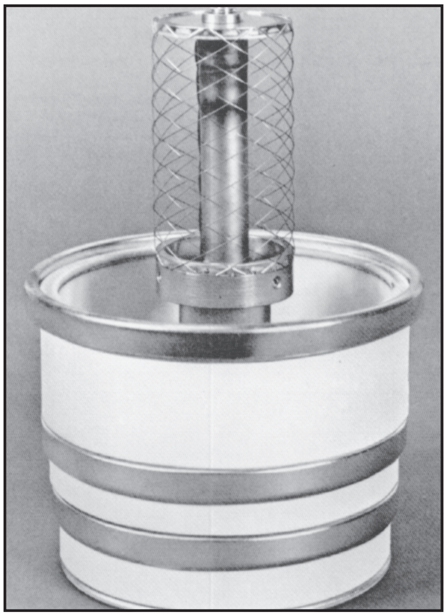


Figure 3.27 Mesh tungsten filament. (*Courtesy of Varian.*)

terception, less power is dissipated in the grid structures. In the case of the control grid, less driving power is required for the tube.

In certain applications, the construction of the filament assembly may affect the performance of the tube, and that of the RF system as a whole. For example, filaments built in a basket-weave mesh arrangement usually offer lower distortion in critical high-level AM modulation circuits.

Velocity of Emission

The electrons emitted from a hot cathode depart with a velocity that represents the difference between the kinetic energy possessed by the electron just before emission and the energy that must be given up to escape. Because the energy of different electrons within the emitter is not the same, the velocity of emission will vary as well, ranging from zero to a maximum value determined by the type and style of emitter.

3.3.3 Grid Structures

The type of grid used for a power tube is determined principally by the power level and operating frequency required. For most medium-power tubes (5 to 25 kW dissipation) welded-wire construction is common. At higher power levels, laser-cut *pyrolytic graphite* grids may be found. The grid structures of a power tube must maintain their shape and spacing at elevated temperatures. They also must withstand shock and vibration.

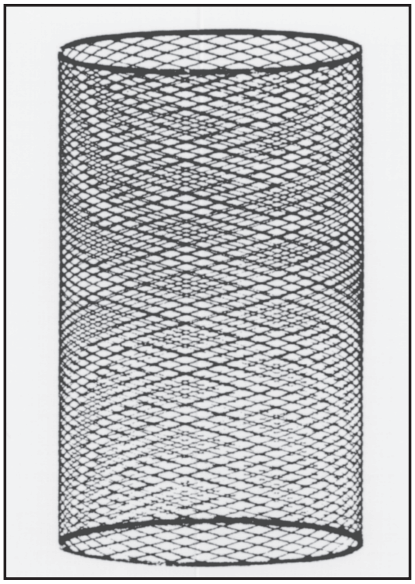


Figure 3.28 Mesh grid structure. (*Courtesy of Varian.*)

Wire Grids

Conventional wire grids are prepared by operators that wind the assemblies using special *mandrels* (forms) that include the required outline of the finished grid. The operators spot weld the wires at intersecting points, as shown in Figure 3.28. Most grids of this type are made with tungsten or *molybdenum*, which exhibit stable physical properties at elevated temperatures. On a strength basis, pure molybdenum generally is considered the most suitable of all refractory metals at temperatures of 1600 to 3000°F. The thermal conductivity of molybdenum is more than three times that of iron and almost half that of copper.

Grids for higher-power tubes typically are built using a bar-cage type of construction. A number of vertical supports are fastened to a metal ring at the top and to a base cone at the bottom. The lower end of the assembly is bonded to a contact ring. The construction of the ring, metal base cone, and cylindrical metal base give the assembly low lead inductance and low RF resistance.

The external loading of a grid during operation and the proximity of the grid to the hot cathode impose severe demands on both the mechanical stability of the structure and the physical characteristics of its surface. The grid absorbs a high proportion of the heat radiated by the cathode. It also intercepts the electron beam, converting part of its kinetic energy into heat. Furthermore, high-frequency capacitive currents flowing in the grid create additional heat.

The result is that grids are forced to work at temperatures as high as 1500°C. Their primary and secondary emissions, however, must be low. To prevent grid emission, high electron affinity must be ensured throughout the life of the tube, even though it is impossible to prevent material that evaporates from the cathode from contaminating the grid surface.

In tubes with oxide cathodes, grids made of tungsten or molybdenum wire are coated with gold to reduce primary emission caused by deposition. The maximum safe operating temperature for gold plating, however, is limited (about 550°C). Special coatings developed for high-temperature applications are effective in reducing grid emission. In tubes with thoriated-tungsten cathodes, grids made of tungsten or molybdenum are coated with proprietary compounds to reduce primary emission.

Primary grid emission is usually low in a thoriated tungsten cathode device. In the case of an oxide cathode, however, free barium may evaporate from the cathode coating material and find its way to the control and screen grids. The rate of evaporation is a function of cathode temperature and time. A grid contaminated with barium will become another emitting surface. The hotter the grid, the greater the emissions.

K-Grid

To permit operation at higher powers (and, therefore, higher temperatures) the *K-grid* has been developed (Philips). The K-grid is a spot-welded structure of molybdenum wire doped to prevent brittleness and recrystallization. To eliminate mechanical stresses, the grid is annealed at 1800 K. It is then baked under vacuum at 2300 K to degas the molybdenum wire. The grid structure next is coated with zirconium carbide (sintered at 2300 K) and, finally, with a thin layer of platinum.

Despite high grid temperatures, the platinum coating keeps primary emissions to a minimum. The surface structure maintains low secondary emissions.

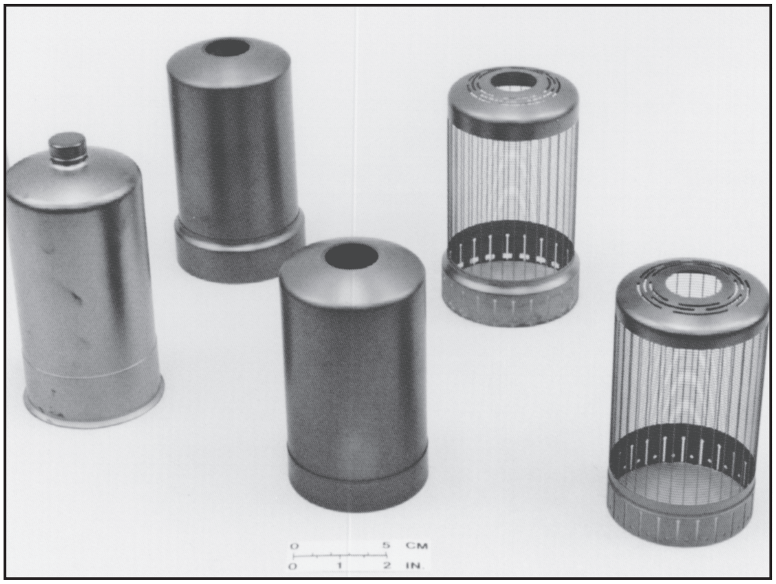
Pyrolytic Grid

Pyrolytic grids are a high-performance alternative to wire or bar grid assemblies. Used primarily for high-power devices, pyrolytic grids are formed by laser-cutting a graphite cup of the proper dimensions. The computer-controlled laser cuts numerous holes in the cup to simulate a conventional-style grid. Figure 3.29 shows a typical pyrolytic-type grid before and after laser processing.

Pyrolytic (or oriented) graphite is a form of crystallized carbon produced by the decomposition of a hydrocarbon gas at high temperatures in a controlled environment. A layer of pyrolytic graphite is deposited on a grid form. The thickness of the layer is proportional to the amount of time deposition is allowed to continue. The structural and mechanical properties of the deposited graphite depend upon the imposed conditions.

Pyrolytic grids are ideal vacuum tube elements because they do not expand like metal. Their small coefficient of expansion prevents movement of the grids inside the tube at elevated temperatures. This preserves the desired electrical characteristics of the device. Because tighter tolerances can be maintained, pyrolytic grids can be spaced more closely than conventional wire grids. Additional benefits are that the grid:

- Is a single structure having no weld points
- Has a thermal conductivity in two of the three planes nearly that of copper



(*a*) (*b*)

Figure 3.29 Pyrolytic graphite grid: (*a*) before laser processing, (*b*) completed assembly. (*Courtesy of Varian.*)

- Can operate at high temperatures with low vapor pressure

Grid Physical Structure

The control, screen, and suppressor grids are cylindrical and concentric. Each is slightly larger than the previous grid, as viewed from the cathode. Each is fastened to a metal base cone, the lower end of which is bonded to a contact ring. Figure 3.30 shows the construction of a typical screen grid assembly. Figure 3.31 provides a cutaway view of a tetrode power tube.

The shape of the control grid and its spacing from the cathode define, in large part, the operating characteristics of the tube. For best performance, the grid must be essentially transparent to the electron path from the cathode to the plate. In a tetrode, the control and screen grids must be precisely aligned to minimize grid current. For pentode tubes, these two conventions apply, in addition to the requirement for precise alignment and minimum beam interception for the suppressor grid.

Secondary Emission Considerations

The relationship of the properties of secondary electrons to the grid structures and other elements of a vacuum tube must be considered carefully in any design. As the

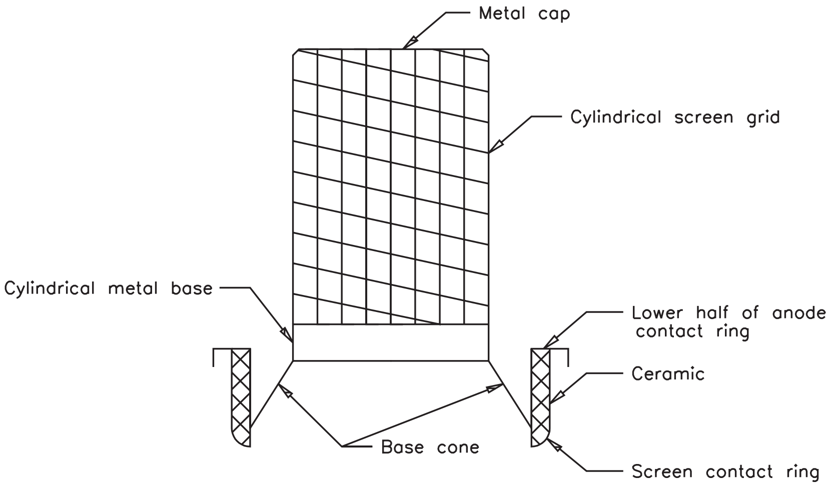


Figure 3.30 The screen grid assembly of a typical tetrode PA tube.

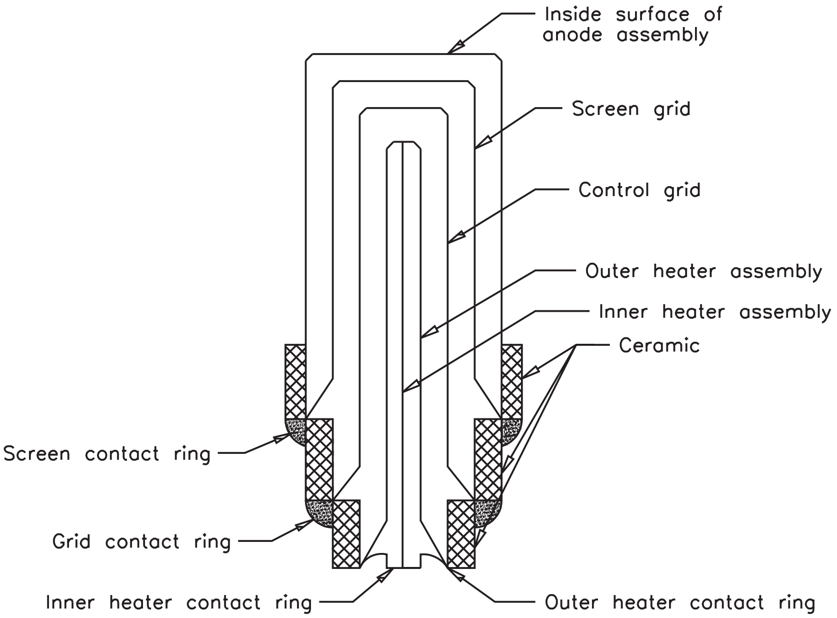


Figure 3.31 The internal arrangement of the anode, screen, control grid, and cathode assemblies of a tetrode power tube.

power capability of a tube increases, the physical size of the elements also increases. This raises the potential for secondary emission from the control, screen, and suppressor grids. Secondary emission may occur regardless of the type of cathode used.

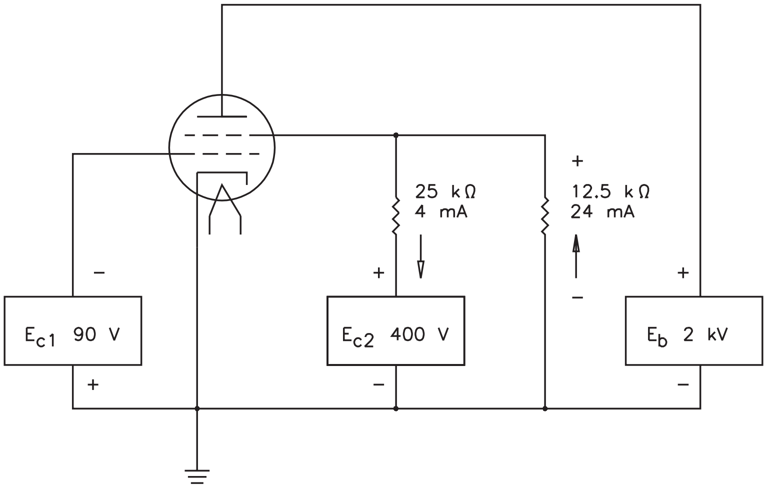


Figure 3.32 Circuit for providing a low-impedance screen supply for a tetrode.

The yield of secondary electrons may be reduced through the application of surface treatments.

In a tetrode, the screen is operated at a relatively low potential, necessary to accelerate the electrons emitted from the cathode. Not all electrons pass through the screen on their way to the plate. Some are intercepted by the screen grid. As the electrons strike the screen, other low-energy electrons are emitted. If these electrons have a stronger attraction to the screen, they will fall back to that element. If, however, they pass into the region between the screen and the plate, the much higher anode potential will attract them. The result is electron flow from screen to plate.

Because of the physical construction of a tetrode, the control grid will have virtually no control over screen-to-plate current flow as a result of secondary electrons. During a portion of the operating cycle of the device, it is possible that more electrons will leave the screen grid than will arrive. The result will be a reverse electron flow on the screen element, a condition common to high-power tetrodes. A low-impedance path for reverse electron flow must be provided.

Tube manufacturers typically specify the recommended value of bleeding current from the screen power supply to counteract the emission current. Two common approaches are illustrated in Figures 3.32 and 3.33. If the screen power supply impedance is excessively high in the direction of reverse electron flow, the screen voltage will attempt to rise to the plate voltage. Note the emphasis on low impedance in the reverse electron flow direction. Most regulated power supplies are low impedance in the forward electron flow direction only. If the supply is not well bled, the reverse electrons will try to flow from anode to cathode in the regulator series pass element. As the screen voltage rises, the secondary and plate currents will increase, and the tube will enter a runaway condition.

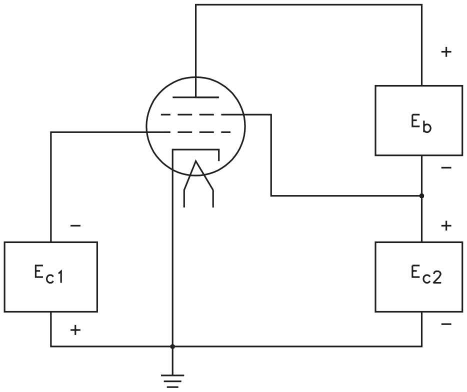


Figure 3.33 Series power supply configuration for swamping the screen circuit of a tetrode.

As shown in Figure 3.33, the addition of a 12.5 kΩ resistor from screen to ground provides a path for screen grid emission (20 mA for the circuit shown). In the circuit of Figure 3.33, plate current flows through the screen power supply, swamping the screen supply. The screen power supply must, obviously, carry the normal screen and plate currents. This scheme is used extensively in circuits where the screen is operated at dc ground potential. The plate-to-cathode voltage is then the sum of the E_b and E_{c2} power supplies.

The suppressor grid of a pentode lessens the effects of secondary emission in the device, reducing the requirement to provide a reverse electron flow path for the screen grid power supply. The screen current requirement for a pentode, however, may be somewhat higher than for a tetrode of the same general characteristics.

The designer also must consider the impedance of the control grid circuit. Primary grid emission can result in operational problems if the grid circuit impedance is excessively high. Primary grid emission, in the case of an oxide cathode tube, will increase with tube life.

The size and power of gridded tubes dictate certain characteristics of electrical potential. As this geometry increases in electrical terms, significant secondary emission from the control grid can occur. Control grid secondary emission can exist whether the cathode is a thoriated-tungsten or oxide emitter, and it can occur in a triode, tetrode, or pentode. A typical curve of grid current as a function of grid voltage for a high-power thoriated-tungsten filament tetrode is shown in Figure 3.34. As shown in the figure, grid current decreases and eventually takes a reverse direction as the grid voltage increases. This reduction and reversal of grid current can be explained by the normal secondary emission characteristics of the metals used in the grid structure.

The secondary emission characteristics of common metals are presented in curve form in Figure 3.35. The ratio of secondary-to-primary electron current is given as a function of primary electron potential. An examination of the chart will show the region between 200 and 600 V to be rather critical as far as secondary emission is con-

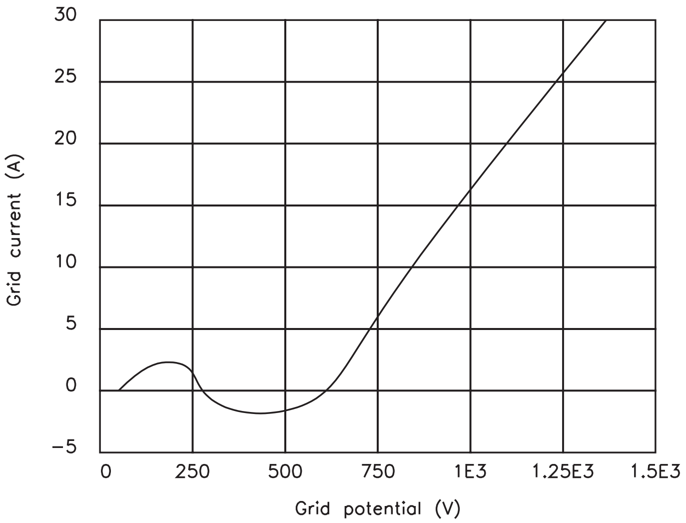


Figure 3.34 Typical curve of grid current as a function of control grid voltage for a high-power thoriated-tungsten filament tetrode.

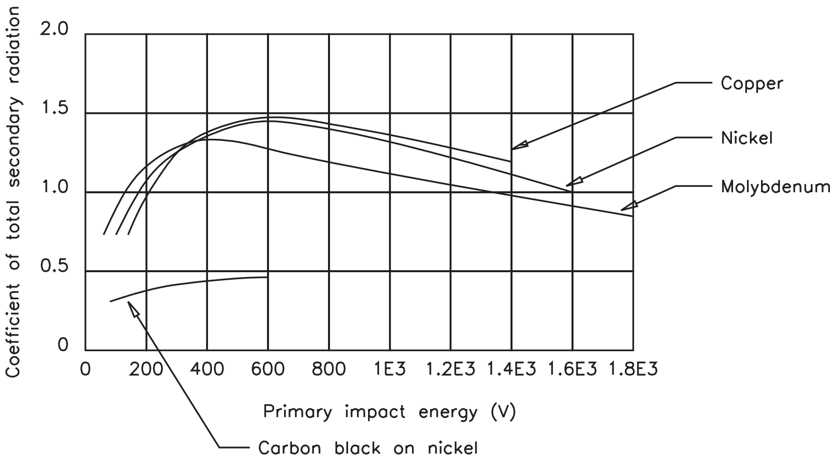


Figure 3.35 Secondary emission characteristics of various metals under ordinary conditions.

cerned. Any power grid tube that normally operates with 200 to 600 V on the grid can exhibit the negative resistance characteristic of decreasing grid current with increasing grid voltage when another electrode—such as the anode in a triode or the screen grid in a tetrode—is at a sufficiently high potential to attract the emitted electrons from the control grid. A driver stage that works into such a nonlinear load normally must be designed in such a manner as to tolerate this condition. One technique involves swamping the driver so that changes in the load resulting from secondary grid emission represent only a small percentage of the total load the driver works into.

3.3.4 Plate Assembly

The plate assembly of a power tube is typically a collection of many smaller parts that are machined and assembled to tight specifications. Copper generally is used to construct the anode. It is an excellent material for this purpose because it has the highest electrical conductivity of any metal except pure silver. Furthermore, copper is easily fabricated and ideally suited to cold-forming operations such as deep drawing, bending, and stamping.

The anode and cooling fins (in the case of an air-cooled device) begin as flat sheets of copper. They are stamped by the tube manufacturer into the necessary sizes and shapes. After all of the parts have been machined, the anode and cooling fins are stacked in their proper positions, clamped, and brazed into one piece in a brazing furnace.

The plate of a power tube resembles a copper cup with the upper half of a plate contact ring welded to the mouth and cooling fins silver-soldered or welded to the outside of the assembly. The lower half of the anode contact ring is bonded to a base ceramic spacer. At the time of assembly, the two halves of the ring are welded together to form a complete unit, as shown in Figure 3.36.

In most power tubes, the anode is a part of the envelope and, because the outer surface is external to the vacuum, it can be cooled directly. Glass envelopes were used in older power tubes. Most have been replaced, however, with devices that use ceramic as the envelope material.

3.3.5 Ceramic Elements

Ceramics are an integral part of modern power vacuum tubes. Three types of ceramics are in common usage in the production of vacuum devices:

- *Aluminum oxide*-based ceramics
- *Beryllium oxide* (BeO)-based ceramics
- *Aluminum nitride* (AlNi)-based ceramics

Aluminum Oxide Ceramics

Aluminum oxide-based ceramic insulators are a common construction material for a wide variety of electric components, including vacuum tubes. Aluminum oxide is 20 times higher in thermal conductivity than most oxides. The flexure strength of commercial high-alumina ceramics is two to four times greater than that of most oxide ceramics. There are drawbacks, however, to the use of alumina ceramics, including:

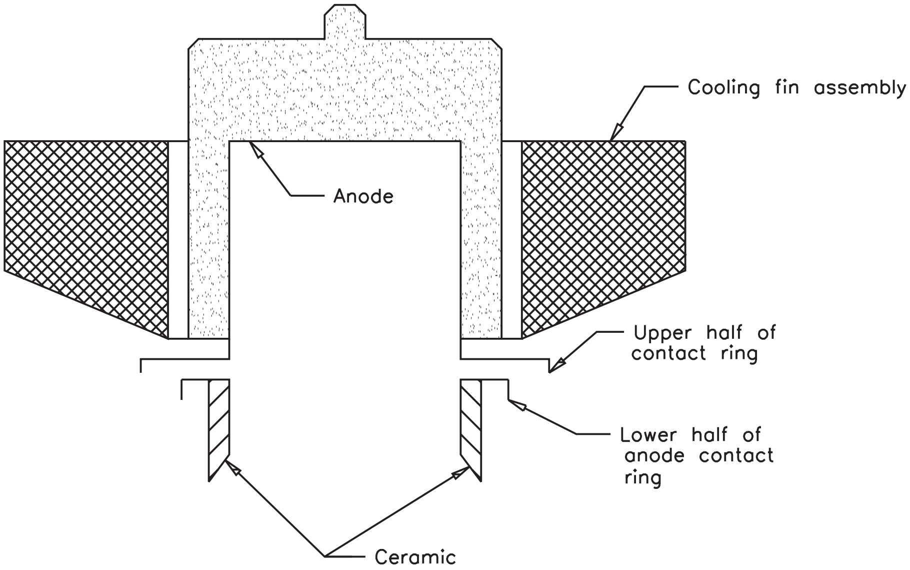


Figure 3.36 A cutaway view of the anode structure of an RF power amplifier tube.

- Relatively high thermal expansion (approximately 7 ppm/°C), compared to other ceramic materials, such as BeO
- Moderately high dielectric constant (approximately 10)

Aluminas are fabricated from aluminum oxide powders with various percentages of *sintering promoters*, which produce the *glassy phase*. The later additives reduce the densification temperatures to between 1500 and 1600°C. Based on the final application, the powders may be pressed, extruded, or prepared in slurries for slip casting or tape casting. The surface finish of aluminas is typically 3 to 25 μm/in as a result of normal processing. For very smooth finishes (2 μm/in), the surfaces may be lapped or polished.

Alumina ceramics for vacuum tube applications rarely are used apart from being bonded to metals. The means by which this is accomplished frequently dictate the processing technique. Metallization of aluminas usually is accomplished by either high-temperature firing or low-temperature thick-film processing. Fired, shaped aluminas usually are postmetallized by refiring the formed article after it has been coated with a slurry of molybdenum and manganese powder or tungsten metal powder. Based on the purity of the alumina, glass powder may be added to the metal powder. The mechanism of metallization requires an internal glassy phase or the added glassy phase for proper bonding. This is accomplished by firing in slightly reducing and moist atmospheres at temperatures above 1500°C. The resulting metallization usually is plated electrochemically with nickel, copper, or both.

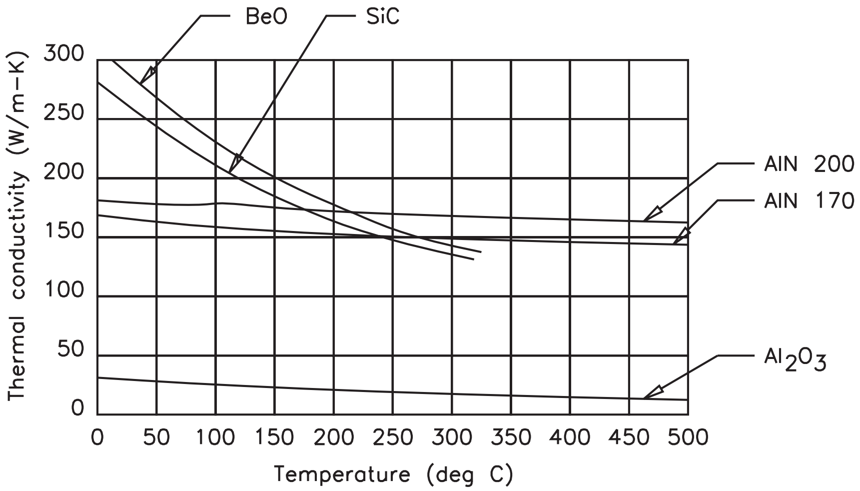


Figure 3.37 Thermal conductivity of common ceramics.

Thick-film processing of alumina ceramics traditionally has been performed in oxidizing atmospheres at moderate temperatures (800 to 1000°C). Precious metals are used, such as gold, silver, platinum, palladium, and their combinations. A glassy phase usually is incorporated in the thick-film paste.

Each approach to metallization has advantages and disadvantages. The advantage of the high-temperature metallization schemes with molybdenum or tungsten is their moderate cost. The disadvantage is the high resistivity of the resulting films. These attributes are reversed for thick-film materials. Another advantage of thick-film metallization is that the process often is applied by the device fabricator, not the ceramic vendor. This can allow for greater efficiency in design modification.

In tubes designed for operation at 100 MHz and below, alumina typically is the ceramic of choice.

Beryllium Oxide Ceramics

Beryllium oxide-based ceramics are in many ways superior to alumina-based ceramics. The major drawback is the toxicity of BeO. Beryllium and its compounds are a group of materials that are potentially hazardous and must be handled properly. With the necessary safeguards, BeO has been used successfully in many tube designs.

Beryllium oxide materials are particularly attractive for use in power vacuum tubes because of their electrical, physical, and chemical properties. The thermal conductivity of BeO is approximately 10 times higher than that of alumina-based materials. Figure 3.37 compares the thermal conductivity of BeO with that of alumina and some alternative materials. As the chart illustrates, BeO has a lower dielectric constant and coefficient of thermal expansion than alumina. It is, however, also slightly lower in strength.

Beryllia materials are fabricated in much the same way as alumina compounds, although the toxic properties of the powders mandate that they be processed in laboratories equipped to handle them safely. Simple cutting, drilling, and postmetallization also are handled by vendors with special equipment. Reliable thick-film systems may be applied to BeO substrates. Such coatings usually necessitate less elaborate safety precautions and are often applied by the device fabricator. General safety precautions relating to BeO ceramics are given in Section 11.3.2.

Other Ceramics

Aluminum nitride (AlNi)-based ceramics have been developed as an alternative to the toxicity concerns of BeO-based materials. As shown in Figure 3.37, the thermal conductivity of AlNi is comparable to that of BeO but deteriorates less with temperature. The dielectric constant of AlNi is comparable to that of alumina (a drawback), but its thermal expansion is low (4 ppm/°C).

Other ceramic materials that find some use in vacuum devices include silicon carbide (SiC)-based substances and boron nitride ceramics.

3.3.6 Tube Construction

Each type of power grid tube is unique insofar as its operating characteristics are concerned. The basic physical construction, however, is common to most devices. A vacuum tube is built in essentially two parts:

- The base, which includes the filament and supporting stem, control grid, screen grid, and suppressor grid (if used)
- The anode, which includes the heat-dissipating fins made in various machining steps

The base subassembly is welded using a *tungsten-inert gas* (TIG) process in an oxygen-free atmosphere (a process sometimes referred to as *Heliarc welding*) to produce a finished base unit.

The ceramic elements used in a vacuum tube are critical parts of the device. Assembled in sections, each element builds upon the previous one to form the base of the tube. The ceramic-to-metal seals are created using a material that is *painted* onto the ceramic and then heated in a brazing oven. After preparation in a high-temperature oven, the painted area provides a metallic structure that is molecularly bonded to the ceramic and provides a surface suitable for brazing.

This process requires temperature sequences that dictate completion of the highest-temperature stages first. As the assembly takes form, lower oven temperatures are used so that completed bonds will not be compromised.

Despite all the advantages that make ceramics one of the best insulators for a tube envelope, their brittleness is a potential cause of failure. The smallest cracks in the ceramic, not in themselves damaging, can cause the ceramic to break when mechanically stressed by temperature changes.

After the base assembly has been matched with the anode, the completed tube is brazed into a single unit. The device then goes through a *bake-out* procedure. Baking stations are used to evacuate the tube and bake out any oxygen or other gases from the copper parts of the assembly. Although oxygen-free copper is used in tube construction, some residual oxygen exists in the metal and must be driven out for long component life. A typical vacuum reading of 10^{-8} Torr is specified for most power tubes (formerly expressed as 10^{-8} mm of mercury). For comparison, this is the degree of vacuum in outer space about 200 miles above the earth.

A vacuum offers excellent electrical insulation characteristics. This property is essential for reliable operation of a vacuum tube, the elements of which typically operate at high potentials with respect to each other and to the surrounding environment. An electrode containing absorbed gases, however, will exhibit reduced breakdown voltage because the gas will form on the electrode surface, increasing the surface gas pressure and lowering the breakdown voltage in the vicinity of the gas pocket.

To maintain a high vacuum during the life of the component, power tubes contain a *getter* device. The name comes from the function of the element: to “get” or trap and hold gases that may exist inside the tube. Materials used for getters include zirconium, cerium, barium, and titanium.

The operation of a vacuum tube is an evolving chemical process. End of life in a vacuum tube generally is caused by loss of emission.

3.3.7 Connection Points

The high power levels and frequencies at which vacuum tubes operate place stringent demands on the connectors used to tie the outside world to the inside elements. Tubes are designed to be mounted vertically on their electrical connectors. The connectors provide a broad contact surface and mechanical support for the device.

The cathode and grids typically are mounted on ring-shaped *Kovar* bases, which also serve as contact rings for the external connections. Kovar is an iron-nickel-cobalt alloy whose coefficient of thermal expansion is comparable to that of aluminum oxide ceramic. The different diameters of the various contact rings allow them to be grouped coaxially. The concentric tube/connector design provides for operation at high frequencies. Conductivity is improved by silver plating.

3.3.8 Tube Sockets

Any one tube design may have several possible socket configurations, depending upon the frequency of operation. If the tube terminals are large cylindrical surfaces, the contacting portions of the socket consist of either spring *collets* or an assembly of spring fingerstock. Usually, these multiple-contacting surfaces are made of beryllium copper to preserve spring tension at the high temperatures present at the tube terminals. The fingers are silver-plated to reduce RF resistance. Figure 3.38 shows a cutaway view of the base of a tetrode socket.

If the connecting fingers of a power tube socket fail to provide adequate contact with the tube element rings, a concentration of RF currents will result. Depending on the ex-

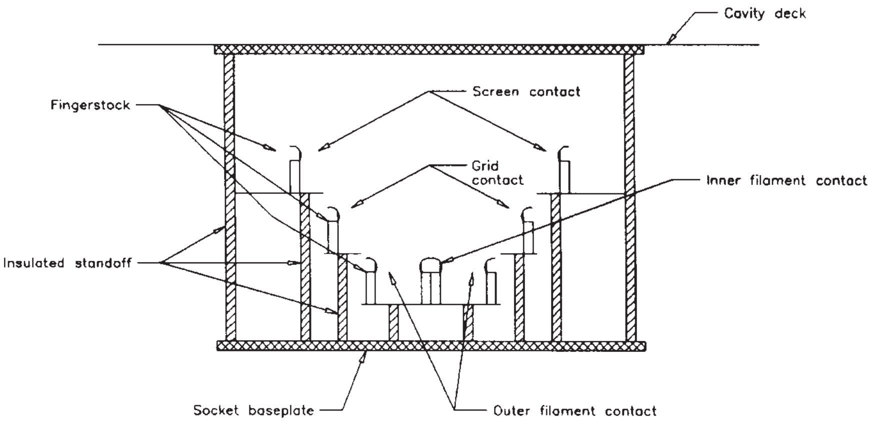


Figure 3.38 Cross section of the base of a tetrode socket showing the connection points.

tent of this concentration, damage may result to the socket. After a connecting finger loses its spring action, the heating effect is aggravated, and tube damage is possible.

A series of specialized power tubes is available with no sockets at all. Intended for cathode-driven service, the grid assembly is formed into a flange that is bolted to the chassis. The filament leads are connected via studs on the bottom of the tube. Such a configuration eliminates the requirement for a socket. This type of device is useful for low-frequency applications, such as induction heating.

3.4 Neutralization

An RF power amplifier must be properly neutralized to provide acceptable performance in most applications. The means to accomplish this end vary considerably from one design to another. An RF amplifier is neutralized when two operating conditions are met:

- The interelectrode capacitance between the input and output circuits is canceled.
- The inductance of the screen grid and cathode assemblies (in a tetrode) is canceled.

Cancellation of these common forms of coupling between the input and output circuits of vacuum tube amplifiers prevents self-oscillation and the generation of spurious products.

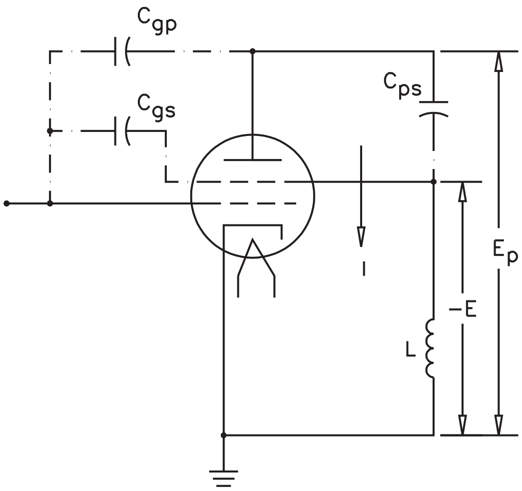


Figure 3.39 The elements involved in the neutralization of a tetrode PA stage.

3.4.1 Circuit Analysis

Figure 3.39 illustrates the primary elements that affect neutralization of a vacuum tube RF amplifier operating in the VHF band. (Many of the following principles also apply to lower frequencies.) The feedback elements include the residual grid-to-plate capacitance (C_{gp}), plate-to-screen capacitance (C_{ps}), and screen grid lead inductance (L_s). The RF energy developed in the plate circuit (E_p) causes a current (I) to flow through the plate-to-screen capacitance and the screen lead inductance. The current through the screen inductance develops a voltage ($–E$) with a polarity opposite that of the plate voltage (E_p). The $–E$ potential often is used as a method of neutralizing tetrode and pentode tubes operating in the VHF band.

Figure 3.40 graphically illustrates the electrical properties at work. The circuit elements of the previous figure have been arranged so that the height above or below the zero potential line represents the magnitude and polarity of the RF voltage for each part of the circuit with respect to ground (zero). For the purposes of this illustration, assume that all of the circuit elements involved are pure reactances. The voltages represented by each, therefore, are either in phase or out of phase and can be treated as positive or negative with respect to each other.

The voltages plotted in the figure represent those generated as a result of the RF output circuit voltage (E_p). No attempt is made to illustrate the typical driving current on the grid of the tube. The plate (P) has a high positive potential above the zero line, established at the ground point. Keep in mind that the distance above the baseline represents increasing positive potential. The effect of the out-of-phase screen potential developed as a result of inductance L_s is shown, resulting in the generation of $–E$.

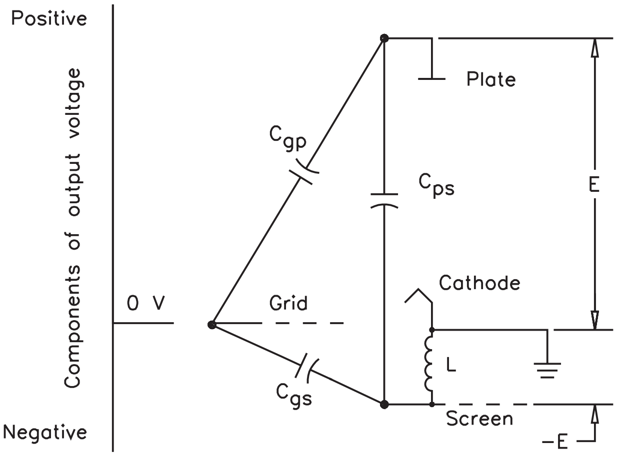


Figure 3.40 A graphical representation of the elements involved in the self-neutralization of a tetrode RF stage.

As depicted, the figure constitutes a perfectly neutralized circuit. The grid potential rests at the zero baseline. The grid operates at filament potential insofar as any action of the output circuit on the input circuit is concerned.

The total RF voltage between plate and screen is made up of the plate potential and screen lead inductance voltage, $-E$. This total voltage is applied across a divider circuit that consists of the grid-to-plate capacitance and grid-to-screen capacitance (C_{gp} and C_{gs}). When this potential divider is properly matched for the values of plate RF voltage (E_p) and screen lead inductance voltage ($-E$), the control grid will exhibit zero voltage difference with respect to the filament as a result of E_p.

3.4.2 Circuit Design

A variety of methods may be used to neutralize a vacuum tube amplifier. Generally speaking, a grounded-grid, cathode-driven triode can be operated into the VHF band without external neutralization components. The grounded-grid element is sufficient to prevent spurious oscillations. Tetrode amplifiers generally will operate through the MF band without neutralization. However, as the gain of the stage increases, the need to cancel feedback voltages caused by tube interelectrode capacitances and external connection inductances becomes more important. At VHF and above, it is generally necessary to provide some form of stage neutralization.

Below VHF

For operation at frequencies below the VHF band, neutralization for a tetrode typically employs a capacitance bridge circuit to balance out the RF feedback caused by

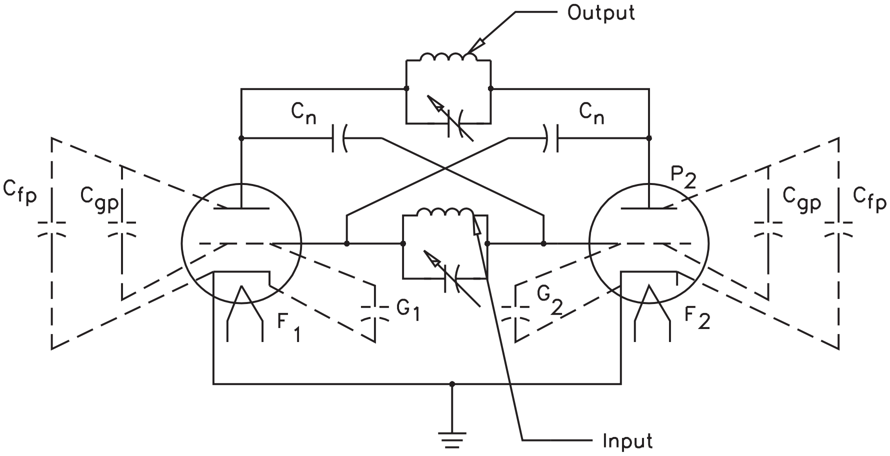


Figure 3.41 Push-pull grid neutralization.

residual plate-to-grid capacitance. This method assumes that the screen is well bypassed to ground, providing the expected screening action inside the tube.

Neutralization of low-power push-pull tetrode or pentode tubes can be accomplished with cross-neutralization of the devices, as shown in Figure 3.41. Small-value neutralization capacitors are used. In some cases, neutralization can be accomplished with a simple wire connected to each side of the grid circuit and brought through the chassis deck. Each wire is positioned to "look at" the plate of the tube on the opposite half of the circuit. Typically, the wire (or a short rod) is spaced a short distance from the plate of each tube. Fine adjustment is accomplished by moving the conductor in or out from its respective tube.

A similar method of neutralization can be used for a cathode-driven symmetrical stage, as shown in Figure 3.42. Note that the neutralization capacitors (C_n) are connected from the cathode of one tube to the plate of the opposite tube. The neutralizing capacitors have a value equal to the internal cathode-to-plate capacitance of the PA tubes.

In the case of a single-ended amplifier, neutralization can be accomplished using either a push-pull output or push-pull input circuit. Figure 3.43 shows a basic push-pull grid neutralization scheme that provides the out-of-phase voltage necessary for proper neutralization. It is usually simpler to create a push-pull network in the grid circuit than in the plate because of the lower voltages present. The neutralizing capacitor, C_n, is small and may consist of a simple feedthrough wire (described previously). A padding capacitor in parallel with C_1 often is added to maintain the balance of the input circuit while tuning. The padding capacitor generally is equal in size to the input capacitance of the tube.

Single-ended tetrode and pentode stages also can be neutralized using the method shown in Figure 3.44. The input resonant circuit is placed above ground by a small amount because of the addition of capacitor C. The voltage to ground that develops

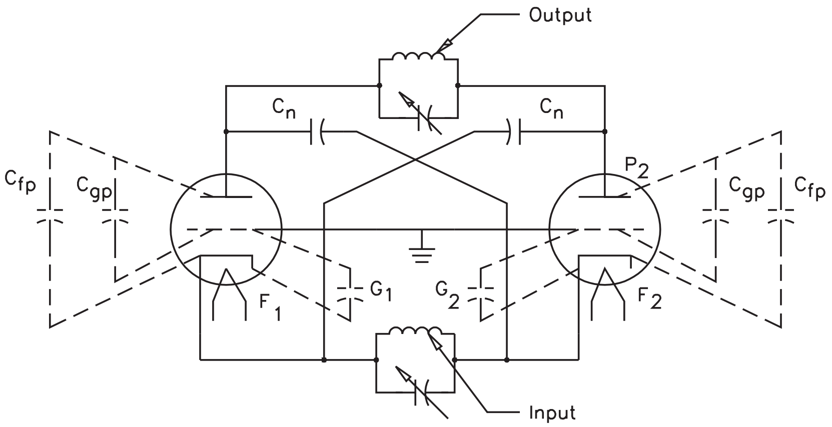


Figure 3.42 Symmetrical stage neutralization for a grounded-grid circuit.

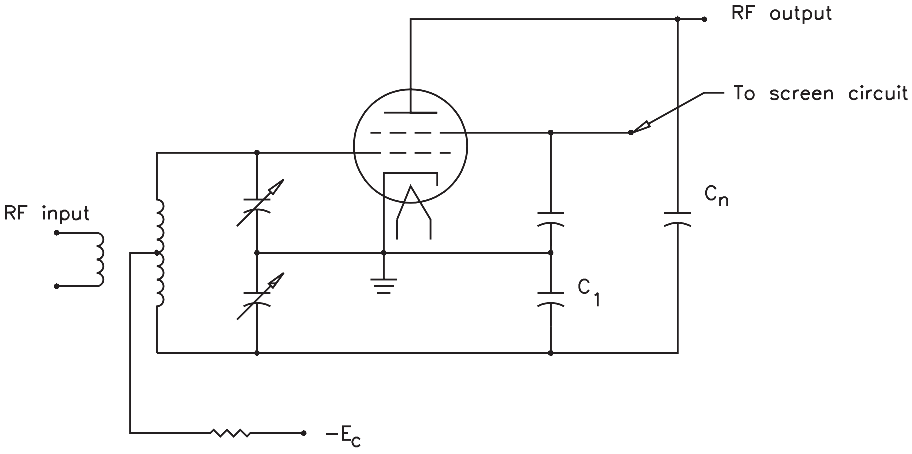


Figure 3.43 Push-pull grid neutralization in a single-ended tetrode stage.

across C upon the application of RF drive is out of phase with the grid voltage, and is fed back to the plate through C_n to provide neutralization. In such a design, C_n is considerably larger in value than the grid-to-plate interelectrode capacitance.

The single-ended grid neutralization circuit is redrawn in Figure 3.45 to show the capacitance bridge that makes the design work. Balance is obtained when the following condition is met:

$$\frac{C_n}{C} = \frac{C_{gp}}{C_{gf}} \tag{3.12}$$

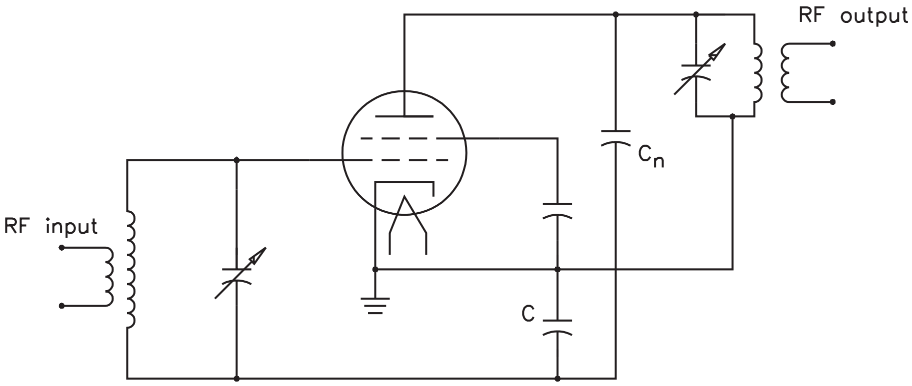


Figure 3.44 Single-ended grid neutralization for a tetrode.

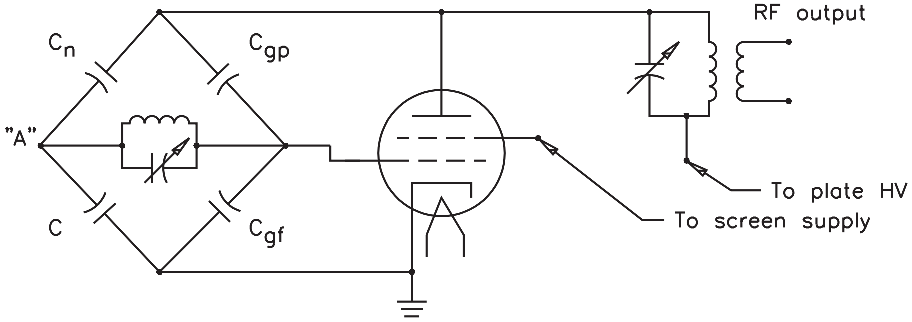


Figure 3.45 The previous figure redrawn to show the elements involved in neutralization.

Where:
C_n = neutralization capacitance
C = input circuit bypass capacitor
C_{gp} = grid-to-plate interelectrode capacitance
C_{gf} = total input capacitance, including tube and stray capacitance

A single-ended amplifier also can be neutralized by taking the plate circuit slightly above ground and using the tube capacitances as part of the neutralizing bridge. This circuit differs from the usual RF amplifier design in that the plate bypass capacitor is returned to the screen side of the screen bypass capacitor, as shown in Figure 3.46. The size of screen bypass capacitor C_s and the amount of stray capacitances in C_p are chosen

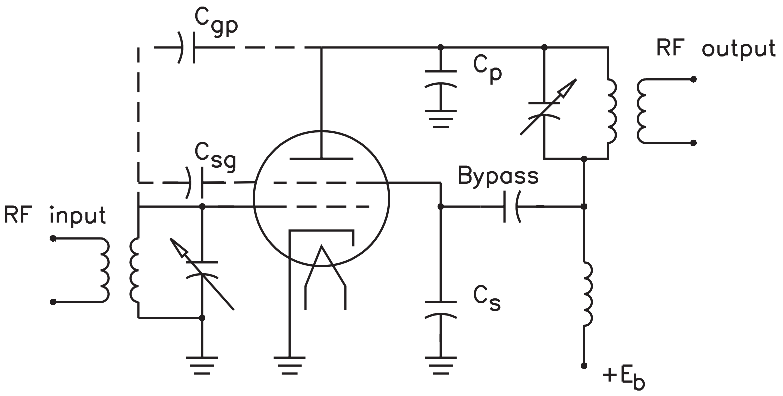


Figure 3.46 Single-ended plate neutralization.

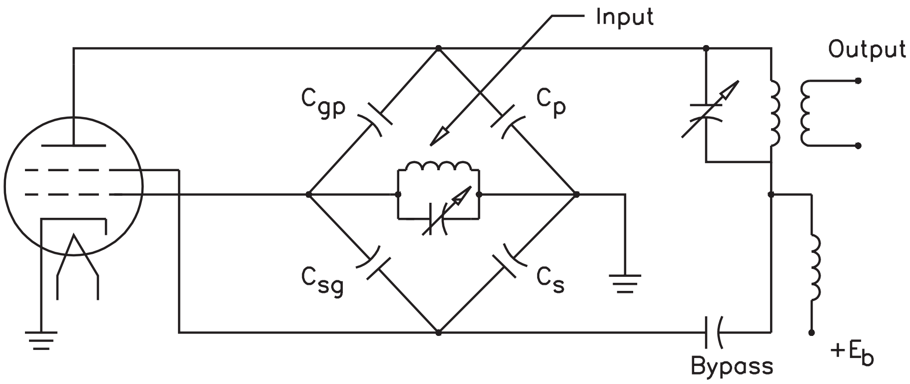


Figure 3.47 Single-ended plate neutralization showing the capacitance bridge present.

to balance the voltages induced in the input by the internal tube capacitances, grid-to-plate (C_{gp}) and screen-to-grid (C_{sg}). This circuit is redrawn in Figure 3.47 in the usual bridge form. Balance is obtained when the following condition is met:

$$\frac{C_p}{C_s} = \frac{C_{gp}}{C_{sg}} \tag{3.13}$$

In usual tetrode and pentode structures, the screen-to-grid capacitance is approximately half the published tube input capacitance. The tube input capacitance is primarily the sum of the grid-to-screen capacitance and the grid-to-cathode capacitance.

Note that in the examples given, it is assumed that the frequency of operation is low enough that inductances in the socket and connecting leads can be ignored. This is basically true in MF applications and below. At higher bands, however, the effects of stray inductances must be considered, especially in single-ended tetrode and pentode stages.

VHF and Above

Neutralization of power grid tubes operating at very high frequencies provides special challenges and opportunities to the design engineer. At VHF and above, significant RF voltages may develop in the residual inductance of the screen, grid, and cathode elements. If managed properly, these inductances can be used to accomplish neutralization in a simple, straightforward manner.

At VHF and above, neutralization is required to make the tube input and output circuits independent of each other with respect to reactive currents. Isolation is necessary to ensure independent tuning of the input and output. If variations in the output voltage of the stage produce variations of phase angle of the input impedance, phase modulation will result.

As noted previously, a circuit exhibiting independence between the input and output circuits is only half of the equation required for proper operation at radio frequencies. The effects of incidental inductance of the control grid also must be canceled for complete stability. This condition is required because the suppression of coupling by capacitive currents between the input and output circuits is not, by itself, sufficient to negate the effects of the output signal on the cathode-to-grid circuit. Both conditions—input and output circuit independence and compensation for control grid lead inductance—must be met for complete stage stability at VHF and above.

Figure 3.48 shows a PA stage employing stray inductance of the screen grid to achieve neutralization. In this grounded-screen application, the screen is bonded to the cavity deck using six short connecting straps. Two additional adjustable ground straps are set to achieve neutralization.

3.4.3 Grounded-Grid Amplifier Neutralization

Grounded-grid amplifiers offer an attractive alternative to the more common grid-driven circuit. The control grid is operated at RF ground and serves as a shield to capacitive currents from the output to the input circuit. Generally, neutralization is not required until the control grid lead inductive reactance becomes significant. The feedback from the output to the input circuit is no longer the result of plate-to-filament capacitance. The physical size of the tube and the operating frequency determine when neutralization is required.

Two methods of neutralization commonly are used with grounded-grid amplifiers. In the first technique, the grids of a push-pull amplifier are connected to a point having zero impedance to ground, and a bridge of neutralizing capacitances is used that is equal to the plate-filament capacitances of the tubes.

The second method of neutralization requires an inductance between the grid and ground, or between the grids of a push-pull amplifier, of a value that will compensate for the coupling between input and output circuits resulting from the internal capacitances of the tubes.

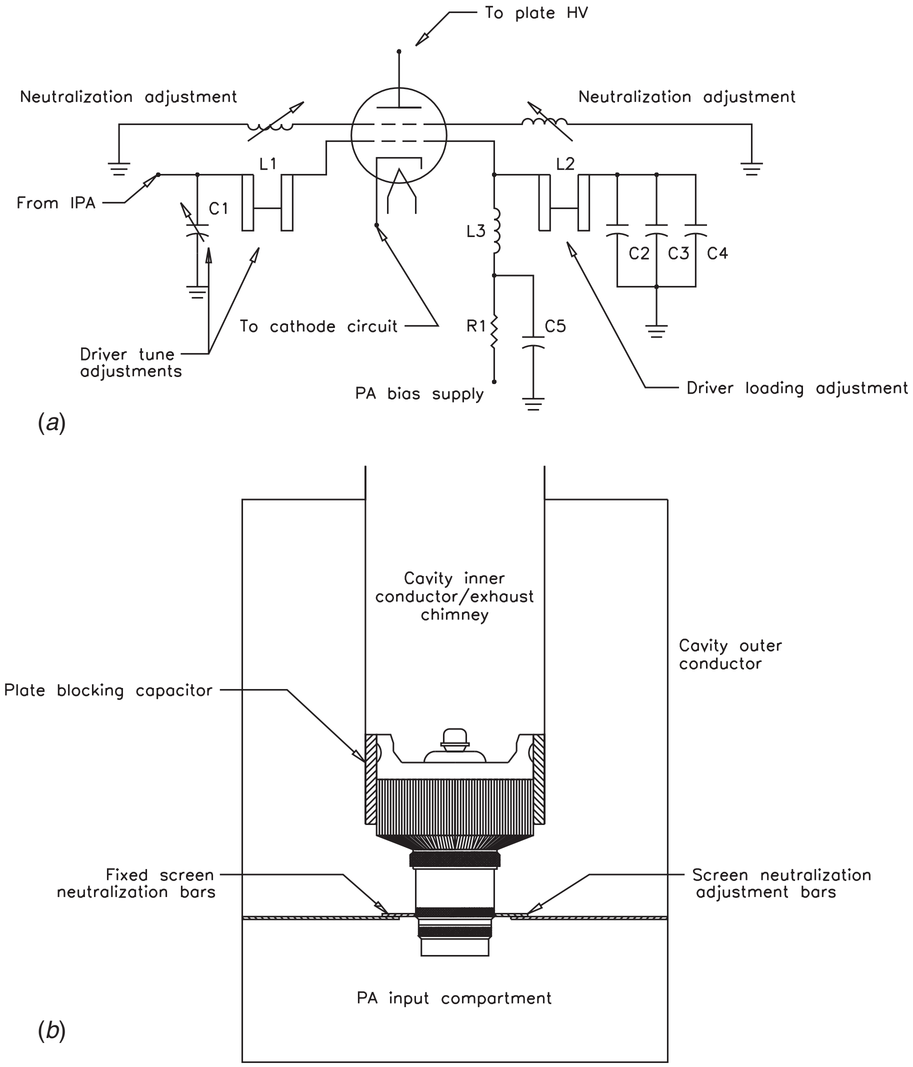


Figure 3.48 A grounded-screen PA stage neutralized through the use of stray inductance between the screen connector and the cavity deck: (*a*) schematic diagram, (*b*) mechanical layout of cavity.

Behavior of these two circuits is quite different. They may be considered as special forms of the more general case in which the neutralizing capacitors have values differing from the internal capacitances of the tubes, and in which an appropriate reactance is connected between the grids. Under these conditions, the value of neutralizing capaci-

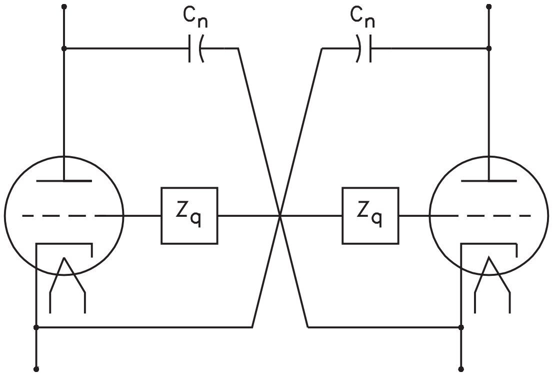


Figure 3.49 Circuit of grounded-grid amplifier having grid impedance and neutralized for reactive currents.

tance permits continuous variation of power amplification, stability, and negative feedback.

Grid Impedance

In the special case of a grounded-grid amplifier having a grid impedance and the reactive currents neutralized, the following equations apply (see Figure 3.49):

$$C_n = C_{fp} - \frac{C_{fg}}{\mu} \tag{3.14}$$

$$Z_g = -\frac{1}{j\omega C_{fg} + C_{gp}(1+\mu)} \tag{3.15}$$

If in solving the equation for C_n the sign is negative, this indicates that in-phase neutralization is required. Conversely, if the sign of C_n is positive, then out-of-phase neutralization is needed. A negative value of Z_g indicates capacitive reactance required, and a positive value indicates that inductive reactance is to be used.

Application Example

If the grids of a push-pull cathode-driven amplifier are not at ground potential because the inductance of the leads is not negligible, coupling may exist between the input and output circuits through the plate-grid capacitances, cathode-grid capacitances, and grid-to-grid inductance. One method of reducing this coupling is to insert between the grids a series-tuned circuit that has zero reactance at the operating frequency. This technique is illustrated in Figure 3.50. This neutralization scheme is use-

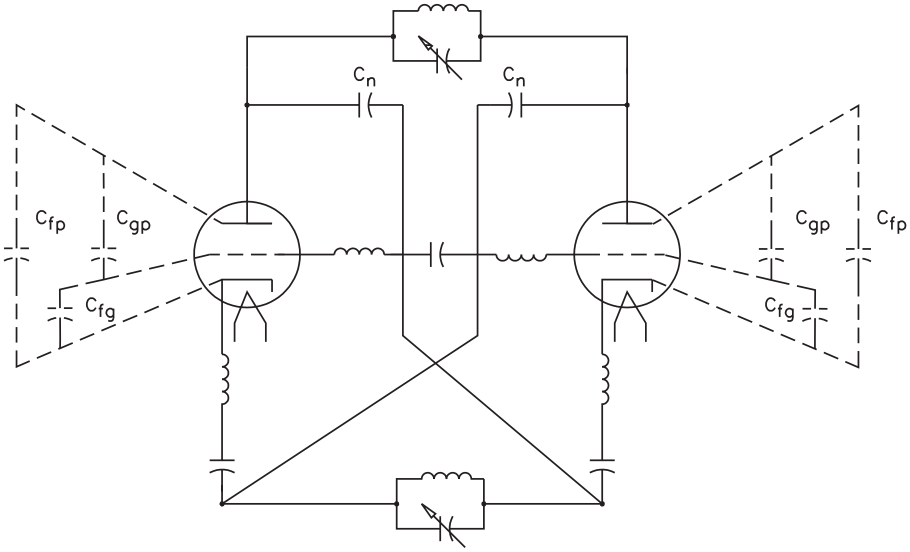


Figure 3.50 Neutralization by cross-connected capacitors of a symmetrical cathode-excited amplifier wth compensation of lead inductance.

ful only for the case in which no grid current flows. If grid current flows, a grid resistance will appear in parallel with the grid-to-filament capacitance. If the resistance is small in comparison with the reactance of this grid-to-filament capacitance, phase modulation will result.

Another important property of the preceding neutralization scheme is that power amplification is a function of the neutralizing capacitance, while the independence of cathode and plate circuits from the viewpoint of reactive currents may be obtained with any value of neutralizing capacitance. If the neutralizing capacitance is less than the plate-to-filament capacitance of the tube, the stage will operate with low excitation power and high power amplification.

If the neutralizing capacitance is greater than the plate-to-filament capacitance, the power amplification will be quite low, but the total output power possible will be increased.

3.4.4 Self-Neutralizing Frequency

The voltage-dividing action between the plate-to-grid capacitance (C_{pg}) and the grid-to-screen capacitance (C_{gs}) will not change with variations in operating frequency. The voltage division between the plate and screen, and screen and ground caused by the charging current (I) will, however, vary significantly with frequency. There will be a particular frequency, therefore, at which this potential-dividing circuit

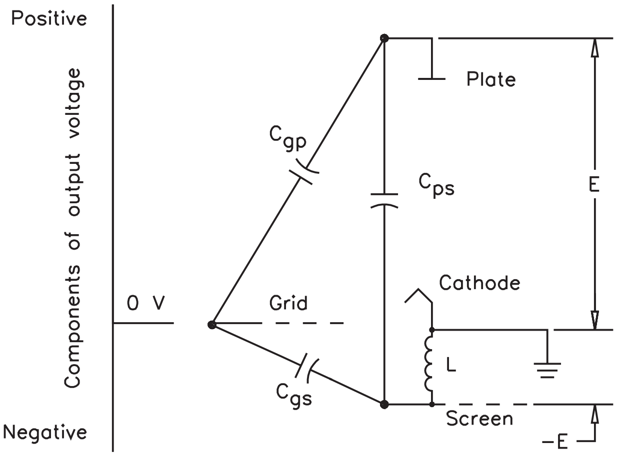


Figure 3.51 Graphical representation of the elements of a tetrode when self-neutralized.

will effectively place the grid at filament potential insofar as the plate is concerned. This point is known as the *self-neutralizing frequency*, illustrated in Figure 3.51.

At the self-neutralizing frequency, the tetrode or pentode is inherently neutralized by the circuit elements within the device itself, and external screen inductance to ground. When a device is operated below its self-neutralizing frequency, the normal cross-neutralization circuits apply. When the operating frequency is above the self-neutralizing frequency, the voltage developed in the screen lead inductance is too large to give the proper voltage division between the internal capacitances of the device. One approach to neutralization in this case involves adjusting the inductive reactance of the screen lead to ground to lower the total reactance. In the example shown in Figure 3.52, this is accomplished with a series variable capacitor.

Another approach is shown in Figure 3.53, in which the potential divider network made up of the tube capacitance is changed. In the example, additional plate-to-grid capacitance is added external to the tube. The external capacitance (C_{ext}) can take the form of a small wire or rod positioned adjacent to the plate of the tube. This approach is similar to the one described in Section 3.4.2, except that in this case the neutralizing probe is connected to the grid of the tube, rather than to an opposite polarity in the circuit.

If the RF power amplifier is operating above the self-neutralizing frequency of the tube and must be tuned over a range of frequencies, it is probably easier to use the screen series-tuning capacitor method and make this control available to the operator. If operation is desired over a range of frequencies including the self-neutralizing frequency of the tube, this circuit is also desirable because the incidental lead inductance in the variable capacitor lowers the self-neutralizing frequency of the circuit so that the neutralizing series capacitor can be made to operate over the total desired frequency range. If this range is too great, switching of neutralizing circuits will be required. A small 50 to 100 pF variable capacitor in the screen lead often has been found to be satisfactory.

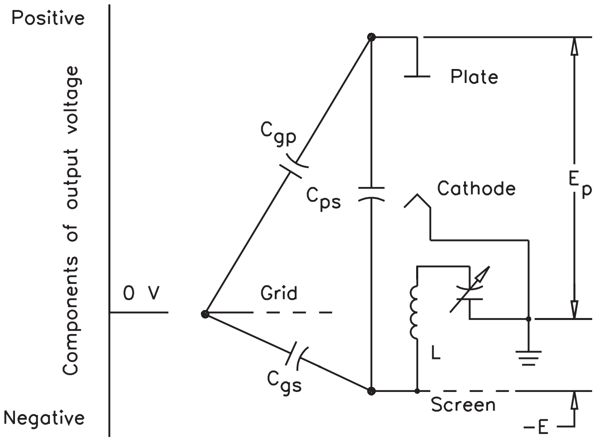


Figure 3.52 Components of the output voltage of a tetrode when neutralized by adding series screen-lead capacitance.

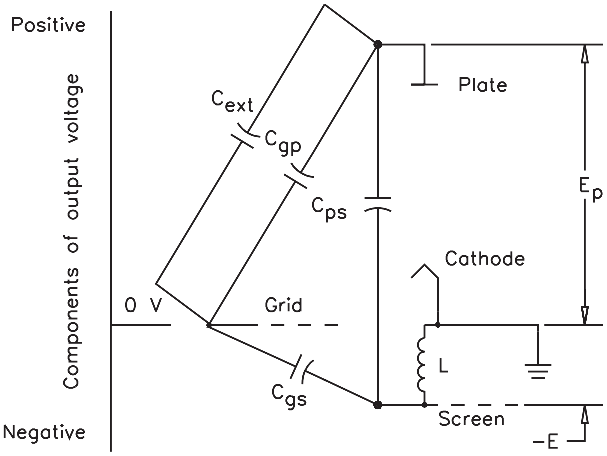


Figure 3.53 Components of the output voltage of a tetrode when neutralized by adding external grid-to-plate capacitance.

Another method of changing the self-neutralizing frequency of a tetrode or pentode can be fashioned from the general bypassing arrangement of the screen and filament shown in Figure 3.54. The screen lead is bypassed with minimum inductance to the filament terminal of the tube. Some inductance is introduced in the common filament and screen ground leads. The grid is shown below the zero voltage or chassis potential, indicating that the voltage developed in the screen lead inductance to chassis is excessive. If the filament is tapped on this inductance, a point can be found where the voltage differ-

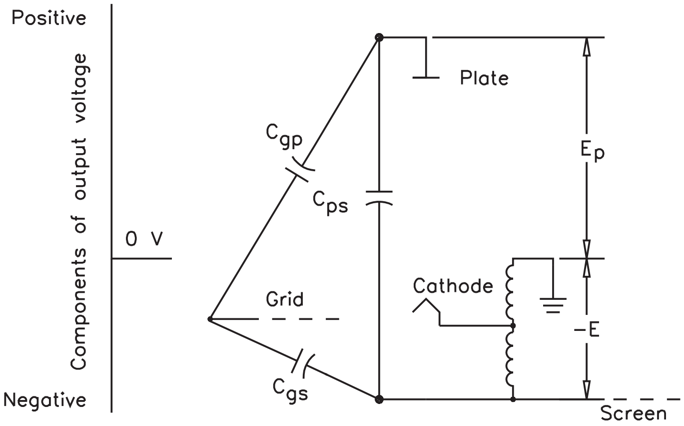


Figure 3.54 Components of the output voltage of a tetrode neutralized by adding inductance common to the screen and cathode return.

ence between the grid and filament is zero, as far as the components of plate voltage are concerned. This arrangement will be found to self-neutralize at a higher frequency than if the filament and screen were bypassed separately to the chassis. Thus, increasing the self-neutralizing frequency of the tube and screen bypass arrangement reduces the tendency of the VHF parasitic to occur.

If the frequency of the VHF parasitic is reduced by increasing the inductance of the plate lead (presuming this is the principal frequency-defining circuit), the circuit can be made to approach the self-neutralizing frequency of the tube and, therefore, suppress the parasitic.

3.4.5 Neutralization Adjustment

Most neutralization circuits must be adjusted for operation at a given frequency. The exact procedure followed to make these adjustments varies from one circuit to the next. The following generalizations, however, apply to most systems.

The first step in the process of neutralization is to break the dc connections to the plate voltage and screen voltage supplies, leaving the RF circuits intact. If the direct current path is not broken, some current can flow in either of these circuits even though the voltages are zero. The presence of this current causes the amplifier to work in the normal manner, generating RF power in the plate circuit. It would then be incorrect to adjust for zero power in the plate circuit. Sufficient RF grid drive must be applied to provide some grid current or to cause a sensitive RF meter coupled to the plate to give an indication of feedthrough power. When the plate circuit is tuned through resonance, the grid current will dip when the circuit is out of neutralization, or the RF meter will peak. The neutralization adjustments are made until the indication is minimum.

Another powerful tool for roughly neutralizing an RF amplifier is to feed the power output from a signal generator into the grid circuit. A sensitive RF detector is inserted between the output connector and the load. Neutralization can then be adjusted for minimum feedthrough. This technique is useful in working with prototype equipment. Actual qualitative measurements can be made. If the insertion loss of the amplifier is less than the expected gain, oscillation will occur. Circuit modifications can be made until the isolation is sufficient to warrant a test with high voltages applied. The advantages of this "cold" system test are that:

- No components are subjected to unusual stress if the amplifier is unstable.
- Circuit adjustments can be made safely because no high voltages are present.

For final trimming of the neutralization adjustment, the stage should be returned to operating condition at reduced power (similar to that used when testing for parasitic oscillations), or under the final loaded operating conditions. At higher frequencies, particularly in the VHF region, it will be found that a small additional trimming adjustment of the neutralization circuit is usually required. When the plate circuit is tuned through resonance, minimum plate current and maximum control grid current should occur simultaneously. In the case of the tetrode and pentode, the dc screen current should be maximum at the same time.

These neutralizing procedures apply not only to the HF radio frequencies, but also to the VHF and UHF regions.

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