CHAPTER III

HOT-CATHODE RECTIFIER TUBES

III-a **Introduction**

Electrical power stations are nearly always equipped with rotary AC generators. These have the advantages over DC generators that the voltage thus produced can be raised by means of transformers, which means smaller losses when the power has to be transmitted over long distances.

DC voltage sources are, however, used for many purposes (traction, regulation of the speed of motors, charging batteries, welding, arc lighting, etc.). Where not much power is involved, an accumulator or battery may be used. If, however, larger powers are needed, then rotary machines such as DC generators or AC-DC convertors must be used. Another possible way of making DC power is based on gas discharges: the available AC voltage is rectified with the aid of gas-discharge tubes. Such tubes are known as *rectifier tubes.*

Tube rectifiers have various advantages over rotary machines, of which we may name:

compactness,
light weight,
no moving parts, little wear,
simple to operate and maintain,
noiseless,
high efficiency.

On the other hand, they are often more fragile, and the ripple in their output current is sometimes a disadvantage.

The ability to rectify is also found with vacuum tubes: the electrons coming from the thermally emitting cathode can only move through the tube in one direction, from the cathode to the anode, as long as the anode is sufficiently positive with respect to the cathode. If the field is applied in the opposite direction, the current is zero because the anode does not emit electrons.

In the gas-filled tube, we also have positive ions, which move along the track of the discharge in the opposite direction to the electrons. Although both types of charge carriers of course contribute to the total current, the contribution of the ions, with their much larger mass, is slight.

The main advantage of the presence of the ions is that they annul the space charge (see I-c-1 and I-g-3-B) so that high currents can be produced at low voltages. If the polarity of the tube voltage changes regularly, both vacuum tubes and gas-discharge tubes pass current only from anode to cathode (the direction of the current is by definition opposed to the direction of motion of the electrons). A gas tube, like a vacuum tube, thus works as a *valve* for current.

Such tubes can be used for all the above-mentioned applications where direct current is employed. Rectifier tubes for low voltages differ considerably from those for high voltages, so the two types will be treated separately in this chapter.

III-b **Low-voltage tubes**

We shall now discuss several types of low-voltage tubes i.e. for anode voltages of up to a few hundred volts, indicating the points which the users of such tubes should be aware of. We shall also mention certain constructional details.

First of all we must mention that there is in practice a lower limit for the voltage, $V_{a\ rms}$, for which there is any point in making a rectifier tube. This is because on the one hand the arc voltage is at least about 7 volts (low-voltage arc), and on the other hand the ignition of the discharge also requires a certain voltage. This lower limit lies in the region of 10 volts, the precise value depending on factors which have been mentioned above (see Chapter I).

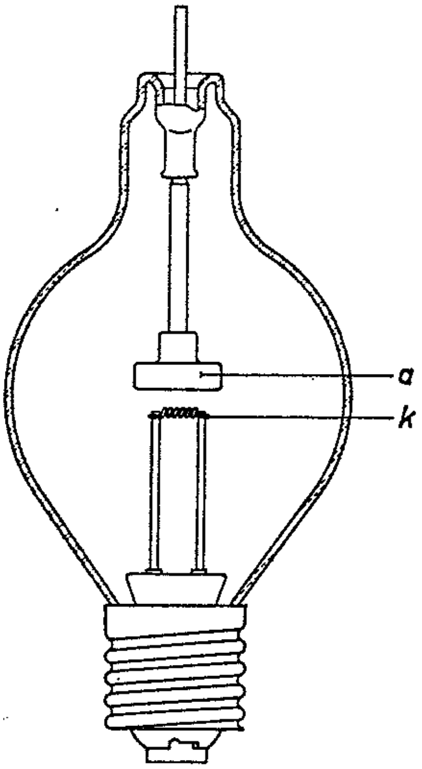

Fig. 46

Tungar tube for single-phase rectification, with incandescent tungsten-thorium spiral cathode *k*, graphite anode *a* and argon filling.

III-b-1 TUBES WITH A SINGLE ANODE

One of the simplest rectifier tubes is the *single-phase* type, i.e. a tube with a hot cathode and one anode, for the rectification of single-phase alternating current; this tube is also known as a single-wave rectifier.

A well-known example is the tungar tube, with its incandescent tungsten-thorium spiral cathode, a graphite anode and an argon filling. Fig. 46 shows a section through the American tube type 189 049 (Philips type 1163), a typical tungar tube. This tube is a battery charger, and can charge a battery of accumulators, (up to 36 lead cells) with a mean current of 6 A.

The W-Th cathode is cheap and robust, but neads a high heater power: the heater voltage is 2.2 V and the current 17 A. Since the cathode has no oxide layer, the heater and anode voltages can be switched on simultaneously. There is no risk of the detaching of cathode particles as long as the final temperature has not been reached (cf. sputtering, II-c-1-a). The cathode is placed a short distance from the disc-shaped anode in an atmosphere of argon (pressure a few cm).

The short distance between the cathode and the anode, which is characteristic of rectifier tubes of this type, is connected with the high cathode temperature needed for emission; in order to prevent too much evaporation of the cathode, the gas pressure must be high; and to prevent anode fall (see I-g-3-B), which would mean a loss of voltage, the product $p \times d$ (gas pressure × electrode distance) must be small. It follows that if p is large, as is the case here, d must be very small.

The most important data of this tube are:

mean anode current	I_{av}	6 A max.
peak anode current	i_{ap}	36 A
peak inverse anode voltage	$v_{ap\ inv}$	375 V
ignition voltage	V_{ign}	16 V max.
arc voltage	V_{arc}	9 V
heater voltage	V_f	2.2 V
heater current (mean)	I_f	17 A

We shall now explain the operation of this tube with reference to a few figures.

Operation of a single-phase rectifier tube

Fig. 47 shows a typical circuit. The alternating anode voltage $V_{a\ rms}$ is given the desired value by means of the transformer T_1: the peak value of this voltage, v_{ap}, must be at least equal to the ignition voltage plus the battery voltage, $V_{ign} + V_b$. In practice, $V_{a\ rms}$ will be chosen higher than this, so that current is passed during a considerable part of the positive half-period.

On the other hand, there is also an upper limit for $V_{a\ rms}$, which lies at about 200 V in connection with the maximum permissible peak inverse voltage of 375 V. With a battery inverse voltage of 97 V (36 lead cells), we have

$$V_{a\ rms}\sqrt{2} + 97 = v_{ap\ inv} = 375\ \text{V},$$

which gives the above-mentioned value of $V_{a\ rms} \approx 200$ V.

The heater voltage V_f is taken from a second transformer T_2. (Because

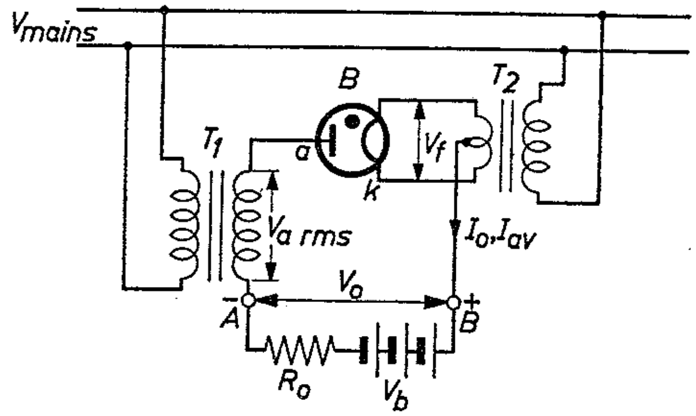

Fig. 47

Circuit for single-phase rectification and battery-charging.
T_1 = anode-voltage transformer,
T_2 = heater-voltage transformer,
B = rectifier tube, V_b = inverse voltage of battery,
R_o = current-limiting resistor.

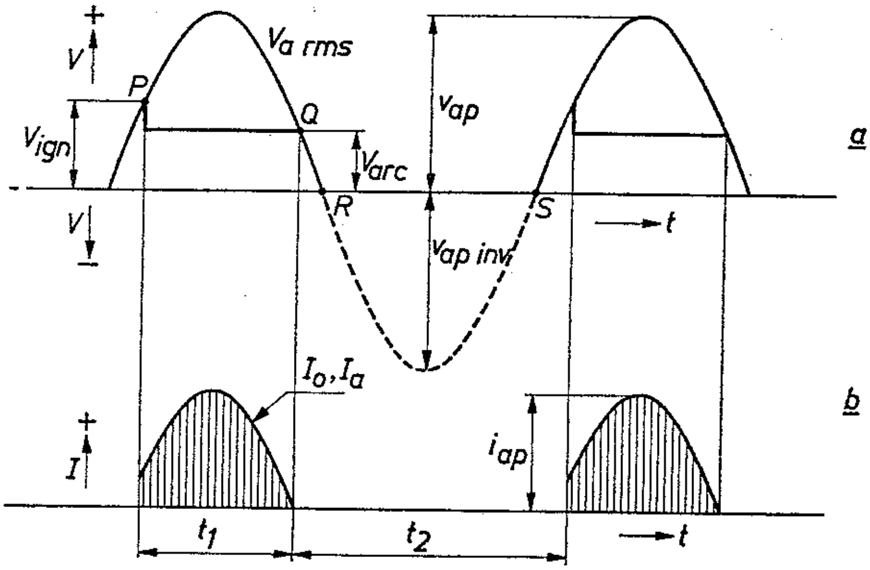

Fig. 48a

Variation of the tube voltage during single-phase rectification for a purely ohmic load.
P = ignition point of the discharge,
Q = quenching point of the discharge.
The maximum value of $_{ap\ inv}$ is $V_{a\ rms}\sqrt{2}$.

Fig. 48b

Variation of the current through tube and current-limiting resistor.
t_1 = part of period during which current is passed, t_2 = rest of period.

V_a and V_f may be switched on simultaneously with this tube, T_1 and T_2 may be combined into one).

The load is taken up between the points A and B. If we assume to start with that the load impedance is purely ohmic, with a value R_o, and $V_b = 0$, then the variation of the tube voltage and current with time will be as shown in Fig. 48a en 48b.

When the sinusoidally varying voltage $V_{a\ rms}$ reaches the ignition voltage V_{ign} at the point P in Fig. 48a, current begins to flow. The tube voltage drops immediately to the arc voltage V_{arc}. We shall assume for the sake of simplicity that the variation of the arc voltage for a tungar tube is the same as for a low-pressure tube with an oxide cathode [40]. V_{arc} remains practically constant until at the point Q the anode voltage falls below the arc voltage and the discharge is quenched. During the negative half-period, from R to S, the tube passes no current and the tube voltage is equal to $V_{a\ rms}$. The corresponding variation of the current through R_o is shown in Fig. 48b.

The initial value of the current is

$$i = \frac{V_{ign} - V_{arc}}{R_o} \tag{1}$$

(ignoring the resistance of the transformer).

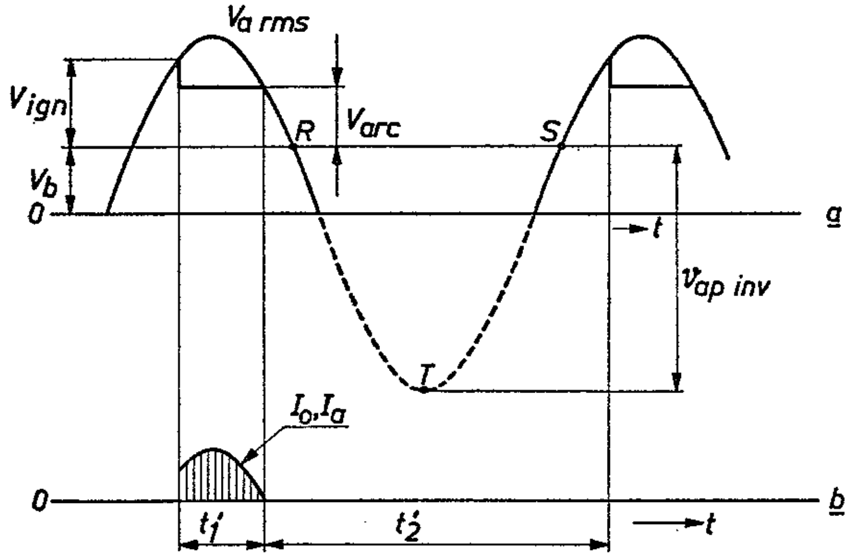

Fig. 49a

Variation of the tube voltage during single-phase rectification with a battery inverse voltage V_b. The maximum value of the inverse tube voltage is reached at T, and is equal to $V_{a\ rms}\sqrt{2} + V_b$.

Fig. 49b

Variation of the current through the tube and the battery. As a result of the inverse voltage of the battery, the part of a period, t'_1, during which current is passed is shorter than when there is no battery load (t_1, Fig. 48b), for a constant value of $V_{a\ rms}$.

Let us now assume that a battery with inverse voltage V_b is connected in series with R_o (which must be retained as a current-limiting resistor; under certain conditions it may be replaced by a choke coil, cf. III-b-2 and Fig. 59). The value of R_o must be chosen large enough to ensure that the maximum permissible peak anode current, i_{ap}, is never exceeded. The value of the tube current at an instant t is given by

$$i_{a1} = \frac{V_{arms}\sqrt{2}\cdot \sin\omega t - V_{arc} - V_b}{R_t}, \tag{2}$$

where R_t is the sum of R_o and the resistance of the rest of the circuit.

If we insert the above-mentioned maximum value of $V_{a\ rms}$, the minimum value of R_t follows from the value of i_{ap}, and the minimum value of R_o can then be calculated from R_t. The variation of the voltage and current in this case is shown in Figs 49a and 49b.

Inverse current

The anode is covered with a glow during a large part of the time that it is negative with respect to the cathode, i.e. a glow-discharge current (inverse current) flows from cathode to anode. Since however this current only amounts to a few milliamps compared to the normal current which is measured in amps, it can be neglected.

It follows from what we have said above that:

1. the arc voltage or burning voltage is practically constant, i.e. practically independent of the tube current.
2. The inverse tube voltage increases with the inverse battery voltage, and so therefore does the inverse current due to the glow discharge.
3. The charging current through the battery is a pulsed direct current, the time during which current is passed decreases as V_b increases.
4. The discharge losses in the tube are equal to the product of the mean anode current and the arc voltage ($W_{arc} = I_{av} \times V_{arc}$). *)

Tube efficiency

The efficiency of the *tube* (i.e. not of the battery charger as a whole) can be written

$$\eta = \frac{W_o}{W_o + W_f + W_{arc}} \tag{3}$$

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*) We have assumed in drawing Fig. 48 a that V_{arc} is constant, which is not strictly true. The average value of V_{arc} is difficult to calculate, but can be derived from the measured value of W_{arc} with the aid of this equation.

where $W_o = V_o \times I_o$ is the DC output power and $W_f = V_f \times I_f$ are the heater losses. In the present case, η can be calculated to be about 85 % at full load. The efficiency increases with W_o, and thus with $V_{a\ rms}$, since W_f and W_{arc} remain more or less constant. An increase in the tube current produces relatively little increase in the values of W_f and W_{arc}. Fig. 50 shows how η of the tube increases with increasing $V_{a\ rms}$. The efficiency of the rectifier as a whole is smaller than that of the tube owing to losses in transformer, R_o and other parts of the circuit.

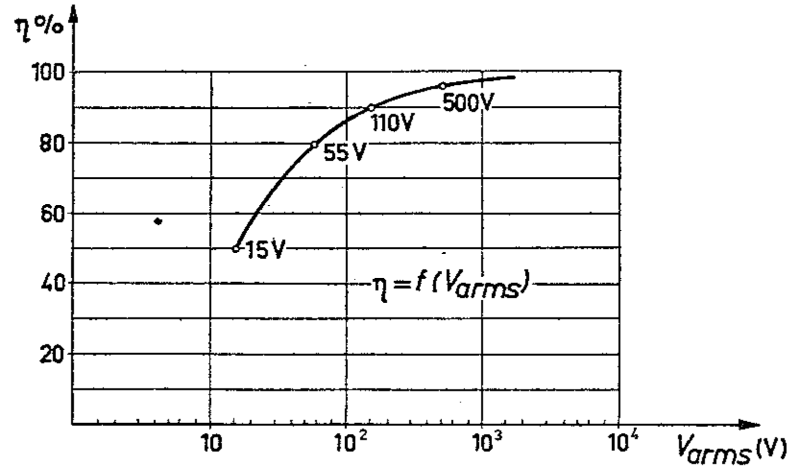

Fig. 50

Tube efficiency η as a function of the AC anode voltage $V_{a\ rms}$.

Inverse voltage

The peak inverse voltage, $v_{ap\ inv}$, of the tungar tube must not exceed 375 V.

The actual value of $v_{ap\ inv}$ depends on the circuit of which the tube forms a part. In the circuit of Fig. 47, $v_{ap\ inv}$ would be $- V_{a\ rms} \times \sqrt{2}$, i.e. the negative peak value of $V_{a\ rms}$, as long as the load is purely ohmic (cf. Fig. 48a).

If however the load contains a back-emf, e.g. from a battery of inverse voltage V_b, the anode voltage starts to become negative at the point R (Fig. 49a), and reaches its maximum negative value at the point T, when

$$v_{ap\ inv} = -(V_{a\ rms}\sqrt{2} + V_b) \qquad (4)$$

Capacitive loading also increases $v_{ap\ inv}$ above $V_{a\ rms}\sqrt{2}$.

The nature of the load must therefore be taken into account when determining the value of the AC anode voltage from the published maximum value of $v_{ap\ inv}$.

Peak current and average current

The tube current, like the inverse anode voltage, must not exceed a certain maximum peak value i_{ap}. For resistive loading, this is given by

$$i_{ap} = \frac{V_{a\,rms}\sqrt{2} - V_{arc}}{R_o} \tag{5}$$

while for charging a battery of inverse voltage V_b we have

$$i_{ap} = \frac{V_{a\,rms}\sqrt{2} - V_{arc} - V_b}{R_o} \tag{6}$$

These equations do not allow for the resistance of transformer and battery, and assume that the value of V_{arc} is independent of the instantaneous value of I_a (see under "Tube efficiency").

The value of the peak tube current is of importance with respect to the life of the cathode: if the maximum permissible value is exceeded, the cathode fall increases and the ion bombardment becomes heavier.

The maximum average tube current I_{av} is also laid down. According to Fig. 48b,

$$I_{av} = \frac{1}{t}\int_0^{t_1} i dt \tag{7}$$

where $t = t_1 + t_2$.

If I_{av} is too large, the cathode temperature rises, leading to excessive evaporation. As the inverse voltage of the battery increases, the time during which the anode can pass current steadily decreases (cf. Fig. 49),

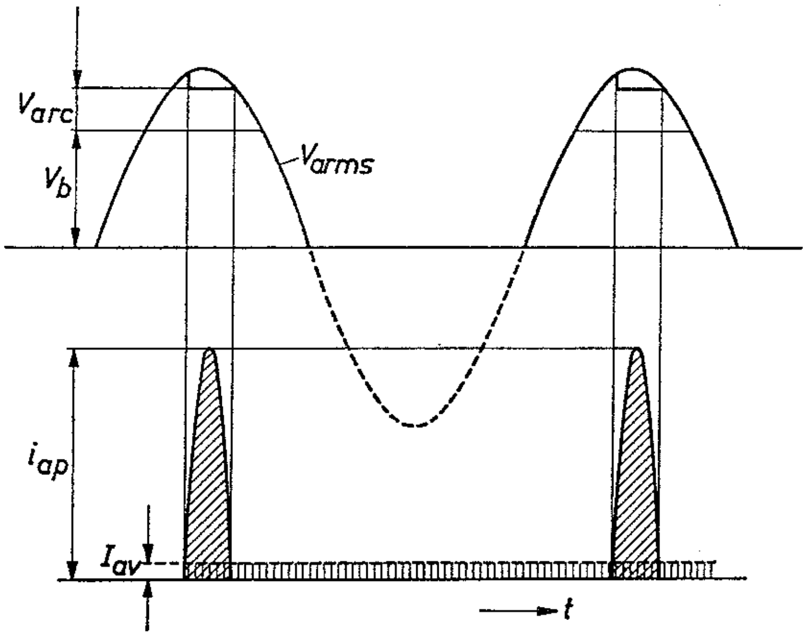

Fig. 51

Variation of tube current and voltage when V_b approaches $V_{a\,rms}$ in value. If the ohter operating conditions are kept as in Fig. 48 and 49, i.e. for the same values of $V_{a\,rms}$ and I_{av}, the peak current i_{ap} becomes high and the duration of the current pulses short.

When charging has proceeded so far that the battery voltage approaches the peak value of $V_{a\ rms}$ while I_{av} still has the maximum permissible value, the charging-current pulses will be so short and have such a high peak value that the cathode will be overloaded (see Fig. 51). The solution in such a situation is either to increase $V_{a\ rms}$ or to accept a lower value of I_{av}, and to increase the resistance in the circuit at the cost of the efficiency.

Averaging time

Finally, a few remarks about the *averaging time,* the period of time over which the average current is calculated. Because of the fluctuations in the tube current, which may be of a periodic or of an irregular nature (due to conducting and non-conducting periods or to considerable variations in the load), it makes a difference to the loading of the tube whether I_{av} is calculated for a short or a long interval. This has to do with the speed with which various parts of the tube are warmed up by the passage of current (their thermal capacity). Let us imagine that the tube current has the irregular variation with time shown in Fig. 52. If we calculated the average current over the short interval t_1, we should find that it exceeded the maximum permissible value, while in fact the tube would not be overloaded: the current in the following interval is much lower. If on the other hand we calculated the average current over the relatively long interval t_2, we would find it to have a permissible value, even though the tube was overloaded during the (shorter) interval t_3. Bearing this in mind, we may say that:

the maximum averaging time t_{av} for calculating I_{av} is the length of time during which the average tube current may not exceed the maximum value laid down for the tube, no matter where the interval of time is chosen.

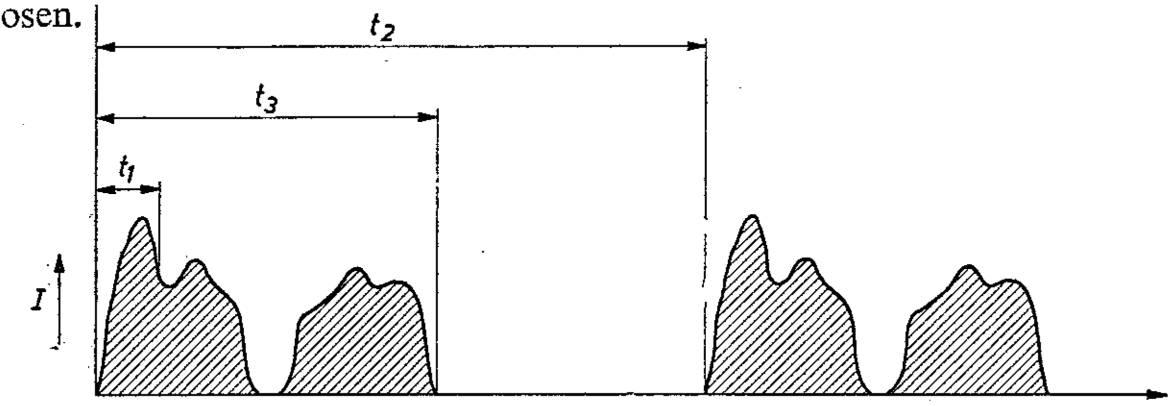

Fig. 52

Figure to illustrate the concept of *averaging time,* met with in the calculation of the maximum permissible mean tube current I_{av}. The curves depict an arbitrarily chosen variation of the tube current I with the time t, which is assumed to repeat itself after a time t_2. It will be clear that it makes a considerable difference whether the averaging is carried out over the interval t_1, t_2 or t_3.

The averaging times for the tubes described in this chapter lie between 5 and 30 seconds.

III-b-2 TUBES WITH MORE THAN ONE ANODE AND A COMMON CATHODE

The presence of gas in a tube makes it possible to allow more than one anode to take part in the rectification. Tubes with 2, 3, 4, 6 and even more anodes are made. For the moment, we shall consider the simplest example, a tube with two anodes.

We have seen during our discussion of the single-anode tube that the direct current only flows for rather less than half of the time; during the negative half-period, the tube does not pass current (see Fig. 48). If we want direct current to flow through the load in both half-periods, we can incorporate a second tube into the circuit, giving *two-phase* (full-wave) rectification. The circuit of such a rectifier is shown in Fig. 53a; the direct current through the load resistance R_o has about the form of a series of half-sine-waves (Fig. 53b). The two tubes pass current alternately.

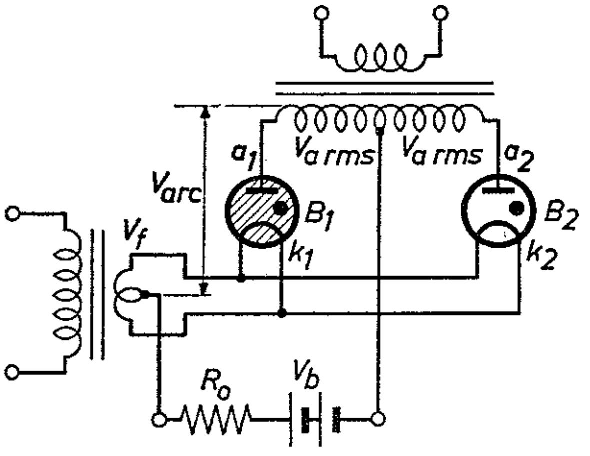

Fig. 53a

Circuit for two-phase rectification, with two single-phase tubes B_1 and B_2. Each of the tubes conducts in turn, while the other is cut off. When a_1 is positive a_2 will be negative, vice versa.

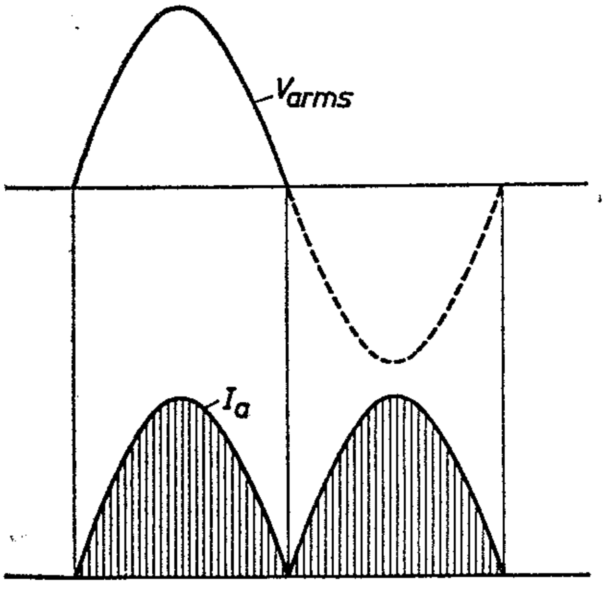

Fig. 53b

Simplified representation of the variation of the current I_a through a resistive load during two-phase rectification.

Another solution is to use a single tube with two anodes and a common cathode. This relatively cheap and simple construction is possible with gas tubes, but not with vacuum tubes. We see from Fig. 53a that the anode of tube B_1 is positive while that of tube B_2 is negative. In a vacuum tube with two anodes under these conditions, the field at the cathode would be zero, so that practically no electron current would flow to the positive anode. The situation is different in a gas-filled tube, where the field distribution is altered by the presence of positive ions.

A gas tube with two anodes needs only one cathode, even though the average current is twice that of a tube with a single anode. This is because the peak current, which mainly determines the size of cathode needed, is the same in both cases. The circuit of Fig. 53a can thus be replaced by that of Fig. 54.

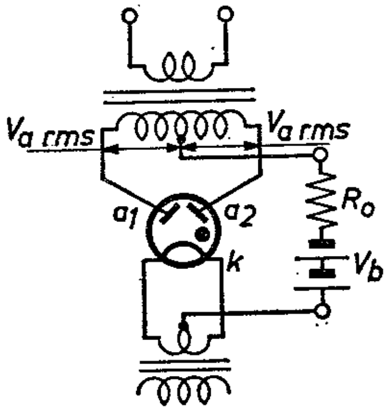

Fig. 54
Circuit for two-phase rectification, using one tube which contains two anodes and a single cathode.

We shall start by considering a simple example of a two-phase rectifying tube, the Philips type 367 (Fig. 55).

The operating data of this tube are given in the following table.

TABLE VI
OPERATING DATA OF THE PHILIPS TUBES 367 AND 1859

		type 367	type 1859
mean anode current	I_{av}	2 x 3A max	2 x 25A max
peak anode current	i_{ap}	18A max	150A max
maximum surge current/duration	i_{surge}/t_s	—	1250A/0,1 sec
peak inverse anode voltage	$v_{ap\ inv}$	140 V max	360 V max
ignition voltage	V_{ign}	16 V	28 V
arc voltage	V_{arc}	9 V	12 V
heater voltage	V_f	1.9 V	1.9 V
heater current	I_f	8 A	60 A

This tube is suitable for charging batteries, up to a maximum of 12 lead cells. The coiled oxide cathode has two leads of nickel wire, and is placed between the two cylindrical graphite anodes, which are screwed on to the ends of the anode leads.

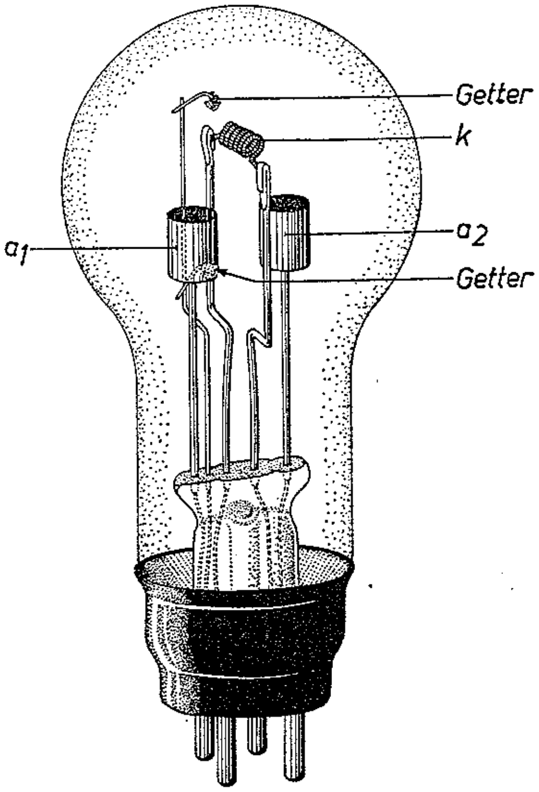

Fig. 55

Two-phase rectifier tube, Philips type 367. The pinch seal encloses the leads of one spiral hot cathode *k* and two graphite anodes, a_1 and a_2, which pass current alternately. The tube contains two getters which serve to purify the inert gas during the manufacturing process.

Let us consider the causes of the heating of the anodes of this low-voltage tube while it is in use; this is of importance because the anodes must not get hot enough to give rise to thermal emission, which would result in arcing during the inverse phase. It has been found that the heating is determined by the arc current in the positive phase, and by the bombardment by ions which the negative anode, acting as a probe, attracts out of the arc discharge to the other anode. The probe current is however

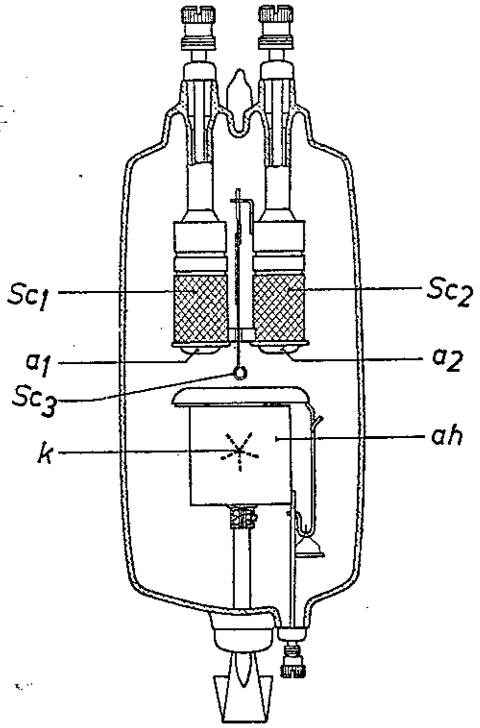

Fig. 56

Two-phase rectifier tube for 2 × 115 V AC anode voltage (Philips type 1859). The anodes a_1 and a_2 are surrounded by gauze screens Sc_1 and Sc_2, which leave little more than the bottom of the anodes exposed, in order to restrict the glow discharge which appears on the anodes during the inverse phase. The "star" cathode *k* is placed inside a metal cylinder a_h which acts as an auxiliary anode. The vacuum-tight seals of the various leads, with the aid of cups of chrome iron sealed on to the glass envelope, can also be seen.

limited by the fact that the positive ions form a cloud round the negative anode, partly counteracting its field.

With a two-phase tube for higher voltages, such as the Philips type 1859 (Fig. 56), whose data are also given in Table VI, another source of heating is added to the two mentioned above: the glow discharge during the negative phase. In fact, at the gas pressure and anode voltage used in this tube, this is the most important source of heating. The maximum value of the glow-discharge voltage between the two anodes $2 V_{a\,rms} \sqrt{2}$ (which is somewhat greater than when two single-phase tubes are used, cf. Fig. 53a). Steps have been taken to reduce the glow-discharge current in this tube. Since the positive current density and the dimensions of the anodes cannot be altered, the solution must be sought elsewhere. The solution actually adopted is to screen off most of the anodes by means of two wire-gauze screens, Sc_1 and Sc_2 placed a short distance away and insulated from the anodes. The glow can then only cover the parts of the anode which are not so screened. If the gauze screen is to be effective, the distance between it and the anode must be less than the width of the Crookes' dark space. The radiation of heat from the anodes is hindered as little as possible by giving the gauze a low "masking effect" (i.e. by making the thickness of the wire small compared to the mesh of the gauze). Moreover, much of the heat transported from the anode is carried off via

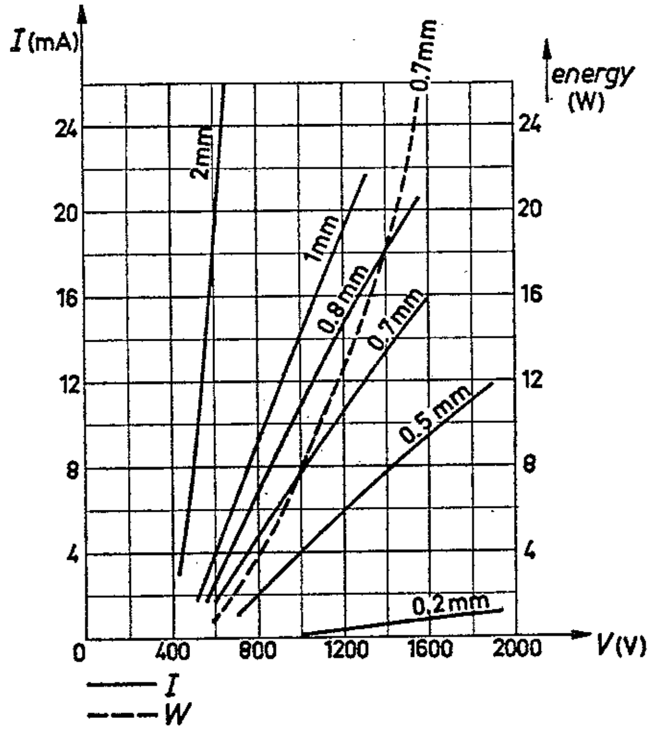

Fig. 57

Glow current *I* and glow energy *W* as functions of the (peak) voltage *V* between the anodes of a two-phase rectifier tube, where no steps are taken to reduce the glow discharge (cf. Fig. 58) [46].

the anode lead. Convection plays hardly any part in these tubes with their low gas pressure. Fig. 58 shows the influence of this screen on the glow-discharge current and power for an anode of surface area 14.38 cm^2. When these figures are compared with those in Fig. 57 for an unscreened anode of half the size, the improvement is striking.

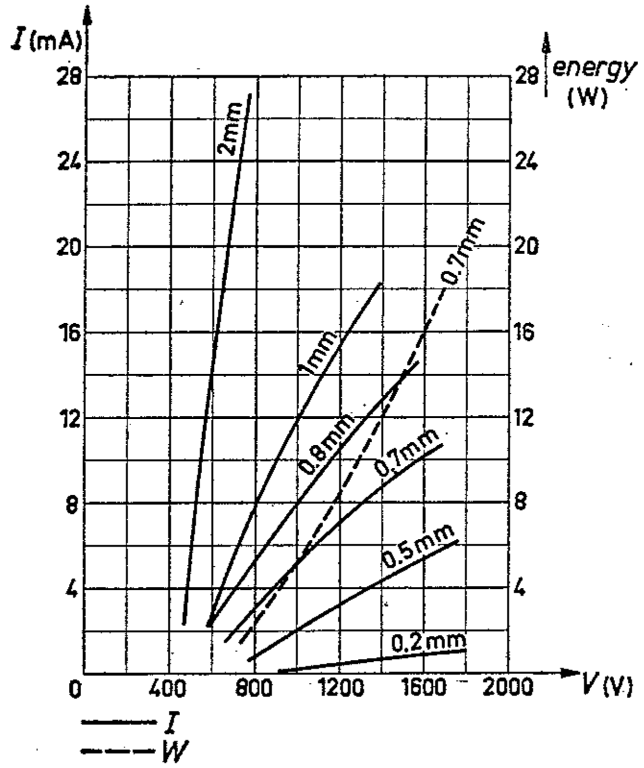

Fig. 58

As Fig. 57, but for a tube whose anodes with a twice as large surface are screened off with gauze cylinders. It will be seen that both *I* and *W* are considerably less than in Fig. 57 [46].

The cathode has the form of a star cathode (flower cathode), which has been described in II-c-1-c, and is also screened. The cathode screen consists of a nickel cylinder with a "lid" just a short distance away from it. It performs many functions. We see for example that the discharge is mainly contained between the walls of the cylinder. The glass envelope receives very few charge carriers; undesirable surface charges, which might adversely affect the ignition, are thus limited. Oxide particles from the cathode are deposited where they can do no harm. If they do manage to get out of the screen, they will go downwards because of the position of the lid, or if they do strike the wall of the tube it will at least be in a downward direction; they cannot land on the anode. This is important in connection with the glow discharge on that electrode. If the normal static state of this discharge should be disturbed by a microscopic particle moving in the glow layer, backfiring might result. The same is true if such a particle should come *from* the glow layer.

Sputtered anode material also lands on the screen and not on the emitter, which considerably increases the life of the cathode. A further advantage is the saving in heater power due to the reflection of some of the radiation by the screen. Finally, since fewer charge carriers land on the tube wall, its temperature is lower and gas clean-up is reduced.

Against all these advantages, there is one possible disadvantage: unless special steps were taken, this thorough screening of the cathode would increase the ignition voltage by tens of volts. To prevent this, an auxiliary discharge is maintained between the screen and the cathode. The screen is insulated from the heater body, and a permanent auxiliary current flows through an extra lead sealed in at the bottom of the glass envelope. This current can simply be obtained, e.g. with the aid of a little auxiliary rectifier fed by the heater-voltage transformer. The auxiliary discharge of about 10 mA remains practically entirely inside the cathode screen. The main discharge is initiated by means of a small current which can flow through a hole in the lid. (This discharge is visible as a little plume.) As the current rises, the discharge makes its way through the slit left between cylinder and lid.

The tube also contains yet another screen, S_{c3}, between the two anodes. This decreases the glow-discharge current still further by increasing the length of the discharge.

The parts of the anode support which could also take part in the discharge if the anode were simply screwed on to its lead must be prevented from doing so: at the inverse voltage of 360 V found in this tube, there would be a considerable chance of backfire if this were not done. As may be seen in Fig. 56, this is achieved by means of an arrangement of glass tubes. All the measures mentioned above increase the ability of the tube to stand high voltages.

The filling of this tube consists of a mixture of argon and mercury; the latter gives the discharge a blue tint. The reason for this addition has already been discussed in Chapter II.

In this connection we may mention the *warming-up time* of the hot cathode. This is the length of time one must wait after switching on the heater voltage before drawing emission current, i.e. before applying the anode voltage; this waiting time is necessary to allow the (big) cathode to reach the desired temperature. The warming-up time of the 1859 is about 2 minutes. With some tubes, e.g. those with a mercury filling without any inert gas (see III-c-4), it is advisable to wait longer than the suggested time if the ambient temperature t_{amb} is low ($< 10\,°C$): the temperature of the mercury must be at least about 15 °C before the vapour pressure is high enough to ensure good ignition and a low burning voltage. The mercury is heated to the required temperature by the heater losses, whence the increased warming-up time.

With a mixed filling, however, there is no need to increase the warming-up time, even for ambient temperatures down to 0 °C. The reason for this will be clear from what has been said in Chapter II.

Surge loading and damping

One of the operating data normally mentioned by the manufacturer of a rectifier tube is the maximum surge current i_{surge} which the tube can stand under certain circumstances, and the length of time that this current surge can last without causing permanent damage to the tube. Such a situation can arise e.g. if there is a short-circuit in the load, or — especially in polyphase circuits — if one of the tubes backfires, which can under certain circumstances be caused by switching manipulations or mains-voltage pulses. It is important in this connection that the circuit should contain sufficient damping: not only does this reduce the short-circuit current but, as has been found in practice, it much reduces the chance of backfire.

The inductive transformer resistance in the circuit provides a measure of damping. The rectifier transformer naturally also has a certain ohmic resistance. The total resistance R_t of the circuit formed by the transformer and the tubes has a minimum permissible value laid down by the manufacturer. If we only consider the secondary circuit, it may sometimes be necessary to supplement the transformer resistance R_{sec} by a resistance R_a in series with each anode in order to reach the stipulated minimum value of R_t:

$$R_a = R_t - R_{sec} \tag{8}$$

(In two-phase rectification, R_{sec} = resistance of half the secondary winding.)

This anode resistance causes energy losses and thus reduces the efficiency; especially with big battery chargers, this can be an important factor. In such cases it is preferable to use inductive damping, i.e. to include a choke coil in the circuit. If we placed a coil in series with each anode, we should have to omit the iron core because of the risk of saturation from the direct anode current. An air choke would however be very large. The solution is to place the choke in the primary circuit of the transformer, which passes alternating current. Fig. 60 shows the variaton of the transformer voltage V_{pr}, the choke voltage V_L and the primary current I_{pr} for the circuit of Fig. 59.

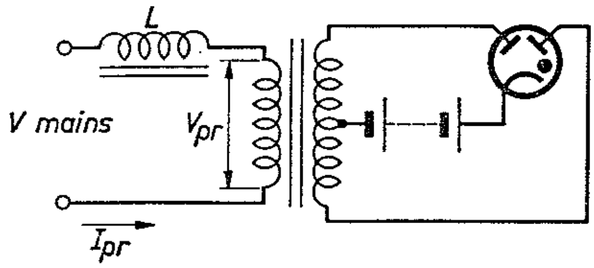

Fig. 59

Low-loss damping of a rectifier circuit with the aid of a choke coil L in series with the primary winding of the anode-voltage transformer.

Three-phase and six-phase rectification

If high powers have to be dealt with, or if it is desired to keep the DC ripple small, it is advantageous to feed the rectifier from a three-phase mains and to use tubes with e.g. three anodes in one envelope. Rectification with three single-phase tubes is also possible, but will not be discussed here. The construction of a three-phase tube does not differ in principle from that of a two-phase tube: it just has one anode more. The ripple can be reduced even further with the aid of a 6-phase circuit, which makes use of six single-phase, three 2-phase or two 3-phase tubes (or even one six-phase vessel, in big mercury-vapour rectifiers). Fig. 61a and 61b show some switching diagrams, of which a large variety exists. One of the attractive points of 3-phase or 6-phase rectification is that in certain cases the anode-voltage transformer can be completely omitted, and the tubes fed directly from the three-phase mains. Fig. 62 shows a 3-phase system fed from a three-phase mains with neutral lead, and Fig. 63 shows a similar circuit without neutral lead (bridge circuit). It may be seen that in the latter case the direct current produced has a six-phase ripple. The further advantages of this much-used circuit come under the heading of circuit theory, and will not be discussed further in this book.

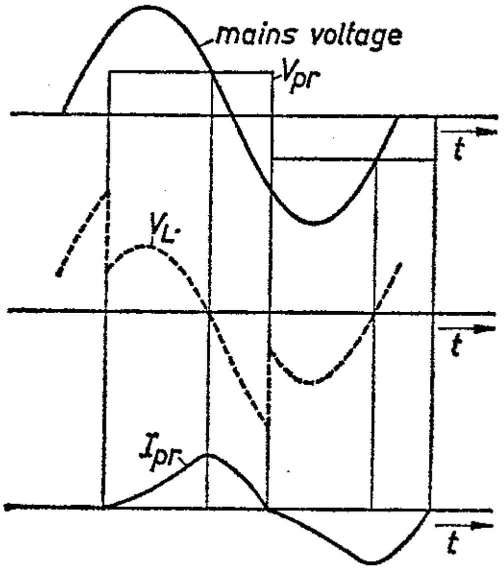

Fig. 60

Variation of the voltage V_L across the choke, the transformer voltage V_{pr} and the current I_{pr} through these components for the circuit of Fig. 59.

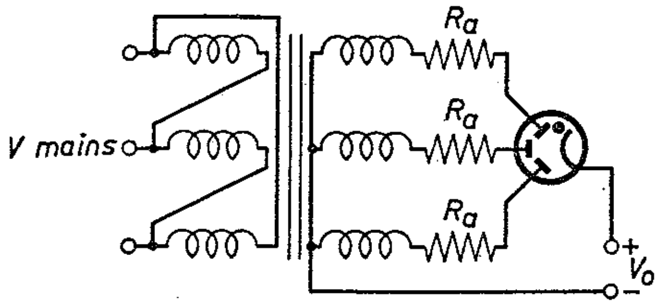

Fig. 61a

Example of a circuit for feeding a rectifier tube with three anodes. The primary windings of the transformer should preferably be connected in a delta circuit.

R_a = anode series resistance.

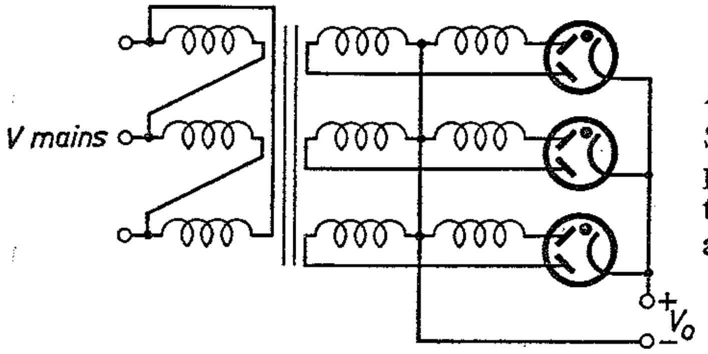

Fig. 61b

Six-phase rectification using three two-phase tubes. A delta circuit is used on the primary side of the transformer, and a star circuit on the secondary side.

If any circuit needs damping, it is this one. Since the transformer with its impedance is missing, we must make up for this by placing another form of impedance in series with each anode (the anode impedance Z_a).

Let us consider the circuit of Fig. 63. At any given moment, two of the six anodes pass current in series through the load. A useful rule of thumb states that the ohmic + inductive voltage drop across the damping element must have the value

$$V_z = 0.07\ V_o \tag{9}$$

where V_o is the output DC voltage.

In the present case, V_z is the voltage drop across the two anode impedances in series, so the voltage drop V'_z across each one is given by

$$V'_z = 0.035\ V_o \tag{9a}$$

If we assume that the tube current has roughly the form of a square-wave, we find

$$V'_z = i_{ap} \times Z_a \tag{10}$$

If we denote the ohmic component, e.g. the minimum circuit resistance prescribed for the tube, by R_t, then it follows that

$$Z_a = \sqrt{(R_t^2 + X_L^2)}$$

where the inductive component X_L must be supplied by an anode choke L. In order to prevent saturation, this coil must have no iron core. The dimensions of the air coil can be calculated with the aid of the standard formulae for self-inductance.

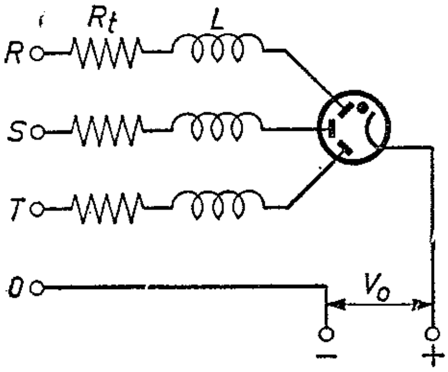

Fig. 62

Three-phase rectification with the aid of a tube with three anodes. The anode-voltage transformer is omitted, and the anodes are supplied directly from a three-phase mains with neutral lead.

R_t = total ohmic resistance in circuit for one anode,

L = inductive component in circuit for one anode.

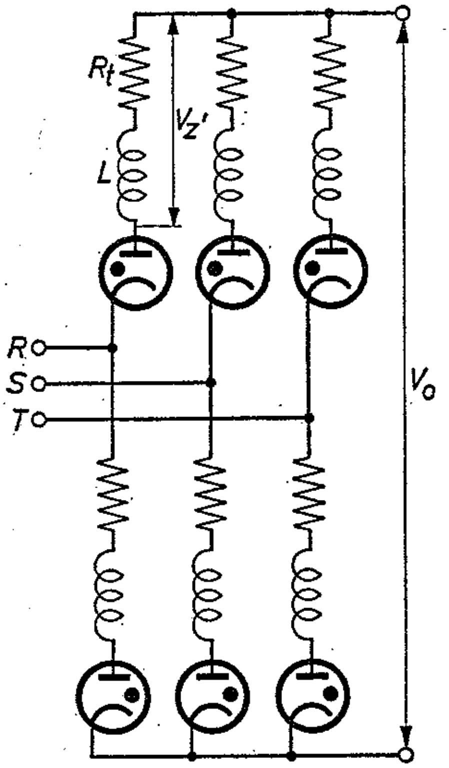

Fig. 63

Rectifier circuit using six tubes each with a single anode, directly fed from a three-phase mains without neutral lead (bridge circuit). The DC output voltage V_0 has a six-phase ripple. It is possible to replace the three lower tubes by one tube with three anodes, because all three cathodes have the same potential.

Since there is no anode-voltage transformer, it is advisable to include some damping ($R_t + L$) in the circuit.

III-b-3 TUBES WITH ANODE SIDE ARMS

If it is desired to increase the AC anode voltage of a multi-phase tube much above 115 V, e.g. to build a tube for 3 × 220 V, the construction we have described above for the Philips 1859 will be quite suitable, as long as great care is taken with the design of the screens and the sealing of the anode leads against undesired discharges.

Long before the principles embodied in this construction were known, a solution was sought in quite another direction, by placing each anode in a separate side arm, whose diameter is small compared to that of the discharge space round the cathode (see Fig. 64). The discharge in these side arms then becomes a column discharge, for which the arc voltage is somewhat higher than for the above-mentioned anode arrangement (15—20 V as compared with 10—12 V). The ignition voltage is also increased by this construction, sometimes reaching values of about 100 V; moreover, the ignition voltage of a given tube of this construction can vary unpredictably. Means of decreasing V_{ign} again have been found, e.g. with the aid of an auxiliary discharge in the cathode space. This construction is expensive, and has the disadvantage of rather unstable inverse voltages, caused by the charges on the wall of the tube. We shall mention tubes with anode side arms again (see VI-c-1), in connection with controlled high-voltage rectifiers (mercury tubes) where this construction is most successful. Apart from these mercury-cathode rectifiers, however, the anode-side-arm construction is of no importance any more.

III-c **High-voltage rectifier tubes** (for voltages above 550 V_{rms})

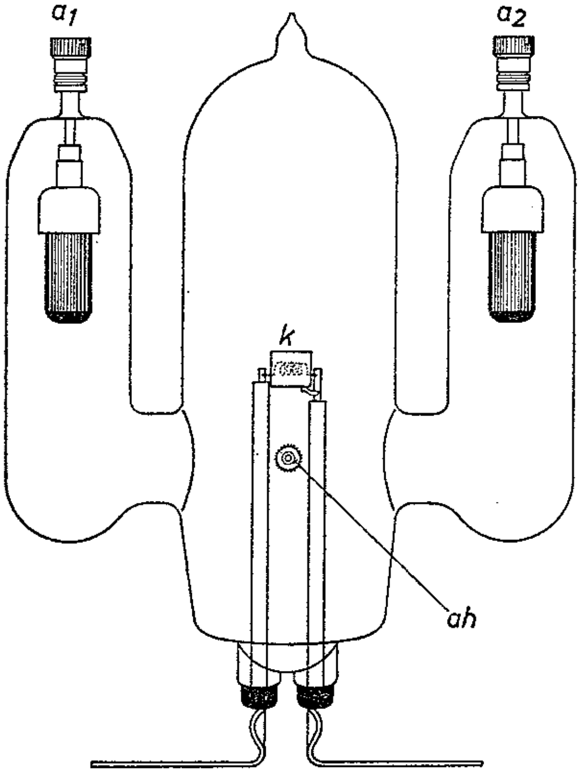

Fig. 64

Example of an obsolete type of glass two-phase tube for an anode voltage of several hundred volts, with an inert-gas filling. Each anode is withdrawn in a glass side arm. A similar construction is still used for metal mercury-pool rectifiers. a_h is an auxiliary anode. An auxiliary discharge of a few milliamps is maintained between a_h and k, to bring the ignition voltage (which can reach rather high values in such tubes), back to a low value.
The cathode leads, consisting of copper strips brazed on to chrome-iron cups sealed into the glass, can be seen.

INTRODUCTION

The use of vacuum triodes, tetrodes and pentodes in HF generators, transmitters, energy transducers, X-ray installations etc. has led to a great need for high-voltage direct current sources for the anode supply of such tubes. The most suitable way to obtain these is by the rectification of high transformer voltages. Gas-filled rectifier tubes can be used here with advantage, thanks to their valuable properties which have been mentioned above.

The vacuum diodes which can also be used for this purpose have certain disadvantages: either the current is low, or if the current is high the efficiency is low and artificial cooling is necessary. If the advantages of gas-filled tubes are to be made use of, the main problem is how to deal with the high inverse voltages.

III-c-1 DEALING WITH THE INVERSE VOLTAGE

The operating conditions (gas pressure, electrode distance, etc.) in a high-voltage rectifier tube with more than one anode will in general be such that the voltage between the anodes in the inverse phase will be above the ignition voltage; some glow current will thus always flow.

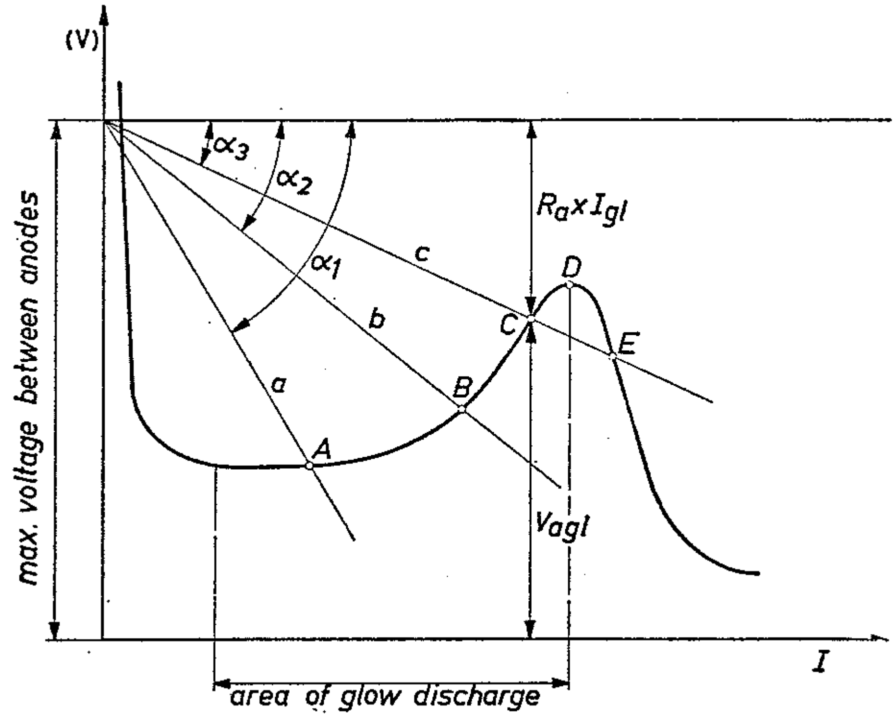

Fig. 65

Blondel diagram.

The thick curved line is the current-voltage characteristic of a gas discharge between two electrodes, e.g. between the two anodes of a two-phase rectifier tube. The glow-discharge region is indicated by the horizontal line. R_a is the resistance in series with an anode. The straight lines *a*, *b* and *c* are "load lines" corresponding to different values of R_a, with slopes α_1, α_2 and α_3 respectively; all the load lines pass through the point on the voltage axis corresponding to the maximum value v_{ap} of the voltage between the anodes. In the glow-discharge region, $v_{ap} = R_a \times I_{gl} + V_{agl}$, where I_{gl} is the glow current and V_{agl} the glow voltage. The operating point of the discharge is the point of intersection of the load line in question and the current-voltage characteristic.

Part of the tube voltage is taken up by the resistance in series with the anode, R_a, and some by the impedance of the rest of the circuit. In the Blondel diagram (Fig. 65), the lines *a*, *b* and *c* are load lines, whose slope α is determined by the value of R_a. The point of intersection of the load line with the curve representing the current-voltage characteristic of a gas discharge is the operating point. If R_a is low (line *c*, slope α_3), there are two points of intersection, *C* and *E*. *C* represents a stable discharge, and *E* an unstable one. The intermediate point *D* is the transition point where the glow discharge changes into an arc discharge. It depends on the temperatures of the anodes at the point *D* whether the situation is critical, i.e. whether this transition will in fact occur.

The problem is thus to keep the glow-current losses low without having to use too large an R_a.

We know that the glow-current losses and thus the inverse current from the negative anode decrease as the pressure is reduced. It would seem at first sight therefore that the gas pressure in the tube should be steadily reduced as the AC voltage to be rectified increases. On the other hand, the anode sputtering increases under these conditions, so that more anode material will be deposited on the walls of the tube and on other electrodes, thus the gas pressure will be decreased even further by clean-up. The sputtering will then become worse, until finally the tube contains too little gas. It is not only the electrode sputtering which causes the tube to deteriorate: it is true that we have seen (II-c-1-a) that the cathode also suffers from sputtering at low pressures, but the life of low-pressure tubes is not mainly determined by deterioration of the cathode. The high-voltage diodes which previously were used for voltages up to a few thousand volts, and whose construction was similar to that shown in Fig. 64, were filled with an inert gas at low pressure (< 0.1 mm), and they had a short life because the gas got used up. It can be said in general that the complications and difficulties met with at low pressures were like those found with mercury tubes (see Chapter VI).

High-voltage tubes are still filled with inert gas nowadays, but they have special electrode configurations and in particular they have no anode

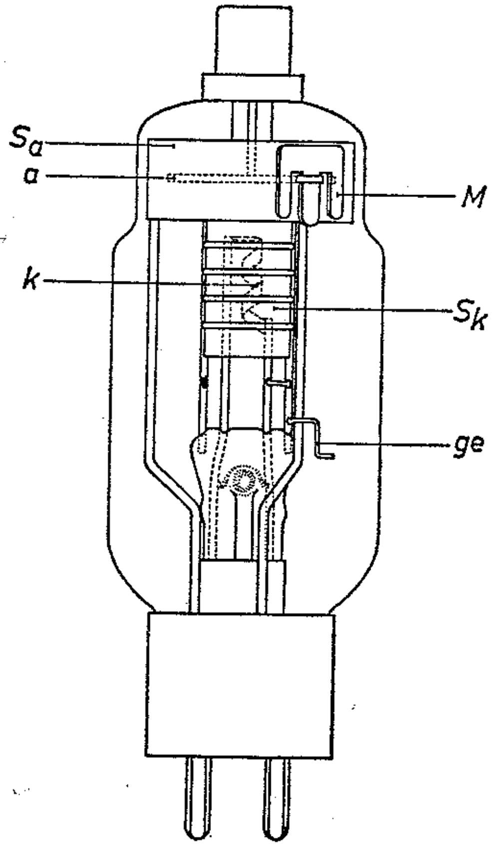

Fig. 66

Sketch of the Chatham type 3 B 28, a typical tube with inert-gas filling for a maximum anode inverse voltage of 5000 V.
The anode a and cathode k are surrounded by metal screens, S_a and S_k respectively.
These screens are maintained at cathode potential by means of a connecting strip.
The discharge is enclosed between these two screens. ge is a getter holder, M one of the mica supporting discs between S_a and the wall of the tube.

side arms. Fig. 66 shows the Chatham tube type 3 B 28 which is filled with *xenon* gas at low pressure. I_{av} may be 0.5 Amax if $v_{ap\ inv}$ does not exceed 5000 V; or $I_{av} = 0.25$ Amax for $v_{ap\ inv} = 10\,000$ V $_{\max}$. Special measures are taken to ensure that this tube has a long life despite the low gas pressure. The disc-shaped metal anode a is surrounded by a box-shaped screen S_a at cathode potential, thus making the effective distance between anode and cathode small. The oxide cathode is made of corrugated nickel tape which is wound in a spiral of large pitch and surrounded by a cylindrical screen S_k. The discharge is completely enclosed between S_a and S_k. The tube also contains a getter *ge*, and the mica discs M provide elastic support between S_a and the glass wall.

The advantage of using xenon is that the ionization and arc voltages are low ($V_{ion} = 12.1$ V), so that the cathode does not suffer much from bombardment by the gas. The large size of the atoms and their low velocities are the reasons why the gas is not easily trapped on walls and electrodes. Even at high frequencies (500 c/s), the cathode of the 3 B 28 has a long life (see under "commutation", Chapter IV). The absence of mercury droplets means that the tube may be placed in any position. For the same reason, the tube can be used at temperatures between —75 and + 90 °C. The life is usually determined by the disappearance of gas.

The absorption of gas could be counteracted by using an extra large glass envelope or by renewing the gas filling from time to time, but both of these methods have obvious disadvantages.

Mercury filling

Another solution which is often more practical is to use a filling of mercury (vapour). It is then however necessary to be much more careful about the temperature, which is of hardly any importance for tubes filled with inert gas. The reason for this is that the saturated vapour pressure of mercury is a function of the temperature (see I-b-2). The ambient temperature and the tube losses must thus be taken into consideration. If the tube contains some liquid mercury, the vapour in the tube will be saturated, and its pressure will remain constant as long as the temperature of the envelope (which we shall assume for the moment to be the same at all points) does not change. In practice, however, different parts of a tube which is in operation will have different temperatures. The pressure is then determined by the temperature of the coldest part of the envelope, which is also the spot where the vapour will condense. (If the mercury temperature is steadily increased, a time will come when all the mercury has evaporated. If the temperature is increased any further, the vapour is *un*saturated.) The advantage of using mercury vapour is obvious: the mercury atoms adsorbed during the discharge are automatically replaced from the liquid phase, which thus acts as a very compact gas reservoir. Even a small drop can give an enormous amount of vapour at the temperatures in question: 1 mm^3 of liquid mercury is equivalent to about 150×10^6 times as much vapour of pressure 1/100 mm at 50 °C. It will be clear that this amount will allow the tube to burn for tens of thousands of hours.

In the last few decades, therefore, mercury-vapour fillings have come into general use for high-voltage tubes.

We must not forget however the disadvantage of mercury fillings, viz the temperature dependence (see III-c-4 and Fig. 1).

A simple example of a tube filled with saturated mercury vapour is the Philips type DCG 1/250 (Fig. 67). The maximum permissible average current is 0.25 A, and $v_{ap\ inv}$ is 3 kV max. The vertical anode plate *a* is placed facing the cathode spiral *k*. Under normal operating conditions, the mercury is present as fine condensation droplets (*Hg*) at the bottom of the envelope.

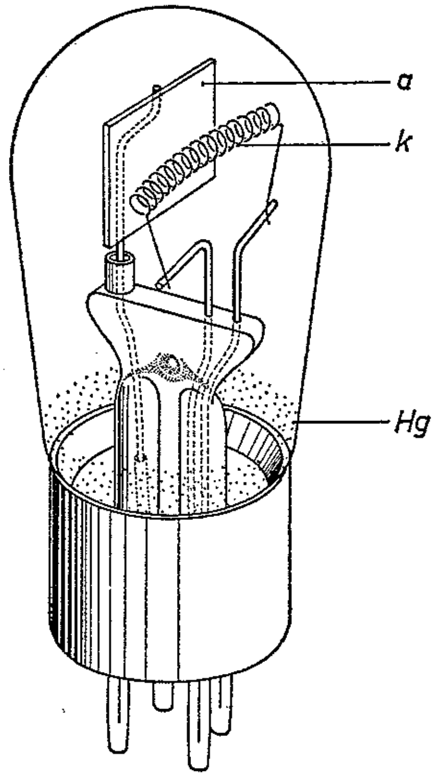

Fig. 67

Example of a simply constructed high-voltage tube filled with saturated mercury vapour. (Philips type DCG 1/250).
Maximum inverse voltage 3 kV, *a* = vertical anode plate, *k* = spiral cathode, *Hg* = spot where mercury condenses.
Because of the relatively low voltage between *a* and *k*, the leads of both of these electrodes can be included in the same pinch seal.

The simple anode construction is possible because of the relatively low anode voltage, but at higher values of $v_{ap\ inv}$ this is no longer possible. A rectifier tube for a somewhat higher power (I_{av} = 0.25 A, $v_{ap\ inv}$ = 10 kV max) is the type 866 A, which is made by various manufacturers in different parts of the world. This tube is shown in Fig. 68. The unusual positioning of the horizontal, blackened nickel anode disc *a*, very near the cathode screen *S*, which is connected to the cathode at one side, can be clearly seen. The reasons for this will be discussed below. Unlike the DCG 1/250, where the anode and cathode leads can still be included in the same pinch seal, the anode lead of the 866 A must be sealed into the top of the envelope because of the higher voltages involved.

III-c-2 THE CATHODE

The cathode of a high-voltage tube must be heavier than that of a low-voltage tube for the same current. Since we are obliged to keep the gas pressure low, we must also accept a relatively high cathode sputtering, since in the positive phase the field is closely concentrated around the cathode. The ions which find themselves in this narrow region of high field have little chance to lose any of the energy ($eV = \frac{1}{2}mv^2$, which they have taken up from the field, by collision with neutral atoms, because at these low pressures there are not many atoms about. The cathode bombardment is thus relatively high, which results in considerable sputtering of the oxide layer. To compensate for this attack, the cathode must be made larger than in low-voltage tubes. The heater-current power increases to 25—35 W per amp mean tube current.

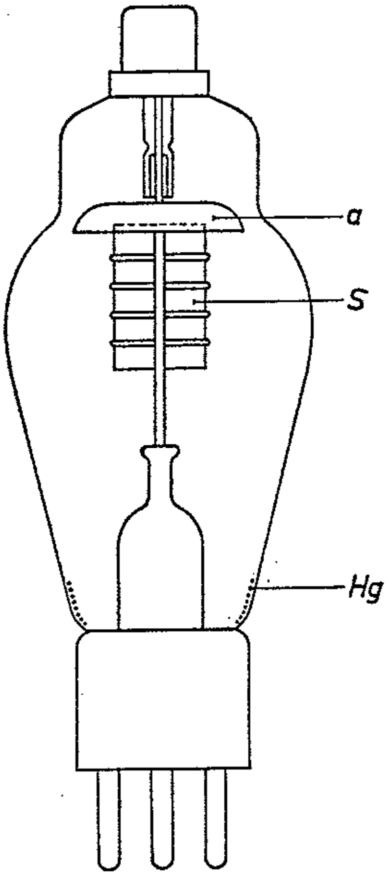

Fig. 68
Rectifier tube with mercury-vapour filling for an inverse voltage of 10 kV. Because of the relatively high anode voltage, the lead of the disc-shaped nickel anode must be led out through the top of the tube, so as to be as far as possible from the cathode lead. S = cathode screen, Hg = mercury condensate.

Summing up, we may say that higher $V_{a\ rms}$ requires lower t_{Hg} and a larger cathode.

Some high-voltage mercury tubes are made with various compartments at different pressures, according to the principle shown in Fig. 69. In the lowest compartment *K* we find the cathode *k* and liquid mercury, which is heated by the cathode losses. The middle compartment *C* acts as a condenser for the mercury vapour, and the upper compartment *A* contains the anode *a*. The various compartments are connected by narrow metal pipes. This construction makes it possible in a single tube that the relatively small cathode emits amidst a high pressure, and thus does not suffer much from sputtering, while the anode is in a low-pressure region so that high voltages can be tolerated. The pressure in *K* can be as much as 20 times that in *A*. Such tubes last a long time, but they are also expensive to make [46].

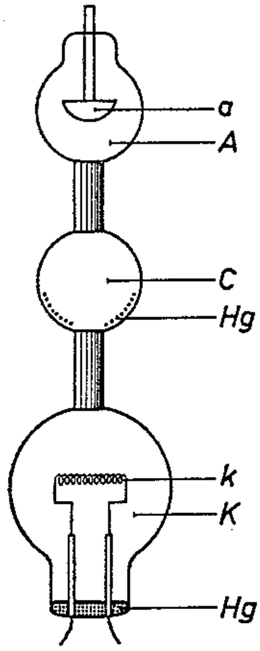

Fig. 69

Sketch of high-voltage mercury-vapour rectifier tube with three compartments, *A*, *C* and *K*, in each of which the mercury vapour pressure is different during the operation of the tube. In the cathode space *K* which contains liquid mercury, the temperature is relatively high because of the cathode losses; the vapour pressure is therefore also high. The vapour condenses in the space *C*, where the temperature and pressure are lower. In the top compartment there is no liquid mercury, and the pressure is lowest there. The pressure differences between the three compartments can be maintained because of the narrow chrome-iron tubes which connect them one with another.

III-c-3 INVERSE CURRENT, BACKFIRE [47]

We shall now consider in somewhat greater detail an effect which is of special importance in high-voltage tubes: the inverse current, which under certain circumstances can degenerate into backfiring. This inverse current flows during the time that the anode is negative with respect to the cathode.

In a polyphase rectifier circuit (see e.g. Fig. 61a), two voltages which differ in phase feed two anodes. Under such circumstances, at regular intervals one of the anodes will be positive and pass current while the other is negative. The two anodes in question may both be situated in the same tube, or they may each be in separate tubes. Now by backfiring we mean the formation of an arc between the negative anode and the positive one, which is accompanied by the passage of a practically unlimited current. The consequences of such a short-circuit, such as overloading of the tube which may result in permanent damage and the blowing of fuses, need hardly be stressed.

Backfiring is usually a result of breakdown: first of all a glow discharge is initiated in the inverse phase, or it may be there already. Under normal circumstances, this does no harm. The glow discharge can however degenerate, under certain circumstances over which the manufacturer has no control. We may in this connection mention the following four points.

First of all, the glow discharge may dissipate enough heat to produce an incandescent spot on the anode which cannot lose enough heat and therefore begins to emit thermally. The glow discharge then degenerates into a low-voltage inverse arc. If a mercury-vapour filling is used, a glow discharge is however unlikely to occur at the usual low pressures of some thousandths of a millimetre and inverse voltages of tens of kV. Here again, the product $p \times d$ is of prime importance, and care must be taken that the temperature does not rise too much (cf. III-c-4).

A second possible cause of backfiring is that the ions left over from the positive phase bombard the now negative anode under the influence of the strong inverse field. A situation now arises where the whole field is concentrated right in front of the anode because of the layer of ions which surrounds it. As a result, the anode may emit a number of electrons (gamma effect). Now if $p \times d$ is large enough, these ions may give rise to a new breakdown, in the wrong direction. There is least risk of breakdown if the electrode configuration is chosen so that $p \times d$ is small, i.e. so that the tube operates in the part of the Paschen curve to the left of the minimum. It is not easy to get a stable state if the tube works to the right of the minimum. One might however imagine that the constructor would always be able to make $p \times d$ small enough to get out of trouble.

This brings us to our third point: there is a lower limit to d, below which field emission or auto-emission of electrons arises. We shall not discuss this any further here, but refer to what has already been said in I-c-2. It may however be mentioned that auto-emission currents of several μA have been measured in mercury tubes with a d of a few mm and field strengths from 2000 to 3500 kV/m; it will be clear that if the electrode separation is made considerably smaller, backfiring may well arise.

Fourthly, if small macroscopic particles find their way into the discharge, they may collide with the negative anode and give rise to electron emission (cf. the discussion of screening in III-b-2).

The designer of a high-voltage tube is thus forced to make compromises. In general, the anode-cathode distance will be 10—15 mm for inverse voltages of up to about 30 kV.

It should however be realized that what is important is not the actual distance between the anode and the cathode, but the length of the longest line of force within the tube between the two, which matters as far as inverse breakdown is concerned (except for field emission, where it is the shortest line of force which counts). The longer this line of force is, the more chance an electron travelling along it will have to cause ionization. The designer must therefore take care that such lines of force as remain within the discharge space (envelope) are short compared with the mean free path of the electrons. An impression of the mean free paths and pressures corresponding to various mercury temperatures is given by the following table.

TABLE VII

THE SATURATED VAPOUR PRESSURE OF MERCURY AT VARIOUS TEMPERATURES AND THE MEAN FREE PATH OF THE MOLECULES IN THE SATURATED MERCURY VAPOUR *)

temperature of mercury (°C)	mean free path in saturated vapour (m)	vapour pressure (mm)
25	1.45×10^{-2}	0.0018
100	1.44×10^{-4}	0.27
150	1.74×10^{-5}	2.8

It will be seen that in e.g. the tube shown in Fig. 70, this has been taken into account. This tube is a controlled high-voltage rectifier, Philips type DCG 12/30. It can deliver an average current of 2.5 A at $v_{ap\ inv}$ = 27 kV max. The significance of the switching grid *g* will be discussed in the chapter on thyratrons. It may however be mentioned here that *g* is practically at the same potential as *k*. The short distance between *a* and *g* will be noted; this is electrically equivalent to a short distance between *a* and *k* as far as avoiding backfiring is concerned. The lines of force between the electrodes are shown in Fig. 71. It will be seen that such lines of force as remain within the envelope are all short.

The great length of the envelope is also plain to see. This ensures that the coldest part of the tube is a long way from the spot where the tube losses occur, so that the vapour pressure of the mercury is low, and high inverse voltages can be tolerated.

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*) After S. Dushman, Scientific foundations of vacuum technique, London, Chapman & Hall Ltd.

Moreover the screen S reduces the radiation of heat from the cathode to the lower parts of the tube.

If the tube has not been in use for some time, all parts will be at room temperature and the mercury may be expected anywhere in the tube. When the tube is switched on again, the mercury vapour may condense at the top of the tube as well as at the bottom. To reduce the chance of backfiring, the condensed mercury should be allowed to evaporate from the anode side of the tube before the anode voltage is applied. Tubes of this type are usually specially designed to shorten this warming-up time. For example, some tubes contain an *anode cap* which surrounds the upper part of the envelope. The warm air rising round the tube is

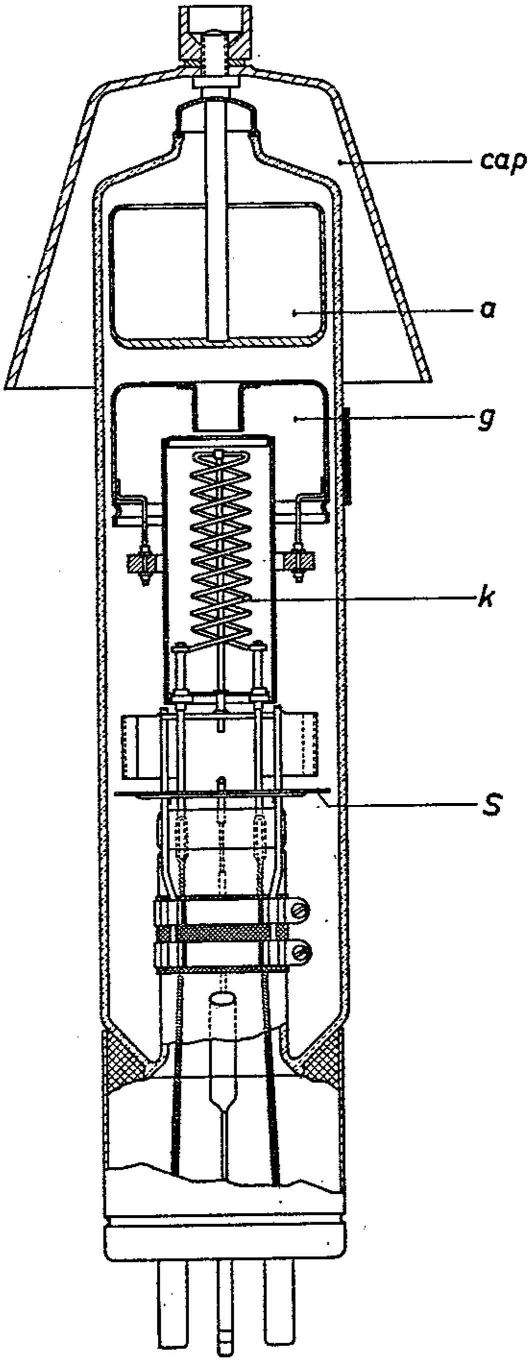

Fig. 70

Controlled high-voltage rectifier tube (Philips type DCG 12/30) with mercury-vapour filling. The short distance between the flat bottom of the anode a and the switching grid g is striking. The latter electrode is practically at cathode potential. The high inverse voltage (27 kV) must be taken up between a and g.
cap is a cap of a thermal insulator around the anode part of the tube. This traps ascending warm air so that, even if there is no anode current flowing, this part of the tube always remains somewhat warmer than the lowest part where the mercury vapour condenses. S is a screen which keeps the heat radiated by the hot cathode k from the lowest part of the tube, so that the temperature of the mercury there, and thus the vapour pressure, remains low.

thus trapped, and will help to evaporate any mercury condensate which may be there.

It will now be clear how well such tubes are designed in the interests of a low mercury vapour pressure.

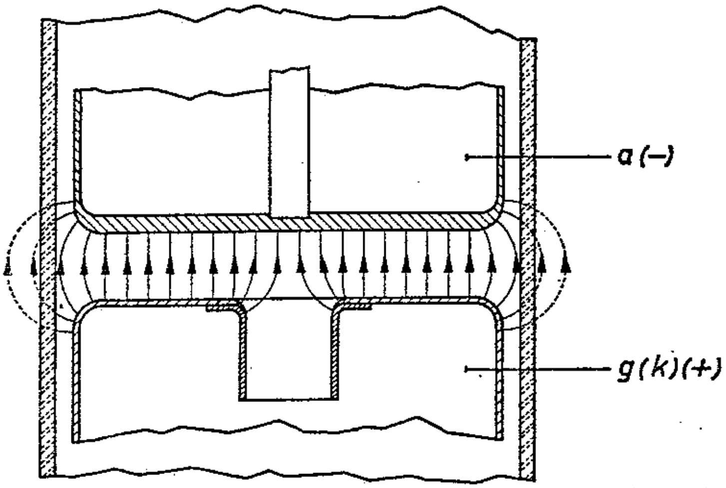

Fig. 71

Distribution of the lines of force between the anode *a* and the grid *g* (or cathode *k*) in the tube of Fig. 70. Because of the compact constructions, only short lines of force are possible within the envelope. The length of these lines of force is small compared to the mean free path of the electrons, which prevents backfiring.

III-c-4 THE MERCURY TEMPERATURE

We now return to the limitation placed on the operating conditions by the use of a mercury filling, in connection with the temperature of the mercury.

It will already have become clear from what has been said above about backfiring that care must be taken not to let the temperature become too high. Fig. 72 shows how $v_{ap\ inv}$ of a high-voltage mercury tube decreases as t_{Hg} increases. But it should not be forgotten that the tube cannot work properly at very low temperatures either. The arc voltage then becomes too high

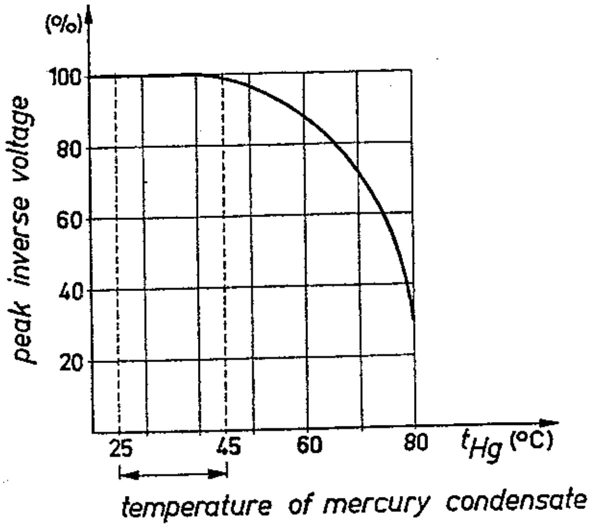

Fig. 72

The temperature of the liquid mercury in a high-voltage tube with a filling of saturated mercury vapour must in general be kept between 25 and 45° C in order to ensure the maximum inverse voltage. At higher mercury temperatures, $v_{ap\ inv}$ decreases as shown in this figure.

owing to the lack of ions, and the arc is quenched too soon. The cut-off periods are associated with undesirable oscillations, which under certain conditions can give rise to high voltages in combination with the supply transformer. The situation begins to resemble that in a vacuum discharge [109].

If it is desired that high-voltage tubes should have a certain (low) vapour pressure in the envelope, and that this pressure should be maintained, then not only must the temperature distribution be properly chosen but fluctuations in the temperature must be limited. The tube must therefore be so designed that the normal variations in the ambient temperature do not cause the temperature of the coldest part of the tube to transgress certain limits. The tube should therefore never be shut up in a cabinet; and it should not be placed near to sources of heat such as transformers. If it is necessary to mount such tubes on a transformer, a screen *S* should be placed between the transformer and the tubes (Fig. 73).

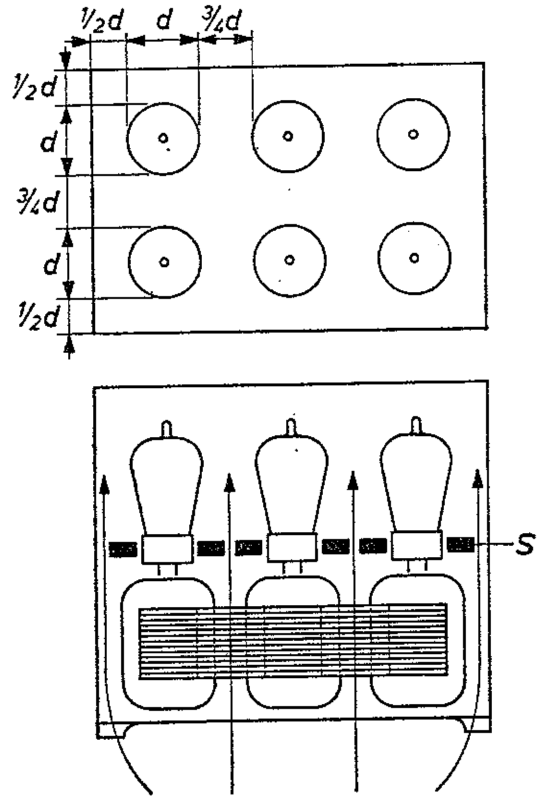

Fig. 73
Sensible arrangement of six tubes in a cabinet with regard to the tube temperature. The heat screen *S* is slotted so that a natural flow of air occurs in the direction of the arrows. On the one hand the power transformer, which is situated under the tubes, is cooled by the circulating air, while on the other hand the warm air which has left the transformer cannot flow past the lowest part of the tubes, which must remain cool. The minimum distances between the tubes, and between the tubes and the wall of the cabinet, are indicated in terms of the diameter *d* of the tubes.

In most tubes of this sort, the temperature of the part of the tube where the mercury condensate is to be found (i.e. the coldest part of the envelope) should not be less than about 15 °C or more than about 75 °C. The corresponding saturation vapour pressures are 8×10^{-4} and 6.5×10^{-2} mm. It will be seen that the restrictions placed on temperature and pressure are not too severe.

There are factors apart from the heat developed in the arc which help to determine the temperature of the mercury, and which should be borne in mind if the tube is to work properly.

First of all, the ambient temperature t_{amb}. For part of the year, t_{amb} will be lower than 15 °C. It is then usually inadvisable to start the discharge in a mercury tube without special precautions. The simplest way to regain the desired temperature of 15 °C is to make use of the heat dissipated in the hot cathode. It is then necessary to wait a certain length of time, until the temperature of the mercury condensate has risen sufficiently, before applying the anode voltage. Now if the tube has been designed properly, the mercury condensate will be found somewhere near the bottom. This is the obvious place for it, since if the tube is cooled by natural convection the air round it will be warmed up and therefore rise, to be replaced by a fresh supply of cold air at the bottom ("chimney effect"). Moreover, if the mercury vapour condenses somewhere in the upper part of the tube, the droplets formed there might fall to the bottom, coming into contact with hot parts of the tube on the way. This could give rise to sudden, though temporary, increases in the vapour pressure which might lead to backfiring. In order to ensure that the lower part of the tube is not much influenced by the warmer upper part, the tube may be made long and thin. This means of course, however, that it will be a long time before the mercury condensate reaches the desired temperature of 15 °C. The warming-up time t_w can be reduced by supplying radiant heat from outside (from an incandescent lamp or small radiator). The direction of the radiation should then be from top to bottom of the tube, so that parts where no condensation should occur are warmed up first. Figure 74 and 75 give some further information about t_w for the DCG 12/30. Fig. 74 shows how fast the temperature of the mercury condensate rises above the ambient temperature (Δt_{H_g}) after V_f has been switched on.

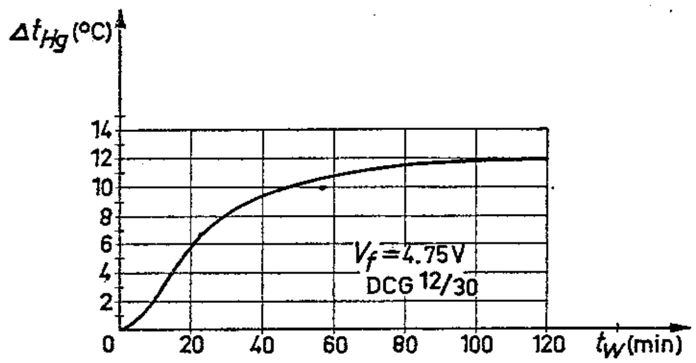

Fig. 74

Temperature of the mercury condensate as a function of time after the cathode of the tube DCG 12/30 has been brought up to temperature. The warming-up time t_w which must elapse before the anode voltage is switched on is determined by the form of this curve.

This graph makes allowance for a possible drop of 5 % in the mains voltage. Fig. 75 shows t_w as a function of t_{amb}, for this tube, t_{H_g} must be at least 25 °C. It takes 1½ minutes just to bring the hot cathode up to temperature. If the tube is turned off for long periods of time (e.g. during the night), and the user would like to be able to switch on the anode voltage without much delay at the beginning of the next operating period, it is a good idea to keep the heater voltage at 60—80 % of its normal value while the tube is switched off.

Another possibility which must be taken into consideration is that the ambient temperature is too high. The tube will in general be designed to give a temperature distribution along the tube which guarantees that the temperature of the condensate does not exceed the maximum permissible value, even if the tube is fully loaded, as long as the ambient temperature remains within limits which are included in the operating data. This entails that, if the tubes are used for polyphase rectification, they should not be placed right next to one another. A separation equal to ¾ of the maximum diameter of the tube is sufficient. The distance between the tube and the surrounding wall should also not be too small. Cooling by natural convection should not be hindered (see Fig. 73). A good rule of thumb is that the distance between tubes and wall should be at least half the maximum diameter of the tube. This suggestion, and the rule that the tube should be placed with the anode on top and the cathode underneath, holds for mercury tubes in general.

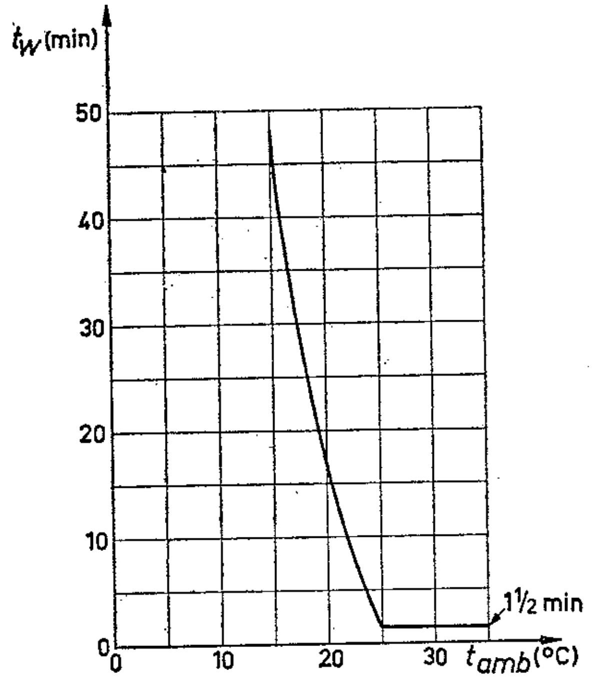

Fig. 75

Influence of the ambient temperature t_{amb} on the time t_w which must elapse before the anode voltage of the DCG 12/30 is switched on. The mercury temperature must be at least 25° C before the anode voltage is applied. If $t_{amb} \geqslant 25°$ C, it is sufficient to wait 1½ minutes after switching on V_f, by which time the cathode will be up to temperature. When $t_{amb} < 25°$ C, one must wait longer.

Of recent years a number of high-voltage tubes have been brought on the market, e.g. the TQ 2/3 made by Brown Boveri with $I_{av} = 3.2$ A and $v_{ap\ inv} = 2$ kV, in which the liquid mercury is replaced by a pill of some mercury compound. This solid compound gradually releases mercury vapour during operation, in such small quantities that condensation does noth give rise to droplets of mercury. Such tubes can be placed in any desired position.

If under exceptional circumstances the mercury temperature should rise above the permissible maximum, forced cooling must be used. A low-power fan gives a considerable cooling effect. It should be placed so as to cooperate with the natural cooling, i.e. *under* the tube if it *blows* or *above* it if it *sucks.*

As we shall see further on (Chapter VI), some types of tubes can also be water-cooled.