CHAPTER IV

THYRATRONS

IV-a **Introduction**

In this chapter we will discuss controlled rectifier tubes with hot cathodes, i.e. *thyratrons.* Other types of controlled rectifiers, such as cold-cathode trigger tubes and tubes with a mercury-pool cathode, will be discussed elsewhere.

A thyratron, relay tube or switching tube is a gas-filled rectifier tube which contains an anode, a hot cathode, and one or more grids. Controlled rectifier tubes with more than one anode also exist; details of these will be found in Chapter VI.

The simplest form of thyratron might be called a gas-filled triode. As in a vacuum triode, the grid is used to control the current. In a vacuum triode, however, the current is continuously and reversibly determined by the grid voltage, while in a gas-filled triode the grid only determines the moment of *ignition.* After the discharge has been ignited the magnitude and sign of the voltage applied to the grid no longer have an appreciable effect on the current, nor can the grid be used to cut off the discharge, because a thin layer of ions or electrons collects around the metal of the grid and screens it off from the discharge. We shall therefore call such a grid a *switching grid* to distinguish it from grids of other kinds, to be discussed below. Devices outside the tube which periodically extinguish

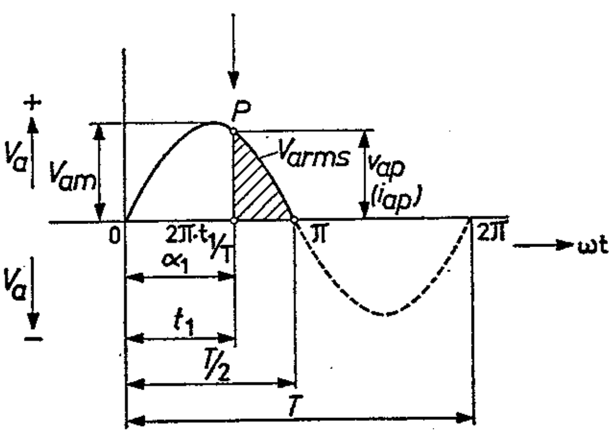


Fig. 76

The current through a thyratron with sinusoidal anode voltage $v_a = V_{am} \sin \omega t = V_{am} \sin 2\pi t/T$ and ohmic load. Ignition at P (time t_1, ignition angle α_1). The current continues until the anode voltage becomes zero at $\omega t = \pi$.
v_{ap} and i_{ap} = maximum momentary voltage and current respectively.

the discharge are used in combination with the grid in order to control the mean current by altering the fraction of the time during which current is flowing.

We can explain the method of control with reference to Fig. 76. If the anode circuit is fed with an alternating voltage $V_{a\ rms}$, no current at all flows during the negative half cycle, and the ignition time t_1 (point P, ignition angle α_1) determines how long current is passed during the positive half cycle of $V_{a\ rms}$. Integrating over the whole period T, we obtain the mean value of the current I_{av}:

$$I_{av} = \frac{i_{am}}{T} \int_{t_1}^{T/2} \sin \frac{2\pi t}{T}\, dt = \frac{i_{am}}{2\pi} \int_{\alpha_1}^{\pi} \sin \alpha\, d\alpha = \frac{i_{am}}{\pi} \cos^2 \frac{\alpha_1}{2} \tag{1}$$

As with diode rectifiers, the ratio of the peak current i_{ap} to I_{av} is of importance. This ratio is plotted as a function of α_1 in Fig. 77.

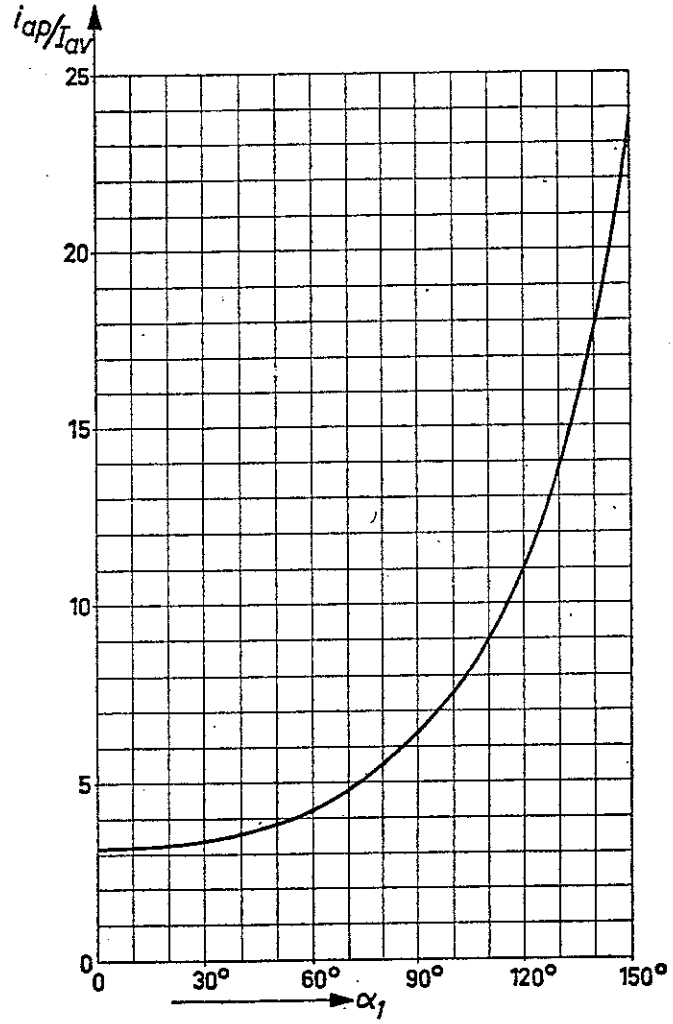


Fig. 77

Value of $i_{ap}/I_{av} = \dfrac{\pi \sin \alpha_1}{\cos^2 \frac{1}{2}\alpha_1}$ as a function of the ignition angle α_1 with reference to Fig. 76.

It is also possible to feed a thyratron with a DC voltage. The external circuit must then be designed so that the anode voltage periodically becomes low enough for the tube to be cut off, so that the mean current can be controlled.

The thyratron, used as a rectifier according to Fig. 76, yields a pulsed direct current. If it is desired to produce a regulated alternating current, a circuit with two thyratrons in "anti-parallel" (Fig. 78) may be used: thyratron A then controls the positive half-cycle, and B the negative half-cycle.

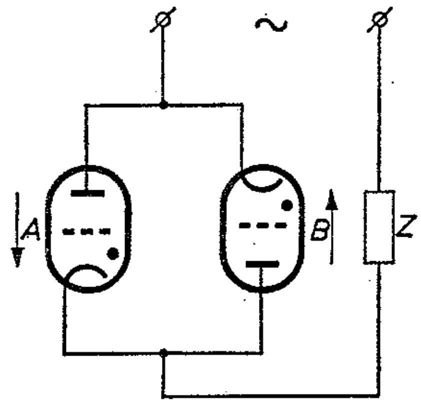


Fig. 78
Basic circuit for two thyratrons A and B in anti-parallel operation in order to obtain an alternating current of regulable value through the load impedance Z; grid circuits not drawn.

IV-b Triodes

IV-b-1 IGNITION WITH THE AID OF A GRID, CONTROL CHARACTERISTIC

We shall give here a brief recapitulation of the mechanism of diode ignition (see I-g-3) which will help us to understand ignition in a triode.

The electrons emitted by a hot cathode form a negative space charge in front of the cathode. If the anode voltage V_a is large and negative the electric field F at the outer edge of the space-charge region is negative and prevents the electrons from leaving this region. With a constant space charge, F becomes less negative as V_a is raised. At a certain value of V_a, which may be slightly negative or slightly positive, the negative field is so small that some electrons can escape from the space-charge region because of their thermal motion and the first small anode current is observed. The current rises gradually as V_a is increased further, until ionization of the gas sets in. In many tubes this will occur soon after V_a has been raised above the ionization voltage V_i; in others the voltage must be higher. The ions formed will then neutralize the space charge in front of the cathode so that the current suddenly rises sharply and attains a value which is only limited by the external circuit or by the saturation current of the cathode. This phenomenon is called the *ignition* of the discharge in the diode, and the anode voltage at which it occurs is called the ignition voltage of the discharge.

The ignition voltage of a triode depends on the grid voltage V_g; the curve showing V_a at ignition as a function of V_g is known as the control or ignition characteristic of the thyratron and is always given among the tube data by the manufacturers. Not only the form but also the significance of this curve differ from that of the control characteristic of a vacuum tube. A typical control characteristic is shown in Fig. 79. This curve shows that in contrast to a diode a triode may have an ignition voltage which is much larger than the ionization potential, if V_g is sufficiently large and

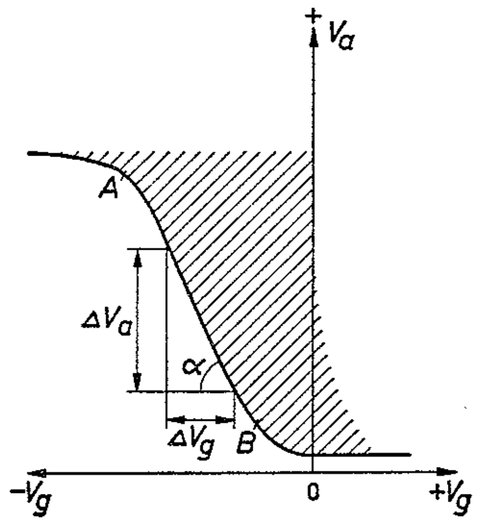


Fig. 79

Control characteristic of a gas-filled triode. In the unshaded area the values of the anode voltage V_a and the grid voltage V_g are such that the tube can be unionized. As soon as the border of the shaded area is attained the tube will ignite. The slope of the straight part AB is given by $\tan\alpha = \frac{\Delta V_a}{\Delta V_g} = \mu$. μ is sometimes called the control ratio of the triode.

negative. The control characteristics may also be regarded as giving the value of the critical voltage $V_{g\,crit}$ as a function of V_a; $V_{g\,crit}$ is the value of V_g at which the tube ignites when the grid voltage is steadily increased from a large negative value at constant anode voltage. The region to the right of the curve (shaded) represents conducting states of the thyratron, and the region to the left non-conducting states.

As long as the tube is not ignited it resembles a vacuum triode and the electric field at the boundary of the space-charge region in front of the cathode is negative. This field is mainly determined by the value of $V_a + \mu V_g$ where the coefficient μ, which is often called the control ratio, is usually considerably larger than unity because the grid is nearer to the cathode than is the anode. The field becomes less negative as V_a or V_g is raised and as soon as the field is virtually zero a small current of electrons will escape from the space-charge region just as with the diode. If now V_a is considerably greater than V_i, these electrons will be given enough energy to ionize the gas between the grid and the anode; the ions formed will pass through the grid and neutralize the space charge in front of the cathode so that the discharge ignites. In other words the thyratron will ignite as soon as $V_a + \mu V_g$ reaches a constant value, which explains the linear part of the control characteristic between A and B in Fig. 79. At lower values of V_a (but still well above V_i) the first electrons escaping from the space-charge region do not acquire the energy needed to produce enough ions to ignite the discharge; it is therefore necessary to increase their number by increasing for example the grid voltage. The control characteristic thus levels off at lower anode voltage as Fig. 79 shows. The curve can be continued to lower values of V_a and consequently to higher values of V_g until V_g becomes positive. Then an appreciable electron current will start to flow to the grid, and a low-current arc will strike between the grid and the cathode at a relatively small positive value of V_g. This determines the upper limit of V_g, but the ignition voltage at the anode can be made somewhat lower by increasing the arc current flowing to the grid (see Fig. 80).

The control characteristic also levels off at high values of V_a, because when the voltage between the grid and the anode approaches the breakdown voltage for a glow discharge, ions will be formed between these two electrodes so that the tube ignites even though the grid is made very negative (see Fig. 79). This region of the characteristic is of no practical use and is not usually shown.

For practical purposes a thyratron control characteristic can be divided into a negative part ($V_g<0$) and a positive part ($V_g>0$). Most thyratrons

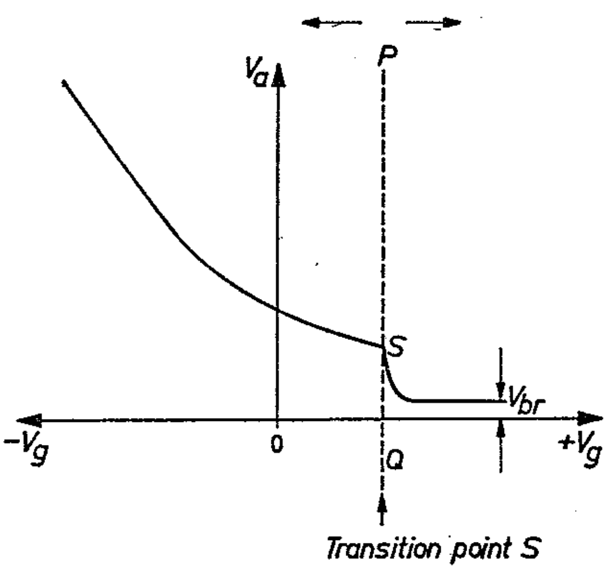


Fig. 80
The control characteristic of a thyratron generally consists of two parts: the (grid) voltage characteristic to the left of the line *PQ* and the (grid) current characteristic to the right. The grid voltage corresponding to *PQ* may be either positive or negative, depending on the construction of the tube.

are so constructed that the control characteristic is mainly, or entirely, situated in the negative region, but some are specially designed to give a large positive part.

The choice between the various constructions is governed by the following considerations. Below a certain value of V_g, which may be zero or slightly positive, the grid current needed for ignition is negligible. Above this value of V_g the grid current necessary for ignition becomes appreciable and increases with decreasing values of V_a. This division of the control characteristic into what we might call a grid-voltage part and a grid-current part is what really matters in practice (see Fig. 80).

It might be thought at first sight that a current characteristic would be generally preferable to a voltage characteristic, since in the latter case a voltage source is needed in the circuit to keep the grid negative as long as no discharge is desired, while in the former case it is enough to keep the grid current small. However, a sturdier grid circuit is necessary with a current characteristic since the grid current needed for ignition and thus the power dissipated in the tube and the grid circuit are larger.

The control characteristic for a given thyratron of a certain type may differ considerably from that of another one of the same type, because of unavoidable differences in the electrodes and the gas filling. Moreover the characteristic of a tube will vary slightly during its life owing e.g. to emitter material sputtered or evaporated from the cathode on to the switching grid. The temperature in particular has a considerable effect on the characteristic of a mercury-vapour filled thyratron because of the change in pressure (Fig. 81, see I-b). This is usually taken into account by giving the limits between which the control characteristic can vary, as shown in Fig. 82, rather than a single curve.

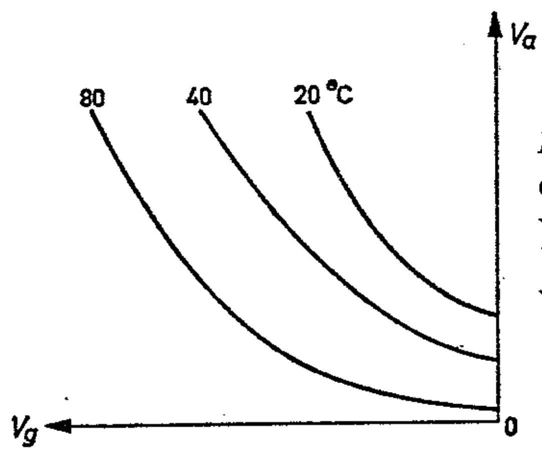


Fig. 81

Control characteristics of the same mercury vapour-filled thyratron for three temperatures. V_a = anode voltage, V_g = switching-grid voltage.

IV-b-2 CONTROL

Control with an alternating voltage in the anode circuit

The control characteristic can be used to construct the variation of $V_{g\,crit}$ (see IV-b-1) with time for a given variation of the anode voltage, as shown in Figure 83 (broken curve) for a sinusoidal variation of V_a. The curve obtained in this way is called the critical grid-voltage curve.

It may be seen from Fig. 83, that the $V_{g\,crit}$ curve for a thyratron which is driven with a sinusoidal anode voltage $V_{a\,rms}$ is also sinusoidal, as long as only the linear part of the control characteristic is used. We shall restrict the following discussion to this part of the characteristic.

The grid voltage applied for the control of the ignition can now be plotted in the same figure. The point where the grid-voltage line first cuts the $V_{g\ crit}$ curve determines the *ignition angle* α_1 (see Fig. 76). In

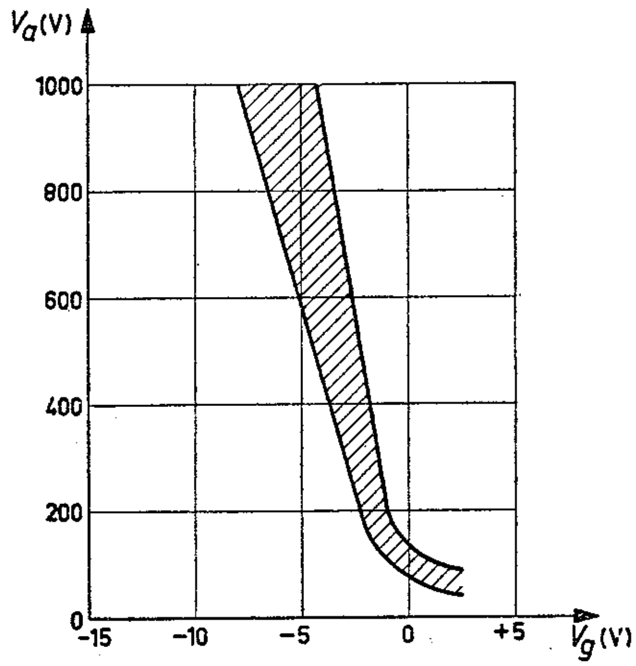


Fig. 82
Spread of the control characteristics of a certain type of thyratron.

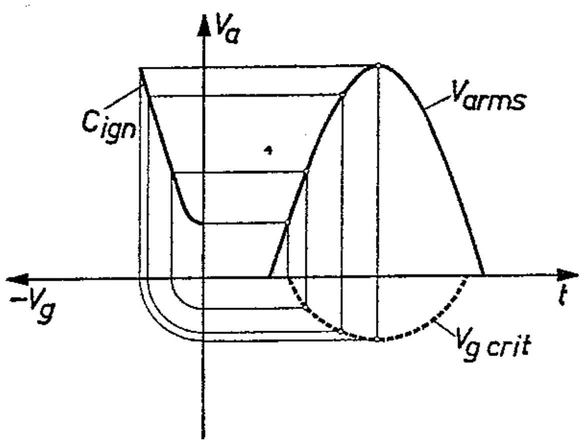


Fig. 83
The dotted line is the critical grid-voltage curve $V_{g\ crit}$ for a sinusoidal anode voltage $V_{a\ rms}$. The construction of the dotted line from the control characteristic C_{ign} and the anode voltage is shown in the figure.

order to change the ignition angle the point of intersection must be displaced. This may be done in four ways, in which the applied grid voltage is:

a. DC
b. AC of variable phase
c. DC modulated by AC
d. DC modulated by a voltage pulse.

Method *a* uses a DC grid voltage of variable magnitude. Figure 84a shows the anode voltage V_a and the corresponding $V_{g\ crit}$ as functions of time (it is clear that we need only consider the positive half-period). If the applied grid voltage has a constant value of $-V_{gI}$, then the tube is ignited at the point A where $V_{g\ crit}$ is equal to $-V_{gI}$ (point B). The current then continues to flow until the point C, at which V_a becomes less than V_{arc} and the discharge is quenched.

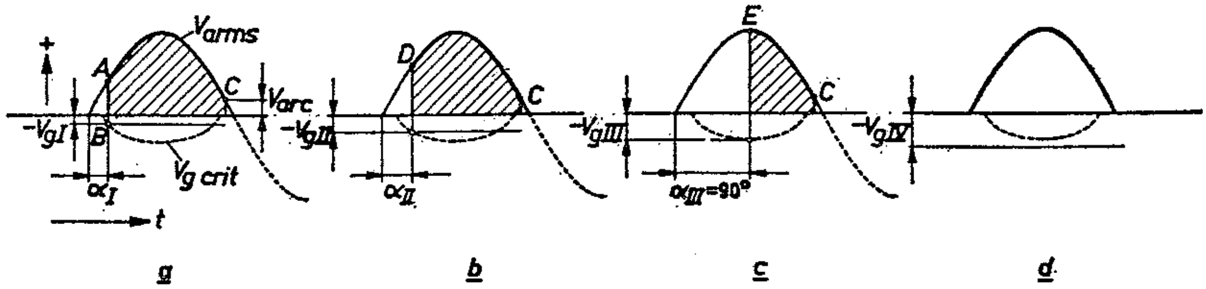


Fig. 84

Current regulation by vertical shift control.
The full line $V_{a\ rms}$ is the anode voltage and the dotted line $V_{g\ crit}$ is the corresponding critical grid-voltage curve. As the DC grid-voltage V_g is made more and more negative from $-V_{gI}$ to $-V_{gII}$ and then to $-V_{gIII}$ the ignition point shifts from A to D and then to E (figures a, b and c). In figure d, V_g is so negative that the V_g line does not intersect the dotted curve for the critical grid-voltage so that the tube does not ignite. The discharge in the tube is quenched as soon as the anode voltage becomes equal to the arc voltage V_{arc} (at C).

If now the grid voltage is reduced to $-V_{gII}$, the tube ignites later (point D, Figure 84b).

Figure 84c shows that, when the applied grid voltage is equal to $-V_{gIII}$, the minimum value of $V_{g\ crit}$, the tube ignites when V_a is maximum (point E), and the tube only conducts for slightly less than a quarter of a period. If V_g is made any more negative ($-V_{gIV}$, Fig. 84d), there is no discharge at all. The *ignition angle* corresponding to $-V_{gIII}$ is 90°, and it cannot be made any larger. The shaded areas give a measure of the DC current passed by the tube. This method of control is called *vertical* shift control, since the magnitude of the DC grid voltage is varied, i.e. the V_g line is displaced vertically.

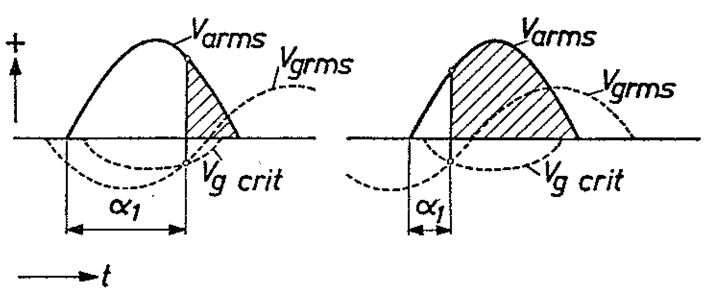


Fig. 85

Current regulation by horizontal shift control. The full line $V_{a\ rms}$ is the anode voltage, the broken line $V_{g\ crit}$ represents the critical grid-voltage curve and the broken line $V_{g\ rms}$ the AC voltage of constant amplitude applied to the grid. The ignition angle α_1 is varied by changing the phase of $V_{g\ rms}$ with respect to the anode voltage.

This method is very simple, but it is has the disadvantages that α cannot exceed 90°, so the value of the mean current can only be changed by a factor of 2, and that the moment of ignition for a given control voltage is dependent on the position and the slope of the critical grid-voltage curve. As we have already seen, the form of this curve will vary somewhat from tube to tube of the same type of thyratron.

The ignition angle α can be made greater than 90° by applying AC voltage of variable phase to the grid (method *b*). In this method the alternating grid voltage $V_{g\ rms}$ has a constant amplitude, but is shifted in phase with respect to $V_{a\ rms}$. It may be seen from Fig. 85 how this causes the ignition point to vary. This is known as *horizontal* shift control as the curve representing $V_{g\ rms}$ is displaced horizontally.

Phase shifting entails rather complicated circuitry as we shall see below. Method *c* is therefore often used instead. In this case the grid voltage is made up of an AC component $V_{g\ rms}$ which is 90° out of phase with $V_{a\ rms}$, superimposed on a DC voltage $-V_g$ (fig. 86). In certain cases it may be better to replace the alternating voltage by a saw-tooth voltage. Here again we have a case of vertical shift control: the phase of $V_{g\ rms}$ remains constant, and the ignition point is displaced as the value of $-V_g$ is varied.

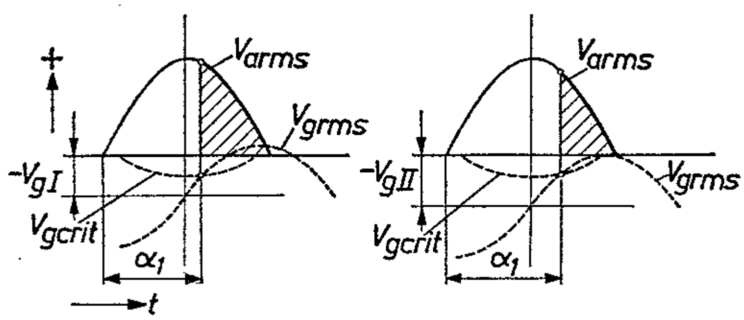


Fig. 86

Current regulation with vertical shift control by means of a variable DC grid voltage $-V_g$ and an AC grid voltage $V_{g\ rms}$ of constant amplitude and constant phase lag of 90° with respect to the anode voltage $V_{a\ rms}$. The ignition angle α_1, is different for the two voltages $-V_{g\text{I}}$ and $-V_{g\text{II}}$.

Inspection of Fig. 86 shows that the intersection of $V_{g\ rms}$ with the $V_{g\ crit}$ curve in the right-hand half of the figure is not very sharp, which is one of the disadvantages of the method as the ignition angle α_1 is not well determined here. This trouble could be solved by increasing the amplitude of $V_{g\ rms}$, but then the voltage difference between the anode and the grid increases at the beginning of the positive half-period so that untimely ignition because of a glow discharge between these electrodes may occur.

Method *d* is a very elegant one, making use of positive voltage pulses

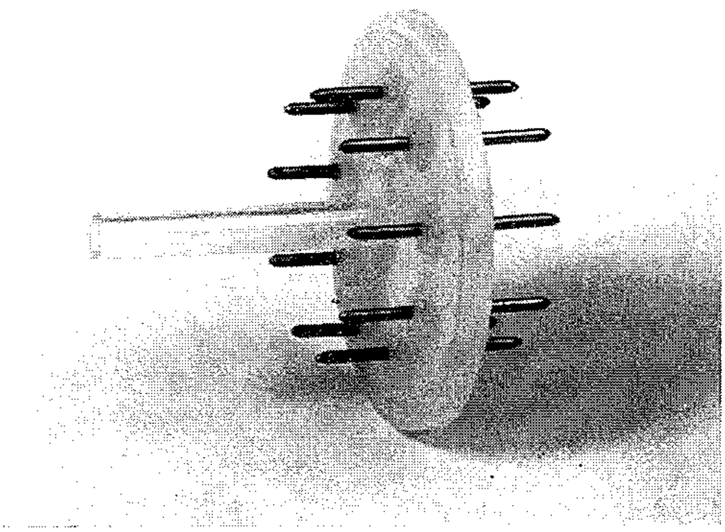


Photo 1

Pressed-glass seal with leads arranged in a ring.

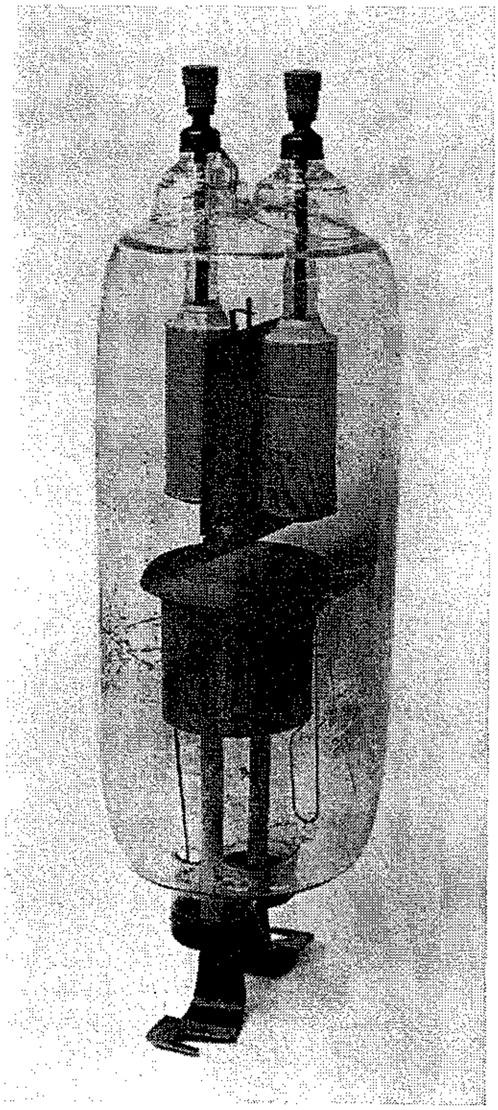


Photo 2

Two-phase rectifier. The glass-metal anode and cathode seals consist of a piece of pressed glass with two cups of chrome seel sealed into it. The leads are soldered on the cups.

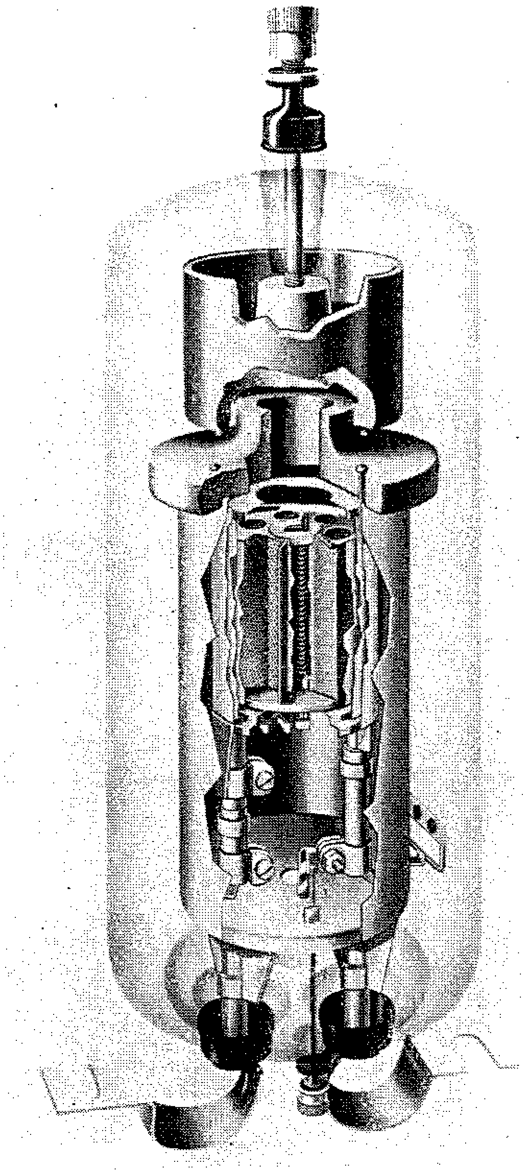


Photo 3

Partly sectional view of mercury vapour thyratron PL 260.

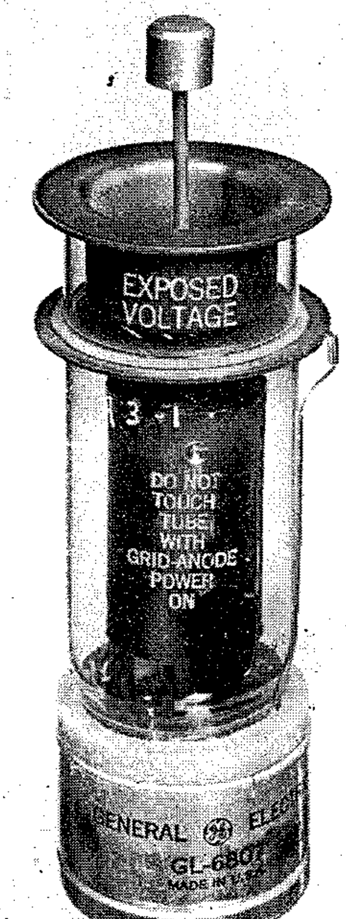


Photo 4

Photograph of thyratron type GL 6807 (General Electric Co.).

superimposed on a negative DC grid-bias voltage. As we have seen, the grid is only needed to initiate the discharge: it does not matter in principle what its voltage is during the rest of the cycle. A sharp peak of short duration defines the ignition angle so well that it may even be said to be

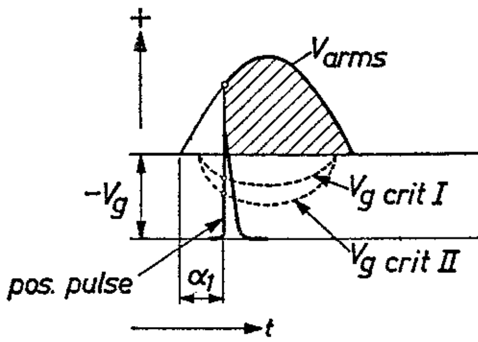


Fig. 87

Current regulation by horizontal shift control by means of a positive voltage pulse superimposed on a negative grid bias voltage $-V_g$. Ignition does not depend on the situation of the critical grid-voltage curve $V_{g\,crit}$. Two such curves $V_{g\,crit\,I}$ and $V_{g\,crit\,II}$ have been given for two thyratrons having different control characteristics. The ignition angle α_1 is varied by shifting the phase of the voltage pulse with respect to the anode voltage $V_{a\,rms}$.

independent of variations in the critical grid-voltage curve, as may be seen from Fig. 87. This figure shows the critical grid-voltage curves for two thyratrons with different ignition characteristics ($V_{g\,crit\,I}$ and $V_{g\,crit\,II}$). The voltage peak cuts both these curves at practically the same time. In order to control the mean current of the tube, the position of the voltage peak is shifted along the time axis, i.e. this is also horizontal shift control.

In methods *b* and *c* the grid may be positive in the negative half-period when the tube has ceased to conduct. A discharge will then persist between cathode and grid. This is often undesirable, as ions from this discharge will bombard the anode and reduce its life, especially in HT tubes. With peak control the grid voltage is negative in the negative half-period of the anode, which is another advantage of this method.

The voltage peaks are produced by special little transformers or by pulse circuits, which may be controlled by the phase of an auxiliary AC voltage. The phase of an AC voltage may be shifted either by altering the position

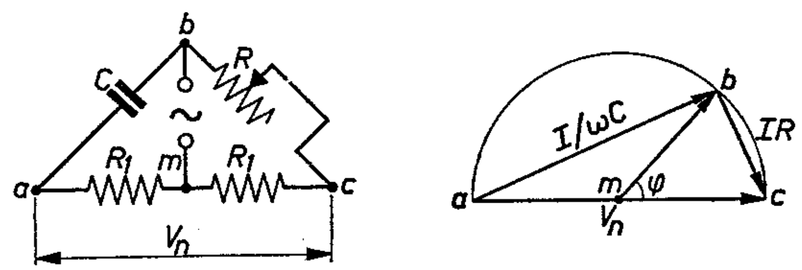


Fig. 88

Circuit and vector diagram of an RC phase-shifting device. The series combination of the capacitor *C* and the variable resistance *R*, as well as the resistors R_1, are connected across the mains terminals *a*, *c*, having a voltage V_n. A voltage $\frac{1}{2}$ V_n is found between the mid-point *m* and the junction *b* of *C* and *R*; the phase of this voltage may be varied over nearly 180° by variation of *R*.

of a stationary coil in the rotating magnetic field of a triphase stator or by means of a bridge circuit such as that shown in Fig. 88.

Control with a DC anode voltage

In certain cases, e.g. time-switch circuits and counting circuits, it is normal to use a DC anode voltage instead of an alternating one. The discharge can then be ignited at any moment by means of a voltage peak or a square-wave voltage on the grid, since the anode is never negative. The periodical extinguishing of the discharge needs special circuits (see V-f-4).

The resistance in series with the grid

Once the method of control has been decided on, the next item that needs attention is the resistance to be inserted in series with the grid.

Minimum value of the series resistance

If the grid is positive with respect to the cathode it acts as a probe in the plasma of the discharge of an ionized tube and an electron current will flow to it. A resistance R_g is therefore connected in series with the grid in order to keep this current within reasonable limits.

In many applications it is further stipulated that the grid voltage V_g must be more positive than –10 V with respect to the cathode while the main current is passing. A negative grid also acts as a probe placed in the main discharge, attracting positive ions, and a strongly negative grid might be damaged by ion bombardment.

The supply voltage V_{gg} applied in the grid circuit depends on the method of control and is generally more negative than –10 V. In order to satisfy the condition $V_g > -10$ V the resistance R_g must have a minimum value which follows from the condition:

$$V_g = V_{gg} - R_g I_g > -10 \text{ V}$$

$$\text{i.e.} \qquad R_g > \frac{V_{gg} - (-10)}{I_g} \qquad (2)$$

This condition must be satisfied during the greater part of the conducting phase. At very low values of I_a; I_g will be low as well. This may lead to large values of R_g, but it may generally be assumed that the condition is no longer important for $I_a < 0.1 \times I_{av\ max}$, as then the grid current is so small that sputtering damage need not to be feared.

As an example, Fig. 89 gives the ion current to the grid as a function of $-V_g$ for a thyratron (type 5544) for which $I_{av\ max} = 3.2$ A. We can now calculate the minimum value which R_g must have in order to ensure that $V_g > -10$ V. We will assume that the grid is controlled by the pulse method (Fig. 87) and that the DC component of the supply voltage for the grid is $V_{gg} = -60$ V. If $I_a = 2.4$ A we see from Fig. 89 that $I_g = -53$ mA so that

$$R_g > \frac{-60 - (-10)}{-53 \times 10^{-3}} \approx 950\ \Omega$$

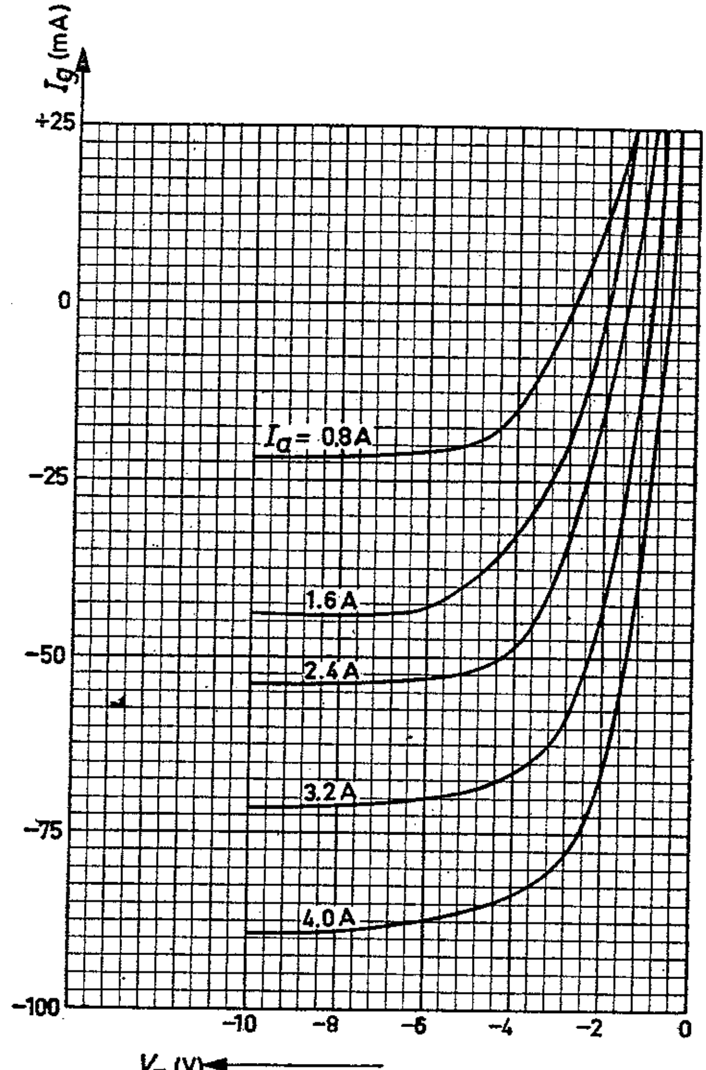


Fig. 89

Grid-current characteristics of thyratron type 5544.
I_g = grid current, V_g = grid voltage, I_a = anode current.

It may further be seen from Fig. 89 that the grid current decreases if I_a decreases, so that for $I_a < 2.4$ A, R_g must be greater than 1000 Ω. For $I_a = 0.32$ A that is 10 % of $I_{av\ max}$ we find $I_g = 8$ mA and $R_g > 6250\ \Omega$.

Maximum value of the grid series resistance

It might be thought that a much larger value of R_g than the minimum value found from the condition $V_g > -10$ V would help to restrict the grid current and thus to reduce the power in the switching grid circuit considerably. There are however reasons why R_g should not be too large.

Spread in the ignition characteristics

The voltage V_{gg} which must be applied in the grid circuit to control the tube is more negative by an amount $R_g \times I_g$, the voltage drop over the resistance, than the voltage V_g at the grid itself. Therefore the spread in the "control characteristics for grid circuit voltage" giving V_a at ignition as a function of V_{gg} (see Fig. 90) is greater than the spread in the control

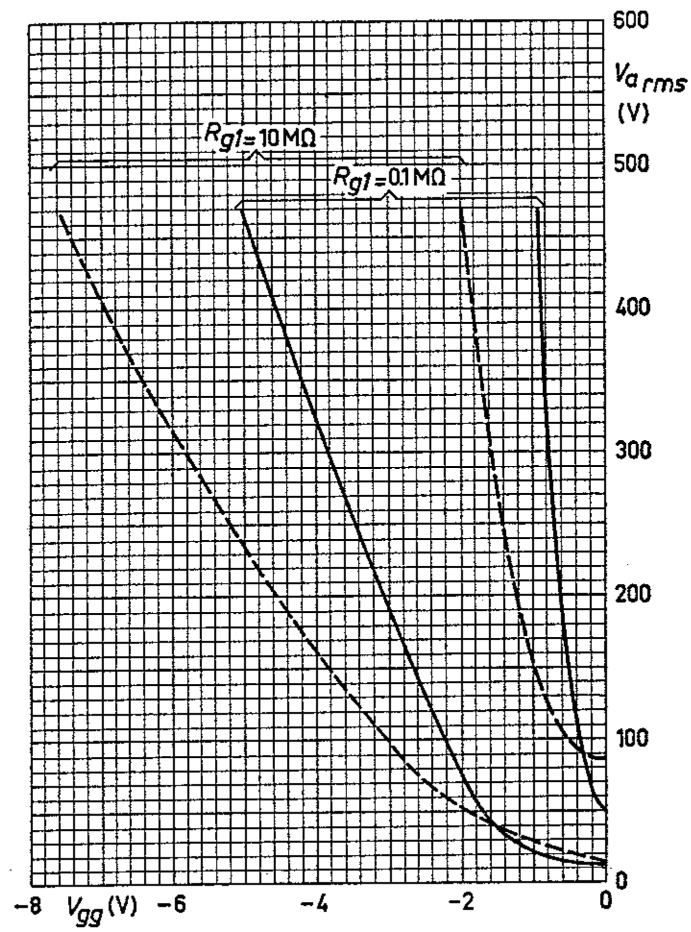


Fig. 90

Spread of control characteristics for grid-circuit voltages for two values of the resistance in series with the grid.
V_{gg} = grid circuit voltage, $V_{a\,rms}$ = anode voltage,
R_{g1} = resistance in series with the grid.

characteristics of Fig. 82 for the same type of thyratron where no grid resistor has been taken into account. Further it is evident from Fig. 90 that the spread for a 10 M Ω series resistance is considerably more than for a 0.1 M Ω resistance R_g. It is obvious that this phenomenon sets an upper limit to R_g as a very large spread in these "control characteristics" is undesirable.

Grid emission

The equilibrium temperature which will be attained by the switching grid during the operation of a thyratron is of great importance. We will see that strong heating of the grid must be avoided if the tube is to work properly. The temperature which is actually reached will be determined by the equilibrium between the heat supplied to the grid and the heat it can get rid of.

Let us consider a thyratron in which the grid is given a permanent negative bias $-V_{go}$, and is made positive only during a relatively short part of the positive half-period (e.g. 0.1 m sec) by means of a peak voltage $+ v_{gp}$ superimposed on $-V_{go}$. There will thus be an ion current flowing to the grid during the greater part of the positive half-cycle of V_a. The grid temperature rises owing to the effect of this ion current and thermal radiation from the hot cathode, the anode etc. At the same time the grid is cooled by conduction, convection and to a certain extent by radiation, and these processes will finally reach equilibrium at a certain temperature.

The equilibrium temperature may be so high that the grid, which is unavoidably covered with an oxide layer consisting of sputtered and evaporated cathode material as time goes by, may start to emit electrons itself (see II-e-2-a). If the main discharge is not ignited and the anode is positive, the grid acts as a cathode in the *g-a* space. An emission current $-I_{gem}$, whose value depends on the grid temperature, will then flow from the grid to the anode, decreasing the effective negative grid voltage as a result of the voltage drop $I_{gem}\ R_g$ in the resistance in series with the grid. If the value of R_g is too high, the voltage drop will be so great that the grid will no longer be able to stop the ignition of the tube. This may be clearly seen from Fig. 86, which shows the critical grid-voltage curve for a thyratron controlled by an alternating voltage superimposed on a negative grid bias. Under the conditions mentioned above, the ignition point shifts towards the beginning of the cycle. This means that I_a increases, so the grid gets hotter, thus increasing the grid emission current even more, and so on. The effect is cumulative, and in the end the grid voltage becomes so high that the tube no longer responds to it.

The manufacturer of a tube has of course taken adequate measures to decrease the chance of grid emission and the user can keep this chance low by careful handling. Still, grid emission sets an upper limit to the value of R_g that can be used for proper control of the discharge.

The measures that can be taken against grid emission include designing the tube so that the grid temperature remains low and that the grid is placed in the best position for being protected against sputtered or evaporated material from the cathode.

The xenon-filled thyratron type 6807 (Photo 4 and Fig. 91) has been specially designed for very low grid emission. The grid and the cup-shaped anode are strongly cooled by convection thanks to their direct contact with the air. Despite high values of v_{ap} and $v_{ap\ inv}$, the clean-up (see II-b-2) is kept low. The rare-gas fillings ensures that the tube can work at high ambient temperatures as well as at low ones, and that it can be placed in any position.

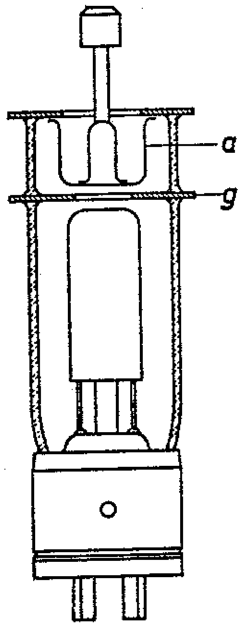


Fig. 91
Construction of thyratron GL 6807.
The anode *a* and the grid *g* are strongly cooled owing to their contact with the surrounding air. At three places a metal-glass weld is used for the vacuum tight seal. The tube is therefore very shockproof. The construction assures long leakage paths between the grid and the other electrodes.

The anode-grid capacitance C_{ag} (see also IV-c-2)
The value of R_g is also limited by the capacitance between the anode and the grid of the thyratron, which is represented by C_{ag} in Fig. 92. In practice, C_{ag} is due not only to the inter-electrode capacitance within the tube but also to the capacitance of the lead wires. The importance of a low value for C_{ag} can be explained with reference to Fig. 93. A sudden fluctuation in

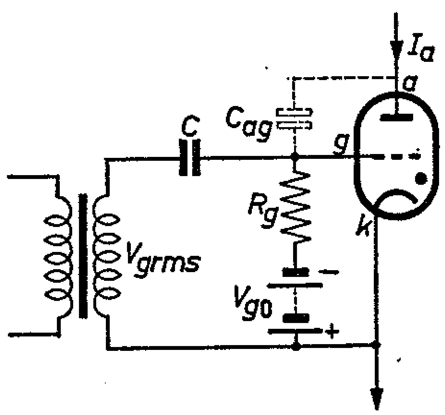


Fig. 92
Example of a control circuit for a thyratron. The grid *g* obtains the sum of a DC negative voltage V_{go} via the resistance R_g and an alternating voltage $V_{g\ rms}$ via the condensor *C*.
k = cathode, *a* = anode,
C_{ag} = anode-grid capacitance,
g = switching grid, I_a = anode current.

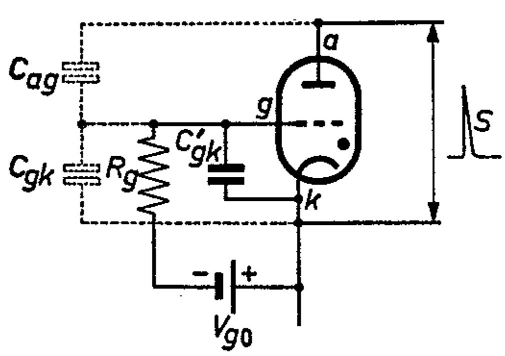


Fig. 93
Interelectrode capacitances of a triode.
A greater or smaller part of an interfering signal *S* between the anode *a* and the cathode *k* will appear on the grid *g*, depending on the ratio C_{ag}/C_{gk}. It may ignite the thyratron prematurely.
V_{go} = DC control-grid voltage.
R_g = resistance in series with the grid.
C^1_{gk} = capacitance to enlarge C_{gk}.

the voltage between a and k, e.g. owing to some disturbance, causes a voltage jump between g and k because C_{ag} and C_{gk} form a potentiometer circuit. This voltage jump is larger as C_{ag} is larger, and is damped by R_g, the more so as R_g is smaller. This means that if the voltage fluctuation of the grid is positive and if the value of R_g is too high, the triode can ignite before it should.

A large value of R_g is therefore only found with small thyratrons, not only because the chance of grid emission is small as a consequence of the low losses, but also because C_{ag} is small. It is best to place R_g as close to the grid terminal as possible, so as not to increase C_{ag} unnecessarily by the parasitic capacitance of the wire.

The grid insulation

A fourth reason for setting an upper limit to the resistance in series with the grid is that the voltage drop in R_g caused by leak current in the grid insulation should be negligible in comparison to the grid voltage itself.

Example of grid-current characteristic

Photo 3 shows a sectional view of a mercury-vapour thyratron for $I_{av} = 25$ A, the Philips type PL 260, which is often used in the grid-current region of its characteristic. The anode and the annular upper part of the grid are made of graphite, which is a good thermal radiator and decreases grid emission considerably. The indirectly heated cathode and the screens are in the middle of the tube. The sturdy construction needed for industrial use can be seen from the heavy cathode leads and terminals for the anode cable and grid connection.

The ignition characteristic is of the combined type, the grid-current part being found at anode voltages below about 500 V.

Fig. 36 shows the influence of I_g (I_{ah}) on V_{ign}. Assuming that the condition for ignition is fulfilled, the grid current for a high-power thyratron like this one must be at least 3 mA in order to ensure sufficiently rapid ignition at low anode voltages. The resistance in series with the grid must therefore be kept rather small ($R_g < 20$ kohm in this case) and the grid circuit must have enough power to give this current.

This type of thyratron is very suitable for the smooth regulation of the speed of DC motors and saves time when starting and braking.

IV-b-3 EXTINGUISHING THE DISCHARGE

As we have mentioned above, it is not in general possible to extinguish the discharge by making the grid negative; in certain very special cases [14, 15], however, this can be done.

A general solution of this problem of stopping the discharge is to be found in the proper design of the anode circuit: this will be discussed further in Chapter V.

IV-b-4 THE BUILD-UP AND DECAY OF THE DISCHARGE

Some time must elapse between the moment the grid voltage reaches the critical value at which the first ions are formed and the moment when the anode voltage reaches the low value V_{arc} [2, 16, 17].

During this time, the ions which are needed to neutralize the space charge in front of the anode and to make up the arc are gradually formed. The operating voltage of the tube is higher than normal in this period, and the dissipation is also high. The ionization time is of the order of a few microseconds: in other words, the plasma reaches its final state in a very short time.

During the first few pulses after the tube is switched on there is also a rather slower build-up process at the cathode, whose surface may not immediately be in the right state to deliver the required peak current. This phenomenon is also found with diodes, but it is of no importance there. In thyratrons, however, if ignition occurs near the peak of an alternating voltage, care must be taken that the value of di/dt is not too high, since if it is, the cathode will be overloaded for the first few pulses. The necessary free barium atoms will not be able to diffuse to the surface of the emitting layer quickly enough, and the cathode temperature will increase excessively so that sputtering occurs. The normal equilibrium will gradually be restored and the inactive layer activated, but the damage to the cathode caused by sputtering cannot be entirely reversed. The rate of current increase which is possible without danger for the cathode of rare-gas or mercury thyratrons is of the order of a few amperes per millisecond.

It may be stated in general that care is to be taken with the design of the circuit in order to prevent excessive cathode sputtering (see also commutation, below).

When the anode voltage falls below V_{arc} at the end of the conducting period, some time is needed before all the ions and electrons have moved towards the walls of the tube and the electrodes where they can recombine (I-e-2). In particular, the ions form a layer on the (negative) grid, and until this layer has been sufficiently removed the grid is not able to prevent a new discharge. The time needed for all the ions to recombine is called the de-ionization time, but in practice the *recovery time* is generally used, i.e. the time between the moment when the voltage falls below V_{arc} and that when the grid has recovered its ability to prevent a discharge (it is not necessary for *all* the ions to have recombined in this recovery time).

The recovery time is of importance for the application of thyratrons, as its limits the frequency of the alternating anode voltage at which the thyratron will function properly: if the positive anode voltage returns before the grid has recovered, the tube will function like a diode.

The main factors which influence the recovery time are:

a. the electrode geometry,
b. the nature of the gas,
c. the gas pressure or vapour pressure (temperature) and
d. the magnitude of the current which passed through the tube before it was cut off.

A rapid de-ionization is furthered by appreciable negative electrode voltages. If the electrodes are too negative, however, the results will not be so good because of new ionizations (Fig. 94).

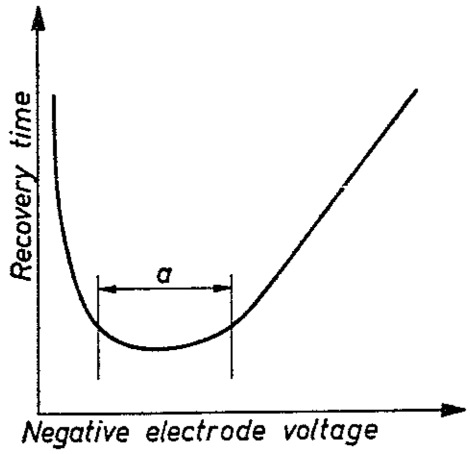


Fig. 94
Recovery time of a thyratron as a function of the negative electrode voltage. If the frequency of the anode voltage is relatively high the best region for operation is *a*.

Large electrodes with a small distance between each other, light gases and low gas pressures all make for rapid de-ionization. The recovery time for the heavy mercury ions is of the order of 1 millisecond; for the rare gases, it is about one tenth of this.

It is obvious that a large current through the tube will produce more ions than a small one, and that the recovery time will therefore also be somewhat longer with large currents.

Commutation.

Heavy mercury thyratrons are often used in polyphase rectifier circuits, in which e.g. six thyratrons in succession pass the desired current I, so that the direct current obtained may be practically free of a ripple. The rest of the circuit ensures that as each thyratron is ignited the current through this tube reaches the desired value I with a certain delay t_δ, while the current in the previous tube decreases to zero.

This process is called commutation and t_δ is called the commutation time. When the current flowing through the tube becomes zero, the anode voltage changes very rapidly from a small positive value to a large negative value. The total voltage change is denoted by $-\Delta V$. The first essential for the proper functioning of the tubes is that the commutation time should be larger than the above-mentioned recovery time.

Care must also be taken that the *inverse anode voltage* (i.e. the anode voltage during the negative half-cycle) does not increase too rapidly during commutation, or the ions in the remaining plasma will bombard the anode, causing excessive anode sputtering and thus gas cleanup, shortening the life of the tube. Under very unfavourable circumstances, this anode bombardment can even lead to arc back, i.e. a discharge through the tube in the reverse direction which will cause a short-circuit.

Naturally, the permissible rate of increase of the inverse anode voltage $-\mathrm{d}V_{inv}/\mathrm{d}t$ depends on the rate at which the plasma recombines, since if there is practically no plasma left a high voltage will not cause much harm, while conversely if the plasma takes a long time to recombine the inverse anode voltage must be increased slowly to avoid the above-mentioned effects.

The *commutation factor* F_c has been found to be of use in dealing with the situation in practice not only for mercury thyratrons but also for thyratrons filled with a rare gas. This factor is defined as the product of the current decrease $-\mathrm{d}i_a/\mathrm{d}t$ in amps per microsecond and the increase of the inverse anode voltage $-\mathrm{d}V_{inv}/\mathrm{d}t$ in volts per microsecond:

$$F_c = \frac{-\mathrm{d}\,i_a}{\mathrm{d}\,t} \times \frac{-\mathrm{d}\,V_{inv}}{\mathrm{d}\,t} \quad \text{in} \quad \frac{\mathrm{A} \times \mathrm{V}}{(\mu\,\mathrm{sec})^2} \tag{3}$$

It is usual to measure $\mathrm{d}i_a/\mathrm{d}t$ for the 10 microseconds immediately preceeding the extinguishing of the current, and $\mathrm{d}V_{inv}/\mathrm{d}t$ for the first 200 V of the increase of the inverse anode voltage. As long as the commutation factor does not exceed the value given by the tube manufacturer the undesirable effects of commutation will be kept within reasonable limits. In practice, this sets a limit on the operating frequency of the tube, and it also means that care must be taken with the design of the auxiliary circuit.

In order to give an idea of the order of magnitude and practical use of F_c, we will consider a thyratron which has been given the number 5545 by several manufacturers. This is a thyratron filled with xenon for $I_{av} = 6.4$ A, $i_{kp} = 80$ A and a maximum inverse anode voltage

$v_{ap\ inv} = 1500$ V. The maximum value of F_c is given as 130 AV/μsec^2 in the tube data.

If this tube were used in a single-phase circuit with a purely ohmic load (a simple example, which is not of much practical significance), where the inverse voltage at the anode is sinusoidal with a peak value of 1500 V while the peak current is 80 A, calculation shows us that the frequency may be as high as 5000 c/s. In practical circumstances, the electrode capacitances of the tube as well as parasitic capacitances and inductances in the associated circuit increase the effective value of F_c. It is very difficult however to take these factors into account in the calculation of F_c for a given circuit. The best source of information about the commutation behaviour of the tube is therefore practical experience. The xenon tube mentioned above operates well at 500 c/s, with a long life; small thyratrons filled with rare gas can get up to 3000 c/s.

Mercury tubes are limited to 500 c/s in the ohmic circuit just mentioned because of the high atomic weight of mercury. In practice they cannot operate above 150 c/s.

Wasserab [56, 57] has investigated the behaviour of mercury-vapour thyratrons under the conditions prevailing in polyphase rectifiers in more detail. He concluded that here the intensity of the ion bombardment to which the anode is subjected, and in particular the risk of arc-back, can be taken into account rather well with the aid of the „Rückzündfaktor" (arc-back factor) F_r which is given by

$$F_r = \left(\frac{-\mathrm{d}\, i_a}{\mathrm{d}\, t}\right)_\delta \times -\Delta V \quad \mathrm{AV}/\mu\,\mathrm{sec.}$$

where $(\mathrm{d}i_a/\mathrm{d}t)_\delta$ represents the rate of change of current at the end of the commutation time.

In polyphase rectifier circuits with inductive loads, and in the transformation of DC to AC with the aid of thyratrons, F_c and F_r can attain considerable values unless special measures are taken. This factor can be reduced to a permissible level by damping circuits, which however fall outside the scope of this book.

IV-b-5 THE HYDROGEN THYRATRON

Thyratrons capable of high switching frequencies and heavy pulse operation are needed for use in radar [18]. Such thyratrons must have a short recovery time, and steps must be taken to ensure that the strong sputtering of the cathode and rapid adsorption of the gas, inevitable under these conditions, do not reduce the life of the tube too much. Hydrogen-filled thyratrons have been developed in order to meet these needs.

The gas in the hydrogen thyratron

It was stated in IV-b-4 that a rare gas deionizes more rapidly than mercury and so short recovery times may be expected from light gases such as helium or hydrogen. At first sight hydrogen does not seem the better of the two as it has the serious drawback that it is easily adsorbed by sputtered materials and by the metal parts of the tube. Moreover hydrogen ions react chemically with almost every material, so that in ordinary tubes the pressure decreases rapidly during operation as is shown in Fig. 95.

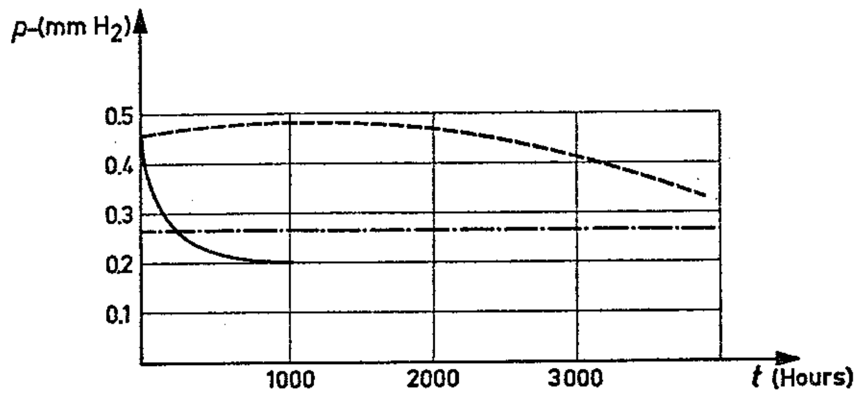


Fig. 95

Decay of the gas pressure during the life of two hydrogen thyratrons, both having an initial gas filling of 0.46 mm of hydrogen.
Full line: a tube without replenisher.
Broken line: a tube containing a replenisher.
Dot-dashed line: lower pressure limit for proper operation of the tube (0.27 mm).

One of the reactions is the reduction of barium oxide in the cathode coating. This however is an advantage for heavy pulse work as free barium atoms are formed during the operation of the tube and the cathode is always prepared to give off heavy current pulses without excessive sputtering.

Although the reduction leads to a relatively fast consumption of barium oxide the life of the whole tube might be increased to a reasonable value if it were possible to store a large amount of hydrogen in it without increasing the initial pressure too much. This has been done in the Philips hydrogen thyratrons. We have seen in II-b-3 that zirconium can adsorb large amounts of various gases, including hydrogen, at low temperatures. At higher temperatures the gas is set free again. This property can be made use of by placing a spiral filament covered with finely divided zirconium in the tube as a hydrogen reservoir or replenisher.

The hydrogen pressure is about 0.5 mm Hg in the new tube. The temperature of the replenisher filament which is connected in parallel with the cathode, is rather low because of strong heat convection and conduction by the hydrogen gas. Therefore hydrogen is given off only slowly and the pressure in the tube rises slightly during the first few hundred hours of operation (Fig. 95). In the meantime, hydrogen is cleaned up by the discharge and after about 1000 hours the amount of gas in the replenisher decreases markedly so that the rate of gas development and also the hydrogen pressure in the tube tend to decrease. This causes the heat convection to decrease likewise and as the replenisher is fed by a constant voltage its temperature increases. Consequently the rate of hydrogen liberation keeps virtually in pace with the clean-up of the gas. In this way the pressure in the tube is held practically constant for many thousands of hours. Below a certain pressure, indicated in the figure, the tube does not work properly because of the high operating voltage (the anode will glow visibly) and the high ignition voltage; but after 3000 hours' operation the actual pressure is still much greater than this.

Before 1945 the hydrogen thyratron was practically only used in military

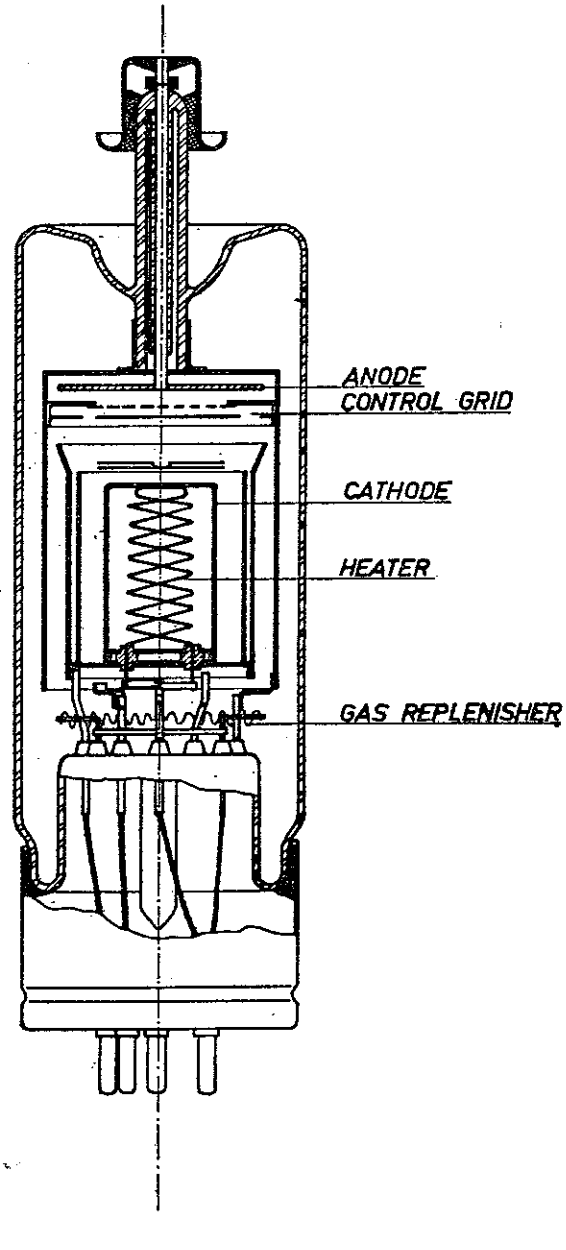


Fig. 96

Section view of the Philips hydrogen thyratron PL 522. The figure shows the cathode and its heather, the switching (control) grid, the anode and the gas replenisher.

radar equipment for navigation and air-traffic purposes, where a long operating life was not the main essential. Now that other possible uses have arisen the demands made on tube life have become higher. For example a modern method of high-frequency heating makes use of a hydrogen thyratron to discharge a capacitor in an oscillating circuit periodically, and for this purpose it is very important that the thyratron should be able to operate reliably for long periods. In rectifying circuits hydrogen thyratrons can handle frequencies up to 5000 c/s [80].

The costs of replacing a tube are also of importance in civil use.

The introduction of the gas replenisher has now made the hydrogen thyratron an industrial proposition.

Construction and some data of a hydrogen thyratron

The electrode arrangement in a hydrogen thyratron is typical of a high-voltage tube intended for pulse operation. It may be seen from the diagrams of the Philips tube PL 522 shown in Photo 5 and Fig. 96, that the disc-shaped anode is closely surrounded by a case which forms part of the grid. The gas pressure and anode-grid distance have been chosen so that the tube works to the low-pressure side of the minimum in the Paschen curve (see I-g-1).

The grid is continued as a cylindrical screen around the cathode, but the most important part as regards its switching function is the perforated plate under the anode. The large, indirectly heated, cylindrical cathode is surrounded by a series of concentric heat-radiation screens. The replenisher filament is placed at the bottom of the tube. The instantaneous power which the tube can handle is 16 kV × 325 A = 5200 kVA; the permissible mean power is 3.2 kVA.

Ignition properties of a hydrogen thyratron

The ignition characteristic of a hydrogen thyratron is a clear example of a current characteristic. If the grid is at the same potential as the cathode, no anode current can flow even if the anode voltage is thousands of volts (e.g. $v_{ap\ fwd}$ = 16 kV for Philips PL 522). The tube ignites at an anode voltage as low as 4500 V, however, if a sufficiently large positive voltage pulse is applied to the grid. For proper ignition such a pulse should have the following characteristics:

peak voltage v_{gp} = at least 200 V
duration of pulse = 2 μsec at least
build-up time = at most 0.5 μsec.

The impedance of the grid circuit must be low, so that the instantaneous grid current can achieve a large value; this also reduces the risk of large voltages between the grid and the cathode: during the ignition of the main discharge, the first ions are formed near the anode and move to the grid, so practically the full anode voltage appears between g and k, if only for a very short time.

Although the build-up time of the main discharge is very short (<0.1 μsec), it must be very constant for radar purposes. The variations (which are known as *jitter*) must be less than 0.01 μsec.

In order to prevent too heavy electrode bombardment (see build-up time, IV-b-4), the manufacturer limits the permissible rate of increase of the anode current $\mathrm{d}i_a/\mathrm{d}t$ (for the PL 522 tube this quantity must not exceed 1500 A/μsec).

IV-c **Tetrodes**

The triode thyratron provides a suitable answer to the demand for a controllable rectifier in many cases where the ignition does not have to satisfy very stringent conditions. If a second grid is introduced between the anode and the switching grid, however, several improvements are produced. The tetrode is more easily manageable than the triode, need not be manufactured to such rigid tolerances, and can be used for rather more applications. Some undesirable properties of the triode, such as a comparatively large anode-grid capacitance and an appreciable grid current, are improved at the cost of a somewhat more complicated construction. Because of its special features a tetrode can be used with a large resistance R_g in the switching-grid circuit. It is therefore possible to use a photocell, which always has a large impedance, as a control element for a tetrode.

The switching grid is indicated in the following by g_1, while the other grid (the screen grid) is denoted by g_2. We will now discuss some of the effects of the introduction of g_2:

1. small switching-grid currents,
2. capacitive screening,
3. possibility of shifting the ignition characteristic,
4. greater reliability of ignition,
5. thermal screening of g_1 from nearby hot electrodes, and
6. screening of g_1 against oxide particles coming from the cathode.

IV-c-1 SMALL SWITCHING-GRID CURRENTS

The current flowing to the switching grid of a non-conducting triode is small, but still has an appreciable influence on the effective grid voltage, especially if the resistance R_g in series with the grid is near the upper limiting value (which usually amounts to a few Mohm). The voltage drop across R_g depends on I_g, and causes the ignition angle in AC operation to differ more or less from the value to be expected from the control characteristic assuming I_g to be zero. It is therefore best to keep R_g on the small side with a triode, but this has the effect of making the power in the switching-grid circuit rather large. Moreover, it may be seen from Fig. 97a that the grid of a triode must be made rather large, to stop the discharge passing from k to a round the grid. A large grid means not only a large electron current to the grid before ignition, but also a large increase in the probe current in the grid circuit afterwards. If g_2 is carefully designed, more or less enclosing g_1, the value of I_{g1} is appreciably reduced (Fig. 97b). Thus a higher value of R_g may be used with a tetrode than with a triode.

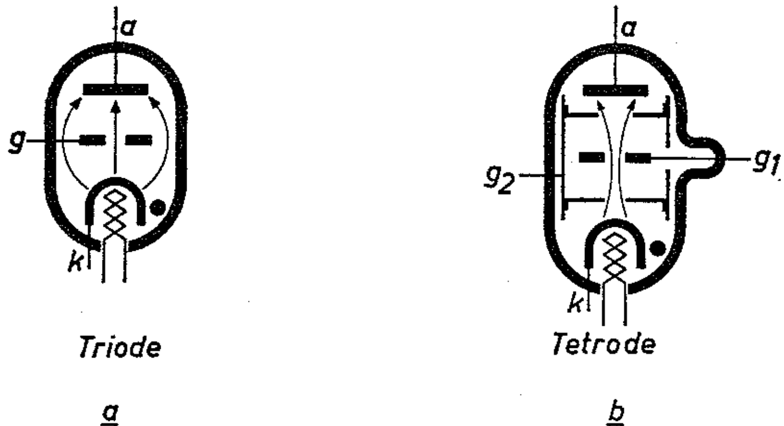


Fig. 97

a. Multiple branching of the electron paths from the cathode k to the anode a in a triode if the grid is too small.
b. The screen grid g_2 in a tetrode can be made to enclose the relatively small switching grid g_1 so that the electrons coming from the cathode k are forced to pass through the central hole in g_1 before they can reach the anode a.

IV-c-2 CAPACITIVE SCREENING

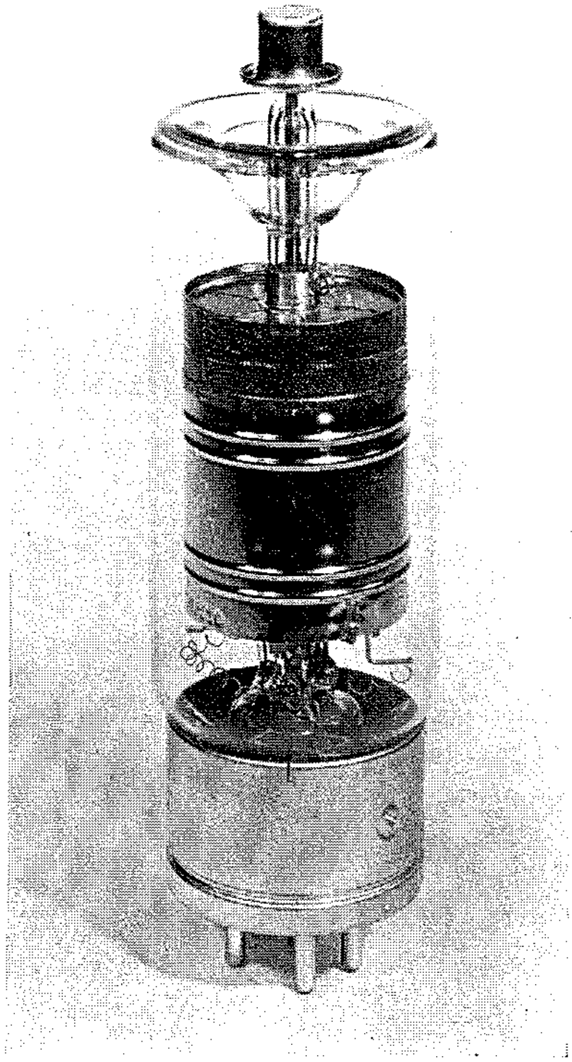
It has been shown in IV-b-2 to be important that the capacitance C_{ag1} between the anode and the switching grid should be low, in order to prevent unwanted ignitions. The effect of the comparatively large value of C_{ag1} for a triode may be corrected by increasing the grid-cathode capacitance C_{g1k}, or by decreasing the resistance R_{g1}; another method is to introduce a screen grid, g_2, and to connect it to k. The screening effect of this grid reduces C_{ag1}, so again it is possible to use larger values of R_{g1} (up to 10 Mohm) with a tetrode than with a triode.

IV-c-3 POSSIBILITY OF SHIFTNG THE IGNITION CHARACTERISTIC

We have already mentioned the spread in the ignition characteristics for different specimens of one type of tube in IV-b-1. It may be desirable, especially when two thyratrons have to co-operate in the same circuit (cf Fig. 78), to be able to apply a correction for these variations. This may

Photo 5

Photograph of the Philips hydrogen thyratron PL 522.



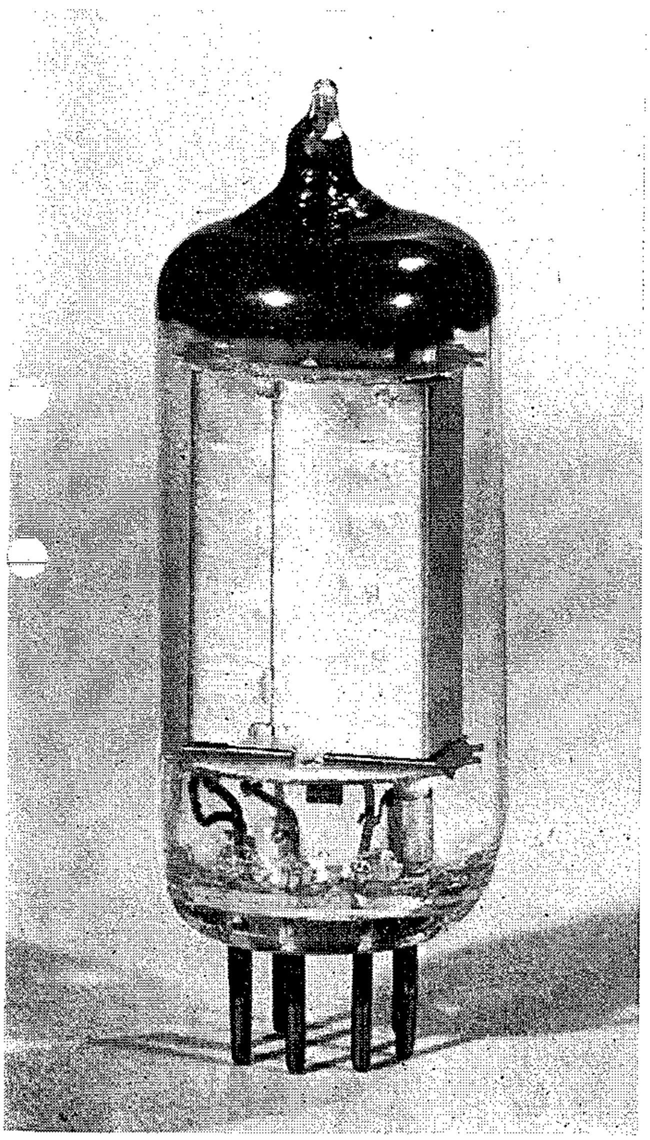


Photo 6

Photograph of tetrode thyratron type PL 2D 21.

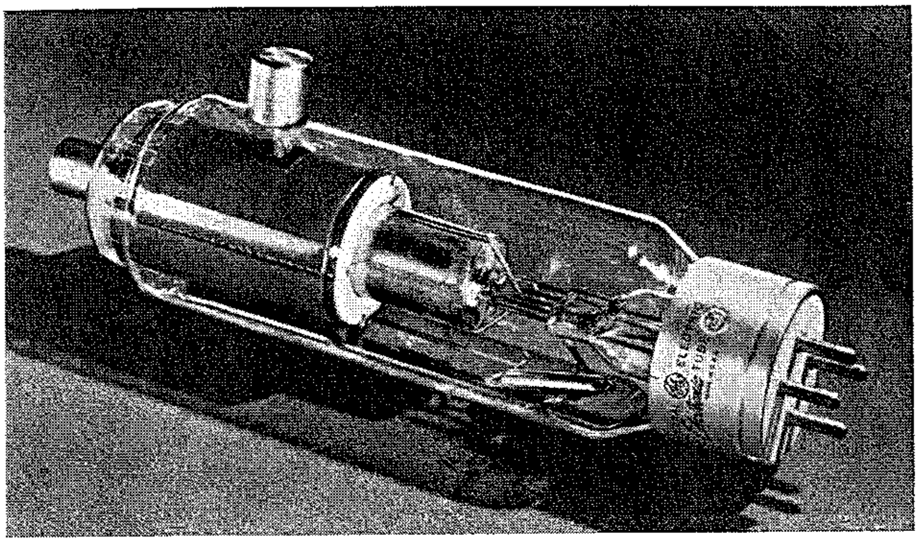
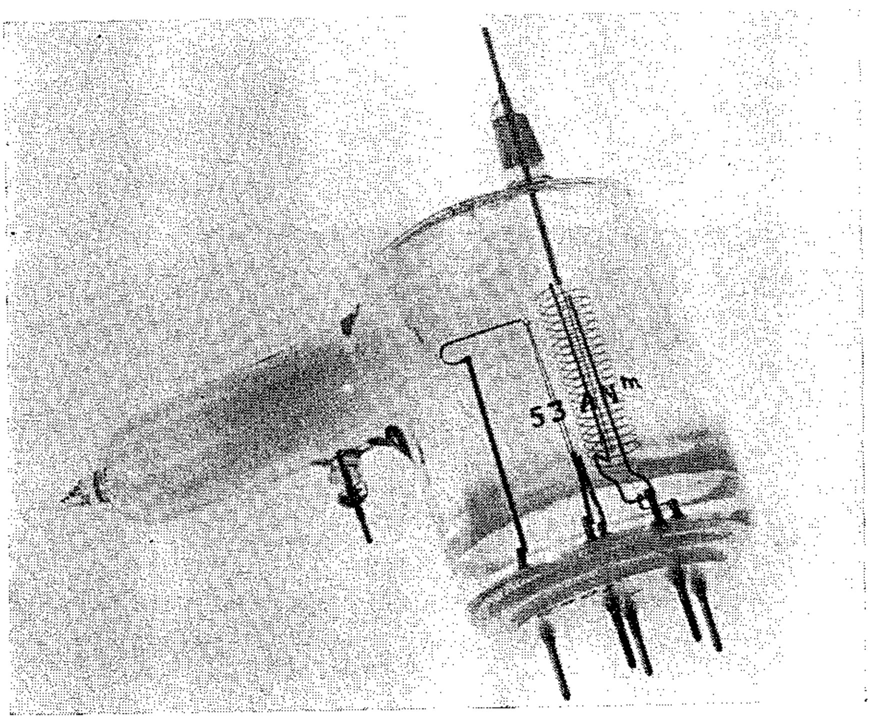


Photo 7

Photograph of tetrode thyratron type FG 105.

Photo 8

Bayard-Alpert ionization gauge. The ion collector is a thin wire placed within the grid-shaped anode; the cathode is outside it. In order to prevent local overheating of the wall, the cathode is placed centrally in the envelope. The glass wall is covered with a conductive layer [59].



be done with the aid of the second grid. A family of characteristics for the tetrode 2 D 21 at different values of V_{g2} are shown in Fig. 98. It may be seen from this figure that as g_2 is made more negative with respect to k, the ignition characteristic for g_1 is shifted to the right.

This phenomenon can also be used to change a voltage characteristic into a current characteristic, which may be useful if ignition must still be prevented even though the negative switching-grid voltage $-V_{g1}$ falls away.

The application of a potential difference between g_2 and k can be used under several other circumstances.

We will only mention here the possibilities of controlling the ignition by means of a DC voltage on one grid and an alternating voltage on the other, or by means of alternating voltages on both grids, with a phase difference between them. The effect of a given method of control on the moment of ignition can always be determined with the aid of curves such as those given in Fig. 98.

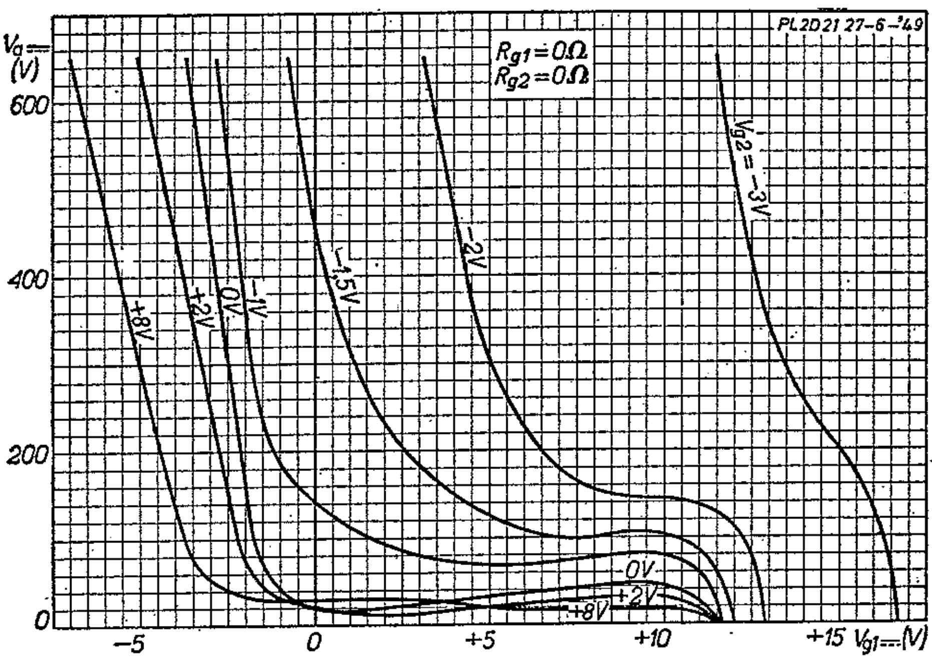


Fig. 98
Control characteristics of a tetrode thyratron
V_a = anode viltage, V_{g1} = switching-grid voltage.
The numbers besides the curves give the screen-grid voltage V_{g2}.

IV-c-4 IMPROVEMENT OF RELIABILITY OF THE IGNITION

If g_2 is designed according to IV-c-1 in order to diminish the switching-grid current, the influence of charges on the wall of the tube on the ignition is also reduced. This improves the reliability of the ignition.

IV-c-5 THERMAL SCREENING OF g_1 FROM NEARBY HOT ELECTRODES

As we have seen, it is necessary to keep the temperature of g_1 low. The chance of the tube becoming uncontrollable is decreased if the heat reaching g_1 from a hot cathode or a hot anode is reduced. The metal screen grid g_2, designed according to IV-c-1 helps in this respect.

IV-c-6 SCREENING OF g_1 AGAINST OXIDE PARTICLES COMING FROM THE CATHODE

Oxide particles sputtered or evaporated from the cathode may be deposited on other electrodes, which has a particulary harmful effect on the switching grid, as we have seen, by increasing the rate of grid emission as a result of a decrease in the work function (I-c) of the grid. If g_2 is designed according to IV-c-1 it will keep this effect within permissible limits.

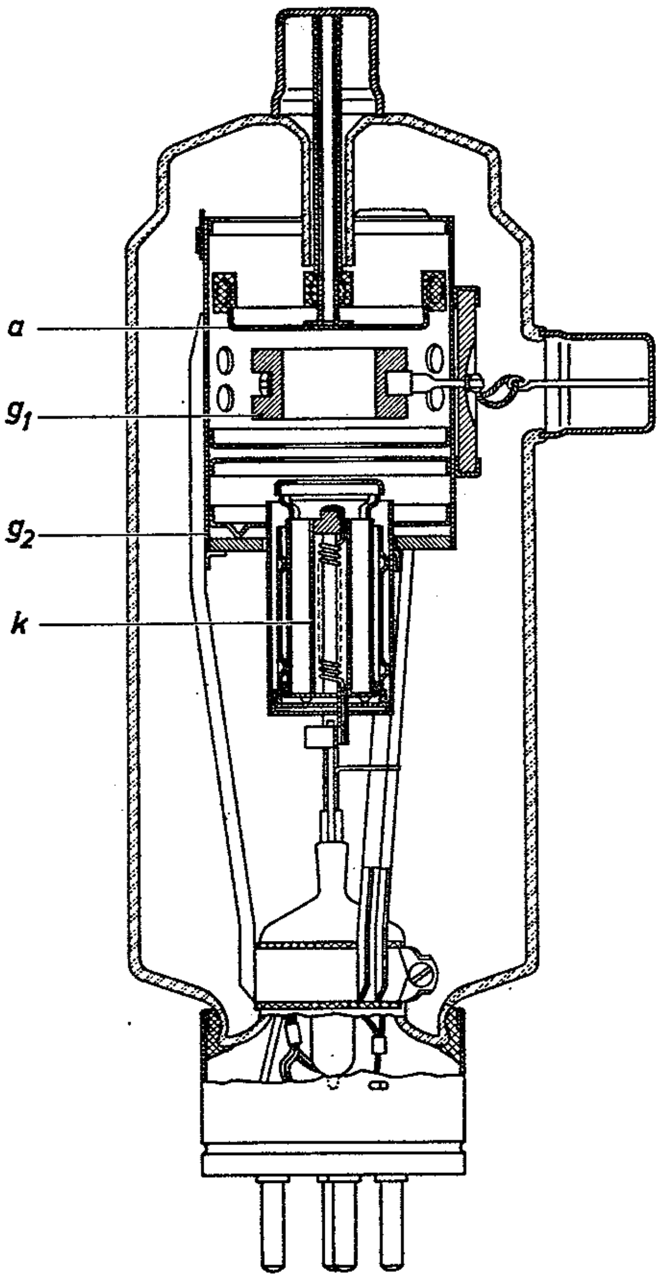


Fig. 99

Section of thyratron type FG 105. The screen grid g_2 encloses the ring-shaped switching grid g_1, which is made of graphite, as well as the anode a and part of the indirectly heated cathode k.

IV-c-7 EXAMPLES OF THE TETRODE THYRATRON

Let us take a closer look at the widely used low-power tetrode thyratron 2 D 21 which has a high-power equivalent GL 5727. The former tube is shown in Photo 6; the electrode arrangement has already been shown in Fig. 40. This tube is filled with argon and has an indirectly heated cathode. It can deliver a mean current of 100 mA with $i_{ap} = 0.5$ A. The value of $v_{ap\ fwd}$ is 650 V max., and $v_{ap\ inv}$ is 1300 V max. The anode-control grid capacitance is only 0.026 pF as a result of the screen grid, so the resistance in series with g_1 may be as high as 10 megohms. The arrangement of g_1 between a mica disc above and a well insulated nickel pole below ensures a small creeping current. If $V_a = 460\ V_{rms}$ and $I_{av} =$ 0.1 A, the grid current is not larger than 0.5 μA. This thyratron is espe-

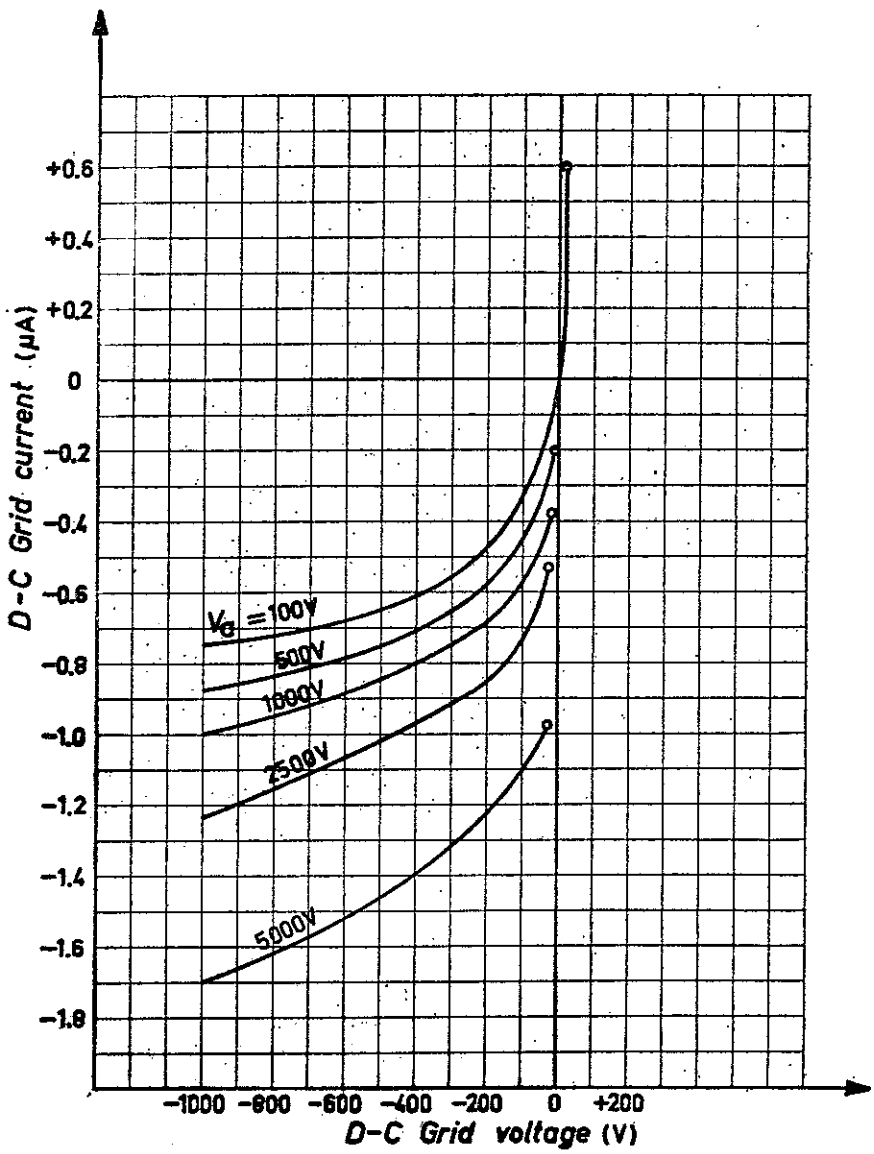


Fig. 100

Switching-grid currents of non-conducting tetrode thyratron FG 105 as functions of the switching-grid voltage.
The different curves are for different values of the anode voltage V_a.

cially well suited for being controlled by a photocell, which always has a high impedance. It is also used for energizing relays e.g. in time-switch circuits [17]. In rectifier circuits the 2 D 21 tetrode thyratron can handle frequencies up to 3000 c/s.

A well known screen-grid tube of much larger power is the General-Electric FG 105 (Photo 7 and Fig. 99), which is filled with mercury vapour and has $I_{av} = 6.4$ A, and $v_{ap\ fwd} = v_{ap\ inv} = 2500$ V. The screen grid consists of a metal cylinder which encloses the control grid and also screens the anode from the wall of the tube. The annular graphite switching grid is supported at three points by insulators which are fixed to the outer wall of g_2. A chrome-iron cap sealed into the wall of the tube acts as the contact for g_1, and a second cap at the top of the tube is the anode contact. The other electrode leads are sealed into the glass base of the tube. The values of I_{g1} under the screening influence of g_2 before ignition may be read from the curves of Fig.100. It will be seen that I_{g1} never exceeds 2 μA.

IV-d The choice of the type of thyratron, with reference to the gas fillings

Now that the reader has been introduced to the various types of gas filling and the permissible temperatures, useful life, etc., associated with each, it would be natural for him to ask which sort of filling is best for a given practical application of a gas triode or a gas tetrode. The choice is often difficult. We have therefore given a summary of the principal properties of the three main types of gas filling i.e. rare gas, mercury and mixed, in table VIII.

Table IX gives the main electrical properties and the gas filling of a number of typical thyratrons.

TABLE VIII

THYRATRONS, TRIODES AND TETRODES OR RELAY TUBES WITH HOT CATHODE; PROPERTIES DEPENDING ON THE GAS FILLING

		RARE GAS	MERCURY	MIXTURE OF MERCURY AND RARE GAS
ANODE VOLTAGE		up to a few kilovolts	up to some tens of kilovolts	up to a few kilovolts
STARTING	FIRST TIME, AFTER TRANS-PORT	as soon as hot cathode has heated up	only after pre-warming, needed to bring drops of mercury to the right places and to provide the necessary vapour pressure	as for mercury filling
	NEXT TIMES, AFTER PERIODIC COOLING	as soon as hot cathode has heated up	only after pre-warming of the mercury condensate	as soon as hot cathode has heated up
RANGE OF AMBIENT TEMPERATURE		about —55 to +75° C	about 10—50° C	about 0—60° C
SPREAD IN IGNITION CHARACTERISTIC FROM TUBE TO TUBE		slight	characteristic depends on ambient temperature	somewhat greater than for rare-gas filling
MAXIMUM FREQUENCY		500—3000 c/s	150 c/s	500 c/s
ABILITY TO WITH-STAND OVERLOAD		good	greater for cathodes with large time constant (indirectly heated) for relatively long time	good
EXPECTED LIFE	LOW ANODE VOLTAGE	long	very long if the temperature is suitable	very long if the temperature is suitable
	HIGH ANODE VOLTAGE	limited by cleanup	long if the temperature is suitable	long if the temperature is suitable
OPERATING POSITION		does not matter	allowing good circulation of cooling air	allowing good circulation of cooling air
EXAMPLES		2 D 21 5544 5545 6807 5684/C 3J	5557 5559 PL 255 PL 260 FG 105	3 C 23 6755 PL 106 PL 150

TABLE IX

OPERATING DATA OF SOME THYRATRONS

Type of thyratron		PL 260	2D21	FG 105	5544	5545	6807	PL 522
gas filling		mercury	xenon	mercury	xenon	xenon	xenon	hydrogen
triode or tetrode		triode	tetrode	tetrode	triode	triode	triode	triode
cathode heating		indirect	indirect	indirect	direct	direct	direct	indirect
heater voltage (V)	V_f	5.0	6.3	5.0	2.5	2.5	2.5	6.3
heater current (A)	I_f	25	0.6	10	12	21	21	10.6
preheating time (min)	t_f	10	1/6	5	1	1	1	5
max. anode voltage in forward direction (kV)	$v_{ap\ fwd}$	1.5	0.65	2.5	1.5	1.5	1.5	16
max. inverse anode voltage (kV)	$v_{ap\ inv}$	2.5	1.3	2.5	1.5	1.5	1.5	16
max. negative switching-grid voltage before ionization (V)	$-V_{g1}$	300	100	1000	250	250	250	—
max. negative screen-grid voltage before ionization (V)	$-V_{g2}$	—	100	500	—	—	—	—
max. negative switching-grid voltage when ignited (V)	$-V_{g1}$	10	10	10	10	10	10	—
max. negative screen-grid voltage when ignited (V)	$-V_{g2}$	—	10	10	—	—	—	—
mean anode current (A)	I_{av}	20—25	0.1	6.4	3.2	6.4	6.4	0.2

TABLE IX (continued)
OPERATING DATA OF SOME THYRATRONS

Type of thyratron		PL 260	2D21	FG 105	5544	5545	6807	PL 522
max. integration time (sec)	t_{av}	15	30	15	15	15	15	—
max. peak anode current (A)	i_{ap}	200—160	0.5	40	40	80	80	325
resistance in series with switching grid (kohm)	R_{g1}	0.5—20	10—10^4	0.5—100	0.5—100	0.5—100	0.5—100	0.5
ionization time (μsec)	t_{ion}	about 10	about 0.5	about 10	about 10	about 10	about 10	0.1
recovery time (μsec)	$t_{de\ ion}$	about 1000	35—75	about 1000	40—400	50—500	100—700	50
arc voltage (V)	V_{arc}	10	8	12	12	12	16	ca. 100
temperature of mercury condensate (°C)	t_{Hg}	35—75	—	40—80	—	—	—	—
ambient temperature (°C)	t_{amb}	—	$^{-75}/_{+90}$	—	$^{-55}/_{+70}$	$^{-55}/_{+70}$	$^{-55}/_{+70}$	$^{-50}/_{+90}$
max. frequency (c/s)	f	150	see text	150	see text	see text	—	20 x 10^3
anode-switching grid capacitance (pF)	C_{ag1}	15	0.026	1.8	0.8	0.8	10	—
switching-grid capacitance (pF)	C_{g1}	60	2.4	—	—	—	—	—
cathode-switching grid capacitance (pF)	C_{g1k}	—	—	5	45	45	10	—

APPENDIX

It seems useful to give a brief summary of the consequences of filling a hot-cathode tube with gas at the end of this chapter on thyratrons. This list is divided into two parts:

a. the effects of a gas filling in diodes, which are also apparent in triodes
b. the specific effects of a gas filling in triodes.

SUMMARY OF THE DIFFERENCES BETWEEN GAS-FILLED AND VACUUM TUBES WITH HOT CATHODES

(a)	Vacuum diode		Gas diode
1	There are only electrons between the electrodes	1	The discharge contains electrons and ions
2	The negative space charge hinders large current densities, high voltage is necessary	2	The negative space charge is compensated by positive ions, so large current densities are possible at low voltage
3	The losses in the discharge are relatively large	3	The losses in the discharge are relatively small
4	The anode current is a continuous and reversible function of the anode voltage	4	The current-voltage characteristic has a discontinuous, unstable region. The value of the current is determined by the external circuit as soon as the tube is ionized
5	The tube size for a given power is relatively large	5	The tube size for a given power is relatively small
6	The ambient temperature is of little importance	6	The ambient temperature is of little importance for gas-filled tubes, but of essential importance for vapour-filled tubes
7	The voltage between the anode and the cathode depends strongly on the current through the tube	7	The voltage between the anode and the cathode is to a first approximation independent of the current through the tube when the tube is conducting
8	The life of the tube is mainly determined by the life of the cathode	8	The life of the tube is usually determined by the life of the cathode which is normally practically unlimited. In certain cases, however, the life of the tube is determined by the cleanup of gas

(b)	Vacuum triode		Gas triode
9	The grid can influence the discharge continuously and reversibly	9	The grid can only ignite the discharge. The extinguishing of the discharge depends on factors outside the tube
10	The tube is more or less conducting. The internal resistance is continuously variable between a (relatively large) minimum value and infinity	10	The tube is either cut off or open, with a relatively small internal resistance
11	The power needed for the control can be very small	11	The power needed for the grid circuit is rather small, and does not increase much with the size of the tube
12	The temperature has no influence on the control characteristic	12	The temperature only influences the control characteristic if the tube is vapour-filled
13	The maximum frequency is very high, and is determined by the dimensions of the tube and the inertia of the electrons	13	The maximum frequency (150-5000 c/s) is determined by the dimensions of the tube and by the inertia of the positive ions of the filling gas