Chapter 16

HOT-CATHODE TUBES

In the normal glow discharge described in the previous chapter the current of discharge products striking the cathode amounts to several ions, metastables, and photons per electron released from the cathode. This relatively large ratio of incident discharge products to emitted electrons is made necessary by the low efficiency of the γ and photoelectric emission processes. Since the discharge is self-sustaining, the emitted electrons must gain sufficient energy to generate the current of discharge products striking the cathode, and consequently the voltage drop in the cathode-fall region must be at least several times the ionization potential of the gas.

If a thermonically emitting cathode is used in place of the cold cathode, and if the thermionic emission current is at least equal to the current flowing in the external circuit, the voltage drop across the tube is much smaller, in many cases less than the ionization potential of the gas. Hot-cathode tubes filled with mercury vapor often conduct currents of several amperes at a voltage drop of 6 to 9 volts, despite the fact that the ionization potential of mercury is 10.4 volts.

The high-current, low-voltage properties of the hot-cathode discharge make possible the design of hot-cathode rectifier tubes for use in high-voltage power supplies, the power losses in the tubes being small compared with the power delivered to the load. The hot-cathode discharge is also used in some switching tubes where a low anode-to-cathode voltage drop is desirable. Both rectifier and switching tubes usually show a nearly constant voltage drop as the current is varied from a relatively small value up to the cathode thermionic emission current At higher currents the anode-to-cathode voltage rises.

In the conducting state most of the interelectrode space of a hot-cathode gas tube is filled with a plasma in which the ion and electron densities are approximately equal, and in which potential gradients are small. Often the potential gradient in the direction from the cathode to the anode is of the order of a few tenths of a volt per centimeter. Between the plasma and the cathode there is a region of nonuniform charge, called a sheath, in which a voltage drop of several volts takes place. Hot-cathode tubes are generally operated with the cathode current space-charge-limited so that there is a small potential minimum just outside the cathode. Ions flow from the plasma toward the cathode, and electrons drawn from the potential minimum flow toward the plasma. Often the electron current in the cathode sheath is several hundred times the ion current.

Sheaths also form between the plasma and the walls of the tube and between the plasma and the anode. The walls are at a negative potential with respect to the plasma, while there is often a small rise in potential in going from the plasma to the anode.

The cathode of a hot-cathode rectifier or switching tube frequently consists of a nickel ribbon or mesh coated with barium and strontium oxides or other emissive material. The cathode is heated by passing a current through it. Other tubes have indirectly heated, oxide-coated nickel cathodes. Because power must be supplied to heat the cathode and hence to maintain the discharge, the discharge is not self-sustaining.

Generally quite low filling pressures are used, in some cases a few tenths of a millimeter of Hg, but often as small as a few thousandths of a millimeter of Hg. The use of low filling pressures serves two purposes. It reduces the cooling of the cathode by the gas, and it makes the product of the pressure and the maximum distance between the electrodes much smaller than that which gives minimum breakdown voltage. As a result, relatively high inverse voltages (anode negative with respect to the cathode) can be applied without cold-cathode breakdown occurring. This is particularly desirable in high-voltage rectifier applications where the anode may be several thousand volts negative with respect to the cathode during part of the ac cycle. The gas fillings are usually noble gases, or mercury vapor in equilibrium with liquid mercury, or a combination of the two. In some special-purpose tubes hydrogen is used. However, gases with diatomic or polyatomic molecules lead to much higher voltage drops and consequently are not generally employed.

In all gas tubes there is a tendency for the discharge to cause a small amount of the filling gas to become embedded or entrapped in the electrodes and walls of the tube. This gas "cleanup" is thought to result from ions impinging on the inner surfaces of the tube where they become entrapped by material sputtered from the cathode. In cold-cathode tubes where the filling pressure is relatively high, gas cleanup is seldom of importance since the fractional loss of pressure is usually quite small. However, in hot-cathode tubes the fractional loss of pressure during the life of the tube can be appreciable because of the much smaller initial filling pressure. Tubes filled with noble gases at too low an initial filling pressure are likely to fail during operation life because of gas cleanup.

The use of mercury vapor in equilibrium with liquid mercury to provide the filling gas has the advantage that gas cleanup merely results in some of the condensed mercury being converted to vapor without any change in pressure. The mercury condenses on the coolest part of the tube, and the temperature of the condensed mercury serves to determine the pressure of the vapor in equilibrium with the liquid. Generally the mercury vapor pressure lies between 10^{-3} and 10^{-1} mm of Hg.

Most of the visible light from the discharge comes from the plasma. If a tube is constructed with a large electrode spacing, and the tube geometry is such that the plasma region is long and narrow, as in the case of the fluorescent lamp, the plasma is said to be a positive column. The light radiation from the positive column is used for illumination purposes in several large classes of tubes, including fluorescent lamps and mercury-vapor lamps. The cathodes of these tubes are heated by ions incident upon the cathode and are said to be ionically heated cathodes. The discharge in this case is a self-sustaining discharge, since no additional power is expended to maintain conduction.

In the first part of this chapter we shall describe the hot-cathode dis-

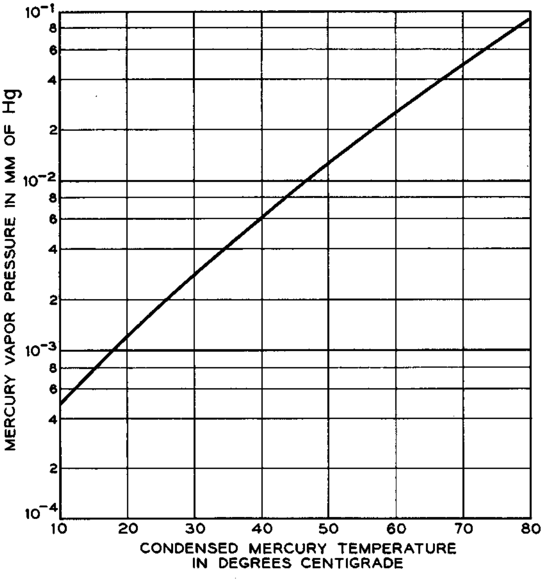

FIG. 16.1-1 Mercury-vapor pressure vs. condensed mercury temperature.

charge in mercury vapor. Later we shall discuss a number of specific types of hot-cathode devices.

16.1 The Hot-Cathode Discharge in Mercury Vapor; Plasmas and Sheaths

The hot-cathode discharge in mercury vapor and in other gases is discussed in references 16.1 to 16.11 listed at the end of this chapter.

Like the noble gases, the molecules of mercury vapor are single atoms. Their effective diameter for collision is not far from that of neon or argon molecules, but their mass is about 10 times that of the neon molecule.

Figure 16.1-1 shows the variation of mercury-vapor pressure as a function of the temperature of the condensed mercury. Many hot-cathode, mercury-vapor tubes are rated for condensed mercury temperatures falling in a range between 20°C and 80°C corresponding to vapor pressures of approximately 10^{-3} to 10^{-1} mm of Hg. If the condensed mercury temperature falls below 20°C, the voltage drop across the tube rises because collisions between plasma electrons and gas molecules become too infrequent. At condensed mercury temperatures appreciably greater than 80°C, the inverse breakdown voltage may fall below the tube rating, since the inverse breakdown voltage decreases rapidly with increasing vapor pressure.

Figure 16.1-2 shows the collision probability P_c for electrons in mercury vapor as a function of the square root of the electron energy.[1] The figure is similar to Fig. 14.3-2. The electron mean free path is given by $L = 1/pP_c$ cm where p is the vapor pressure in millimeters of Hg. At a pressure of 10^{-2} mm of Hg, the mean free path of a 10-electron-volt electron in mercury vapor is approximately 1.4 cm, and the mean free path of a 2-electron-volt electron is approximately 0.4 cm.

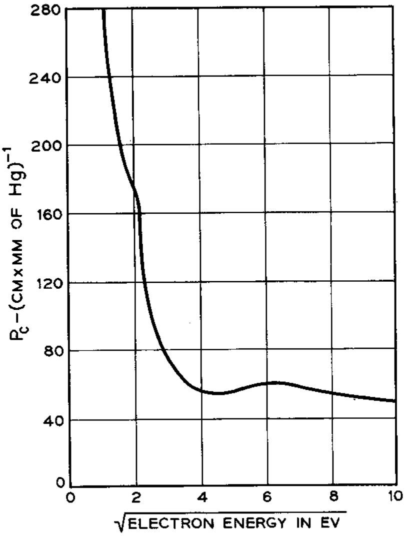

FIG. 16.1-2 The quantity P_c plotted as a function of the square root of electron energy for electrons in mercury vapor. (From R. B. Brode, *Revs. Modern Phys.* 5, 257, 1933)

Figure 16.1-3 shows a schematic illustration of a hot-cathode tube with a

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[1] Reference 16.12.

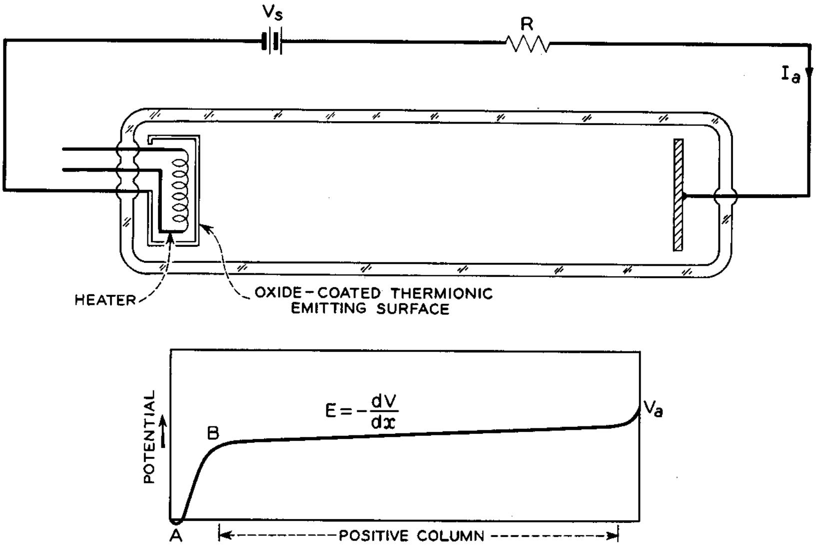

FIG. 16.1-3 A hot-cathode discharge tube with planar electrodes.

planar oxide-coated cathode and a planar anode. A plot of the potential along a line running from cathode to anode is also shown in the figure. Close to the cathode there is a potential minimum, the current drawn from the cathode being space-charge-limited. Just beyond the potential minimum the potential rises steeply, accounting for much of the potential difference between the electrodes. The remainder of the interelectrode space, except for thin sheaths close to the anode and glass walls, is filled with a plasma in which the ion and electron densities are approximately equal. If the length of the tube were increased, the voltage drops close to the cathode and anode would remain essentially unchanged, but the positive column would become longer, and the same potential gradient would continue over its full length. Tubes used in rectifier and switching applications usually have relatively small electrode spacings so that the voltage drop in the plasma will be small.

It will be convenient to describe the plasma and sheaths under separate headings below. Our objective will be twofold: (1) To present orders of magnitude for the principal physical quantities involved, and (2) to make plausible the current-voltage relationship of the hot-cathode discharge.

(*a*) *The Plasma*

If a voltage well below the ionization potential of the gas is applied to a device such as that shown in Figure 16.1-3, only a very small current is drawn from the cathode and practically no ionization takes place. However, if the applied voltage is raised somewhat above the ionization potential of the gas, the rate of generation of ions increases rapidly. Both the ions and electrons tend to diffuse in the direction perpendicular to the axis of the tube, but because the electrons are very much faster, the walls become negatively charged, and an excess positive charge accumulates in the interior of the tube. Electrons are drawn toward the region of excess positive charge with the result that the plasma is formed. Once the plasma is established, the voltage drop of the tube generally falls below the value needed to initiate the discharge. Since the walls are insulating, the electron current striking the walls in the steady-state condition equals the ion current.

The approximate uniformity of potential within the plasma can be attributed to the much greater mobility of the electrons compared with that of the ions. The electrons are drawn toward a region in which the potential is maximum, and they flow away from a potential minimum. The net result is that potential gradients within the plasma are small, and the density of ions and electrons is very nearly equal. The electrons are almost entirely responsible for conduction through the plasma, the drift velocity of the ions being extremely small compared with that of the electrons. The fact that the potential gradients in the direction of conduction are small means that the plasma is effectively a good conductor.

The electrons cross and recross the plasma many times, experiencing frequent collisions with neutral molecules, ions, and other electrons. Because the potential falls away at the edge of the plasma, the electrons, for the most part, are reflected back toward the plasma by the sheaths. Measurements of the distribution of electron velocities in the plasma indicate that it is very nearly a Maxwell-Boltzmann distribution. The random nature of the electron velocities is thought to result from interactions between the electrons themselves rather than interactions with ions or neutral molecules.[2] Two factors are important here:

1. In electron-molecule or electron-ion collisions, the energy exchange is extremely small, provided the collisions are elastic, because of the much greater mass of the molecule or ion. However, in electron-electron interactions, an appreciable energy transfer can take place since the masses of the colliding particles are equal.
2. The electron-electron interactions result from interactions of the fields of the particles and, hence, are not of a hard-sphere nature like electron-

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[2] Another mechanism which may contribute to the randomizing of the electron velocities in low-pressure discharges is discussed in Reference 15.13. The mechanism involves space-charge oscillations in the sheaths.

molecule or intermolecular collisions. The potential caused by the field of an electron at a distance r angstroms from its center is $14.4/r$ volts, so that the electron-electron interactions can take place at appreciably larger interparticle distances than electron-molecule or intermolecule interactions. Consequently the "cross section" for electron-electron collisions is much larger than for electron molecule collisions.

The Maxwell-Boltzmann distribution of electron velocities is generally characterized by a relatively high temperature, often one to a few tens of thousands of degrees Kelvin. Measurements of the electron temperature T_e for a positive column in mercury vapor are shown in Figures 16.1-4 and 16.1-5. The average electron kinetic energy is given by $(\frac{3}{2})kT_e = T_e/7700$ electron volts. For $T_e = 15{,}000°K$ the average electron kinetic energy is about 1.9 electron volts. It is the few very high-energy electrons in the Maxwell-Boltzmann distribution that are responsible for the excitation and ionization taking place in the plasma. In a mercury vapor discharge at a

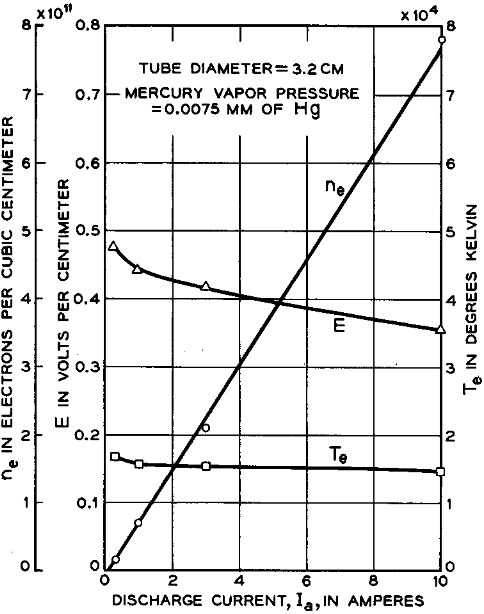

FIG. 16.1-4 The electron density n_e, the electron temperature T_e, and the axial electric field intensity E vs. the discharge current. (From B. Klarfeld, *Tech. Phys. USSR* **5**, 913, 1938)

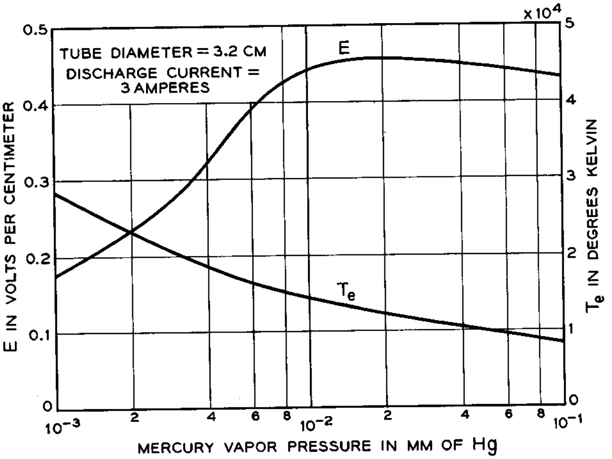

FIG. 16.1-5 The axial electric field intensity E and the electron temperature T_e vs. mercury-vapor pressure for a discharge in mercury vapor. (From B. Klarfeld, *Tech. Phys. USSR* **5**, 913, 1938)

condensed mercury temperature of 40°C, most of the ionization results from two-stage processes in which the molecules are raised to an excited state in a first collision and ionized in a second collision.[3] The excited states principally involved are metastable states with excitation energies of 5.46 and 4.66 electron volts.

Also shown in Figure 16.1-4 are the electron density n_e and the potential gradient E along the axis of the positive column. The electron density n_e is an average of the electron density measured on the axis and at the edge of the plasma. The ratio of n_e to the density of gas molecules is shown in Fig. 16.1-6. For the discharge conditions indicated in the figure only about one molecule in a thousand is ionized.

The ion kinetic energies are much smaller than those of the electrons, the average ion kinetic energy being at most a few times the thermal energy of the gas molecules. Interactions with other ions and neutral molecules lead to a randomizing of the ion velocities and an approximately Maxwell-Boltzmann distribution of velocities.

Ions reaching the edges of the plasma are drawn into the sheath and accelerated toward the walls of the tube, causing a depletion of the ion density toward the edge of the plasma. As a result, the potential along the axis of

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[3] References 16.5 and 16.6.

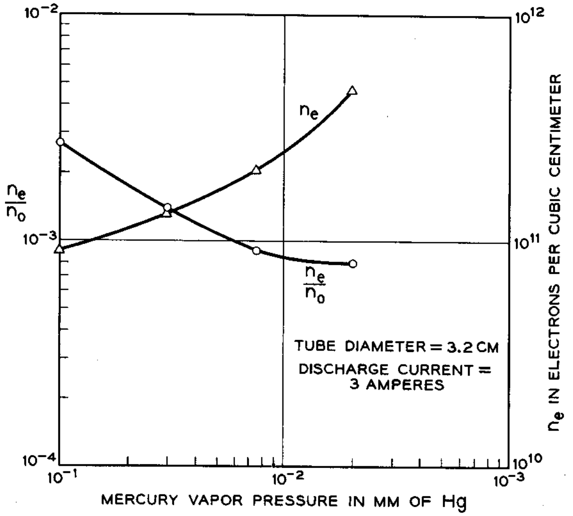

FIG. 16.1-6 The electron density n_e and the ratio of n_e to the density of gas molecules n_o as a function of mercury-vapor pressure. (From B. Klarfeld, *Tech. Phys. USSR* 5, 913, 1938)

the positive column of a device like that shown in Figure 16.1-3 is likely to be several volts higher than at the edges of the plasma, and the radial electric field tends to accelerate the ions toward the sheaths.

It is convenient to regard the plasma ions as being characterized by an average lifetime equal to the average time spent by the ions within the plasma. Over a range of filling pressures p and positive-column radii R, the average ion lifetime is a function of the product pR, since constant pR means a constant number of mean free paths from the tube axis to the tube walls. High filling pressures and large radii are associated with long lifetimes, whereas low filling pressures and small radii lead to short lifetimes. To a first approximation the average lifetime depends only on the product pR and is independent of the ion density or the current conducted along the positive column. The metastable molecules generated by the discharge are similarly characterized by an average lifetime.

The concept of an average ion lifetime is helpful in describing the balance of events taking place in the plasma:

1. The electron and ion currents to the walls are equal, and the rate of generation of ion-electron pairs per unit length of the positive column equals the current of electrons or ions striking unit length of the glass walls.
2. Since the ion and electron densities are approximately equal, each plasma electron must on the average generate one ion-electron pair once

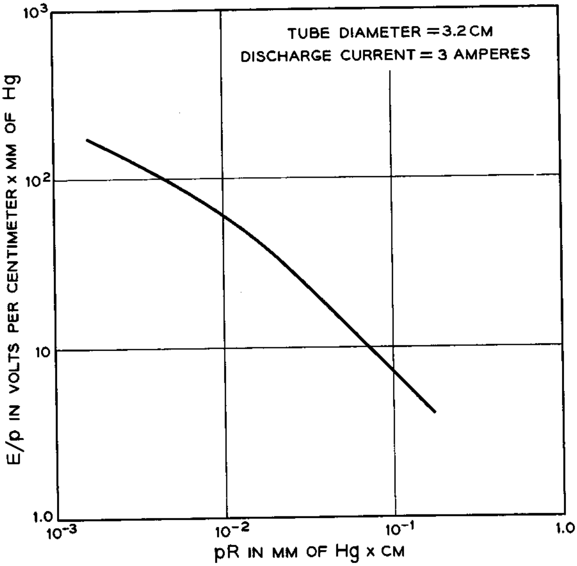

FIG. 16.1-7 *E/p* vs. *pR* for a discharge in mercury vapor. (From B. Klarfeld, *Tech. Phys. USSR* **5**, 913, 1938)

every average ion lifetime in order to maintain the supply of ions in the plasma.

In the steady-state condition the electric field intensity *E* parallel to the axis of the positive column becomes that value which enables the electrons to gain sufficient energy to meet Condition 2 above. The average electron kinetic energy is, of course, a function of *E/p* rather than *E* alone. Figures

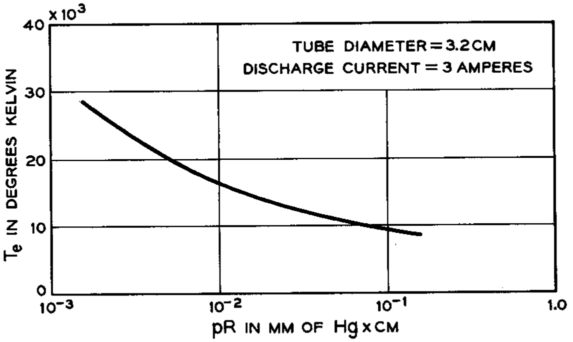

FIG. 16.1-8 The electron temperature T_e vs. *pR* for a discharge in mercury vapor. (From B. Klarfeld, *Tech. Phys. USSR* **5**, 913, 1938)

16.1-7 and 16.1-8 show plots of E/p and T_e vs. pR for a positive column in mercury vapor. As pR increases, corresponding to longer lifetimes, both T_e and E/p decrease.

The electron drift velocity parallel to the axis of the tube, $\bar{u}_e$, is also determined by E/p and, hence, by Condition 2 above. If the ion lifetimes are short, E/p is large, and $\bar{u}_e$ is large. If A is the cross-sectional area of the positive column, and n_e is the average electron density over the area A, the total current conducted by the positive column can be approximately expressed as

$$I_a \approx |n_e \bar{u}_e A e| \tag{16.1-1}$$

where e is the charge on the electron, and where the drift velocity of the ions parallel to the axis of the tube is assumed to be small compared with $\bar{u}_e$. To the extent that E, and hence E/p, are independent of I_a, $\bar{u}_e$ does not change with I_a, and *the electron density n_e is directly proportional to I_a*, as is evident from Figure 16.1-4. Since the ion density is nearly equal to n_e and since the average ion lifetime is to a first approximation independent of I_a, *the rate of generation of ion-electron pairs per unit volume also increases linearly with I_a*. We shall make use of this result later when we discuss the nature of the current-voltage relationship for the discharge.

(Actually both E and T_e decrease slightly with increasing I_a [Figure 16.1-4] because the frequency of two-stage ionizing events tends to increase in proportion to the product of n_e and the density of excited atoms.)

The product of E and I_a can be equated to the sum of the power radiated as light energy per unit length of the positive column and the power expended per unit length as heat energy.

As a final point we shall use Equations (14.1-4) and (16.1-1) to determine the ratio of the average electron velocity u_{avg} to the electron drift velocity $\bar{u}_e$ for the discharge conditions indicated in Figure 16.1-4. From the data given in the figure, A is equal to $(\pi/4) \times (3.2)^2 = 8$ cm², and $I_a/n_e \cong (\frac{4}{3}) \times 10^{-11}$ amp cm³/electron. From Equation (16.1-1) we find that $\bar{u}_e = 1.04 \times 10^7$ cm/sec. The average electron velocity characteristic of the Maxwell-Boltzmann distribution can be obtained from equation (14.1-4). If $T_e = 15{,}000$°K, $u_{\text{avg}} = 7.6 \times 10^7$ cm/sec, or 7.3 times the electron drift velocity.

(*b*) *The Sheaths*

In considering the nature of the sheaths it will first be convenient to imagine that a planar conducting probe is inserted part way into a plasma. If the probe is held at a negative potential with respect to the plasma, it becomes surrounded by a thin layer of ions that are drawn from the plasma and accelerated toward the probe. Upon striking the probe, the ions lose their charge and become unexcited molecules. The thickness of the sheath adjusts itself to account for the potential difference between the probe and plasma. Field lines extend from ions in the sheath to negative charges on the surface of the probe, and the integral of the electric field intensity from the probe to the plasma accounts for the potential drop in the sheath. If the discharge conducts a large current, the rate of arrival of ions at the edge of the plasma is large, and the electric field intensity in the sheath is large. The thickness of the sheath is therefore small. If the discharge current is reduced or if the potential difference between the probe and plasma is increased, the sheath thickness increases. In the case of a probe in a mercury vapor plasma, the sheath thickness is a small fraction of a millimeter except at very small discharge currents or high sheath voltages ($\gg$ 10 volts).

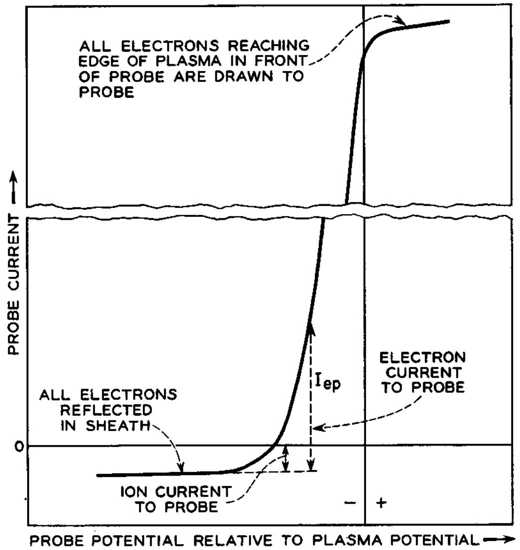

FIG. 16.1-9 Current to a probe in a plasma vs. potential of probe relative to that of the plasma.

Figure 16.1-9 shows qualitatively a plot of current to a probe in a plasma as a function of the probe potential relative to that of the plasma. At high negative probe potentials, the current to the probe is almost independent of the probe potential and equals the ion current drawn into the sheath. However, as the probe potential is made more positive, some of the high-energy electrons reaching the edge of the plasma are able to overcome the retarding field in the sheath and strike the probe. If the electrons have a

Maxwell-Boltzmann distribution of velocities and if the electron mean free path is large compared with the sheath thickness, the fraction of electrons able to overcome a potential V is ϵ^{-eV/kT_e}, where T_e is the electron temperature. The current of electrons reaching the probe can therefore be expressed as

$$I_{ep} = I_e \epsilon^{-eV/kT_e} \qquad (16.1\text{-}2)$$

where I_e is the electron current reaching the edge of the sheath in front of the probe, and V is the voltage drop in the sheath. A plot of the electron current to a probe as a function of the probe voltage is shown in Figure 16.1-10. The linear part of the curve can be expressed as

$$\ln I_{ep} = \alpha - \frac{V}{1.2} \qquad (16.1\text{-}3)$$

where V is in volts, and where V is taken to be the potential rise from the probe to the plasma. The temperature of the plasma electrons is therefore $1.2(e/k) = 1.2 \times 11{,}600 = 13{,}900$°K. When the probe potential equals or exceeds the plasma potential, all the electrons reaching the edge of the plasma in front of the probe are drawn to the probe, and the curve of I_{ep} vs. V bends to the right.

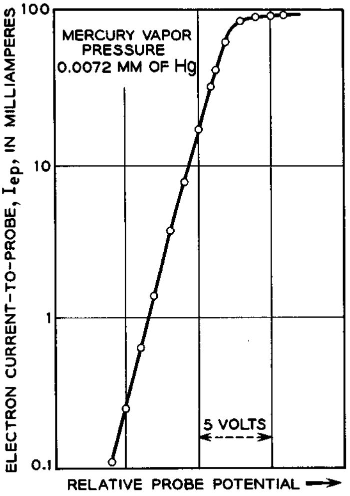

Fig. 16.1-10 Measurements of electron current to a probe in a mercury-vapor plasma vs. probe potential. (From B. Klarfeld, *Tech. Phys. USSR* 4, 44, 1937)

The ion current drawn to a probe biased negatively with respect to a plasma has been studied analytically by Allen, Boyd, and Reynolds.[4] Curves given in their paper show the potential distribution within the sheath and near the edge of the plasma.

When a mercury-vapor discharge is established in a device like that shown in Figure 16.1-3, the voltage drop in the sheath between the plasma and the glass walls is of the order of 8 volts.[5] This sheath voltage serves to reduce the current of electrons reaching the walls to a value equal to the ion current.

Between the plasma and the anode of the tube shown in Figure 16.1-3 there is probably a small rise in potential. Ions generated in the sheath

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[4] Reference 16.14.

[5] Reference 16.11.

flow toward the positive column and serve to match boundary conditions with respect to ion flow at the anode end of the positive column. (Within the positive column the ion drift velocity has a component parallel to the axis of the tube and directed toward the cathode. There is therefore effectively a flow of ions along the positive column in the direction of the cathode. Ions generated in the anode sheath serve to match this flow.) If the anode is made very small, the voltage rise in the anode sheath may be appreciable, and a region of more intense glow surrounds the anode. In other tubes in which a cylindrical anode surrounds a cylindrical hot cathode, the electron current reaching the edge of the plasma in front of the anode may exceed the current flowing in the external circuit, in which case there is probably a small fall in potential in going from the plasma to the anode.

Because the work function of the anode is usually a few volts greater than that of the cathode, the anode-to-cathode voltage drop of a hot-cathode tube as measured in the external circuit is a few volts greater than it would be if the electrodes were of the same work function.

The cathode sheath represented by the region AB in Figure 16.1-3 is sometimes called a double sheath. Electrons flow from A toward B, and ions flow in the opposite direction. Electrons also enter the sheath from the plasma but for the most part are reflected back to the plasma. Field lines extend from ions in the B side of the sheath to electrons in the A side. Since the electric field intensity at A and B is very nearly zero, there is approximately one ion in the sheath for every electron.

Now the velocity of an electron or ion of given kinetic energy is inversely proportional to the square root of the mass of the particle. Consequently, if the potential in the sheath were symmetrical about the midpoint between A and B, the ratio of the time required for an ion to travel from B to A to the time required for an electron to travel from A to B would be $(m_i/m_e)^{1/2}$, where m_i is the ion mass, m_e is the electron mass, and where it is assumed that the particles start with zero velocity and experience no collisions on the way. For mercury ions, this ratio is 604. Consequently, the electron current flowing from A to B in a mercury discharge is probably several hundred times the ion current flowing from B to A.

The voltage drop in the cathode sheath is such as to assure that the electrons arriving at the plasma from A will have sufficient energy to generate the ions needed to make up for ion losses from the cathode end of the positive column. If the electron and ion currents in the cathode sheath are denoted by I_e and I_p, respectively, then $I_e + I_p = I_a$. Since I_e/I_p is to a first approximation determined by factors other than the discharge current I_a, both I_e and I_p are directly proportional to I_a. And *since the ionization taking place in the plasma is directly proportional to* I_a, *the current*

I_p of ions arriving at the cathode end of the positive column is proportional to I_a, and the voltage drop in the cathode sheath does not change with I_a. Because the voltage drop in the plasma also shows little change with I_a, the voltage drop in mercury-vapor rectifier tubes is nearly independent of current up to a current equal to the cathode thermionic emission current. At higher currents the anode-to-cathode voltage rises.

The thickness of the cathode sheath varies with the discharge current I_a and is such as to assure that the necessary electron current is drawn from the potential minimum at A. When I_a is large, the electric field intensity at the midpoint between A and B is large, and the sheath thickness is small.

16.2 Three Examples of Hot-Cathode Tubes

In this section we shall describe three hot-cathode tubes, two used in rectifier applications and one used as a switching element. The first is the 249B, a two-electrode mercury-vapor tube used in high-voltage rectifier applications. The second is the 393A, a three-electrode tube filled with both mercury vapor and argon and used as a rectifier in regulated power supplies. The third is the 2D21, a four-electrode tube filled with xenon and used as a switching element.

The 249B

Figure 16.2-1 illustrates the construction of the 249B. The cathode consists of a nickel mesh filament coated with barium and strontium oxides. The filament is surrounded by a nickel heat shield which helps to reduce the power needed to heat the filament and which is connected electrically to the center of the filament. During conduction a thin sheath forms between the heat shield and the plasma, with the result that the heat shield has little effect on conduction through the plasma. The anode consists of a nickel disc on which carbon has been deposited to increase heat radiation.

During assembly of the tube a small glass pellet containing liquid mercury is attached to the lower part of the cathode supporting structure by means of a nickel mesh which completely encloses the pellet and which is welded to the cathode supporting structure. Ater the tube has been pumped and before it is sealed off from the pump station, the nickel mesh is heated with rf causing the glass pellet to soften and admit liquid mercury to the inside of the tube. The nickel mesh serves to retain the ruptured glass pellet.

Principal electrical characteristics and ratings for the tube are shown in Table 16.2-1. The filaments of hot-cathode tubes are designed to operate at low voltages so that the voltage drop from end to end of the filament will be small compared with the anode voltage drop. The condensed mer-

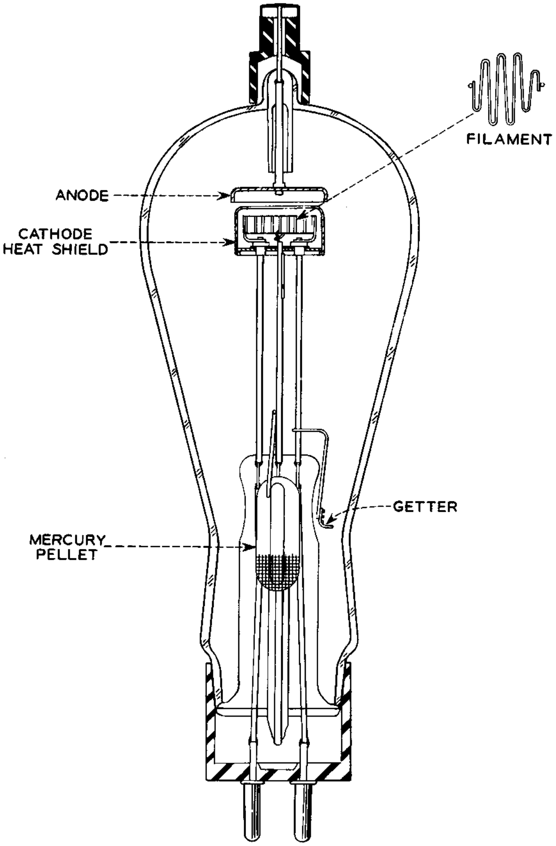

FIG. 16.2-1 The construction of the 249B diode rectifier tube. The overall height of the tube is 19.4 cm.

cury temperature is assumed to be the temperature of the lowest part of the glass envelope, just above the base.

Figure 16.2-2 shows a plot of anode voltage drop vs. anode current for a particular 249B. The plot shows a nearly constant anode voltage drop over a wide range of currents, as would be expected from our earlier discussion. The curve should be compared with the I_a-V_a curve for a space-charge-limited vacuum diode in which $I_a \propto V_a^{3/2}$.

Figure 16.2-3 shows a plot of anode voltage drop vs. condensed mercury temperature for a particular 249B. Below a condensed mercury temperature of 20° to 25°C, the anode voltage drop rises because collisions between the electrons and gas molecules become too infrequent. It has

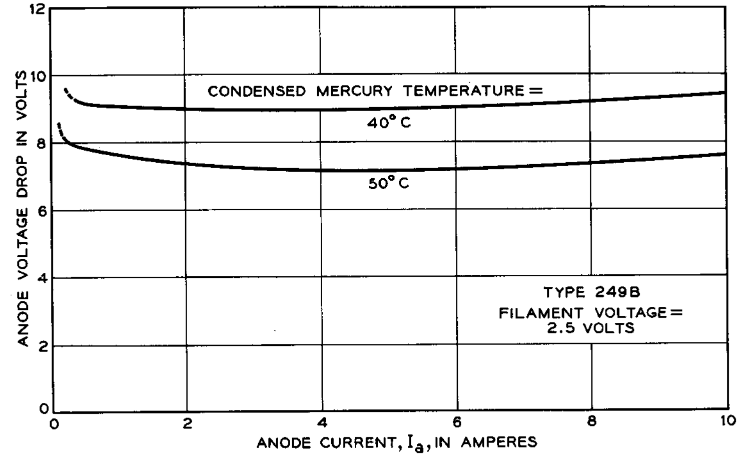

FIG. 16.2-2 Anode voltage drop vs. anode current I_a for a particular 249B.

TABLE 16.2-1 WE 249B OPERATING CHARACTERISTICS

Maximum Ratings	
Peak inverse anode voltage, volts	7500
Peak anode current, amps	2.5
Average anode current, amps	0.64
Condensed mercury temperature, °C	+20 to +70
Electrical Data	
Anode voltage drop, volts	7 to 11*
Filament voltage, volts ac	2.5
Filament current, amps ac	7.5

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*Typical values for new tubes at a condensed mercury temperature of 40°C.

been found that the sputtering of the cathode coating in hot-cathode mercury-vapor tubes increases rapidly with increasing anode voltage drop above about 25 volts. Consequently, operation for extended periods at condensed mercury temperatures below 15° or 20°C leads to greatly reduced life.

Other commercially available mercury-vapor diode rectifiers are capable of conducting average currents as high as 20 amps.

The 393A

Figure 16.2-4 illustrates the construction of the 393A rectifier tube. The tube has a third electrode, called a grid, which serves to control initiation of the discharge. Hot-cathode tubes with such a control elec-

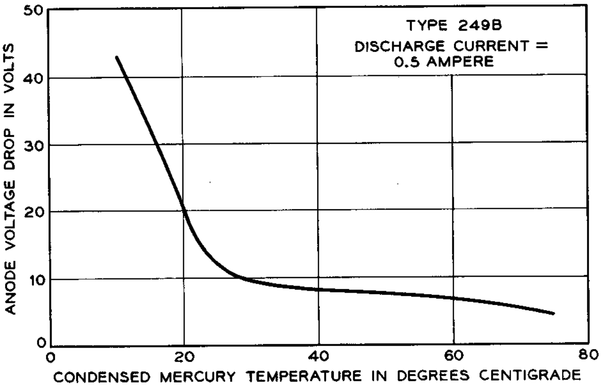

FIG. 16.2-3 Anode voltage drop vs. condensed mercury temperature for a particular 249B.

trode are called thyratrons. Like the 249B, the cathode is a nickel mesh filament coated with barium and strontium oxides, and the anode is a carbonized nickel disc. The grid electrode, also made of carbonized nickel, very nearly surrounds the cathode. The tube is filled with both argon at a pressure of 0.1 mm of Hg and mercury vapor in equilibrium with liquid mercury.

If the grid is biased to about −10 volts with respect to the cathode and if the anode voltage is then raised from zero to +1000 volts, essentially no anode-to-cathode conduction takes place. The negative bias on the grid in this case is sufficient to cause electrons emitted from the cathode to be returned to the cathode and the breakdown voltage between the anode and grid is considerably in excess of 1000 volts. However, if the grid bias is gradually reduced with the same applied anode voltage, a point is reached, perhaps at a grid bias of −5 volts, at which a small current of electrons is drawn through the slot at the upper end of the grid. The electrons passing through the slot enter a region of relatively strong electric field intensity in the grid-anode space and are accelerated toward the anode. On the way some cause ionization. If sufficient current flows to initiate a plasma, the tube quickly transfers to the high conduction state in which the anode voltage drop is of the order of 12 volts, and the anode current is limited by the resistance in series with the supply voltage. In this second state the grid is surrounded by a sheath which accounts for the voltage drop between the grid and plasma and which is thin compared with the width of the slot in the grid. Increasing the negative voltage applied to the grid in this case has little effect on conduction through the tube, except at extremely small anode currents.

Figure 16.2-5 shows a control characteristic measured for a particular 393A (solid curve) at a condensed mercury temperature of 40°C. Points to the left of the curve correspond to operating conditions in which the tube does not conduct provided the grid bias is applied before the anode voltage. However, if the grid bias is reduced so that the operating point moves to the right and crosses the curve shown in the figure, conduction is initiated at the point of crossing. The broken curves in the figure show the published limits for the tube. At higher condensed mercury temperatures the control characteristic moves to the left, and at lower condensed mercury temperatures it moves to the right. The spread between the two broken curves includes variations within the rated condensed mercury temperatures, variations during life, and variations from tube to tube.

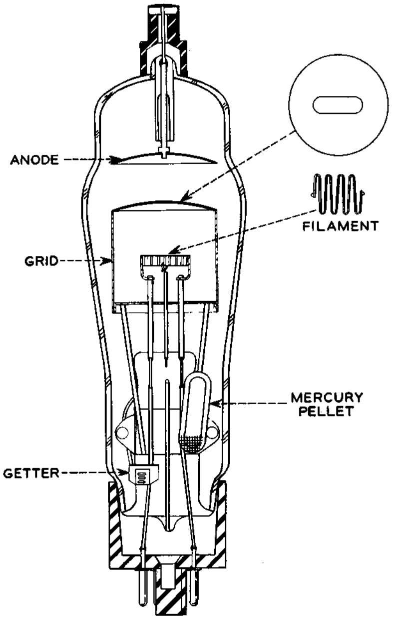

FIG. 16.2-4 The construction of the 393A thyratron. The overall height of the tube is 16.8 cm.

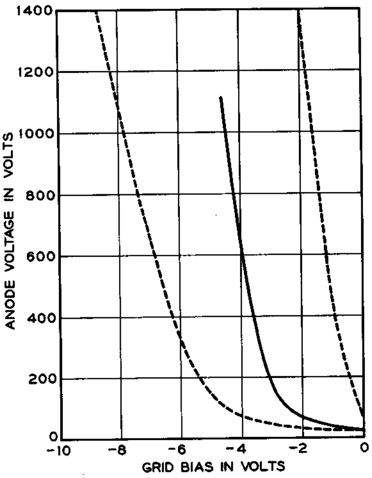

FIG. 16.2-5 Control characteristic for the 393A.

If the grid potential is raised above that of the plasma, the grid becomes an anode, and practically the full current of the discharge is drawn to it. The voltage drop of the tube with the grid tied to the anode is often 6 to 9 volts at a condensed mercury temperature of 40°C. Figure 16.2-6 shows the variation of grid current with grid voltage, the grid voltage being measured relative to the cathode potential. In most applications a resistance is placed in series with the grid to limit the grid current.

During operation of the tube the grid is heated by radiation from both the cathode and anode. Since some of the cathode coating is generally sputtered onto the grid, sufficient heating of the grid will result in electron emission from the grid. Part of the emission current is drawn to the anode and, if the current flow is sufficient, the control action of the grid is lost. The average current handling capabilities of the tube are therefore limited by the need to avoid overheating the grid.

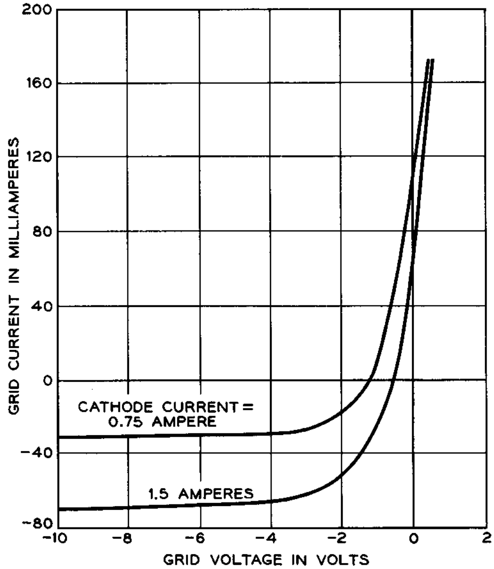

FIG. 16.2-6 Grid current vs. grid voltage for a 393A.

The use of a filling of both argon and mercury vapor permits operation of the tube at ambient temperatures as low as −55°C. If the condensed mercury temperature is below 15° or 20°C when conduction is first initiated, the discharge starts off as an argon discharge, the mercury vapor density being insufficient to support the discharge. Because the ionization potential of argon is higher than that of mercury (15.8 volts compared with 10.4 volts), and perhaps because the lifetimes of the lighter argon ions are shorter than those of the mercury ions, the anode voltage drop of the argon discharge is a few volts higher than that of the mercury discharge, and the electron temperature is similarly higher. As conduction continues, heat is dissipated in the electrodes and conducted and radiated to the envelope. This causes the condensed mercury temperature to rise and increases the mercury vapor pressure. When the condensed mercury temperature reaches 20° or 25°C, the mercury vapor density is sufficient to support the discharge, and the anode voltage drop falls. Since the electron temperature is lower when the mercury discharge is established, very little ionization of the argon molecules takes place. It is found that cleanup of the argon occurs primarily while the argon discharge is established, and that it is greatly reduced when the mercury discharge takes over.

Principal electrical characteristics and ratings for the 393A are summarized in Table 16.2-2. The condensed mercury temperature limits apply only to starting conditions. The tube must be operated in an environment which will permit the equilibrium condensed mercury temperature to reach at least 20°C, since operation at lower condensed mercury temperatures for prolonged periods leads to cleanup of the argon and shortens the life of the tube.

TABLE 16.2-2 WE 393A OPERATING CHARACTERISTICS

Maximum Ratings	
Peak anode voltage, forward or reverse, volts	1250
Peak anode current, amps	6
Average anode current, amps	1.5
Average electron current to grid, ma	10
Condensed mercury temperature, °C	−55 to +80
Electrical Data	
Anode voltage drop, volts	10 to 14*
Filament voltage, volts ac	2.5
Filament current, amps ac	7.0

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*Typical values for new tubes when the grid is held at a negative potential with respect to the plasma, and when the condensed mercury temperature is 40°C.

The deionization time or recovery time of a thyratron is the time required for the grid to regain control of the discharge after conduction has been stopped by removing the anode voltage. Often several hundred microseconds elapse before the ion and electron densities in the interelectrode space become sufficiently small that the grid regains control. The deionization time increases with the vapor density, with the discharge current before interruption, and with decreasing grid bias. At a condensed mercury temperature of 40°C and an anode current of 1.5 amps, the deionization time of the 393A is of the order of a few hundred microseconds.

Other commercially available mercury-vapor thyratrons conduct average currents as high as 30 amps. Inverse anode voltages of some mercury-vapor thyratrons range as high as 15,000 volts.

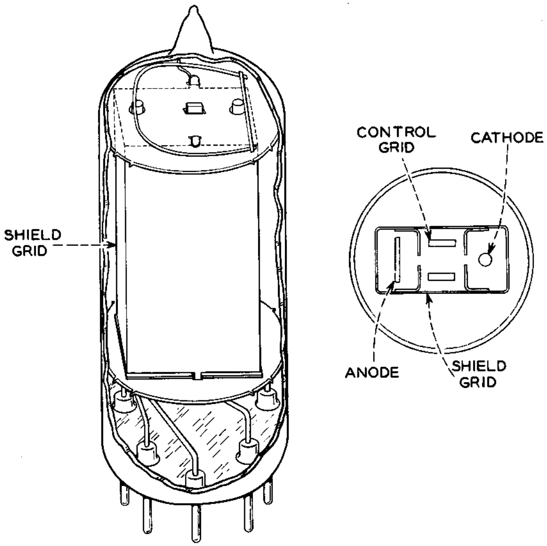

Fig. 16.2-7 The construction of the 2D21 shield-grid thyratron. The overall height of the tube is 5.4 cm.

The 2D21

Figure 16.2-7 shows the construction of the 2D21 shield-grid thyratron. The tube has an indirectly heated cathode, a control grid, an anode, and an additional electrode called a shield grid. The shield grid virtually surrounds the other electrodes, and baffles in the shield grid serve to separate the remaining electrodes from one another. The tube is filled with xenon to a pressure of 0.16 mm of Hg.

The use of a shield grid has several advantages:

1. It reduces heat radiation to the control grid from the cathode and anode, and it reduces the amount of cathode coating sputtered onto the control grid. Grid emission is thus greatly reduced.

2. The shield grid also reduces capacitive coupling between the grid and anode. Without the shield grid or other circuit protection, the grid-anode capacitance of a thyratron is sometimes sufficient to cause the grid to be driven positive by a fluctuation or surge of anode voltage, thereby permitting faulty initiation of the discharge.

3. The shield grid provides an additional means for controlling initiation of the discharge. Figure 16.2-8 shows the control characteristic of the tube for several values of shield-grid voltage. By making the shield grid a few volts positive or negative with respect to the cathode, the control char-

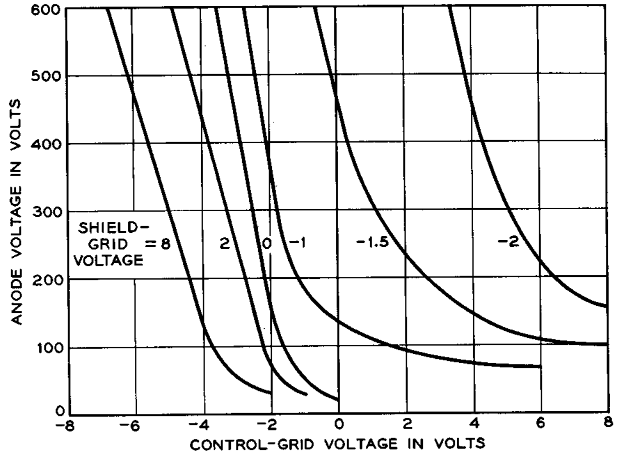

FIG. 16.2-8 Control characteristic for the 2D21 for several values of shield-grid voltage.

acteristic can be moved to the left or right, respectively. The shield grid can thus be used to switch the grid control circuit in and out of operation.

The 2D21 is principally used in switching applications. Because the grid emission and grid-anode capacitance are both small, the tube can be driven by high impedance sources.

Principal electrical characteristics and ratings for the 2D21 are listed in Table 16.2-3.

TABLE 16.2-3 2D21 OPERATING CHARACTERISTICS

Maximum Ratings	
Peak inverse anode voltage, volts	1300
Peak anode current, ma	500
Average anode current, ma	100
Ambient temperature, °C	−75 to +90
Electrical Data	
Anode voltage drop, volts	8
Heater voltage, volts ac	6.3
Heater current, amp ac	0.6

16.3 Other Types of Hot-Cathode Tubes

(*a*) *The Tungar*

This is a hot-cathode diode frequently used as a half-wave rectifier in storage-battery chargers. The tube is filled with argon to a pressure between 50 and 100 mm of Hg and has a thoriated tungsten filament. The filament operates at about 2200°C, or about 200°C higher than thoriated tungsten filaments used in transmitting tubes. The higher filament operating temperature is made possible by the high argon filling pressure, which reduces the rate of evaporation of thorium atoms from the cathode. Tungars typically conduct average currents of 2 to 15 amps. The filament voltage is often 2.0 or 2.5 volts, and the filament current may be as high as 15 to 25 amps. The high argon pressure leads to relatively low peak inverse voltages, of the order of 300 volts.

(*b*) *Hydrogen Thyratrons*

A class of hydrogen filled thyratrons has been developed for use in power supplies which deliver driving power to magnetrons and klystrons in radar applications. The hydrogen thyratron is generally connected in series with a pulse transformer across a charged delay line, and the microwave tube is connected to the output of the pulse transformer. A positive pulse applied to the control grid of the thyratron serves to discharge the delay line through the transformer and thyratron. Between periods of conduction the delay line is recharged with energy for the next pulse. Pulse currents as high as 1 to 3 thousand amps are conducted by some hydrogen thyratrons.

The use of a hydrogen filling leads to shorter deionization times than can be obtained with other fillings.[6] Deionization times of hydrogen thyratrons are typically 2 to 10 microsec with some very high-current tubes ranging as high as 50 microsec. The short deionization times permit operation of the magnetron or klystron at pulse rates of several kilocycles.

The anode voltage drops of hydrogen thyratrons are much higher than those of mercury-vapor or noble-gas filled thyratrons, often between 90 and 150 volts. The relatively high voltage drops result partly from the short lifetimes of the hydrogen ions, and partly from the fact that most of the inelastic collisions between plasma electrons and gas molecules result in excitation of the vibrational and rotational states of the molecules and in disassociation of the molecules rather than excitation of electronic states or ionization.

Hydrogen thyratrons almost always have indirectly heated, oxide-coated, nickel cathodes. The filling pressure frequently lies between 0.2 and 1.0 mm of Hg. Because gas cleanup is appreciable in high-current tubes, the filling is often obtained by means of a "hydrogen reservoir" consisting of a

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[6] (1) Because the lighter ion mass leads to shorter ion lifetimes in the decaying plasma at the end of a pulse; (2) it is thought that recombination of ions and electrons in the decaying plasma may be appreciable; (3) there are no hydrogen metastables. Probably (1) is the most important reason.

quantity of titanium hydride in contact with an auxiliary heater. When heated, the titanium hydride evolves hydrogen until the surrounding gas reaches an equilibrium pressure at which the rate of evolution of hydrogen equals the rate of reabsorption. Higher reservoir temperatures lead to higher equilibrium pressures, and when the reservoir heater is turned off, the gas filling is reabsorbed, and the tube pumps down to very nearly a vacuum.

(c) *Tubes with Ionically Heated Cathodes*

A number of gas tubes used for illumination purposes have cathodes that are heated to thermionic emitting temperatures by the current of ions incident upon the cathode rather than by passing a current through the cathode. The discharge in this case is in many respects similar to the thermionic arc. Familiar examples of tubes using such ionically heated cathodes are the fluorescent lamp and mercury-vapor lamps used for street-lighting. These tubes frequently have two ionically heated cathodes, one at either end of a discharge tube, and are operated from an ac supply.

The cathodes consist of a coil of fine tungsten wire coated with oxides suitable for thermionic emission and wound on a somewhat heavier tungsten support wire. Often the coil is itself wound into a larger coil, and sometimes this in turn is coiled once more giving a "triple coil" structure. Usually the discharge heats only a portion of the cathode to thermionic emitting temperatures. Sometimes the heated region slowly moves along the cathode, and other times it remains stationary. The multiple-coil structure provides a large amount of cathode area with closely controlled thermal and electrical resistance to the current carrying support wire. Starting the discharge is accomplished by passing a current through the support wire for a short period or by applying a sufficiently high voltage between the electrodes that the discharge starts as a cold-cathode discharge.

Fluorescent lamps usually contain argon or krypton at a pressure of about 3 mm of Hg and mercury vapor in equilibrium with liquid mercury. The noble-gas filling aids in starting the discharge and serves to increase the lifetimes of ions and metastables once the discharge is established. However the noble-gas ions do not otherwise take part in the discharge once it is established. The discharge converts as much as 60 per cent of the input power to ultraviolet radiation of wavelength 2537 angstroms. Phosphors coated on the inside of the bulb serve to transform part of the ultraviolet radiation to visible light, hence the term "fluorescent."

Mercury-vapor lamps generate visible light directly, the efficiency being increased by operation at high mercury-vapor pressures, often several atmospheres.

More detailed descriptions of gas-discharge lamps are given in References 16g, 16h, and 16i.

REFERENCES

Several texts on gas-discharge phenomena are listed at the end of Chapter 14. The performance of hot-cathode tubes, particularly diode rectifiers and thyratrons, is discussed in the following references:

16a. W. G. Dow, *Fundamentals of Engineering Electronics,* Chapter 18, John Wiley and Sons, Inc., New York, 1952.
16b. J. Millman and S. Seely, *Electronics,* 2nd Ed., Chapter 11, McGraw-Hill Book Co., Inc., New York, 1951.
16c. D. S. Peck, *Electrical Engineers Handbook,* 4th Ed. (H. Pender and K. McIlwain, Eds.) pp. 4–58ff., John Wiley and Sons, Inc., New York, 1950.
16d. D. E. Marshall, *Industrial Electronics Reference Book* (Westinghouse Electric Corp.), Chapter 6, John Wiley and Sons, Inc., New York, 1948.
16e. J. D. Cobine, *Gaseous Conductors,* Chapter 11, McGraw-Hill Book Co., Inc., New York, 1941.
16f. F. A. Maxfield and R. R. Benedict, *Theory of Gaseous Conduction and Electronics,* Chapter 11, McGraw-Hill Book Co., Inc., New York, 1941.

Gas-discharge lamps are described in the following references:

16g. W. E. Forsythe and E. Q. Adams, *Fluorescent and Other Gas Discharge Lamps,* McGraw-Hill Book Co., Inc., New York, 1948.
16h. J. Millman and S. Seely, *Electronics,* 2nd Ed. pp. 324ff., McGraw-Hill Book Co., Inc., New York, 1951.
16i. *General Electric Glow Lamp Manual,* General Electric Co., East Cleveland, Ohio.

The hot-cathode discharge in mercury vapor is described in the following references:

16.1. I. Langmuir, *Phys. Rev.* **33,** 954, 1929.
16.2. I. Langmuir, *J. Franklin Inst.* **275,** 1932.
16.3. T. J. Killian, *Phys. Rev.* **35,** 1238, 1930.
16.4. B. Klarfeld, *Tech. Phys. USSR* **4,** 44, 1937.
16.5. B. Klarfeld, *Tech. Phys. USSR* **5,** 913, 1938.
16.6. R. M. Howe, *J. Appl. Phys.* **24,** 881, 1953.

The hot-cathode discharge in noble gases at higher pressures of the order of a few mm of Hg is described in the following references:

16.7. M. J. Druyvesteyn and F. M. Penning, *Rev. Modern Phys.* **12,** 87, 1940.
16.8. L. Malter, E. O. Johnson, and W. M. Webster, *RCA Rev.* **12,** 415, 1951.
16.9. W. M. Webster, E. O. Johnson, and L. Malter, *RCA Rev.* **13,** 163, 1952.

The discharge in mixtures of mercury vapor and a noble gas is described in the following references:

16.10. C. Kenty, *J. Appl. Phys.* **21,** 1309, 1950.
16.11. J. F. Waymouth and F. Bitter, *J. Appl. Phys.* **27,** 122, 1956.

Other references covering specific subjects discussed in this chapter are:

16.12. R. P. Brode, *Rev. Modern Phys.* **5**, 257, 1933.
16.13. D. Gabor, E. A. Ash, and D. Dracott, *Nature* **176**, 916, 1955.
16.14. J. E. Allen, R. L. F. Boyd, and P. Reynolds, *Proc. Phys. Soc.* (*London*), B, **70**, 297, 1957.