Chapter 15

THE GLOW DISCHARGE AND COLD-CATHODE TUBES

If the current drawn by a neon-molybdenum device with planar, parallel electrodes is increased beyond about 10 microamps, events which occur with a frequency proportional to the square of the current density such as metastable-metastable interactions and electron-metastable interactions begin to show their influence on the discharge. These interactions lead to the generation of a greater number of ions for each electron leaving the cathode.[1] Since almost every ion is drawn to the cathode, but less than half the metastables reach the cathode, the voltage needed to sustain the discharge is reduced below that of the Townsend discharge, and hence below the breakdown voltage.

At about the same current, or perhaps at somewhat lower current, the space charge caused by relatively slow-moving ions drifting toward the cathode becomes sufficient to raise the potential close to the cathode. This causes an increase in E/p at the cathode surface. If E/p at breakdown is less than that which gives maximum emission coefficient γ, the emission coefficient increases with the increase in E/p, and the voltage needed to sustain the discharge falls still further.

At a current of about 20 microamps, a region of diffuse glow can be seen in the interelectrode space, and the glow is observed to fill only a portion of that space. As the current is increased from 20 microamps to 200 microamps, the boundaries of the glow region become more clearly defined, and, for relatively large *pd*, the glow is observed to be closer to the cathode than the anode. At currents above 200 microamps, the glow area tends to increase linearly with current up to the point where the cathode is covered with glow.

[1]When the two metastables interact, one becomes ionized, and the other returns to the ground state. Collisions between fast electrons and metastables frequently result in ionization of the metastables.

The discharge in this range of currents is said to be a normal glow discharge and is characterized by a nearly constant sustaining voltage. If the current is increased beyond the point where the cathode is covered with glow, the sustaining voltage rises, and the discharge is said to be an abnormal glow discharge. At still higher currents it becomes an arc, and the anode-to-cathode voltage falls to a value comparable with the ionization potential of the gas.

The sustaining voltage of the normal glow discharge depends on such quantities as the emission coefficient γ, the product pd, and the functions which give the probabilities of excitation and ionization for electron collisions with the molecules as a function of the incident electron energy. Because it is possible to process tubes so that the cathode remains relatively clean over long periods, and hence γ remains nearly constant, and because the other factors determining the sustaining voltage are essentially constant with time, it is possible to obtain sustaining voltages which change only a fraction of a per cent in a year of continuous service. Voltage-reference tubes used in regulated power supplies are so processed.

In voltage-regulator tubes, use is made of the fact that the sustaining voltage is nearly constant with current over a range of currents from about 200 microamps up to the current at which the cathode is covered with glow. The tubes are operated in parallel with a load of variable impedance, and the parallel combination is connected through a series resistance to a power supply. The voltage drop across the load therefore equals the sustaining voltage of the tube, the circuit parameters being so chosen that the tube operates in the normal glow discharge. As the current drawn by the load increases, the current drawn by the tube decreases, and the voltage drop across the combination remains nearly constant.

A cold-cathode diode is essentially a two-state device. If a voltage less than the breakdown voltage is applied to the tube, practically no conduction takes place, and the device is characterized by almost infinite impedance. However, if the supply voltage, in series with a suitable resistance, is raised above the breakdown voltage, the glow discharge is established. The discharge in this second state is characterized by appreciable current conduction, a much lower impedance, and a sustaining voltage which is less than the breakdown voltage. By reducing the supply voltage sufficiently, the discharge can be caused to return to the low-conduction, or essentially nonconducting, state. This two-state nature of the tubes makes possible their use both as storage elements and as switching elements. In some tubes designed for switching applications, a third electrode located closer to the cathode is added to initiate the glow discharge.

15.1 The Glow Discharge, Ionization Time, and the Arc Discharge

(a) *The Glow Discharge*

The visible glow of the normal glow discharge is caused by excited atoms undergoing radiative transitions to lower states. It is observed only where there is an appreciable current of fast moving electrons which have sufficient energy to excite neutral atoms. Since the glow region of the normal glow discharge covers only a portion of the electrode area, this must be the only region where there is an appreciable current of fast electrons, and we must conclude that nearly all the cathode emission comes from the

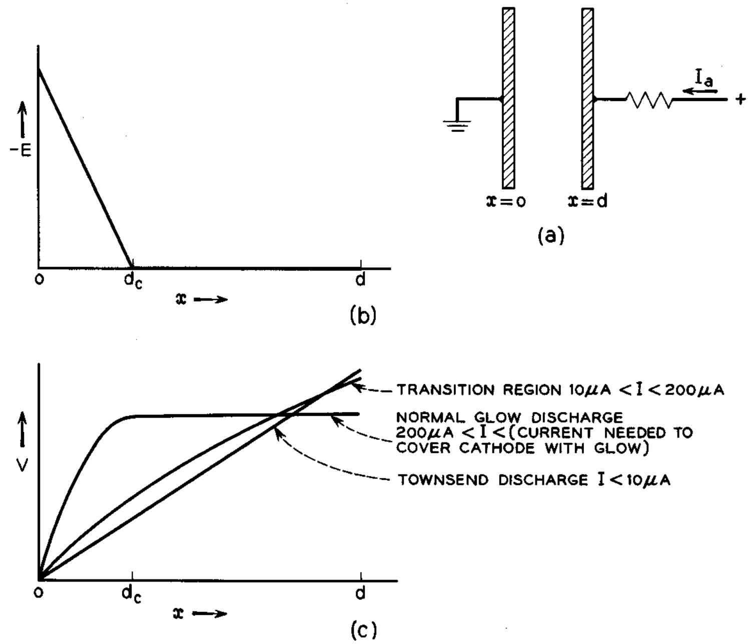

FIG. 15.1-1 Approximate plots of the electric field intensity and potential in the interelectrode space of a gas tube with planar, parallel electrodes.

glow-covered part of the cathode. Furthermore, since the glow area of the normal glow discharge is linearly proportional to the current drawn by the tube, it follows that the normal glow discharge is characterized by a constant current density over the glow area. For molybdenum electrodes and neon gas, this current density is found to be $J = 5p^2$ microamps/cm^2, where p is the pressure in millimeters of Hg.

In a search for a better understanding of the mechanisms involved in the glow discharge, a number of investigators have made probe measurements of the potential in the interelectrode space of glow-discharge devices.[2] Unfortunately, such measurements always tend to disturb the field under observation, so that the information obtained is only approximate. However, most observers have concluded that the electric field intensity E falls off in a nearly linear manner with distance from the cathode, becoming zero, or almost zero, at some distance d_c from the cathode. A plot of the electric field intensity in the interelectrode space of a glow-discharge device may be something like that shown in Figure 15.1-1(b). Qualitative plots of the potential in the interelectrode space for three different ranges of currents are shown in Figure 15.1-1(c). The plots for the transition region and the normal glow discharge are made along a line running through the glow area perpendicular to the cathode.

The part of the glow discharge extending from the cathode out to d_c is known as the cathode-fall region, since nearly all the voltage drop in the tube takes place in this region. A linear decrease of E from the cathode out to d_c and no electric field intensity beyond d_c would imply a uniform net density of positive charge from the cathode out to d_c and no net charge beyond that point. Beyond d_c there is an ion-electron "plasma" consisting of approximately equal numbers of ions and electrons diffusing through the gas and perhaps drifting under the influence of weak electric fields. It is believed that the probability of ion-electron recombination in this region is small.

Because most of the potential drop in the glow discharge takes place close to the cathode, the metastables and photons produced in the discharge are, for the most part, generated closer to the cathode than in the Townsend discharge. This increases the probability of their reaching the cathode and provides a further reason for the lower sustaining voltage of the glow discharge.

The foregoing picture of the glow discharge leads to a number of questions about the mechanisms involved. Unfortunately, present understanding of the glow discharge is not at all complete, and a quantitative explanation of the shape of the potential distribution between the electrodes is not available. However, we can write down several conditions which mathematically describe the discharge. For a device with planar electrodes these are:

1. The discharge is self-sustaining. This implies that at the cathode

$$J_-|_{x=0} = \gamma(J_+|_{x=0} + GJ_-|_{x=0}) + \text{(contribution caused by photons striking the cathode)} \qquad (15.1\text{-}1)$$

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[2]References 15.1 to 15.5.

where $J_+|_{x=0}$ is the ion current density at the cathode, $J_-|_{x=0}$ is the electron current density at the cathode, and G is the average number of metastables striking the cathode per electron released from the cathode.

2. The electric field intensity is given by

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon_o} = (n_+ - n_-)\frac{e}{\varepsilon_o} \tag{15.1-2}$$

where n_+ and n_- are the ion and electron densities, respectively.

3.
$$V(x) = \int_0^x E dx$$
$$V_a = \int_0^d E dx \tag{15.1-3}$$

where V_a is the sustaining voltage of the discharge, and d is the electrode spacing.

4.
$$J_+ = n_+ u_+ e$$
$$J_- = n_- u_- e \tag{15.1-4}$$
$$J_+ + J_- = J$$

where u_+ and u_- are, respectively, the ion and electron mean velocities, and J is the total current density.

The quantities J_+, J_-, n_+, n_-, u_+ and u_- are all functions of distance x from the cathode, whereas $J = J_+ + J_-$ is independent of x. The values of u_+ in the cathode-fall region are probably close to those plotted in Figure 14.3-1, but may differ slightly because of the rapidly changing field. However, very little is known about the distribution of electron velocities in the cathode-fall region and beyond. This means that η cannot be obtained from the data given in Figure 14.3-3 which are valid only for a uniform electric field intensity. For similar reasons few data are available on the generation of metastables and photons in the cathode-fall region and beyond. At the present time opinions differ between experimenters on what fraction of the ions is generated in the cathode-fall region and what fraction is generated beyond the cathode-fall region.

If the coefficient $\eta'(x)$ giving the average number of ions generated by a single electron per volt potential rise were known together with the rates of generation of ions from metastable interactions, we could add one more equation to those given above, namely

5.
$$\frac{dJ_+}{dx} = \frac{dJ_+}{dx} = \eta'(x)\,|J_-|\,|E| + \text{(contributions from processes leading to metastable ionization)} \tag{15.1-5}$$

Because so many of the processes taking place in the glow discharge are interrelated, a complete mathematical description of the discharge would be very complex indeed. (It may be well to note once more that the voltage drop V_c of the cathode fall is determined by the condition that the electrons passing through the cathode-fall region must gain sufficient energy to generate the current of discharge products which strike the cathode and which serve to maintain the electron emission. If γ is 0.2, about 5 ions and metastables must strike the cathode for each electron leaving the cathode. Of course, additional energy is lost by the electrons in exciting atoms to radiating states, in increasing the thermal energy of the gas, and in generating metastables which do not reach the cathode. Consequently the voltage drop of the cathode fall must be at least several times the ionization potential of the gas. In a neon-molybdenum device, γ is about 0.2 and V_c is close to 110 volts, or 5.1 times the ionization potential of neon.)

Some further understanding of the problem can be obtained by assuming that the electric field intensity really does vary as shown in Figure 15.1-1(b). In this case we can use the preceding equations to estimate E, ρ, and d_c in the cathode-fall region in terms of the voltage drop V_c across the cathode-fall region and the observed cathode current density J.

Let the electric field intensity in the cathode-fall region be given by

$$E = -\frac{2V_c}{d_c}\left(1 - \frac{x}{d_c}\right) \qquad (15.1\text{-}6)$$

where V_c is the voltage drop of the cathode fall, and the minus sign in front of the right-hand side implies that the direction of E is that of decreasing x. V_c is approximately equal to V_a over a range of pd values up to $pd = 20$ mm of Hg $\times$ cm for neon-molybdenum devices, but at higher pd there is a voltage rise in front of the anode. Since several ions on the average are needed to release one electron from the cathode and since the electron velocities in the cathode-fall region are many times those of the ions, the space charge in the cathode-fall region is primarily caused by ions. We can therefore write that

$$\frac{dE}{dx} = \frac{\rho_+}{\varepsilon_o} = \frac{J_+}{\varepsilon_o u_+} = \frac{2V_c}{d_c^2} \qquad (15.1\text{-}7)$$

Note that since E decreases linearly with x, ρ_+ is independent of x, and J_+ is proportional to u_+. From Equation (15.1-7), it follows that

$$(pd_c)^2 = \frac{2\varepsilon_o V_c u_+}{J_+/p^2} \qquad (15.1\text{-}8)$$

It will be convenient to rewrite Equation (15.1-1) in the form

$$J_-|_{x=0} = \gamma' J_+|_{x=0} \qquad (15.1\text{-}9)$$

where γ' is greater than γ by an amount that accounts for the contributions to the electron current density at the cathode caused by metastables and photons striking the cathode. Combining Equations (15.1-9) and (15.1-4), we obtain

$$J_+|_{x=0} = \frac{J}{1+\gamma'} \tag{15.1-10}$$

Since J_+ is proportional to u_+, in the cathode-fall region, we can use the values of both J_+ and u_+ at $x = 0$ in Equation (15.1-8). Combining that equation with Equation (15.1-10), we obtain

$$(pd_c)^2 = \frac{(1+\gamma')2\varepsilon_o V_c u_+|_{x=0}}{J/p^2} \tag{15.1-11}$$

Now from Equation (15.1-6),

$$\left.\frac{E}{p}\right|_{x=0} = -\frac{2V_c}{pd_c} \tag{15.1-12}$$

For a planar molybdenum cathode and neon gas, $V_c = 110$ volts and $J/p^2 = 5$ microamps/cm^2 $\times$ (mm of Hg)^2. E/p at the cathode is of the order of 200, so that $\gamma = 0.20$ (Figure 14.5-3). γ' may be of the order of 0.30 assuming that the metastables striking the cathode give rise to about a third of the cathode emission and that the contribution caused by photons is small. (A change of 20 per cent in the assumed value of γ' would only change pd_c by about 2 per cent.) Equations (15.1-11) and (15.1-12) are consistent for one particular value of pd_c only. A choice of $pd_c = 1.08$ mm of Hg $\times$ cm is easily shown to satisfy both equations. From the second equation we find that $(E/p)|_{x=0} = 204$ volts/cm $\times$ mm of Hg. According to Figure 14.3-1 the corresponding value of $u_+|_{x=0}$ is 2.3×10^3 meters/sec. Substituting for J/p^2, $u_+|_{x=0}$, and $1 + \gamma'$ into the right side of the Equation (15.1-11), we obtain $pd_c = 1.08$ mm of Hg $\times$ cm, confirming our choice. (One must be a little careful of units in this last substitution. If J is expressed in amperes per square centimeter, u_+ in meters per second, and V_c in volts, then d_c is in centimeters.) If the gas pressure in the device is known, d_c is determined from $pd_c = 1.08$ mm of Hg $\times$ cm. The electric field intensity can be obtained using Equation (15.1-6), and ρ_+ can be obtained using Equation (15.1-7).

The fact that pd_c is a constant means that the cathode-fall region is a definite number of mean free paths in thickness, the number being independent of pressure. A rough estimate of the number of mean free paths involved can be obtained using the data for the collision probability P_c plotted in Figure 14.3-2. The electron mean free path is given by the reciprocal of P_c divided by the gas pressure in millimeters of Hg. For electrons of 15 to 30 electron volts in neon $P_c \simeq 12$ (cm $\times$ mm of Hg)$^{-1}$, and the mean free path $\simeq 1/(12p)$ cm, where p is in millimeters of Hg. Combining this with $d_c = 1.08/p$ cm, we find that the cathode-fall region is approximately 13 mean free paths in thickness. (However this does not mean that only 13 collisions are made by the electrons on their way through the cathode-fall region, since in some of the collisions the electrons are deflected through large angles.)

Still another calculation of interest is the ratio of ions to gas molecules in the cathode-fall region. Now from Equation (15.1-7)

$$\rho_+ = \frac{2\varepsilon_o V_c p^2}{(pd_c)^2} \tag{15.1-13}$$

The density of ions is given by ρ_+/e, and the ratio of ions to gas molecules is ρ_+/ne, where n is the density of gas molecules. For a gas at 0°C, $n = 3.54 \times 10^{22}\, p$ molecules/meter^3, where p is the pressure in millimeters of Hg. In the cathode-fall region the gas temperature is usually somewhat higher than 0°C, but for the purpose of an order-of-magnitude calculation it will suffice to use $n = 3.54 \times 10^{22}\, p$. For neon gas and planar molybdenum electrodes the ratio of ions to gas molecules in the cathode-fall region is therefore

$$\frac{\rho_+}{ne} = \frac{2\varepsilon_o V_c p}{3.54 \times 10^{22} e (1.08 \times 10^{-2})^2} = 3.0 \times 10^{-9} p \tag{15.1-14}$$

For $p = 50$ mm of Hg, there is one ion for approximately 7 million gas molecules in the cathode-fall region.

Next let us consider the scaling of gas-discharge devices. It was pointed out earlier that the breakdown voltage of a gas diode with planar, parallel electrodes is a function of pd, where p is the gas pressure and d is the electrode spacing. It was also noted that if all the linear dimensions of a gas diode having arbitrarily shaped electrodes are scaled by a factor k, and if the

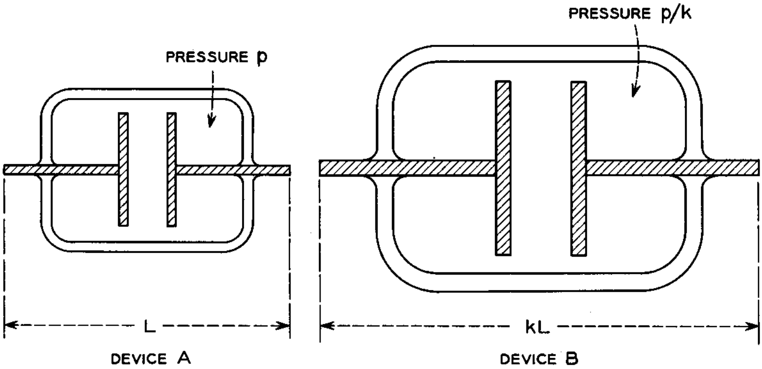

FIG. 15.1-2 The linear dimensions of device B are k times those of device A, and the pressure of the gas filling in device B is $1/k$ times that in device A.

pressure is changed by $1/k$, the breakdown voltage to a first approximation remains unchanged. This is so because the average velocity gained by an electron in the interval between collisions is the same for the same applied voltage, and the average number of collisions which an electron makes in traveling between the electrodes is unchanged. (Or, stated another way, E/p is the same.)

The same scaling law applies to glow discharges. Figure 15.1-2 shows two gas-discharge devices A and B. If the linear dimensions of device B are k times those of device A and if the pressure of the gas filling in device B is $1/k$ times that of device A, the number of mean free paths between the cathode and anode of each device is the same. Consequently electrons traveling from the cathode to the anode of the two devices make the same average number of collisions on the way. If glow discharges are established in the devices, we would expect that the voltage difference per mean free path along a line joining the cathode and anode would be the same in each case (remembering that the discharges are self-sustaining). This means that the voltage at corresponding points between the electrodes would be the same, and the sustaining voltages would be the same. The latter point is, in fact, experimentally verified.

Now from Poisson's Equation we know that the net charge density ρ is proportional to $\nabla^2 V$. But since V is the same at corresponding points between the electrodes of the two devices, and since the dimensions of device B are k times those of device A, $\nabla^2 V$ in the interelectrode space of device A is k^2 times that at corresponding points in device B. Consequently, the charge density ρ in the interelectrode space of device A is k^2 times that in device B. And since the voltage gained per mean free path is the same, the mean drift velocities of the charged particles at corresponding points between the electrodes is the same. Consequently, the cathode current density $J = \rho u$ of device A is k^2 times that of device B, and J/p^2 is the same for the two devices. Since the cathode area of device B is k^2 times that of device A, the cathodes are covered with glow at the same current.

Figure 15.1-3 shows how the sustaining voltage of a discharge tube with planar molybdenum electrodes and a neon filling varies with pd, where d is the electrode spacing. The measurements were taken by varying d with p constant. For $5 < pd < 20$ mm of Hg $\times$ cm, the sustaining voltage is virtually constant. However, if d is decreased so that pd falls below 5 mm of Hg $\times$ cm, the sustaining voltage rises, apparently because the anode enters a region in which some of the excitation and ionization contributing to the discharge takes place. A discharge in a neon-molybdenum device with $pd < 5$ mm of Hg $\times$ cm is said to be "obstructed." (Since pd_c for the cathode-fall region is only 1.08 mm of Hg $\times$ cm, it is evident that some of the metastables and ions reaching the cathode are generated well beyond

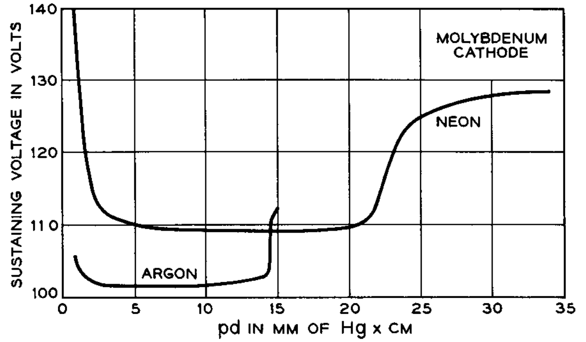

FIG. 15.1-3 The normal-glow-discharge sustaining voltage of devices with planar molybdenum electrodes and neon and argon fillings as a function of *pd*. In obtaining the curve for neon *p* was held at 50 mm of Hg, and *d* was varied. In obtaining the curve for argon *p* was held at 25 mm of Hg, and *d* was varied.

the cathode-fall region.) It would be reasonable to expect that the current density J of the normal-glow discharge would be principally determined by events taking place at $pd < 5$ mm of Hg $\times$ cm. This is in fact the case, for if d is varied with p constant, J remains unchanged provided $pd > 5$ mm of Hg $\times$ cm. When this result is combined with the scaling law for J/p^2 dis-

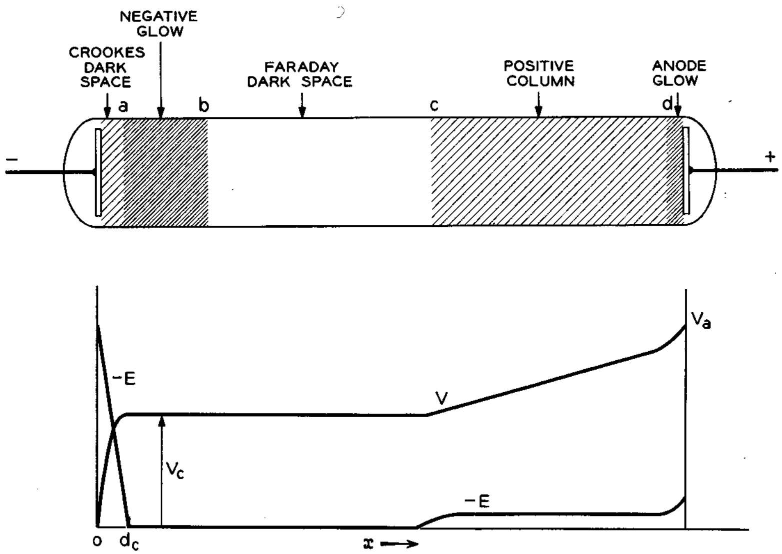

FIG. 15.1-4 The potential V and electric field intensity E in a long tube with $pd \gg 20$ mm of $Hg \times$ cm.

cussed above, it follows that J/p^2 for the normal-glow discharge is constant for all neon-molybdenum devices with planar electrodes and $pd > 5$ mm of Hg $\times$ cm.

If pd is increased beyond about 20 mm of Hg $\times$ cm the sustaining voltage V_a again rises. At somewhat higher values of pd, a region of glow appears in front of the anode and oscillations in the discharge can be detected. Figure 15.1-4 shows a tube in which pd is assumed to be much greater than 20 mm of Hg $\times$ cm together with a plot of potential V and the electric field intensity E. Several regions of visible glow can be distinguished in such a tube. The cathode-fall region extends from the cathode out to a. Relatively little light is emitted from this region, and it is frequently called the *cathode dark space,* or the *Crookes dark space.* Between a and b a much brighter region of glow known as the *negative glow* can be seen. In devices with $pd < 20$ mm of Hg $\times$ cm most of the visible glow comes from this region. Excitation and ionization in the region are thought to be largely due to fast electrons arriving from the cathode fall. In a neon-molybdenum device the outer edge of the negative glow corresponds to a pd of about 5 mm of Hg $\times$ cm. Between b and c there is a region, known as the *Faraday dark space,* from which very little radiation takes place, apparently because most of the free electrons do not have enough energy to excite the gas molecules. Between c and d a region of diffuse glow known as the *positive column* can be seen; and finally, between d and the anode, there is a somewhat more intense glow known as the anode glow.

The negative glow region, the Faraday dark space, and the positive column are all plasmas, or regions in which the ion and electron densities are approximately equal. Because the electron velocities in the plasma are much greater than the ion velocities, the current of electrons reaching the edge of the plasma in front of the glass walls is much greater than the ion current. The walls therefore become negatively charged, and a "sheath" forms between the plasma and the glass. The voltage drop in the sheath serves to reduce the electron current reaching the glass walls to a value equal to the ion current. (Since the walls are insulating, the electron and ion currents to the walls must be equal.) Some discussion of plasmas and sheaths is given in the first section of Chapter 16.

Fast electrons from the cathode fall expend most of their energy in the negative-glow region where most of the excitation and ionization needed to support the cathode emission take place. In the Faraday dark space few electrons have sufficient energy to cause excitation. Conduction through the Faraday dark space results largely from diffusion of electrons from the negative-glow region to the cathode end of the positive column. Ions enter the Faraday dark space both from the negative glow and from the positive column.

The electron current reaching the sheath at the edge of the plasma is generally hundreds of times greater than the ion current, so that electrons reaching the edge of the plasma, for the most part, are reflected by the sheath. However ions reaching the edge of the plasma are drawn into the sheath and neutralized upon reaching the walls. A nearly uniform gradient of potential extends over the length of the positive column giving the electrons sufficient energy to generate ion-electron pairs needed to make up for ion and electron losses to the walls. The nature and appearance of the positive column depend considerably on the product of the filling pressure and tube radius as well as on the current density. A variety of types of positive column can be obtained by varying these factors,[3] but a discussion of the possible forms of positive column would be outside the scope of the present treatment. The positive column is responsible for the radiation observed from "neon" advertisement signs and gas lasers and is indirectly responsible for the radiation emitted from fluorescent lamps.

If the current drawn by a cold-cathode tube is increased beyond the point where the cathode is completely covered with glow, the voltage drop across the tube rises, and the current density of the discharge increases linearly with the total current. Such a discharge is said to be an abnormal glow discharge. The fact that the discharge is restricted to a cathode of fixed size area implies a further boundary condition for the abnormal glow discharge in addition to the conditions listed earlier for the normal glow discharge. Probe measurements of the cathode-fall region of the abnormal glow discharge[4] show that d_c decreases with increasing current, as would be expected from Equation (14.1-11).

(*b*) *Ionization Time*

The ionization time of a cold-cathode device is defined as the time that elapses between the application of a voltage greater than breakdown between the anode and cathode of the tube and the initiation of the glow discharge. We shall assume we have a device in which pd is a little greater than the pd value which gives minimum breakdown. If a voltage just above breakdown is applied to the anode, an electron leaving the part of the cathode surface closest to the anode on the average will generate sufficient excited atoms and ions to release slightly more than one electron from the cathode. A current buildup results which soon produces sufficient space charge to initiate the glow discharge.

The ionization time is made up of two parts. One part is the delay which occurs between the application of voltage to the anode and the release from the cathode of the electron or electrons which initiate the current buildup.

[3]Reference 15.6, p. 155.

[4]Reference 15.1.

The second part is the time required for the current to increase to the point where the glow discharge is established. In general, both parts decrease as the excess of the applied voltage over the breakdown voltage increases.

Some means to initiate the release of electrons from the cathode is generally provided in cold-cathode tubes. Often a spot of radioactive material is painted on the inside of the envelope close to the anode-to-cathode gap. This ensures frequent ionizing events in which high-energy α or β particles are released into the filling gas causing ionization of the gas. A few of the ions and electrons generated in this manner diffuse through the gas to the anode-to-cathode gap. When voltage is applied to the anode, the electrons are drawn to the anode, perhaps causing further ionization on the way, and the ions are drawn to the cathode, where some may release electrons by the γ process. Because only a few charged particles reach the interelectrode space, several ionizing events may take place before the current buildup is initiated.

If the radioactive material used is a compound of radium, a small quantity of radioactive radon gas is generated by the radium. The radon mixes with the filling gas and ensures some radioactivity throughout the interior of the tube.

In some tubes a radioactive isotope of krypton, known as krypton 85, is added to the filling gas. The nucleus of this isotope undergoes a radioactive decay in which it releases a β particle which in turn causes ionization of the filling gas.

Tubes in which radioactive material has been placed for the purpose of obtaining short ionization times are said to have a radioactive keep-alive. The ionization time of these tubes is, of course, a function of the amount of radioactive material, the proximity of the decaying particles to the anode-to-cathode gap, and the excess of the supply voltage over the breakdown voltage, a quantity referred to as the "overvoltage." If the overvoltage is 10 volts, average ionization times of a few hundred microseconds can readily be obtained with a radioactive keep-alive. The time required for the current buildup with such an overvoltage may be several tens of microseconds. Because of the random nature of the radioactive decay, the ionization time is a statistical quantity and is best described by a distribution of individual measurements.

In some tubes a low-current discharge between auxiliary electrodes is operated continuously as a keep-alive mechanism. Such a discharge is called a dc keep-alive. Generally, the current drawn by the dc keep-alive is of the order of a few microamperes, although smaller currents are sometimes sufficient. Ions and electrons generated by the auxiliary discharge find their way to the gap between the main anode and cathode and are responsible for initiating the current buildup in the main gap.

A third keep-alive mechanism, known as a photoelectric keep-alive, involves the use of a surface which emits photoelectrons and which is held close to cathode potential. If light falls on such a surface, a current of photoelectrons is emitted. When voltage is applied to the anode, the photoelectrons are drawn to the anode causing ionization on the way and initiating the discharge.

If no keep-alive mechanism is provided in a cold-cathode tube, the discharge is eventually initiated by residual radioactivity within the tube or by a cosmic ray event. In such cases ionization times of the order of a second or more may be encountered.

Finally, if a very high voltage is applied across a short gap, the discharge may be initiated by field emission from the cathode. Two common gas-discharge devices in which the discharge is initiated by field emission are the spark plug and the carbon-block lightning protector used on telephone lines to prevent voltage surges from reaching central office or subscriber equipment.

(c) *The Arc Discharge*

If the current density of the abnormal glow discharge is increased sufficiently, the sustaining voltage V_a reaches a maximum, after which it decreases either continuously or abruptly. The drop in V_a is accompanied by a transition to a form of discharge known as an arc. The arc is a self-sustaining discharge which is characterized by a high current density ($\sim 10^3$ to 10^6 amps/cm^2) and a low sustaining voltage ($\sim$10 to 20 volts). Usually the area of the cathode surface covered with glow from the discharge is quite small. The visible light from the discharge always contains strong spectral lines of the cathode material.

The low sustaining voltage implies that electrons are emitted from the cathode by some supplementary mechanism in addition to the γ process. It has been shown that thermionic emission plays an essential role in arcs formed with carbon and tungsten cathodes, the intense heat needed to maintain the thermionic emission being generated by ion bombardment of the cathode. However the electron-emission mechanism involved in arcs formed with copper or liquid mercury cathodes seems less certain. Field emission is a possibility.[5] (It can be shown that the temperatures needed

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[5]Reference 15.6, p. 140; References 15.7 and 15.8. See also discussion of other possible mechanisms by A. Von Engel, *Ionized Gases*, Oxford University Press, Oxford, England, 1955, Chapter 9 Sections 5 and 6, and discussion by J. M. Meek and J. D. Craggs, *Electrical Breakdown of Gases*, Oxford University Press, Oxford, England, 1953, Chapter 12.

for appreciable thermionic emission from copper or liquid mercury cathodes would be sufficient to vaporize the cathode material.) If field emission is the mechanism involved, the large fields needed to release electrons from the cathode are probably generated by a high density of ions drifting toward the cathode.

15.2 Three Examples of Cold-Cathode Tubes

In this section we shall describe three cold-cathode tubes manufactured by the Western Electric Company, each of a different construction and each used for a different purpose. The first is the 423C, a two-electrode device used as a voltage-reference tube in power supplies. The second is the 427A, a three-electrode tube used as a voltage regulator in power supplies. The third is the 426A, a three-electrode tube used as a switching element in a telephone circuit which permits selective ringing of subscribers on party lines.

The 423C

Figure 15.2-1 illustrates the construction of the 423C voltage reference tube. The electrodes are molybdenum and the gas filling is argon, a combination that has been found to give sustaining voltages which are par-

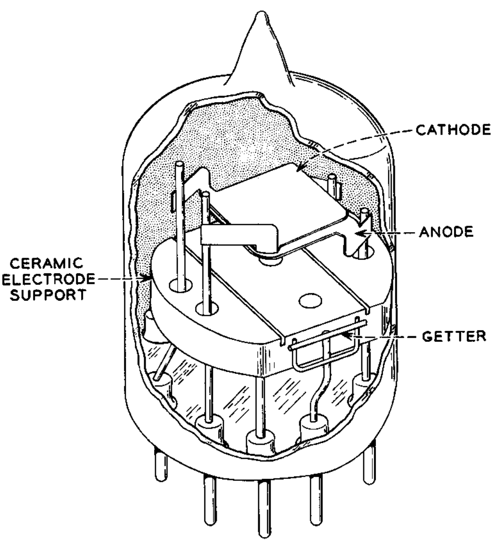

FIG. 15.2-1 The 423C voltage reference tube. The overall height of the tube is 4.4 cm.

ticularly stable with time. The back of the cathode is coated with powdered nickel which has a higher work function and hence lower γ than molybdenum. This serves to restrict the glow to the inner face of the electrode. A small amount of radioactive krypton gas is added to the argon filling gas as a radioactive keep-alive. The getter shown in the figure is used to evaporate a thin film of barium on the inside of the glass envelope during processing of the tube. The barium "getter flash" serves to adsorb molecules of the non-noble residual gases within the tube.

Principal electrical characteristics of the tube are shown in Table 15.2-1.

TABLE 15.2-1 WE 423C OPERATING CHARACTERISTICS

	Typical Values
Breakdown voltage, volts	135
Sustaining voltage, volts	100
Operating current, ma	4 to 8

The pressure of the gas filling is 32 mm of Hg, and the electrode spacing is 0.05 cm. The product *pd* is therefore 1.6 mm of Hg $\times$ cm. This choice of *pd* represents a compromise between a desire to obtain minimum breakdown voltage and a desire to keep out of the obstructed-discharge region. Figure 14.6-3 shows that minimum breakdown voltage for a device with planar molybdenum electrodes and an argon filling is obtained at a *pd* of 1.0 mm of Hg $\times$ cm. However, Figure 15.1-3 indicates that the discharge is obstructed at this *pd*. Minimum breakdown voltage is desirable from the standpoint of the power supply applications in which the tube is used, but since the sustaining voltage of an obstructed discharge is thought to be less stable on a long-term basis, a somewhat larger *pd* is used.

The cathode area of the tube is 0.46 cm, and the normal glow discharge covers the cathode at a current of 8 milliamps. The parameter J/p^2 is therefore 17 microamps/cm^2 $\times$ (mm of Hg)^2. Using this value of J/p^2 and assuming $\gamma' = 0.12$, the quantity pd_c can be calculated from Equations (15.1-11) and (15.1-12). It is found that $pd_c = 0.45$ mm of Hg $\times$ cm. Since $pd = 1.6$ mm of Hg $\times$ cm, the cathode-fall region of the discharge extends about 0.3 of the way from the cathode to the anode.

Tubes of the 423C type are found to drift less than a volt in sustaining voltage in a year of continuous operation. Part of this stability is achieved through careful processing to ensure that the electrodes are particularly clean and hence that γ remains constant throughout the life of the device. The processing includes heating the electrodes inductively with rf to bright red temperatures while the tubes are being pumped. This cleans the electrode surfaces and drives contaminant gas from the interior of the metal. After pumping is completed, the tubes are filled with the argon-krypton 85 mixture and sealed off. They are then subjected to operation at relatively high currents including pulsed operation at currents of the order of several amperes. This processing, known as aging, causes molybdenum to be sputtered from the surface of the cathode onto the anode and the surrounding walls, leaving the cathode particularly clean. The sputtering results from positive ions striking the cathode and imparting their kinetic energy to molybdenum atoms or groups of atoms at the surface. The high current densities at which the tubes are aged (and which place the discharge far into the abnormal-glow region) are found to increase the sputtering rate greatly. At normal operating currents of 4 to 8 ma, the cathode sputtering is very slight.

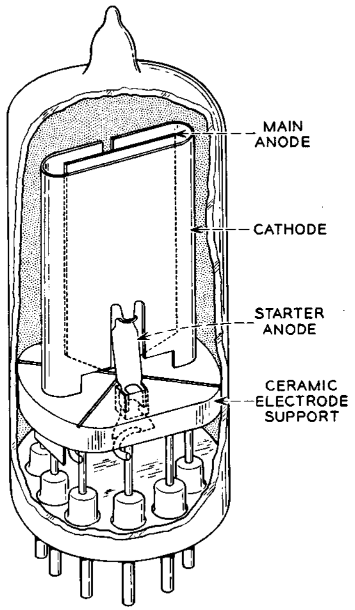

FIG. 15.2-2 The 427A voltage regulator tube. The overall height of the tube is 5.5 cm.

The 423C is capable of almost indefinite life, since at normal operating currents there is nothing which "wears out" in the tube.

The 427A

Figure 15.2-2 shows the construction of the 427A voltage regulator tube. The electrodes are molybdenum and the gas filling is a mixture of argon and a small amount of krypton 85 at a pressure of 21 mm of Hg. The electrode configuration shown in the figure gives electrical characteristics which are similar to those of devices with planar, parallel electrodes. By folding the cathode around the anode, a relatively large cathode area can be enclosed in a relatively small envelope. Like the 423C, the outside of the cathode is coated with a material which restricts the glow to the inner surface of the cathode.

Important electrical characteristics of the tube are shown in Table 15.2-2.

TABLE 15.2-2 WE 427A OPERATING CHARACTERISTICS

	Typical Values
Main-anode breakdown voltage, volts	165
Main-anode sustaining voltage, volts	100
Starter-anode breakdown voltage, volts	125
Recommended operating current, ma	5 to 40

The product *pd* for the main-anode gap is equal to 3.0 mm of Hg × cm.

The tube is processed in a manner similar to the 423C, and its main-anode sustaining voltage is almost as stable as that of the 423C. Like the 423C it is capable of almost indefinite life.

A typical circuit in which the tube might be used is illustrated in Figure 15.2-3. As the load increases, the current drawn by the 427A decreases. If the current drawn by the 427A falls in the range from 5 to 40 ma, the sustaining voltage of the tube is very nearly constant, and the voltage drop across the load remains nearly constant.

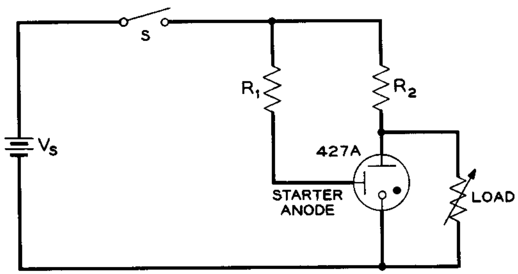

FIG. 15.2-3 A circuit in which the 427A is employed as voltage regulator.

The supply voltage V_s in Figure 15.2-3 must at least equal the starter-anode breakdown voltage if conduction is to take place when the switch *S* is closed. If V_s is greater than the starter-anode breakdown voltage, closing the switch initiates a discharge between the starter anode and the main cathode. If the current of this discharge is greater than about a tenth of a milliampere, the discharge transfers immediately to the main anode. For smaller starter currents, transfer of the discharge to the main anode depends on the applied anode voltage.

The 426A

The construction of the 426A switching triode is illustrated in Figure 15.2-4. The tube is used in an application which requires a low sustaining voltage and a high main-anode breakdown voltage. The stability of the sustaining voltage is not at all critical, and the total life of the tube does not need to be more than 100 hours at a current of 30 ma. Two features of the design contribute toward a low sustaining voltage:

1. The cathode consists of nickel sheet coated with a mixture of barium and strontium oxides. This gives a low work function and a high γ.

2. The gas filling is a neon-argon mixture consisting of approximately 95 per cent neon and 5 per cent argon. The neon-argon mixture gives a

high η because neon metastables ionize argon molecules. (The gas pressure is 40 mm of Hg. A very small amount of krypton 85 is added to the filling gas as a radioactive keep-alive.)

High main-anode breakdown voltage is obtained by locating the anode far from the cathode. This in turn leads to oscillations in the discharge, but

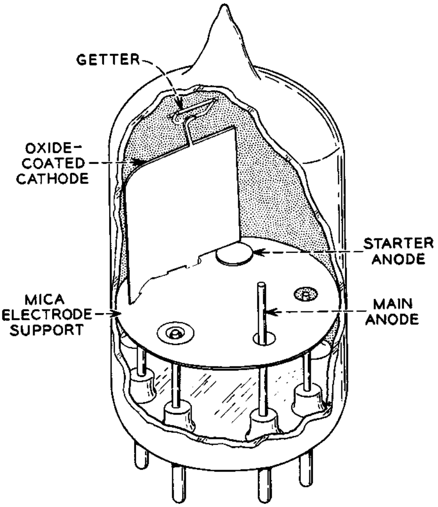

FIG. 15.2-4 The 426A switching triode. The overall height of the tube is 4.4 cm.

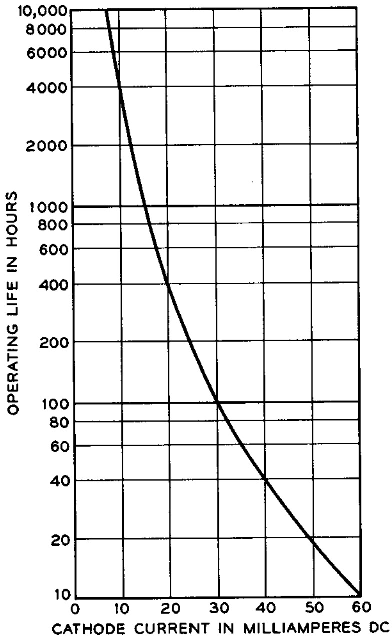

FIG. 15.2-5 Expected life of the 426A in hours as a function of the cathode current.

the oscillations are not a concern in the applications in which the tube is used.

Principal electrical characteristics of the 426A are shown in Table 15.2-3.

TABLE 15.2-3 WE 426A OPERATING CHARACTERISTICS

	Typical Values
Main-anode breakdown voltage, volts	>180
Main-anode sustaining voltage, volts	69
Starter-anode sustaining voltage, volts	72
Operating current, ma	30
Ionization time, starter gap, milliseconds	10

The starter-gap ionization time is measured with an applied voltage which exceeds the starter-gap breakdown voltage by 15 volts.

The life of cold-cathode tubes with oxide-coated cathodes is found to decrease rapidly with increasing current because of a corresponding increase in the sputtering of the cathode coating. When most of the oxide coating is sputtered away, the sustaining voltage starts to rise. End-of-life of tubes of this type is frequently measured in terms of a rise in sustaining voltage above a preselected value. Figure 15.2-5 shows how the expected life of the 426A varies with current. The cathode is covered with glow at about 10 milliamps.

15.3 The Hollow-Cathode Discharge and the Stepping Tube

If a cold-cathode device is constructed in which the cathode has a re-entrant or "hollow" part, a quite different form of glow discharge can sometimes be obtained. The phenomenon is known as the hollow-cathode discharge. Figure 15.3-1 shows several possible forms of hollow-cathode. The

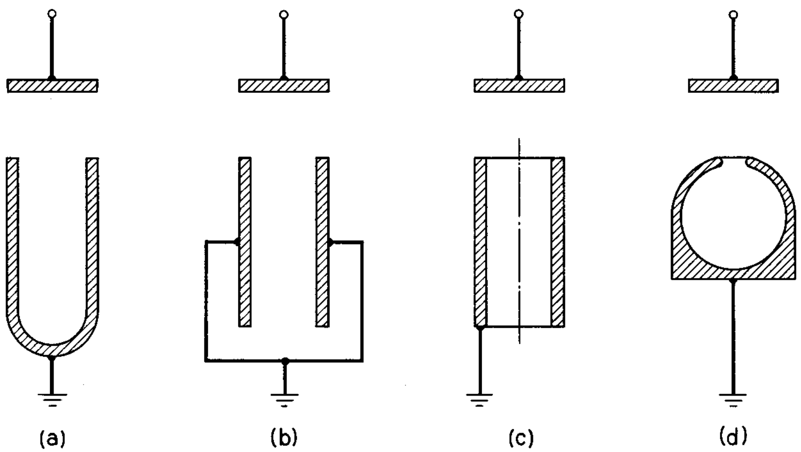

FIG. 15.3-1 Several possible forms of hollow cathode.

effect can be obtained with a U-shaped cathode, two parallel planar cathodes, a cylinder, or a spherical cavity. In order to obtain the hollow-cathode discharge, the product of the filling pressure p and the distance a across the hollow must be such that electrons leaving opposite inner sides of the hollow enter a common negative-glow region in the central portion of the hollow. In the case of a neon-molybdenum device with two parallel, planar cathodes, a is taken to be the distance between the cathodes, and the product pa must be less than about 10 mm of Hg × cm and greater than some lower limit, which probably is less than 1 mm of Hg × cm.

Characteristics of the hollow-cathode discharge are:

1. Except at very low discharge currents, the sustaining voltage of the hollow-cathode discharge is lower, for a given discharge current, than the sustaining voltage of a device with a planar cathode having the same surface area as the hollow cathode. This means that when the discharge is first initiated, the current emission and glow build up on the inside of the hollow, drawing the anode voltage below the sustaining voltage for a discharge on the outside of the cathode. Consequently, over a wide range of discharge currents, very little glow is observed on the outside. (However, if the discharge current is increased sufficiently, the glow eventually spreads to the outside of the hollow.)

2. Depending on the filling pressure and the dimensions of the cathode, the current needed to cover the inner sides of two parallel planar cathodes with glow is sometimes as much as several hundred times that needed to cover an equal area of a planar cathode. The same applies to devices with U-shaped cathodes or cylindrical cathodes.

The mechanisms responsible for the anomalous behavior of the hollow-cathode discharge are not well understood at present, and we shall not attempt an explanation of them.

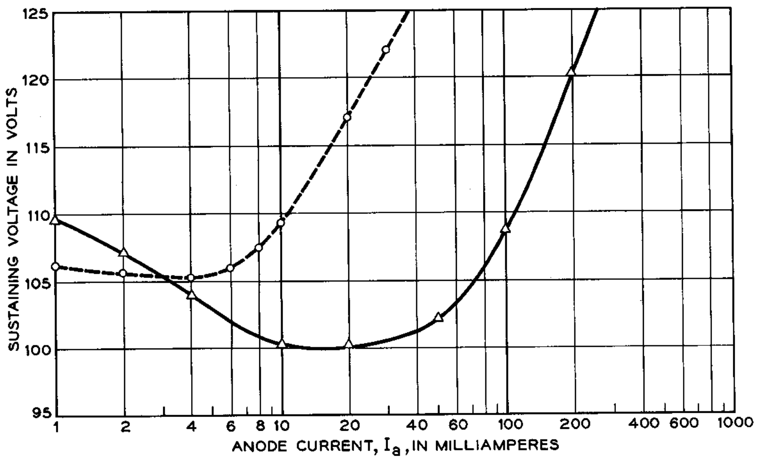

FIG. 15.3-2 (——) Anode voltage vs. anode current curve for a device with a hollow cathode of the type shown in Figure 15.3-1(d). (- - -) Anode voltage vs. anode current curve for a device with planar, parallel electrodes. Both tubes have molybdenum cathodes and neon fillings.

In Fig. 15.3-2 the solid curve shows a plot of sustaining voltage vs. discharge current measured for a cathode of the type shown in Figure 15.3-1 (d) The cavity diameter was 0.75 mm, and the tube was filled with neon to a pressure of 98 mm of Hg. The product of pressure and diameter was therefore close to 7.5 mm of Hg × cm, and the area of the inside of the cavity was close to 0.017 cm^2. A planar cathode of equal area would be covered with glow at a current of about 0.8 milliamp at the same filling pressure.

The broken curve in the Fig. 15.3-2 shows a plot of the sustaining voltage vs. discharge current measured for a neon-molybdenum device with a planar cathode of area 0.45 cm^2, a planar, parallel anode, and a filling pressure of 60 mm of Hg. The cathode was covered with glow at about 8 ma. (The product pd for the device was 7.5 mm of Hg × cm, where d is the anode-to-cathode spacing.) The back of the cathode was coated with a material of lower γ than that of molybdenum so that the glow would remain only on the face toward the anode. The higher sustaining voltage of the cavity cathode at very low currents can probably be attributed to the constriction of the discharge by the small opening to the cavity.

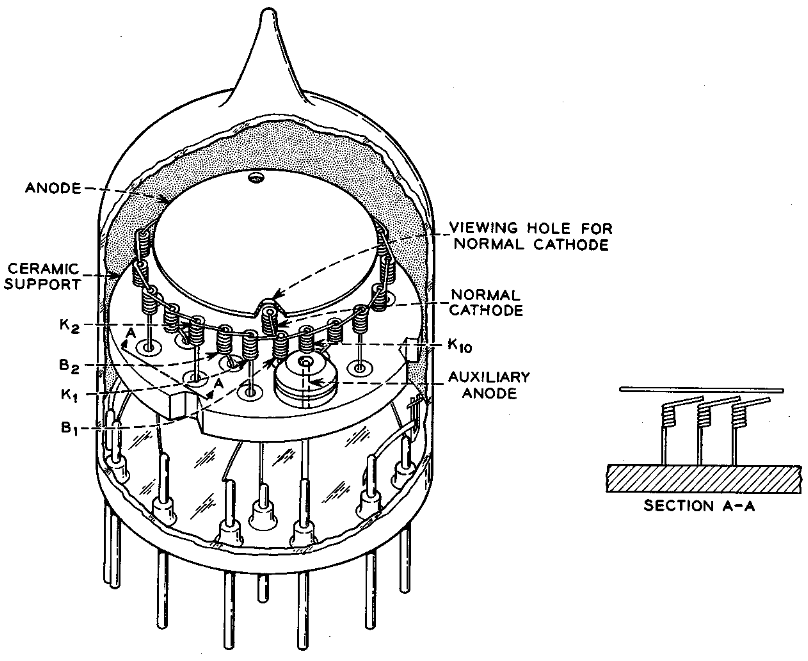

FIG. 15.3-3 The construction of the 439A stepping tube. The overall height of the tube is 5.6 cm.

The hollow-cathode effect is used in the 439A counting or stepping tube illustrated in Fig. 15.3-3. The tube has 20 cathodes arranged in a ring around a common disc-shaped anode. Alternate cathodes, called output cathodes, are connected to external leads and identified as K_1, K_2, . . . K_{10}. The remaining cathodes are called stepping cathodes and identified as B_1, B_2, . . . B_{10}. The stepping cathodes are joined together internally in two groups of five, each group having an external lead. For most circuit applications the two groups of five are connected together externally.

The tube is operated so that the discharge is normally on one of the K cathodes. A negative pulse applied to the stepping cathodes causes a discharge on K_1 to transfer to B_2 during the pulse and to K_2 at the end of the pulse. A second pulse causes the discharge to transfer to K_3, and so on. The electrode arrangement permits both electrical and visual counting of the pulses. A normal cathode inside the ring of 20 can be used to "zero" the position of the discharge before a counting operation. An auxiliary anode located under K_{10} can be used to obtain an output every tenth pulse so that several tubes can be used in a "decade counter." In a three-tube decade counter, one tube counts every pulse, a second tube counts every tenth pulse, and the third tube counts every hundredth pulse.

The key to the transfer mechanism lies in the shape of the cathodes. Each cathode consists of a molybdenum wire wound into a coil forming a hollow region with a straight portion of the wire, called a pick-up tab, at the upper end. The discharge is normally in the hollow part of the cathode, since it is more efficient there, and the sustaining voltage is lower. The pick-up tab extends over the end of the hollow part of an adjacent cathode and serves as a preference mechanism which causes the discharge to transfer in one direction only. The discharge current is usually about 2 ma. (The tube is filled with neon to a pressure of 105 mm of Hg.)

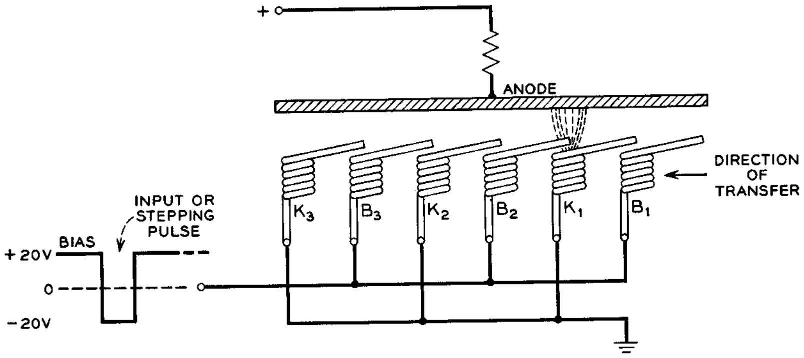

FIG. 15.3-4 A number of B and K cathodes arranged in a row.

Figure 15.3-4 shows a number of B and K cathodes arranged in a row. Alternate B cathodes are connected together and serve to step the discharge from one K cathode to another. The discharge is shown to be on K_1 in the figure, and the pick-up tab of B_2 extends into the region of ionization of the discharge. The B cathodes are biased 20 volts positively with respect to the K cathodes. A negative pulse of -40 volts superimposed on the bias voltage makes the voltage difference between B_2 and the anode greater than the sustaining voltage for a discharge on the pick-up tab of B_2. The discharge therefore quickly builds up on the pick-up tab of B_2, drawing the anode voltage down so that it is less than the sustaining voltage for the discharge on K_1. The glow on K_1 therefore extinguishes. Transfer of the discharge to the pick-up tab of B_2 is rapidly followed by a buildup of current in the hollow of B_2, since the sustaining voltage of the discharge in the hollow is less than on the pick-up tab. This causes the anode voltage to fall still further, and the glow on the tab extinguishes.

Thus the negative pulse applied to the B cathodes causes the glow to transfer from the hollow part of K_1 to the hollow part of B_2. Removal of the pulse makes the B cathodes more positive than the K cathodes and causes the glow to transfer from the hollow of B_2 to the hollow of K_2. Successive pulses applied to the B cathodes cause the discharge to advance one more K cathode to the left for each pulse.

By applying a sufficiently large negative pulse to the normal cathode, the discharge can be transferred from any of the K cathodes to the normal cathode, since the anode voltage falls to a value insufficient to maintain a discharge on any of the other cathodes. The stepping cathode B_1 has two pick-up tabs which enable it to transfer the discharge to K_1 from either the normal cathode or K_{10}.

In most circuit applications the auxiliary anode is connected through a series resistance to the anode supply. Because the auxiliary anode is shielded from all cathodes except K_{10}, it draws current only when the discharge is on K_{10}. When the glow transfers to K_{10}, the auxiliary anode potential falls giving a negative output pulse which can be used to drive a second stepping tube. Positive output pulses can be obtained from any of the K cathodes by placing a resistance of suitable size in series with the cathode load.

With suitable external circuitry the 439A can be used to count pulses at repetition rates as high as five kilocycles.

REFERENCES

Several texts on gas tubes and gas-discharge phenomena are listed at the end of Chapter 14. A particularly good description of the glow discharge is given by G. Francis, *Handbook of Physics*, Vol. 22, p. 53, Julius Springer, Berlin, 1956.

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