CHAPTER II

THE CONSTRUCTION OF A GAS-DISCHARGE TUBE

II-a Introduction

As often happens in modern technology, there is rather less confusion about how to make and use gas-discharge tubes than about what to call them: recent reference books on electronics talk of gas tubes, gas-filled tubes, gas-discharge tubes and gaseous discharge tubes; and the word "tube" is often replaced by "valve" in English, rather than in American literature. In this book the name "gas-discharge tube" will be used.

Another aspect of nomenclature which might lead to confusion is the name given to the electrodes. Most discharge tubes contain two or more electrodes, and the main current generally flows between two of them. When one of the two is always positive with respect to the other, it is called the anode and the other the cathode, but in many cases their polarity is periodically reversed. However, it usually happens that much more current flows when one of the electrodes is positive. This one is then called the anode, and the other the cathode, no matter what their polarity at any given moment.

In this chapter a general discussion is given of *the gas filling, the electrodes* and *the envelope* of a gas-discharge tube. The details of construction and characteristics of the various gas-discharge tubes are discussed in the following chapters.

II-b The gas filling

While care must be taken to remove all the free and absorbed gas from a vacuum tube, the presence of a certain amount of gas is essential in order to give a gas-discharge tube its special characteristics.

We will discuss here the various types of gas and the reason for using them, their pressure and the purity of the gas.

II-b-1 THE GASES USED

Most gas-discharge tubes are filled with an inert gas (He, Ne, A, Kr, Xe) or a mixture of inert gases. These have the great advantage that they do not react chemically and they also give better reproducibility of the tube characteristics than do non-inert gases.

Hydrogen and nitrogen are also sometimes used for filling the tubes.

Finally, a *vapour* filling may sometimes be used, viz. mercury vapour or a mixture of mercury vapour and an inert gas, or a halogen or an alcohol. The choice of the type of gas mainly depends on the demands made on the tube.

Pure inert gas may be used to fill tubes where the difference between the burning voltage and the breakdown or ignition voltage must be large, e.g. in trigger tubes. The reason for preferring a pure inert gas in this case can be made clear with the aid of the Paschen curves (Fig. 19). The choice of a sufficiently high value of p_0d gives a high breakdown voltage, while the burning voltage does not depend very strongly on p_0d. (A very low value of p_0d also gives a high breakdown voltage, but this part of the Paschen curve is difficult to realize in practice). The values of p_0 and d needed to give this high breakdown voltage can be achieved in practice with pure inert gases better than with inert-gas mixtures.
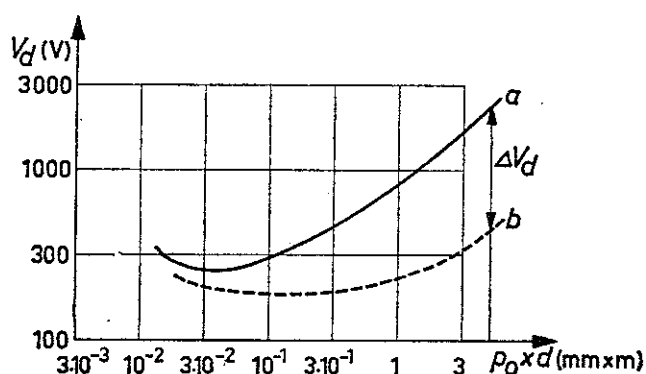

Fig. 19

Typical Paschen curves, showing the breakdown voltage as a function of the product of pressure and interelectrode distance for
a. neon,
b. neon + 0.1 % argon.

The addition of a small percentage of another inert gas, with an ionization voltage lower than the excitation voltage of the metastable state of the main gas, makes the Paschen curve appreciably flatter and its minimum lower (curve *b* Fig. 19, cf. Penning effect, Chapter I-d-3). Such a gas mixture is used e.g. for a voltage-stabilizing tube, where the breakdown voltage V_{ign} for the glow discharge should only be slightly greater than the burning voltage V_{br}. It is then possible to use a lower supply voltage and a smaller resistance in series with the tube than would be necessary if $V_{ign} - V_{br}$ were large.

Mercury vapour may be mixed with the inert gas when the energy lost in the tube should be low, and the life of the tube long. This combination gives for instance a low V_{ign} and V_{arc} in a hot-cathode tube, so the

transformer voltage for a rectifier may also be low (this is used in e.g. an LT accumulator charger).

Industrial rectifier tubes for a few hundred volts contain saturated mercury vapour and a little inert gas. Since the anode voltage is quite high, the pressure of the inert gas must be relatively low in connection with the backfire voltage. Nevertheless it helps to support the discharge when the mercury temperature is still too low, while the tube is warming up. After the tube has been warmed up, the mercury vapour takes over most of the discharge. The result is that such a tube can be started cold (as soon as the cathode has been warmed up); moreover, the mercury ensures a long life which would not be obtained if the tubes were only filled with inert gas at a low pressure.

If however the anode voltage of such a tube should be some kilovolts (as in an HT rectifier), then the permissible gas pressure is so low that the inert gas would be cleaned up very quickly (see II-b-2); so only saturated mercury vapour can be used here. The vapour pressure of the mercury (which depends on the temperature) must also be low, so these tubes are specially designed not to get too hot. The reserve of liquid mercury ensures a long life for the tube despite the low vapour pressure, since the vapour is replenished as fast as it is used up during the operation of the tube.

Sometimes unsaturated mercury vapour is used in a mixture, but then the life of the tube is not so long, since the vapour can no longer be replaced as it gradually disappears.

Hydrogen gas is used in e.g. radar thyratrons where a current pulse with very steep flanks is desired, since in hydrogen the build-up and the recovery time (see I-e-2 and IV-b-4) are much shorter than in other gases.

Nitrogen at rather high pressures is sometimes used in surge arresters because of the short build-up time, which allows the tube to respond rapidly to rapid increases in the voltage.

We may finally mention the use of halogens and alcohols. Their strong electron affinity and absorption of the UV light produced by the discharge ensure that the discharge is quickly damped. These substances, mixed with inert gases, are therefore used in e.g. some radiation counting tubes.

II-b-2 THE GAS PRESSURE

After the sort of gas to be used has been decided, the pressure to be used must also be fixed. We have seen in Chapter I that in order to give a clear understanding of the phenomena occurring in a gas-discharge tube, the amount of gas present can best be expressed as the gas *density*, but

that it is simpler in practice to use the gas *pressure* at a given temperature; p_0 will be used here for the pressure reduced to 0 °C.

The gas pressure or density has an effect on:

1. the breakdown or ignition voltage
2. the current density
3. the operating voltage
4. the backfire voltage
5. the life of the tube
6. cathode sputtering.

In each particular case the designer of a tube has to decide which of these factors is most important. We will now give some examples of the considerations used to fix the pressure in a gas-discharge tube.

The relationship between the pressure p_0 and the current density j in a glow discharge is given to a good approximation by the equation

$$V_a = \mathrm{f}\ (j/p_0{}^2)$$

This means that the anode voltage V_a remains practically constant if j is varied in proportion to the square of p_0. Under these circumstances, however, an increase in the current density leads to an increase in the heating of the cathode surface. If p_0 is increased too much, the cathode begins to emit thermally, and the discharge changes into an arc, the anode voltage decreasing sharply to the arc voltage V_{arc}. In hot-cathode tubes, the value of V_{arc} increases as the pressure is increased, owing to collision losses; and it also increases as the pressure is decreased to very low values, where the supply of ions is very small. The plot of V_{arc} against p_0 for argon (Fig. 20) shows a minimum at a pressure of about 6 mm Hg (with an inter-electrode distance of about 10 mm).
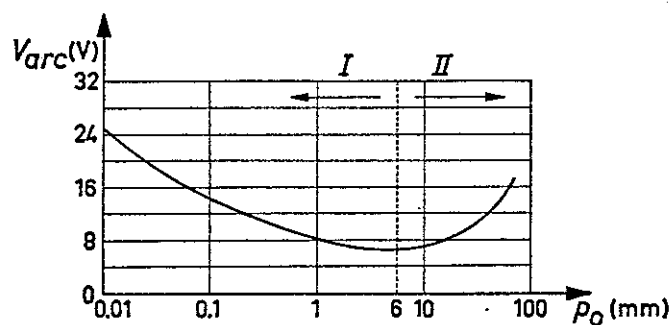

Fig. 20

Influence of the gas pressure p_0 on the burning voltage V_{arc} of an arc discharge. The curve has a minimum at $p_0 \approx 6$ mm.

The current in the glow discharge occurring at the anode of a rectifier tube during the negative phase must be kept as low as possible, since it

interferes with the rectification effect. If the pressure is high enough and if the resistance of the circuit belonging to the reversed discharge is low enough, this glow discharge may degenerate into an arc. The inverse current then increases so much that the rectification effect is lost. The ignition voltage for this arc discharge at a given pressure is called the *backfire voltage*. Its value varies considerably from tube to tube of the same type. Tube specifications include a maximum permissible value of the inverse voltage, below which no backfire will occur.

Let us now consider the relationship between the pressure and the life of the tube. At low pressures, the ions pass through a large voltage difference between two collisions, so that the cathode bombardment becomes vigorous with the result that heavy cathode sputtering occurs, limiting the life of the tube. At high pressures the ions strike the cathode with lower velocities, but there are many more of them. However, many of the atoms knocked out of the cathode collide with gas atoms and return to the cathode, so sputtering (and evaporation) is considerably reduced at high pressures. A good example of this effect is to be found in the "Tungar" rectifier tube. The tungsten cathode of such a tube must be at a high temperature in order to give the required emission (cf. I-c-1 and III-b-1); but at these high temperatures the evaporation of the material reaches considerable proportions. The evaporation is however kept within reasonable limits by the high pressure in the tube (10—15 cm Hg).

The material removed from the cathode by sputtering is also deposited on other parts of the tube, where it may lead to short-circuits. This is another reason for having the gas pressure on the high side.

Cathode sputtering is not the only thing which determines the life of a tube, gas may also disappear during the discharge, for a number of reasons. This phenomenon is known as *cleanup*.

The first phase of this cleanup consists in an adsorption of gas atoms on the walls or the electrodes. This gas is thus lost from circulation and the gas pressure decreases. Furthermore, e.g. in high-voltage tubes, which are normally filled with gases at low pressures, the high voltage give rise to *fast* gas ions which can easily penetrate into the surfaces mentioned. This decrease in pressure may determine the life of the tube.

A second phase consists in the trapping of gas during the deposition on the walls of the tube of material released from the electrodes by the discharge (sputtering). The amount of sputtering depends on the energy of the ions, their nature, the gas pressure, the sort of electrode material used and its surface condition (oxidized surface, etc.).

The ion bombardment does not only affect the cathode. The metal particles sputtered from the other electrodes also pick up gas atoms on their way to the walls, thus decreasing the pressure.

Moreover, cleanup may occur by the adsorption of gas on these metallic layers deposited on the walls of the tube. We may also mention for the sake of completeness the tendency of certain gases to react chemically with materials in the tube. This may sometimes be a serious problem with non-inert gases, which can even be activated by the discharge.

One of the great advantages of the use of saturated vapours, such as mercury vapour, in filling tubes is that as long as there is liquid mercury present in the tube, the vapour pressure will not be affected by cleanup, since the losses due to adsorption are made up by replacement from the liquid. This does not hold for unsaturated vapours, of course.

Another way of keeping the gas pressure constant during the life of the tube is the use of a *replenisher*. Materials which under suitable conditions can adsorb large quantities of certain gases *(getters)* are discussed in the next section; a replenisher is a getter acting in reverse. If a metal wire covered with such a material is heated in a glass bulb, the adsorbed gas is released, and on cooling the gas is adsorbed again. The gas pressure may thus be controlled by means of the temperature of the wire. As we will see later on (IV-b-6), this is used in hydrogen thyratrons.

To sum up what we have said above, if certain conditions must be imposed on e.g. the ignition voltage, inverse voltage and/or operating voltage in the design of a tube, these often impose contradictory limitations on the value of the gas pressure. It is therefore necessary to make a compromise. If we think of the relation between the mean free path and the pressure, it is clear that the distances between the electrodes and/or their distance to the wall must be chosen to correspond to the pressure chosen: as a rule the mean free path must be small compared with these dimensions, so that ionizing collisions can occur.

The gas pressure chosen for a gas-discharge tube will be somewhere between 10^{-3} and 10^3 mm Hg, though the most usual range is from 1 to 10 mm Hg.

II-b-3 THE PURITY OF THE GAS, GETTERS

The inert gas in a tube must be kept pure. The presence of impurities, even in very small amounts, can have a considerable effect on the ignition and operating voltages. These voltages are generally increased by the presence of non-inert gases, since electrons which collide with such molecules lose their velocity or may even be trapped. Their presence may

easily be detected from the colour of the discharge. Each pure gas gives a typical colour in a low-pressure discharge (see table III). The same gas may give different colours in discharges of different kinds (e.g. a high-pressure arc).

TABLE III

THE COLOUR OF THE INERT GASES, AND OF A NEON-ARGON MIXTURE, HYDROGEN AND MERCURY VAPOUR IN LOW-PRESSURE DISCHARGE

helium	yellowish pink (green at very low pressures)
neon	orange-red
argon	violet
neon-argon	yellow-orange
krypton	pale lilac
xenon	blue
hydrogen	reddish violet
mercury vapour	blue-green

The colour changes slightly as soon as another gas or vapour is added. Traces of mercury vapour generally give a blue colour which masks the colour of the main component. If some air has leaked into a tube the colour of the discharge will usually be pale, milky or sometimes reddish. Magnesium vapour gives a clear green colour.

There are three conditions for the purity of the gas filling:
a. thorough degassing of the tube
b. filling with pure gas and
c. purifying the gas again, once the tube is sealed.

a. Before a tube is filled with inert gas at the pump, the walls and electrodes (and the getter) must be freed as well as possible from the gases which they contain. This is done by heating the whole tube to as high a temperature as possible and at the same time pumping out until a vacuum of 10^{-5} to 10^{-6} mm Hg or better is obtained. The electrodes are also heated separately by placing them in an HF field. A hot cathode may be heated by passing the heater current for some time.

TABLE IV

SPECIFIC EVAPORATION OF SOME METALS IN KG/M²/SEC AT VARIOUS TEMPERATURES [9]

	700 °K	800 °K	900 °K	1000 °K	1200 °K
W	—	—	—	—	3.22×10^{-26}
Mo	—	—	—	1.37×10^{-23}	2.44×10^{-18}
Ni	8.41×10^{-20}	2.35×10^{-16}	1.08×10^{-13}	1.42×10^{-11}	2.00×10^{-8}
Ba	1.7×10^{-7}	9.1×10^{-6}	2.0×10^{-4}	2.5×10^{-3}	1.0×10^{-1}

The vapour pressure of the electrode materials is still low at temperatures sufficient for degassing [9]. The table below gives some data on the specific evaporation of tungsten, molybdenum, nickel or barium at various high temperatures.

High-quality tubes must be degassed with great care in order to reduce the residual pressure of gaseous contaminations in the sealed tube to as low a value as possible. For example, a residual pressure of 10^{-8} mm of oxygen is enough to cover the metal electrodes with a monomolecular oxide layer in a few hours.

b. Various methods can be used for filling a tube with pure gas from a reservoir so that the amount of other gases or vapours introduced is kept to a minimum. A detailed description of these methods is beyond the scope of this book.

c. Once the gas has been put into the tube and the tube sealed off, the gas may still be purified by means of *getters* [8] in order to remove impurities introduced into the gas filling during and after sealing. Getters are substances which can adsorb or react with non-inert gases. The getter material is placed in the tube in a getter holder; when required for use, it may be evaporated from this holder (evaporating getter) or it may remain in the holder (non-evaporating getter). The alkaline earth metals, especially barium, are mainly used as evaporating getters, while zirconium is the usual choice for a non-evaporating getter. Sputtered layers can also be used as getters.

Evaporating getters

A certain amount of the getter, either as the pure element or in combination with other substances, is placed in a holder on a little rod inside the tube, and the holder can be heated by an external HF field as described above. When it is thus heated to a high temperature, the getter material evaporates and is deposited as a thin film over the cooler parts of the tube. It is thus given a very large surface area, which is as we will see essential for the purification of the gas.

Before evaporating, the getter must be degassed at a temperature low enough to prevent appreciable evaporation, so that it is initially as free from gas as possible. Some getter materials, e.g. barium, are placed in a sealed holder which is designed to open when heated to a temperature higher than the degassing temperature of the tube. Such getters cannot naturally be degassed *in situ*.

The non-inert gases are not only taken up during the time when the getter is evaporated, but also after: the thin getter layer, or mirror, which

is deposited on the cooler parts of the tube is also able to combine chemically with reactive gases. A good layer is formed if the evaporation occurs through a gas, and not in vacuo, since then it is given a spongy structure and thus a great surface area, which is essential for strong and fast gettering. If a getter mirror is present it is thus able to trap impurities which may be released from the electrodes or walls of the tube during operation.

Non-evaporating getters

Some substances, such as zirconium and titanium, are very active not only as a layer formed by evaporation or sputtering, but also in the form of pellets, wires, etc. They adsorb selectively as a function of temperature; so e.g. zirconium can be used as a getter at various temperatures. At low temperatures (below 200 of 300 °C) zirconium getters are in particular able to adsorb oxygen and nitrogen [11]. When used in the high-temperature range (at about 900 °C), it can adsorb e.g. oxygen and nitrogen, or hydrocarbons and carbon monoxide. When the tube is constructed in
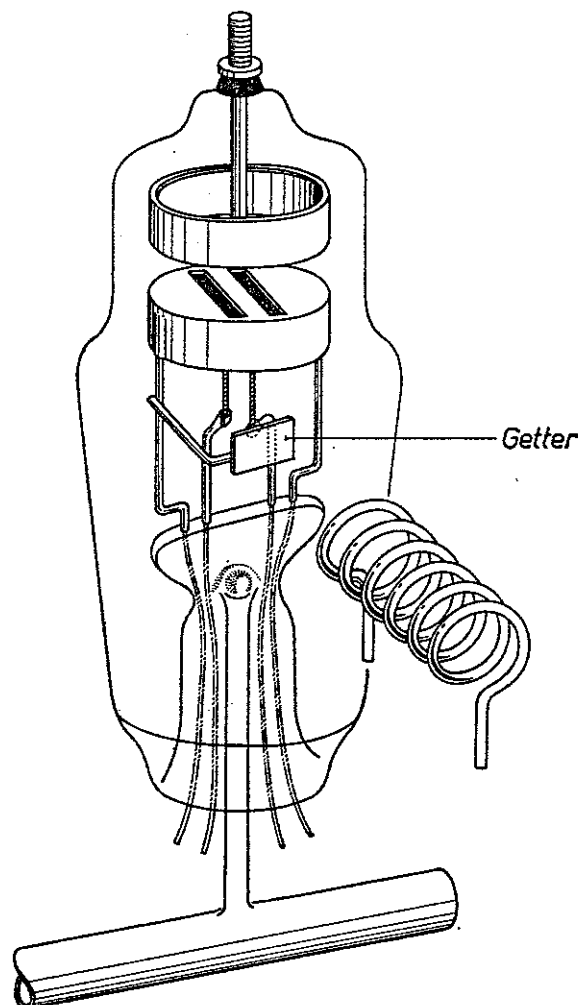
Fig. 21

The zirconium getter of this tube is being heated by an HF field while the tube is pumped out by a vacuum pump.

such a way that different parts of the getter operate at different tempe-ratures, zirconium can therefore adsorb all the above-mentioned gases. A specially prepared Zr getter or a sputtered Zr layer can also adsorb all these gases at a single temperature. Since zirconium does not amalgamate with mercury, it can be used in mercury-vapour rectifiers [8], which is not the case with e.g. a Ba getter.

We will not give any details of gettering speed and the like, which are of importance for the manufacturer but not for the user. Interested readers can find various studies of these points in the literature [10]. We will, however, say something about the getter holder.

The active getter must often not be exposed to the air, to prevent saturation with atmospheric gases which would make it useless for puri-fying the gas in the tube.

Chemical substances which can release the getter are therefore often enclosed in nickel boxes, which are pinched together at the edges to keep out the air. When such a box is heated in an HF field in vacuo (see Fig. 21), the metal is released by a chemical reaction. When the vapour pressure in the box is high enough to force it open slightly, the vapour is "squirted" out. Care must be taken that the getter lands on the right places, and not where it can hinder the proper functioning of the tube. The getter mirror must not, for example, cause short-circuits between the electrodes. The position of the box must therefore be chosen very carefully.

The getter holder need not however always be closed. Fig. 22 shows some examples of open ones.
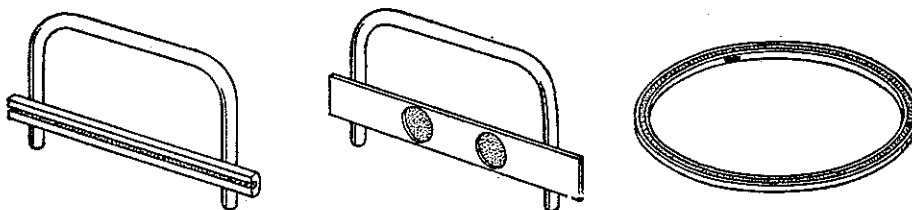

Fig. 22

Various types of open getter holders. In contrast with the type described in the text, these getter holders do not completely enclose the getter-producing substance, which is indicated by dotted areas. The first two types are provided with a metal loop, which is needed to form a closed circuit for the HF current.

Sputtered layers

Another method of forming a getter layer is by means of sputtering, where a discharge is used to eject metallic particles from the cathode by ionic bombardment, after which the particles are again deposited on the walls of the tube.

Atoms of the contaminating gas can be trapped by the metallic particles during sputtering, and deposited with them on the walls of the tube. The sputtered layer can also act as a getter.

For example, in some glow-discharge tubes (e.g. reference tubes, see V-a-2) a molybdenum cathode is sputtered in order to keep the inert gas filling pure.

II-c The cathode

A hot cathode or a cold cathode may be used as the electron source in a gas-discharge tube. Such cathodes are commonly made of metals, which may or may not be oxide-coated. The work functions may have various values (see Table I, Chapter I). A list of the various types of cathode in use is given below.

1. Hot cathode (directly or indirectly heated)
   - Uncoated (Bright emitters)
     - Tungsten
     - Thoriated tungsten
   - Coated (Dull emitters)
     - Tungsten or nickel or mixtures of the two coated with alkaline earth oxides

2. Cold cathode
   - Uncoated
     - Nickel
     - Graphite
     - Iron
     - Molybdenum
     - Zirconium
   - Coated
     - Nickel or iron coated with barium oxide

3. Mercury-pool cathode

4. Photo-cathode
   - caesium-caesium oxide
   - caesium-antimony

II-c-1 HOT CATHODES

The most obvious way of creating a source of electrons — and this is what the cathode in a gas-discharge tube is — is to heat a metal.

According to the Richardson formula (Chapter I-c-1) the electron emission is proportional to $T^2 . \varepsilon^{-e\varphi/kT}$. The work function φ of a metal is high, so a high temperature is needed to give enough emission, and this leads to considerable evaporation. This method is therefore only used in special cases. Another method is to deposit a layer of a substance with

a low φ on the metal. The same emission can then be achieved at a lower temperature, and less energy need be supplied because the heat losses are smaller.

Uncoated cathodes

The use of uncoated tungsten is now practically restricted to some vacuum tubes. A filament temperature of about 2250 °C is normal. As far as gas tubes are concerned, thoriated tungsten wire is used in low-voltage rectifiers. This alloy contains a low percentage of thorium. The spirally wound cathode wire is heated to about 1900 °C, which causes a layer of thorium atoms to be formed on the surface. It is not certain whether thorium oxide as well as thorium is present in this outer layer. The thorium, which disappears from the surface during operation, is replenished from within. The life of the tube is thus determined by the supply of thorium. The high temperature is necessary to give an emission of 10 to 20 × 10⁴ A/m². The evaporation at this temperature is limited by a relatively high gas pressure (a few centimetres of mercury). An emission current of about 0.3 A per watt filament power can be obtained.

Coated cathodes

It is possible to increase the emission from the cathode by using a core of tungsten coated with a layer of alkaline earth oxide so formed as to give a spongy structure. Most gas-discharge tubes contain cathodes of this type. The emission temperature is much lower than for uncoated cathodes, being in the range 800—850 °C (about 1100 °K), because the low work function of the oxyde layer means that a sufficient emission is produced at such temperatures (see I-c-1). The attainable current density is 0.5 to 2.5 × 10⁴ A/m², and can rise to as much as 100 × 10⁴ A/m² during pulse operation (saturation) [12]. The emission current per watt filament power is about 0.6 A.

Fig. 23 compares the emissive power of four types of cathodes. The variable actually plotted is the specific saturation current I_{sat} in A/m².

The life of the cathode will be discussed below; but we will mention here that the main causes of deterioration of the cathode are evaporation and sputtering. A well-designed coated cathode will give very slight evaporation and sputtering, as long as the current remains below the saturation current. If the tube is operated under suitable conditions, both these causes of deterioration can be neglected.

The emission due to the γ effect (emission of electrons due to bombardment by positive ions, see Chapter I-g-1) is small as long as the current

remains below I_{sat}. If the current exceeds this value, the γ effect increases considerably, and so does cathode sputtering.
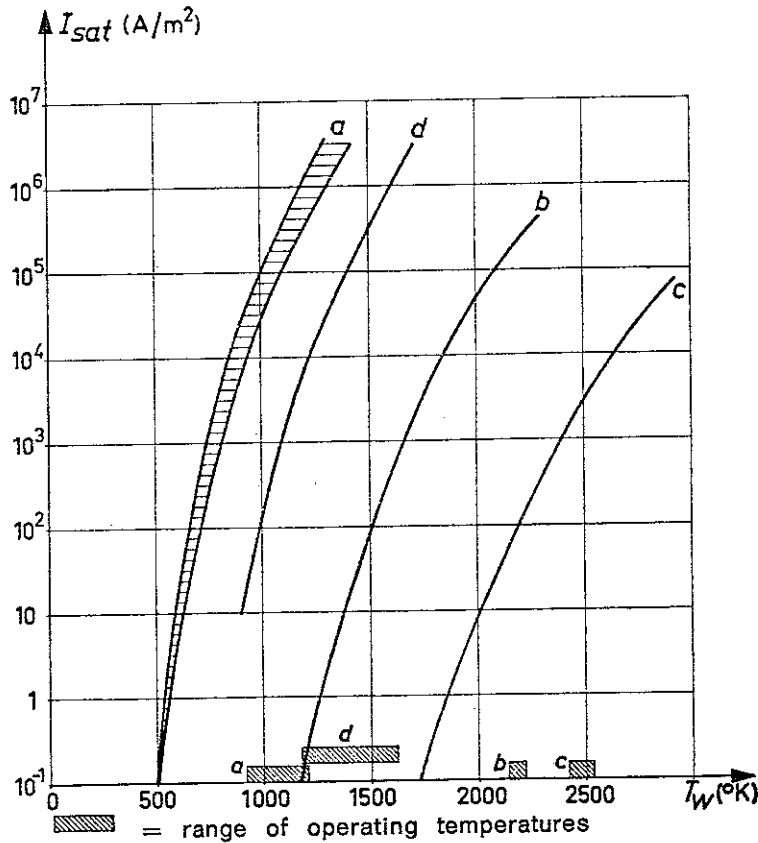

Fig. 23

Saturation current density I_{sat} as a function of the true temperature T_w of the cathode for:
a. oxide-coated cathode, (Ba, Sr)O,
b. thoriated tungsten cathode,
c. tungsten cathode,
d. L cathode,
(after Herrmann and Wagener [1]).
The range of operating temperatures is shown by hatched blocks.

As the emission current is increased from zero, a time comes when the saturating emission current is exceeded, i.e. more electrons are produced than can come from thermionic emission. The remainder are obtained by means of the γ effect, as the number of ions bombarding the cathode increases. An increase in the tube voltage will then be observed; this is needed to produce more ions. The ions will strike the cathode with a higher kinetic energy, and this increase in the number and energy of the ions will lead to a sharp increase in the sputtering.

II-c-1-a.   *Some phenomena peculiar to the oxide-coated cathode*

The emitting layer

Careful investigation of a tube with an oxide-coated cathode during

operation over a long period will help us to understand the working of such a cathode. The cathode is first heated to incandescence by the heating current through the cathode. As soon as a discharge current passes through the tube, the cathode will be seen to heat up. It is true that the energy needed to free the electrons from the oxide layer (equal to $I \varphi$, the product of the current and the work function) will have a cooling effect on the cathode, but against this we have the heat supplied by the bombardment by ions and the joule heating by the flow of current in the cathode [1]. In general, the heating effects predominate, so that the cathode temperature increases.

The cathode is prepared by applying a mixture of carbonates, e.g. $BaCO_3$, $SrCO_3$ and $CaCO_3$ (triple carbonate) to a wire which forms the core. A nickel wire may be used, for example. The cathode is first heated in vacuum to about 800 °C to degas it; the carbonates also decompose to the oxides and carbon dioxide is evolved at this temperature. Then the heater current is increased so that the temperature rises to about 1000 °C and is kept at this value for some minutes. This whole process is known as activation of the cathode. Some of the barium oxide at the surface of the nickel is reduced to metallic barium, thus giving a mixture of Ba and BaO. The low work function is maintained as long as both BaO and Ba are present at the surface. When Ba atoms disappear from the surface, they may be replaced from within the oxide layer, by the migration of Ba along the surface of pores, etc. The low value of φ (1.2 e.V) means that considerable thermionic emission occurs even at 850 °C (cf. Chapter I-c-1).

Evaporation of Ba from the monatomic layer is slight at low temperatures, but increases strongly with the temperature above 800 °. The oxide itself evaporates much less, whereas the evaporation of the (nickel) core wire can be neglected. This means that at 800—850 °C the cathode may have a very long life.

Sputtering

The name sputtering includes not only the detaching of atoms from the cathode, but also the detaching of macroscopic particles from this electrode. As the emission current is increased until the current density reaches considerably too high values, the latter form of sputtering gradually begins to predominate. The same thing happens if the cathode temperature is too low, or at high current density as occurs at high gas pressures. The brittle oxide layer becomes locally overheated, and chips jump off.

The same result can also be produced if the filament current of the oxide cathode is reduced to zero during normal operation. The discharge does not normally cease under these circumstances; the arc current becomes concentrated on the windings at that end of the cathode spiral which is most negative with respect to the anode. Thus even if the energy involved is slight, a very large temperature increase is produced locally. Depending on the value of the current density, the emission is accompanied by abnormally strong evaporation of the barium, by strong sputtering of atoms, or in the worst case by the detaching of particles. The latter form of sputtering can quickly lead to destruction of the cathode.

A special case of sputtering is found if the anode voltage and the filament are switched on simultaneously when the cathode is cold. An arc discharge may start before the cathode has reached its normal emission temperature. Sputtering then occurs until the filament reaches the temperature needed for the desired emission current. This way of starting the arc reduces the life of the cathode. It is therefore desirable not to switch on the anode voltage in gas tubes with oxide cathodes until the filament voltage has been applied and the cathode has been given time to reach the right temperature.

II-c-1-b.   *The life of the hot cathode*

As has been mentioned, a hot cathode is damaged by evaporation and sputtering. One might ask how long a hot cathode is able to carry out its task, and whether the life of the cathode can be increased by good design of the tube. It has been found possible to design tubes which satisfy the required conditions of voltage, current, etc., and which also have a very long life. The way in which this may be done varies from tube to tube, according to conditions of gas pressure and electrode configuration, as will be shown by the examples given below.

An HT rectifier tube must in general have a low gas pressure, so a mercury-vapour filling is the obvious choice. It is sometimes preferable to have the anode in a region of low pressure and the cathode in a region of high pressure. This can be achieved by having a separate anode and cathode space, linked by narrow channels, with the cathode space at high temperature, resulting in a high mercury vapour pressure. Such a construction is shown in Fig. 24; this has a condensation space C, connected on both sides by metal tubes to the anode space a, and the cathode space k. A pressure ratio of $1:20$ has been realized in practice. The life of the cathode is then practically unlimited.

In the Philips "1800" series of tubes (115 V series), the cathode is

surrounded by a sort of maze of overlapping shields (see Fig. 56). This arrangement makes the positive ions undergo several collisions with the screens before reaching the cathode, thus losing a considerable part of their energy.
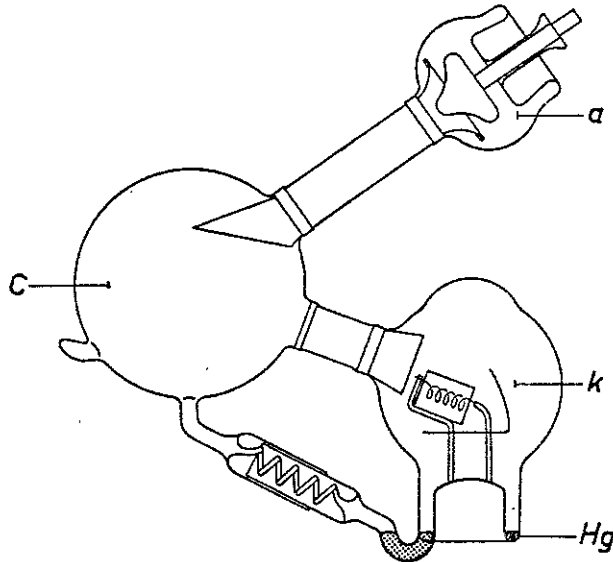

Fig. 24

An obsolete type of mercury-filled high-voltage rectifier tube. The condensation space C is connected to the anode space a and the cathode space k by narrow tubes, which allows the pressure in k during operation to be up to 20 times that in a. This increases the life of the cathode very considerably.

In a last example (Fig. 25) the coated cathode is made hollow, so that some of the material which leaves the cathode as a result of evaporation or sputtering is deposited on another part of the cathode, thus increasing its life.
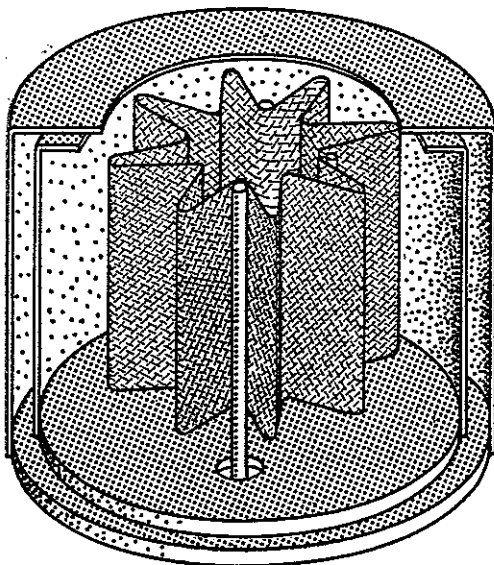
Fig. 25

A hollow cathode of large surface area, made of nickel gauze bent in the form of a star and surrounded by a double screen to reduce heat losses.

These examples, and similar ones which could be brought forward, show that it is certainly possible to design tubes so that the life of the

cathode is practically unlimited. But in practice, demands are often made on the tubes which make it necessary to deviate from the ideal design. Requests from the user concerning size, heating time, operation under certain conditions of temperature, price, etc., often force the designer to a compromise which has an adverse effect on the life of the cathode.

The designer should in any case bear the following factors in mind, in order to make the life of the cathode as long as possible:

a. the influence of the magnitude of the variation of V_f (the filament voltage) due to variations in the mains voltage. If this is large, V_f should be stabilized; in general a tolerance of $\pm$ 5 % is permissible.
b. The choice of the gas pressure,
c. the specific cathode load (see section II-c-1-c),
d. the phase relationship between $V_{f\ rms}$ and $V_{a\ rms}$.

By suitable manipulations of these degrees of freedom, the designer will be able to achieve satisfactory results.

It should be remarked finally that the life of the tube need not be limited by that of the cathode.

II-c-1-c. *Construction*

The cathode construction needed to allow the required electron current to be emitted from its surface depends on several factors, such as the emitting material, the wire core which supports the former, and the way of heating.

A certain emitting area is necessary for a given emission current. The specific emission must not be too high, in order to reduce evaporation and sputtering and thus to increase the life of the cathode. 2 to 4×10^4 A/m² is a suitable value for directly heated cathodes at a few mm gas pressure.

The loss of cathode material can be further reduced by:

a. making the coated cathode hollow (see Fig. 25 and 29), so that most of the material leaving the cathode by evaporation and sputtering is deposited on another part of the cathode, thus reducing the loss.
b. by continually supplying material with a low φ at the surface of the cathode as it is used up. (See the L cathode, page 52).

The cathode may be directly or indirectly heated. The difference between the two methods of heating is that in a directly heated cathode the heating and the emission are carried out by the same body, while the two functions are carried out by different parts in the indirectly heated cathode.

We mentioned previously that the attainable emission current per watt filament power (i.e. the specific load) is about 0.6 A/watt. It must be remembered that under various circumstances other values may hold. The gas pressure at the cathode must be taken into account, and a cathode rated at 0.6 A/watt can under certain circumstances have a long life at twice that load. Directly heated cathodes can in general have slightly higher specific loads: 1.3 A/watt may be possible. This is the value in the absence of a discharge; the effective value during the operation of the tube will be somewhat lower, because the discharge also contributes to the filament power. Similarly, the filament current I_f is quoted as the current in the absence of a discharge. It is thus possible for the emission current I_e to be greater than I_f.

Directly heated cathodes

The filament current in a directly heated cathode must be high, since the voltage V_f is restricted. The voltage between the ends of the cathode must not be large, to prevent an arc from being struck between the two ends. It is therefore necessary to make V_f less than the breakdown voltage V_d for this arc discharge (when using a.c. $V_f < \dfrac{V_d}{\sqrt{2}}$).

If V_f is made too small, I_f will become so large that the losses in the leads and in the cathode poles will increase considerably. A further restriction is imposed by the emission current I_e, which must also flow through the wire. If this is large, the wire could be destroyed by the extra temperature increase. In order to keep this within limits, I_e must therefore be less than I_f most of the time. The ratio I_e/I_f thus also determines the choice of the filament.

In short, the voltage must be low, and the heater current high.

In vacuum tubes, the emitter is usually in the form of a straight wire, but the cathode of a gas tube may have any of a number of forms, thanks to the presence of ions. The ions together with the electrons form the conducting plasma, which allows the electric field to penetrate even into cavities. The ions also serve to neutralize the space charge of the electrons. Some possible forms for the cathode are shown in Fig. 25, 26 and 27.

The simplest possibility is to coil the tungsten wire core into a spiral. Fig. 26 shows a cathode in which a nickel wire is wound around a tungsten core, which is then coiled into a spiral. Even better is the double-spiral arrangement shown in fig. 27. This method gives one big emitting surface, in effect. The coiling of the wire improves the heat balance: the adjacent

windings and the parts inside the cavity irradiate each other, and thus save radiant energy. The temperature of these W-Ni cathodes is 850—900 °C. In the arrangement shown in Fig. 25, tungsten is no longer used as the heater: the oxide film coats a strip of nickel gauze folded into a star, which is heated by the passage of current.
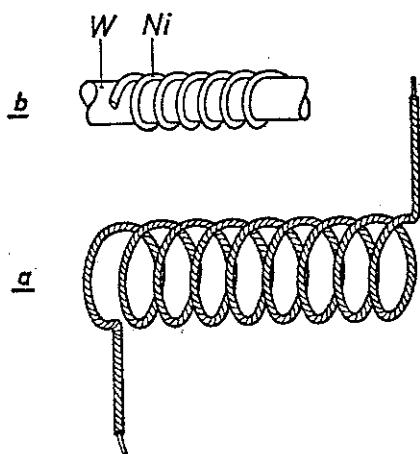

Fig. 26

a. Directly heated cathode consisting of a helical tungsten core with nickel wire wound around it.

b. Magnified view of part of the cathode shown in *a*.

For high currents, a number of spirals could in principle be connected in parallel. This would however involve the use of disproportionally large amounts of metal, since the surface of a wire is proportional to $l \cdot d$ (*l* = length, *d* = diameter) and the volume to $l \cdot d^2$. Other cathode constructions have therefore been developed.
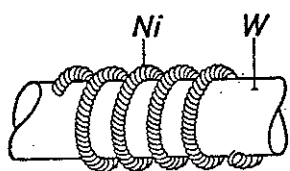

Fig. 27

Magnified view of part of a cathode with a "coiled-coil" configuration.

Such a construction is the "flower" or "star" cathode. This is formed of a number of uniform elements, the precise number used depending on the desired emission. Such an element consists of a tungsten wire core in the form of a sine wave, surrounded by a nickel winding (Fig. 28). These elements are connected in parallel to give a symmetrical many-sided flower or star shape. Such a parallel connection of the cathodes is possible if the cooling due to emission exceeds the heating: otherwise there would be a tendency for all the emission to come from one cathode, because higher emission would cause the temperature to rise, thus increasing the emission even further. The equipotential points on the axis of the system are connected with each other, giving sections with a low V_f and easy mutual heat exchange which prevents extreme heating of any one part. This construction is cheap in mass production, applicable for cathodes of all sizes, and thermally efficient.

The indirectly heated cathode is however sometimes used for higher currents, for reasons which will be mentioned below.
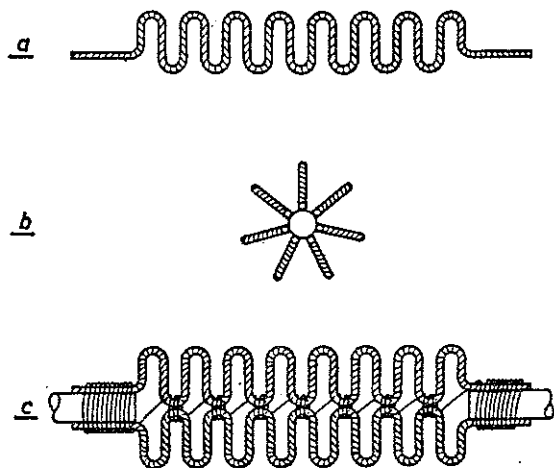

Fig. 28

*Diagram of a "flower" or "star" cathode.*
a. One element of the cathode.
b. The assembly of the various elements.
c. The connection between two elements, shown in detail. The equipotential points on the axis are joined by means of wire.

Fig. 29

An indirectly heated cathode.
The heater spiral is surrounded by oxide-coated gauze strips, and radiation losses are reduced by the double metal screen.
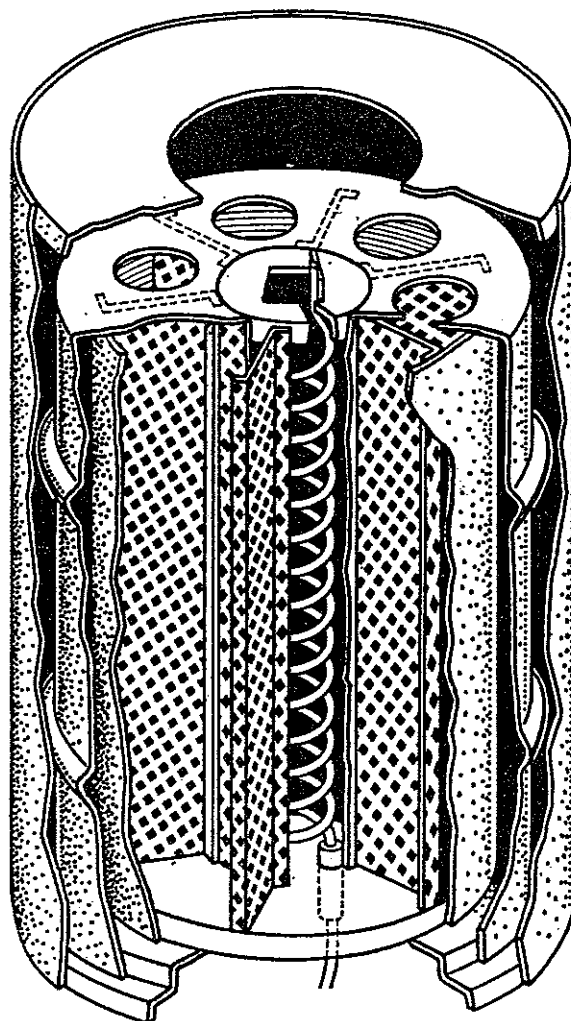
Indirectly heated cathodes

If the heating element does not at the same time perform the emission, we speak of an indirectly heated cathode, of which a typical construction is shown in Fig. 29. The heater spiral, which is heated to a temperature of about 1200 °C, is placed within a metal envelope on which the emitting material is applied. The emitting surface is increased still further by connecting the inner cylinder with an outer cylinder by means of radial partitions. This also has the advantage of keeping the emitting material in the enclosed space if sputtering occurs. The surface thus obtained may

be compared to a number of cathodes in parallel, and can only be used at low gas pressure, since at high pressures there is a tendency for the discharge to concentrate in one of the cathode spaces, which may lead to damage of this part of the cathode.

The leads of the filament must be shielded to prevent a discharge occurring between them, if V_f is too high. A double or three-fold screen is usually placed around the outer cylinder, in order to reduce radiation losses.

It may be seen from this example that indirect heating has the following advantages:

1. the useful emitting area can be large
2. the potential of the surface does not vary from place to place (equipotential cathode)
3. the choice of V_f can be wider than with direct heating, if the heating filament and its supports are properly shielded. This makes it possible to obtain I_e larger than I_f.

The disadvantages are:

1. the more complicated construction
2. the longer heating-up time, due to the large heat capacity of the whole cathode construction.

An indirectly heated cathode is usually more easily overloaded than the directly heated type, since the latter is designed to carry a current $I_f + I_e$, and the former only carries I_e. An increase in the emission current will therefore do more harm to the indirectly heated cathode.

We will mention here another example of indirectly heated cathodes, although this has so far not found much application in gas-discharge tubes. This is the L cathode [13], which is a typical example of a dispenser cathode, and which is shown in Fig. 30a and 30b.

This cathode allows emission current densities of many millions of amps per m² to be produced for short periods of time (pulse emission). It is made of porous tungsten containing Ba and BaO in the pores and on the surface. The Ba at the emitting surface can be replenished from a supply of Ba which is contained in a space behind the porous tungsten wall, the Ba atoms migrating along the surface of the pores. For the rest, the emission is like that of other indirectly heated cathodes. The temperature of the L cathode lies between that of the oxide cathode and the W-Th, and may vary between 900 and 1200 °C. The corresponding saturating emission naturally also varies considerably, from about 3×10^4 A/m² to 10^6 A/m², while the life becomes shorter as the temperature increases.

Fig. 30   *a*   *b*
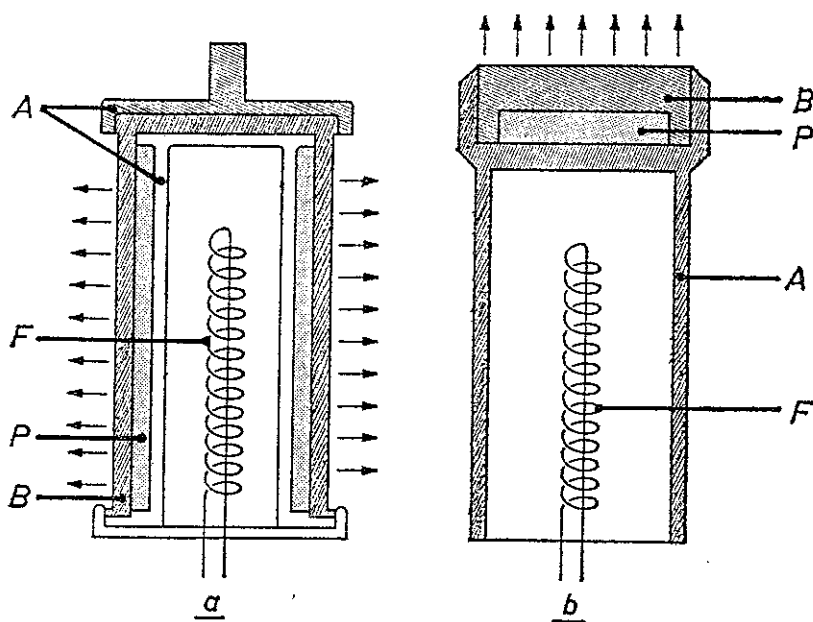
Sectional views of the two basic types of L cathode [13].
a. with cylindrical emitter,   b. with flat emitter.
A = molybdenum wall, B = porous tungsten wall,
P = (Ba, Sr)O paste, F = filament.

II-c-2 COLD CATHODES

II-c-2-a. *Emission mechanism and discharge characteristic*

A hot cathode emits electrons spontaneously as a result of its high temperature. Under certain circumstances, a cold cathode can also emit electrons. We have already seen in Chapter I (see I-g-1) that the electron emission in a glow discharge is mainly due to the bombardment of the cathode by positive ions. The current density depends mainly on the gas used and its pressure, and is of the order of tens of amperes per m² of the cathode surface at a pressure of 10 mm. The cathode fall (which is usually approximately equal to the burning voltage) is 100—200 V, so the energy dissipated at the cathode is of the order of thousands watt per m². The cathode temperature therefore in general remains so low that thermal emission is out of the question; we thus have a *cold cathode*.

In order to give a large current with a normal cathode fall, the surface area of the cathode must be large; or the pressure must be large. But in the latter case the temperature will become too high, and the glow discharge may change into an arc discharge (see Chapter I-g-3).

A cold cathode is usually made of uncoated metal, though in certain cases it may be coated e.g. by an oxide layer. A cold mercury cathode is also possible.

II-c-2-b. *Uncoated metal cathodes*

An important factor in connection with a metal cathode is the burning

voltage, V_{br}, obtainable with it. In most applications the burning voltage is practically equal to the cathode fall, and we will neglect the difference between the two here.

The burning voltage is mainly determined by the cathode material and the nature of the gas; the pressure is not of great importance. For a given gas, the lower the work function of the cathode material, the lower will be V_{br}.

The following table gives an impression of the influence of these factors.

TABLE V

THE CATHODE FALL (IN VOLTS) OF A GLOW DISCHARGE WITH VARIOUS CATHODE MATERIALS AND GASES

	helium	neon	argon	neon + 1% argon	krypton	xenon
nickel	159	**136** (at 40 mm)	181	114	—	—
iron	**150**	**129**	—	95	—	—
molybdenum	109.5 (at 42 mm)	107.1 (at 40 mm)	103.4 (at 20 mm)	83 (at 40 mm)	114.8 (at 13 mm)	133.6 (at 13 mm)
zirconium	—	105.4 (at 40 mm)	92.1 (at 10.2 mm)	—	—	—

NOTE: The most reliable values, which have been determined on clean surfaces, are printed in bold type. The other values are uncertain, because they were determined on insufficiently cleaned surfaces. The pressure at which the determination was carried out is given in brackets as far as known.

To get a constant cathode fall, the surface of an uncoated cathode should be very clean, because slight traces of impurities can have a considerable effect on the work function. Since the area occupied by the glow discharge on the cathode surface increases as the current increases, the operating voltage will only remain constant in the normal cathode-fall range if the cathode surface is homogeneous. This normally requires careful laboratory work, but methods have been worked out for achieving this in mass production, e.g. in the manufacture of voltage-stabilizing tubes.

The breakdown voltage (as well as the burning voltage) may be of importance in determining the choice of the cathode material. This voltage is determined by the cathode material, the nature and pressure of the gas, and the distance between the electrodes (Paschen's law, see I-g-4).

The characteristic form of the curves of the breakdown voltage V_d against $p_0 \times d$ is shown in Fig. 31 [67, 107]. The cathode material has a

strong influence on V_d near the minimum, but in the right-hand converging branches the influence of the gas predominates.

It is to be expected that the life of the cathode is limited by sputtering, which removes atoms gradually from the surface; but when the proper cathode material, gas and pressure are chosen, and the tube is burning in the normal glow-discharge region, then a cold cathode can have an almost unlimited life [7].
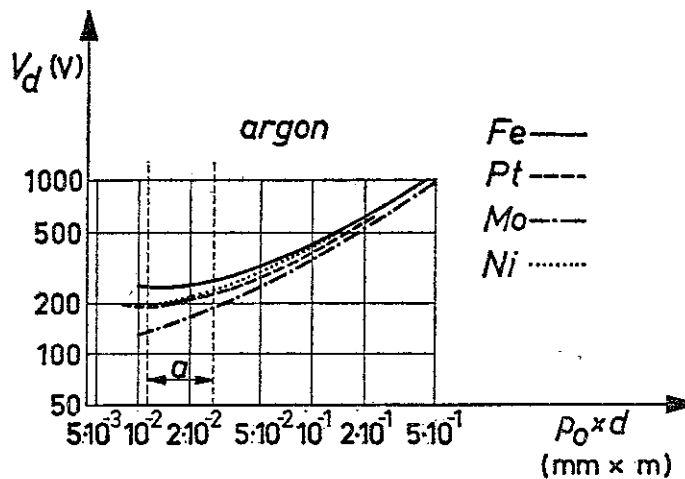

Fig. 31

Paschen curves for a discharge in argon between parallel plate electrodes of Fe, Ni, Pt [67] and Mo [107]. The influence of the cathode material is strongest in the region *a*.

One example of a well designed tube is the voltage-stabilizing tube, Philips type No. 85 A2, which will be discussed in greater detail in Chapter V. The life of this tube may be said to be practically infinite. A case is reported in England where the quality of such a tube was unchanged after operating for 120 000 hours under favourable conditions.

II-c-2-c. *Coated cathodes*

The metal cathode is sometimes coated, in order to reduce the work function. This coating almost always consists of barium oxide, which has a low φ. As with the hot cathode, a certain amount of free barium is produced during the processing of the cathode. This is then gradually used up during the discharge.

The oxide layer makes the coated cathode much more sensitive to wear than the uncoated cathode.

As the barium disappears, φ increases. Sputtering is linked with adsorption of gas and gradual alteration of the electrical properties of the tube. The extent to which this occurs depends on the type of gas used; for example, neon is not so good in this respect as argon.

As with hot cathodes (cf. II-c-1-a and b), the manufacturer is often forced to alter the design to meet the needs of the user. If for example

the tube must be small, the cathode surface area may be so small with respect to the rated current that the tube operates in the anomalous discharge region. Some glow-discharge tubes are made with a small cathode to increase the intensity of the light produced, but a black film is rapidly formed on the inside of the envelope, and the cathode is finally destroyed.

II-c-3   THE MERCURY CATHODE

A third type of cathode, which differs considerably from the two types mentioned above, is the mercury-pool cathode. If mercury is used as the cathode, then it follows, in contrast to the other types of cathode, that mercury vapour which can carry the gas discharge must be present also. Both a glow discharge and an arc discharge are possible with a mercury cathode. The glow discharge will occur with low current densities. As the current is increased to a certain value, the discharge may change to the arc type, with a much higher current density. The discharge will then be associated with only a small spot on the surface of the mercury pool, called the cathode spot.

Many tentative explanations of the *emission mechanism* at the mercury cathode during an arc discharge have been put forward, but the last word has certainly not been spoken on this subject yet.

Ecker [31] distinguishes four possibilities:
1. thermal emission (T)
2. field emission (F)
3. combined T and F emission
4. emission due to individual field components (I-F).

Thermal emission cannot be the answer. It has been found that the temperature of the cathode spot is 200—300 °C, which is much too low to account for the observed emission of 10^{10}—10^{11} A/m^2 [32].

The idea behind the field-emission hypothesis is that the field due to a layer of ions near the cathode is so large that it gives rise to the emission of electrons. This would necessitate a field strength of at least 10^9 V/m, while calculations have shown that the actual field strength cannot be expected to be more than 10^7 V/m. And while deformation of the mercury surface can increase the field strength, this increase is still not enough to account for the observed phenomena.

Calculations involving the assumptions that the mercury surface is somewhat rough and that the work function of the mercury is decreased by impurities or by the presence of the gas have shown that the combination of the thermal and field effects could lead to the production of the observed

current densities. However, these assumptions have been definitely proved wrong in a number of cases.

Ecker and Müller brought forward the fourth theory, that of I-F emission (individual-field emission). They assume that the field at the surface of the cathode is characterized by a probability distribution, because the individual charge carriers, the ions, are distributed at random over the space-charge zone. The field at any given point of the surface will fluctuate with time as a result of the random fluctuations in the space charge, and a large electron emission may be produced when the field fluctuations are sufficiently large. By the influence of this individual field component, Ecker and Müller explained the emission mechanism without further assumptions.

The influence of various factors such as oxide layers, impurities, and surface roughness is still uncertain. We may in short conclude from the above that there is still no generally acceptable explanation for the electron emission at the cathode spot.

During the arc discharge, the spot moves erratically over the mercury surface owing to asymmetrical evaporation of mercury around the spot. Magnetic fields may also effect the motion of the spot. It is however possible to fix the cathode spot in a given position, e.g. by means of a nickel or platinum "anchor" (see Chapter VI).

II-c-3-a.   *Initiation of the discharge*

The difficulty in starting an arc discharge between the anode and a mercury-pool cathode lies in the formation of the cathode spot. Once the spot has been developed, it is easy to increase the arc current and the size of the spot. A cathode spot always appears when a contact between the anode and the mercury pool is broken, but it is not easy to get the same result merely by applying a voltage between the two electrodes. The discharge in a tube with a mercury cathode must therefore be triggered; there are various standard methods of doing this, all of which are based on the production of a suitable auxiliary discharge which can trigger the arc discharge.

In the most usual case, where the anode is fed with an alternating voltage, the discharge must often be initiated periodically in time with the mains frequency. Some of the methods described below are suitable for periodic operation, but some are too slow-acting.

We may distinguish:

a. *the immersion electrode,* which is a springy conductor which comes to just above the mercury surface when it is at rest. It can be briefly

immersed in the mercury by means of an external electromagnet. As the contact is broken, a small arc discharge arises between the positive immersion electrode and the negative mercury. This method is generally not suitable for fast periodic operation.

b. *the tilting method.* This method is very similar to the previous one, and makes use of a trigger electrode which normally ends just above the surface of the mercury, but dips into it when the tube is tilted. If the tube is then placed in its proper position again an arc is produced as the contact between the trigger electrode and the mercury is broken. This method is no use either for exciting the discharge in time with the mains frequency.
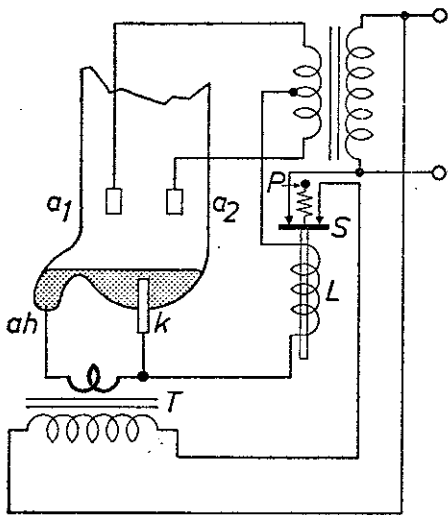
Fig. 32

Production of the cathode spot by breaking a thread of mercury. If there is no discharge between a_1 or a_2 and k, the coil L is unloaded and the switch S is closed by the spring P. The secondary of transformer T then passes a heavy current through the thread of mercury joining the auxiliary anode a_h to k. The mercury thread breaks under the action of the field produced by the current passing through it, and a spark appears across the gap. This spark initiates the main discharge, and the iron core of L is pulled down, opening S.

c. *contraction ignition* (Fig. 32). In this case, use is made of a thread of mercury which connects the mercury cathode to an auxiliary anode a_h, also of mercury. If a high current of short duration is passed through this mercury thread, it will break as a result of its own field or by evaporation, producing a spark which can ignite the main discharge. The mercury circuit will then close again, and the ignition cycle will continue as long as a potential difference exists between k and a_h. This method also works too slowly to be used for periodic ignition.

Fig. 33
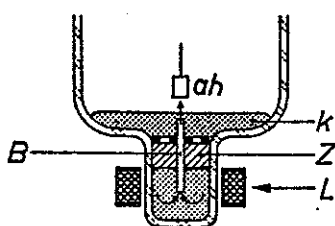
Production of the cathode spot by means of a jet of mercury. When the coil L is energized the plunger Z is pulled downwards, forcing a jet of mercury upwards through tube B. This jet strikes the auxiliary anode a_h, thus making contact between this electrode and the mercury cathode k. When the current through L is stopped, the mercury jet is broken off and an auxiliary discharge is initiated between a_h and k. This auxiliary discharge forms the cathode spot, thus allowing the ignition of the main discharge.

d. *interruption of a mercury jet*. When the magnet coil L shown in Fig. 33 is excited, the plunger Z is pulled downwards, thus forcing the mercury in the central tube B upwards and giving a jet of mercury which impinges on the auxiliary anode a_h. This jet is broken when the current through the electromagnet L is switched off, and a spark is formed between k and a_h.

All the methods mentioned so far are unsuitable for rapid periodic repetition, because they are all based on mechanical interruption of the current, leading to a spark which triggers the main discharge. The two methods described below, however, are suitable for periodic operation.
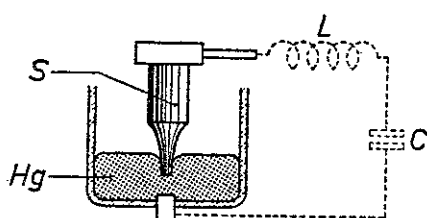
Fig. 34

Production of the cathode spot by means of a pulse discharge. A rod S of semi-conductor material, with a specially shaped point, is dipped into the mercury. The cathode spot is formed by passing a pulse discharge between S and the mercury.
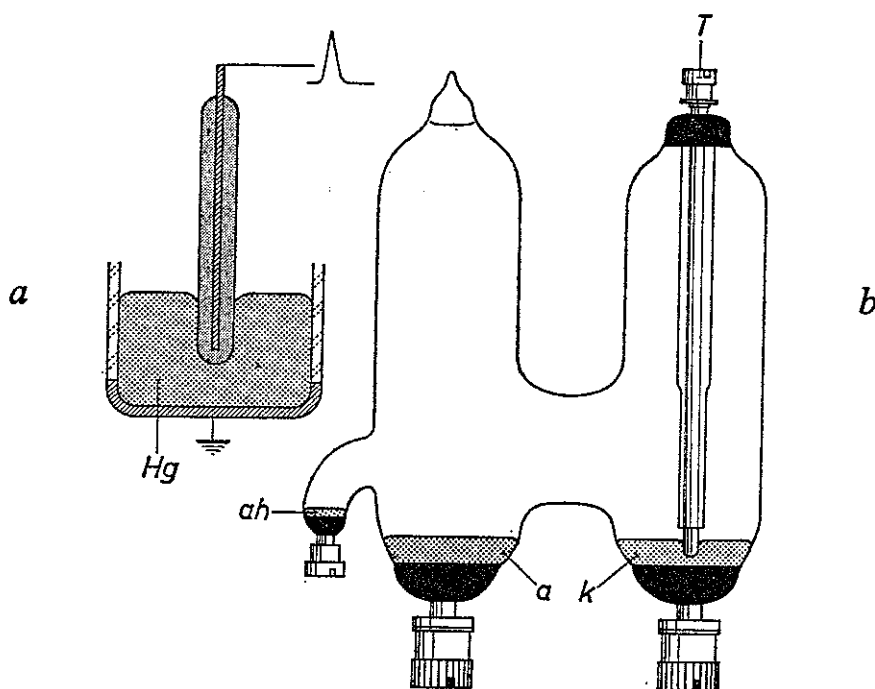

Fig. 35a

Production of the cathode spot by means of a spark discharge. A metal rod covered with a layer of glass is placed in the mercury cathode. A high-voltage pulse passed between the rod and the mercury will cause a spark at the point of contact, which initiates the cathode spot.

Fig. 35b

The H-tube or sendytron. Both the cathode and the anode are of mercury. The cathode spot is formed with the aid of a spark discharge (see Fig. 35a), and is maintained by means of an auxiliary discharge between a_h and k until the main discharge is ignited (a_h is connected to the trigger rod T for this purpose).

e. *igniting rod with pulse load*. A rod of semiconducting material makes contact with the mercury surface with its specially shaped point. The rod and the mercury are connected to a charged capacitor C in series with a self-inductance L, and the capacitor is discharged (Fig. 34). If the current produced is large enough, a cathode spot is produced, and the main discharge can now be initiated.

The cathode spot can also be produced when the trigger electrode is connected to the anode (anode triggering). As soon as the anode voltage becomes large enough the discharge will be taken over by the anode. The anode voltage will then drop and the arc between the rod and the mercury will be broken off, so the rod only passes current for a very short time (possibly periodic).

f. *Capacitive triggering* (Fig. 35a). This is the last method we will mention here. A metal rod coated with a layer of hard glass or quartz is dipped into the mercury, but makes no electrical contact with it. If the small capacitor formed by the rod and the mercury is suddenly (periodically) charged by means of a pulse circuit, then a spark is produced between the glass covering of the rod and the mercury, if the voltage is large enough. This spark can then ignite the main discharge (see sendytron fig. 35b and Chapter VI-i).

II-c-3-b. *Maintaining the discharge*

An arc, once produced, will only be able to continue as long as the current density is large enough. In practice, it seems that the arc current must not fall below about 3 A, otherwise the arc may stop after some time. The arc can also be broken off in a mercury tube fed with alternating voltage each time the anode becomes negative. The cathode spot must again be produced by the trigger electrode at the start of the next positive half-cycle so that the discharge is periodically ignited, and the alternating regime thus maintained. Apart from periodic re-excitation, the cathode spot can be made to be present at the right moments by means of an arc between an auxiliarly anode and the mercury, fed by a d.c. voltage.

II-c-3-c. *Deterioration of the mercury pool*

The mercury cathode is naturally not subject to wear in the normal sense of the word, so it might be thought that tubes with a mercury cathode would have an unlimited life. While it is true that these tubes do have a very long life, their life is sometimes limited by amalgamation of the mercury surface with sputtered materials or because the meniscus near the trigger rod gets an unsuitable shape due to impurities, which may be due to particles produced by attack of the trigger or other electrodes.

II-c-4 THE PHOTO-CATHODE

The last type of cathode we will mention here is the photo-cathode, a light-sensitive cathode used in gas-filled photo-cells. Since the photo-electric effect has already been discussed in Chapter I, we will only give some practical details here.

The typical characteristic of a cathode which emits owing to irradiation by light quanta is its low work function. The current density of a photo-cathode is much smaller than that of the other cathodes mentioned above. For most photo-electric cells it is limited to a few μA.

In complete darkness, a very slight emission current can still be measured. This is due to thermal emission, and at room temperature is about 10^{-6} A/m^2. The sensitivity of a photo-cathode in vacuo hardly decreases at all with time, but in a gas-filled photo-tube the bombardment by ions does cause the sensitivity to fall off gradually. A specific load of 0.5 mA/m^2 cathode surface is permissible for both types, but with this load the sensitivity of a gas-filled cell may fall to about 60 % after 1000 hours' operation. By judicious treatment, in particular by ensuring that the maximum anode voltage is never exceeded, i.e. that the breakdown voltage of the gas is never reached, the life of the gas-filled photo-cell can be extended to several thousand hours.

Some other properties of the photo-cathode will be discussed in Chapter VII.

II-d The anode

The influence of the anode on the discharge is much less than that of the cathode. Care must however be taken that the anode temperature does not become too high or it will emit electrons, and the anode material may even evaporate.

As long as the anode is only fed with a d.c. voltage (e.g. in voltage stabilizing tubes), the emission is of no importance. If, however, the anode is sometimes negative with respect to the cathode, as in e.g. rectifier tubes, then the emissivity of the anode does matter. In order to ensure that the tube passes no current in the reverse direction, the emission from the anode must be kept to a minimum: this means that the work function must be large and the temperature not too high. The temperature of the anode depends on the balance between the heat dissipated in it and the removal of the heat, and thus also on its dimensions.

II-d-1 HEAT DISSIPATION IN THE ANODE

We will consider the factors which lead to the dissipation of heat in the anode. These are:

1. the electron velocity, sometimes increased by the
    anode fall
2. the electron affinity of the anode
3. the ohmic losses in the anode

$\left.\begin{array}{l}\\ \\ \\ \\\end{array}\right\}$ anode positive

4. the glow current when the anode is negative.

The current-carrying electrons strike the anode with a certain velocity. When the electron temperature in the plasma is of the order of 10,000 °K, the electrons reach the anode with an energy of about 1 eV. If there is any anode fall, however, in other words if the anode is somewhere outside the dark space, then the voltage increases considerably, e.g. to 10—20 V, so that the electrons have considerably more energy when they reach the anode. This energy is dissipated in the anode as heat.

We have already (Chapter I-c-1) seen that some work must be done to free the electrons from the cathode, this work being measured by the work function of the cathode material. Conversely, when electrons enter the anode they do work at a rate equal to $I \varphi$, where I is the electron current and φ is the work function of the anode material (also called the electron affinity) which is between 4 and 5 V in most cases. This work is also mainly in the form of heat.

Thirdly, the passage of current through the anode gives heat losses equal to RI^2 where I is the current and R is the resistance of the anode, during the positive phase. These ohmic losses are however only a small part of the total heat dissipated.

The fourth cause of heat production is only found in the negative phase. The conditions under which a glow discharge will be formed have already been discussed in I-g-2. If the tube voltage is sufficiently high, the ion bombardment on the anode — which is now the cathode as far as the glow discharge is considered — is considerable because of the large "cathode" fall, but the current is much smaller than when the anode is positive.

In tubes with more than one anode, e.g. two-phase rectifiers (Chapter III-b-2), the one anode is negative with respect to the other in a part of each cycle, and it then behaves like a probe. This means that ions are extracted from the plasma, also giving rise to heat dissipation in the anode. The heat generated by this probe current and by the glow current can in some cases be as large as that due to the first and second factors.

II-d-2 COOLING

If the factors mentioned above determine the amount of heat dissipated in the anode, the final temperature of the anode will also be influenced

by the rate at which it gives up heat to its surroundings. This depends on the conduction via the anode lead, the convection via the gas filling, and to a lesser extent on the radiation. With graphite anodes the radiation does count, especially at temperatures above about 800 °C. The blackening of nickel anodes will also improve the radiation to a certain extent. But in general the temperature is mainly determined by conduction and convection. The final temperature is reached when the heating and the cooling are in equilibrium. Forced cooling is not generally used, though the cooling surface of the anode lead is sometimes increased by means of fins (see Fig. 173). The size of the anode itself is also increased in tubes which take large currents, in order to keep the temperature within proper limits.

II-d-3 ANODE MATERIAL

The anode material is only a problem when the polarity of the tube is subject to change, as in a rectifier. The most important requirements are then a high work function, purity, slight sputtering, ease of treatment (working, degassing), and good heat conduction.

Nickel, iron and graphite are the usual materials. The choice between them is sometimes difficult, and depends largely on the specific demands made on the tube in question.

The work function of nickel lies between 3.7 and 4.9 eV, and that of graphite between 4.3 and 4.8 eV. At low current densities, nickel is quite satisfactory; it is easy to work, and can be well degassed. If the current is high, graphite is often better. It has a low density (1.9—2.3), and is not affected by high temperature, it is backfire-proof, i.e. it does not melt if there is a short-circuit or a backfire, and it is a good radiator of heat because it is black. One disadvantage is that it has to be degassed for a long time.

In certain cases, it is necessary to use other materials for the anode. We will only mention the sendytron (Fig. 35 b) in this connection: it has a mercury anode. This tube is meant for large current pulses of short duration, and the reason for choosing a mercury anode is to minimize the contamination of the cathode surface by particles from the anode.

We will have occasion to discuss other anode materials in the detailed descriptions of various tubes.

II-e Other electrodes

So far, we have been talking about tubes with only two electrodes, the cathode and the anode. Many tubes have more than two electrodes, however.

The extra electrodes can be divided into the following groups:

a. auxiliary anodes;
b. switching electrodes;
c. screens.

II-e-1 AUXILIARY ANODES

Where it is necessary to keep a plasma in existence or to facilitate re-ignition, an auxiliary discharge is generally maintained. This is struck between an auxiliary anode and the cathode. These auxiliary discharges make ignition easier. The dependence of the ignition voltage on the current of the auxiliary discharge is illustrated in Fig. 36 for a hot-cathode diode and in Fig. 150 for a cold-cathode tube.

An auxiliary discharge is also used to prevent delay in the ignition of the main discharge.
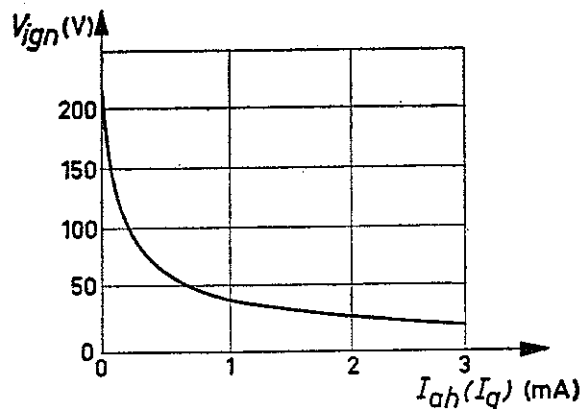
Fig. 36

Dependence of the ignition voltage V_{ign} of a hot-cathode diode on the current I_{ah} of the auxiliary discharge (grid current I_g).

II-e-2 SWITCHING ELECTRODES

While it is quite common to control the current in vacuum tubes by altering the heater voltage of the cathode, this method is not effective in gas-filled tubes, and leads to sputtering (cf. II-c-1-a). A separate electrode is needed to control the average current in a gas-filled tube, as is indeed often used in a vacuum tube. The effect of the control electrode is however completely different in vacuum tubes and gas tubes. In a vacuum tube this electrode is called the control grid as the anode current is controlled by variation of the grid voltage. This name would give the wrong idea if applied to the corresponding electrode in a gas tube. We will talk here of a *switching grid* (cf. IV-a), which indicates its mode of operation rather better. This grid is used to prevent the ignition of the discharge up to the desired moment, so that the tube acts as a switch in the circuit. The value of the discharge current is not however influenced by the grid, which is also not capable of quenching the discharge. The working of the grid can be described as follows: if it has a negative potential with respect to the cathode, it can prevent the ignition of discharge; a suitable positive voltage

applied to the grid will ignite the discharge at the desired moment. By choosing the moment at which this happens, the duration of the discharge in each half period can be controlled. The grid control will be described in greater detail in the chapter on thyratrons. Other control methods (trigger electrode, external electrode, etc.) will be discussed under the accounts of the tubes in which they occur.

II-e-2-a. *Temperature of the grid*

Grid emission is most undesirable in controlled tubes, since it may give rise to an unwanted discharge where the grid acts as a cathode; the tube will then no longer be under control. Grid emission may be caused by the deposition of oxide particles from the cathode, if the grid temperature becomes too high. The user should therefore take care that the grid load does not exceed that laid down in the tube specifications, in order to keep the temperature within proper limits. Similarly, the cathode must be prevented from evaporating too much, which might lead to the deposition of a mixture of barium and barium oxide on the grid.

The heat dissipation in the anode is largely caused by the current through the tube (kinetic energy of electrons), but the current going to the grid is very small because of the high resistance usually placed in series with it. The source of heat here is rather the plasma of the main discharge, together with radiation from the anode and cathode. Electrons and ions which land on the grid owing to diffusion can transfer energy to the grid by means of collisions and recombination. The collision yields heat owing to loss of kinetic energy. The recombinations of ions and electrons leads to the formation of slow atoms, and the ionization energy released can be given up to the grid. Heat can also be conducted through the hot gas of the discharge; but this contribution is normally only of secondary importance.
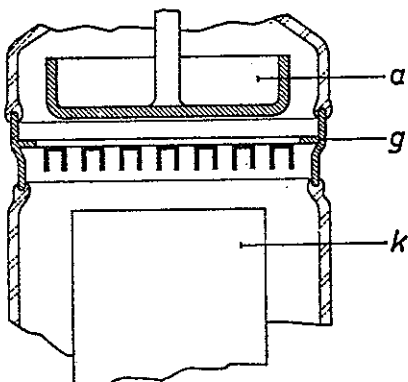

Fig. 37
A sectional view of part of a thyratron. The switching grid *g* consists of rods of prepared nickel or iron, of *U*-shaped cross-section, welded on to a ring of chrome iron. The ring is sealed directly into the glass envelope. This construction gives a large area of contact between *g* and the surrounding air, thus allowing effective cooling.

The grid must also get rid of its heat. It can be made larger than otherwise necessary, in order to aid the cooling, or it may be artificially cooled.

It is an advantage if the tube can be so constructed that a cold stream of gas inside or outside the tube can contribute to the cooling. The external grid is an example of this (see Fig. 37, 91 and Photo 4).
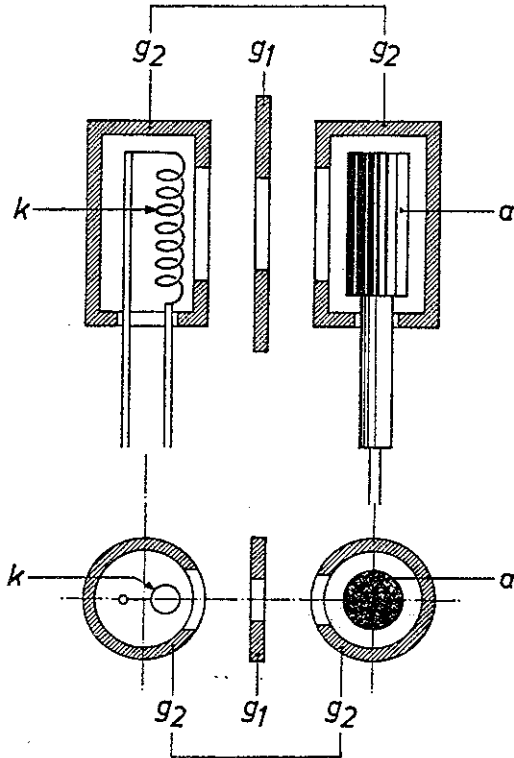
Fig. 38

The arrangement of the grids in a low-power tetrode. The cathode k and the anode a are surrounded by slotted cylindrical screen grids g_2. A switching grid g_1 consisting of a metal plate with a rectangular hole in it is placed between k and a.

Although the temperature range in question is not high enough for thermal radiation to be very important, it may be helpful to blacken the grid, or to coat it with suitable fine granular material: this both increases the heat radiated away from the grid and helps to prevent a lowering of the work function due to deposition of cathode material.
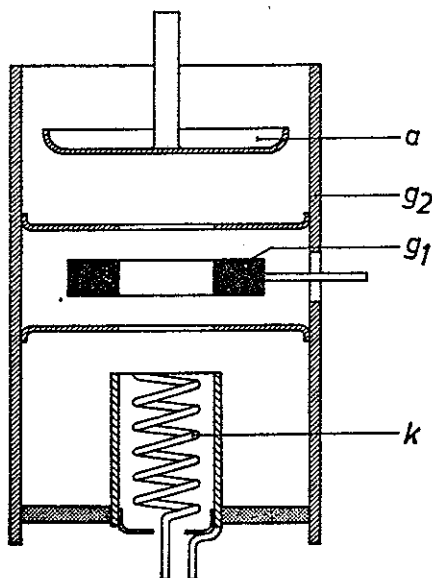

Fig. 39

The arrangement of the grids in high-power tetrode cf. Fig. 99 and Photo 7. The switching grid g_1 is a graphite ring.

Grids may be made of graphite as well as metal. The reasons governing the choice are similar to those already mentioned for anodes (II-d-3). The

grid must have a large heat capacity and sturdy construction when large powers are involved. The forms usually used are cylinders, rings and the like or discs with relatively wide openings in the form of slits or holes. Figures 37 to 40 give some examples of possible constructions.
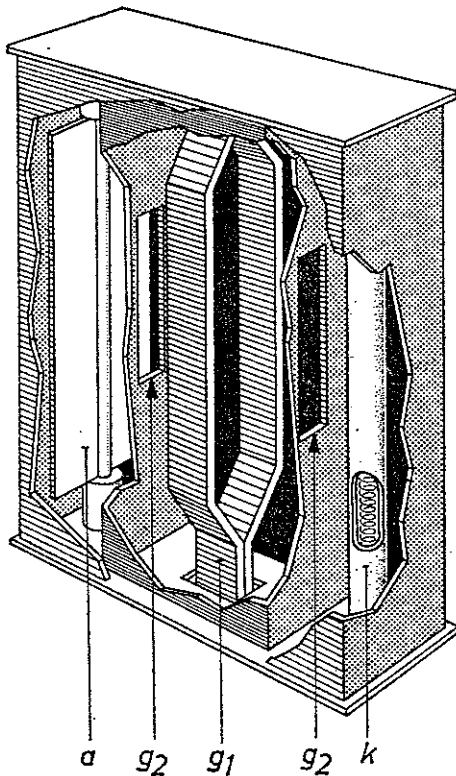
Fig. 40

Cut-away view of the electrodes in the tetrode thyratron PL 2D21. Comparison with Fig. 38 makes further explanation unnecessary.

II-e-3   SCREENS

The four electrodes mentioned so far (cathode, anode, auxiliary anode and switching grid) can carry out the most important functions of any gas tube. Of subsidiary importance are further conductors or insulators which are normally placed in the discharge space and are called screens.

They are needed to:

1. prevent solid particles from being deposited on certain places;
2. keep the discharge away from places where it is not wanted;
3. shield certain parts from radiation of heat;
4. reduce electrode capacitances.

Fig. 41
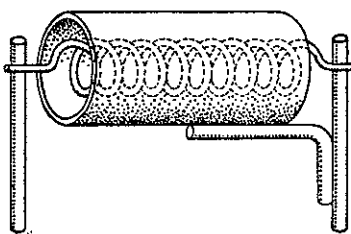
A helical hot cathode surrounded by a cylindrical nickel screen. Oxide particles sputtered from the cathode are caught by the screen, to that they cannot reach the anode where they might give rise to backfire. The oxide layer deposited on the screen can also emit electrons, since the screen is heated by radiation from the cathode; after the tube has been in use for some time, this emission current will make up an appreciable part of the whole.

The most important screens may be described as cathode screens and anode screens.

A simple example of point 1 is shown in Fig. 41. The screen here consists of a metal cylinder placed concentrically with the cathode spiral. This reduces the deposition of cathode material on the anode, since most of the sputtered or evaporated particles of the cathode will land on the screen. It also helps to improve the heat economy by reducing the power lost as radiation, but this function is of secondary importance.

Figures 42 to 44 illustrate point 2: little glass tubes round the glass-metal seal where leads enter the tube prevent a discharge on the leads near the
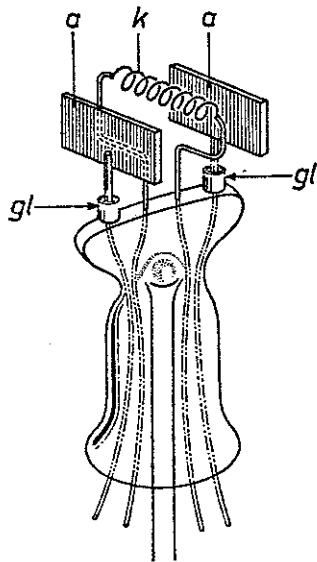

Fig. 42

Electrode assembly of a two-phase rectifier tube. The anode leads are fitted with small glass collars (*gl*), which help to keep the metal-glass seals intact by preventing discharges and the deposition of sputtered material near them and also improve the insulation of the leads by increasing the length along the surface of the insulation.

seal, which might cause cracks, and also prevent the deposition of sputtered material near the leads which might cause electric leaks. Moreover the screen *S* in Fig. 43 prevents the ignition of a discharge between the two anodes.

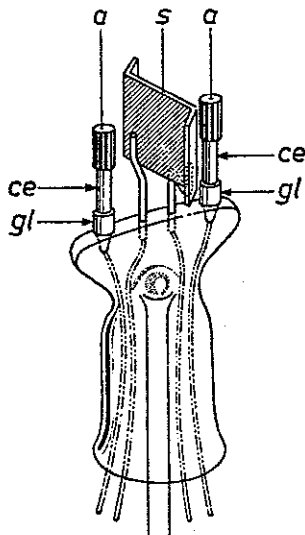An example of the third function is the metal screen *S* placed between

Fig. 43

Anode assembly of a two-phase rectifier tube with a hot cathode. The two graphite anodes *a* are separated by a screen *S*, which prevents any discharge between them. Discharge between the anode leads is prevented by the closely fitting ceramic tubes *ce* and the glass collars *gl*.

the incandescent cathode and the condensation space in a high-tension mercury-vapour rectifier tube (Fig. 45). This keeps the mercury condensate at the bottom of the tube cool.

——a
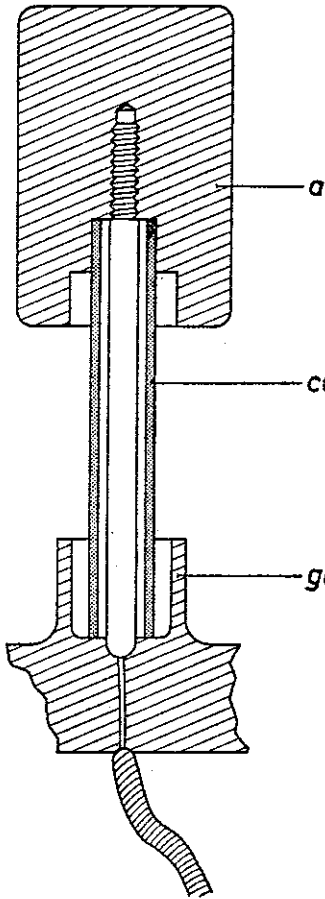
——ce *Fig. 44*

Detail of the assembly of Fig. 43, showing the "labyrinth" holes at both ends of the anode lead, which prevent the deposition of sputtered material near the seals.

——gl

Finally, an example of the fourth type is the screen grid. This electrode is important as an electrostatic screen between the switching grid and the anode, reducing the capacitance between these electrodes (cf. IV-c), and also having some effect according to points 1 and 3.

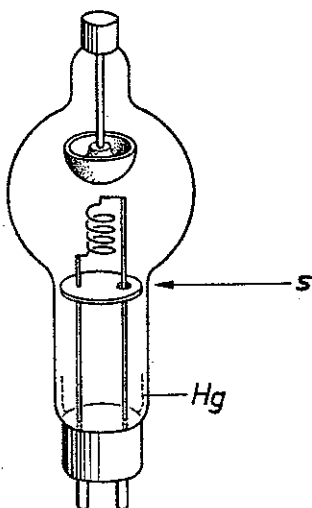More examples will be met later on in the book.

Fig. 45

High-voltage mercury-filled rectifier tube. The lower part of the envelope must be kept cool so that the mercury can condense there; it is therefore shielded against radiation of heat from the hot parts of the tube by the metal screen S.

——s

——Hg

II-f The envelope

The envelop of a gas-discharge tube may be made of glass or metal, depending on the amount of heat to be dissipated.

Glass can still be used up to currents of about 500 A and arc voltages of 20 V (10 kW dissipation). The tube losses can in such cases still be transmitted through the glass walls to the outside air, if necessary with the aid of forced air cooling. If the energy dissipation is higher than about 10 kW the glass envelope needed would be impractically large, so a metal envelope is necessary. The maximum permissible temperature can then be higher, and better cooling is possible, if necessary with the aid of air or water. The better cooling possibilities also enable the designer to make metal tubes smaller than the corresponding glass ones would be. Since glass envelopes are cheaper, however, most gas-discharge tubes are made with glass.

It is also sometimes possible to use envelopes made partly of metal, and partly of glass. At very high powers, however, the envelope must be made entirely of metal, except that glass (or ceramics) is needed to insulate the various electrodes. In any case, the envelope must allow the electrodes, etc., to be firmly fixed in place in the proper positions relative to each other, and the whole gas space to be properly sealed off without leaks.

In high-voltage tubes, the electrodes must be placed far enough apart to prevent breakdown at undesirable places, or "creep" discharges along the walls. Although it has proved possible to use ceramic envelopes, which can stand high temperatures, no gas-discharge tubes with ceramic envelopes are yet on the market.

II-f-1 MATERIALS

The above-mentioned demands made on the envelope mean that all the component parts, conducting as well as insulating, must come up to very special requirements.

When glass is used as the insulating material, a suitable metal must be used in combination with it. Many types of glass-metal seals are used, among which we may name hard glass with tungsten, copper or Fernico (an alloy of iron, nickel and cobalt); and soft glass with copper, molybdenum-nickel or chrome-iron. The choice is determined by the demands to be made on the tube, by the ease of working, the maximum permissible temperature, etc.

It is also possible to make ceramic-metal and ceramic-glass seals, which are free from vacuum leaks and heat resistant. These techniques are however not yet used much in making gas-discharge tubes.

Finally, mica is used in various tubes for insulation and other functions and even as the window in radiation-counter tubes (see Chapter V-d-10). It has been found that mica can give vacuum-tight joints with chrome steel.

II-f-2 TYPICAL CONSTRUCTIONS

We will briefly illustrate what has been said above about the envelopes by some examples. Fig. 42 shows a "pinch" seal for a two-phase rectifier tube. The leads, with a bit of glass tubing round each one, are heated in the gas flame and the semi-molten glass and the leads are pressed together to a solid whole with a pair of tongs. The flanged glass edge is later sealed into a cylindrical glass bulb.

Photo 1 shows how the leads, arranged in a ring, are placed in a special jig and surrounded by powdered glass, which is then pressed around the leads with the application of heat to give a vacuum-tight seal (pressed-glass seal).

When large currents are involved, the construction shown in Photo 2 for a tube with two anodes can be used. The anode leads are soldered on to little cups of chrome steel, which are then sealed into a specially shaped piece of pressed glass. This construction is short-circuit-proof and has a good mechanical strength. A similar construction is used for cathode poles.

Other constructions will be met with in the descriptions of the various types of tubes in the following chapters.