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

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

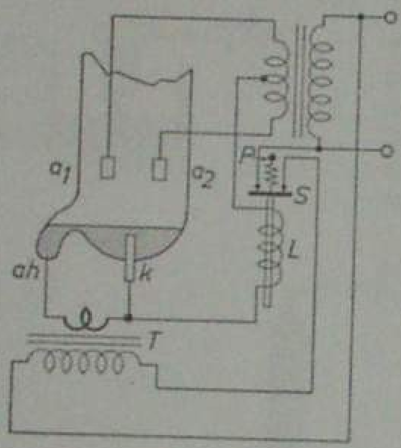


Fig. 32

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

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

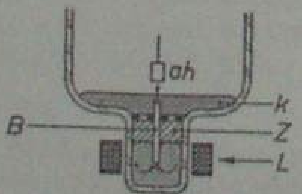


Fig. 33

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

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

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

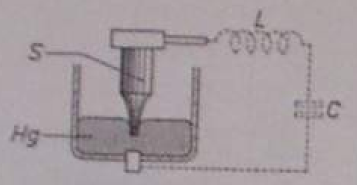


Fig. 34

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

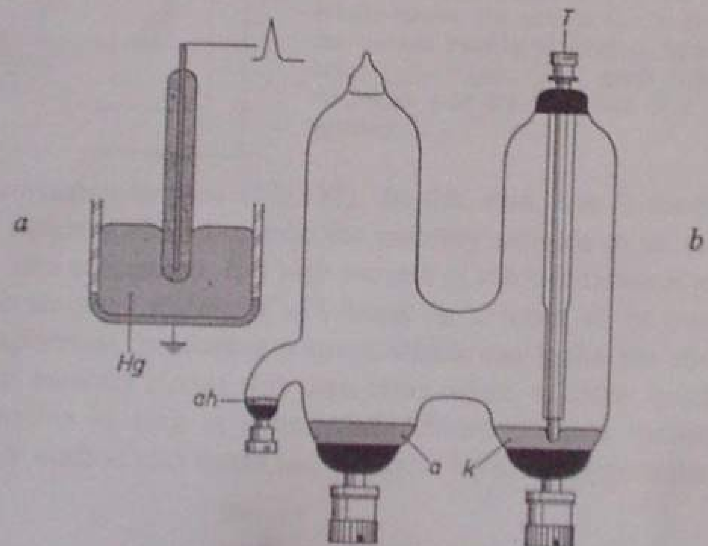


Fig. 35a

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

Fig. 35b

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

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

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

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

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

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

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

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

maintained by means of an auxiliary discharge between a_h and *k* until the main discharge is ignited (a_h is connected to the trigger rod *T* for this purpose).

that relatively few ions reach the negative anode, and these with a low velocity.

Another way to get the required voltage distribution is to use the valves in series. The probability of backfire is reduced quadratically; this method is so effective that it would be a good idea to use it at lower voltages.

Fig. 189 shows a G.E.C. ignitron type GL 6228/506, which can stand 20 kV in the forward and inverse directions at a maximum peak current of 900 A. Table XVIII gives some further data.

TABLE XVIII

LOAD DATA OF THE G.E.C. TUBE GL 6228/506 (SEE FIG. 189)

V_{ap} (forw. and inv.)	20 kV
i_{ap}	900 A
I_{av} max.	150 A (continuous) 200 A (for 2 hours) 300 A (for 1 minute)
rate of flow of cooling water	12 l/min.
temperature of cooling water	min. 35 °C max. 45 °C

Three grids surround the anode. The one nearest to the cathode separates the vapour-rich mercury-pool compartment from the second grid, the switching grid. The third grid acts as an intermediate anode, whose function has been described above. It is connected outside the tube with both the anode and the cathode, via large equal resistances of the order of megohms. Further details will be found in the caption to the figure.

VI-i Sendytrons

The sendytron is a mercury-pool tube with capacitive ignition (see VI-b-4). This tube is suitable for switching heavy current pulses of short duration. The oldest form was a glass bulb with a mercury pool and an anode, with a metal band around the outside of the tube at the height of the mercury meniscus. If a voltage pulse of about 10 kV was applied between the band and the mercury, a spark was produced at the edge of the meniscus which could be used to initiate a cathode spot (Cooper Hewitt 1901).

It is better to use an internal ignitor in place of the external band, because the wall of the bulb will gradually be attacked by the sparks. The ignitor used by the Japanese investigators Watanabe, Kasahara and Nakamura in 1938 consisted of a small ball or rod of an insulating material, e.g. quartz, filled with a conductor. The end of this ignitor dipped into the mercury, and the spark which helped to initiate the cathode spot was produced at the junction between the quartz and the mercury.

As an exemple of the modern design of a sendytron, we shall discuss the Philips type PL 5 (Fig. 35). In this tube, both the cathode and the anode consist of a pool of mercury. The anode is made of mercury because if it were made of metal or graphite, particles from this electrode would contaminate the mercury, making the ignition at the ignition rod irregular. This is also the reason for the shape of the tube — vertical cathode and anode compartments connected by a horizontal tube, forming a letter *H*. A side tube situated in a cold region contains an auxiliary anode, which is also of mercury for the reason given above.

This tube can stand current pulses of e.g. 1000 A peak value lasting for 10^{-5} seconds. Such loads are encountered when the tube is used in stroboscopic investigations, as a switch for the flash lamp (see below). Further data of this tube are given in Table XIX.

TABLE XIX

LOAD DATA OF SENDYTRON TYPE PL 5

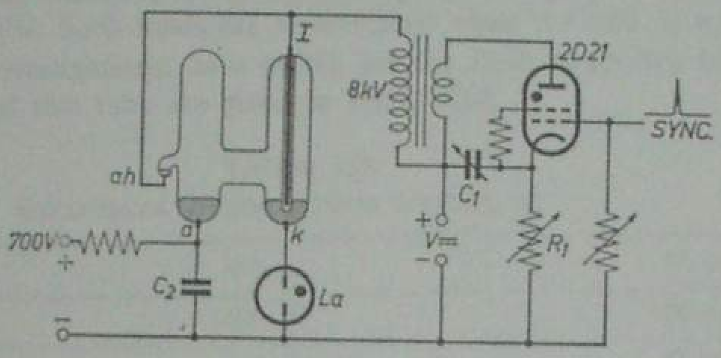
I_{av}	=	0.5 A	3.5 A
i_{ap}	=	1000 A	100 A
V_{arc}	=	40 V	15 V
V_a	=	500 V_{rms} max. 20 V_{rms} min.	500 V_{rms} max. 20 V_{rms} min.
$v_{ap\ inv}$	=	1500 V max.	1500 V max.
$v_{ap\ fwd}$	=	1500 V max.	1500 V max.
V_{ign}	=	< 32 V (main discharge) 12—15 kV (ignition rod)	
f	=	300 c/sec max	
t_{Hg}	=	10—40 °C	

capacitance rod-cathode = 10 pF
ignition power of rod ½ CV^2 = 12—25 mW. sec

Ignition

As we have seen, ignition is initiated by a spark produced between the downwardly curved mercury meniscus and the ignition rod of metal, coated with hard glass or quartz, which dips into the mercury. A ceramic could also possibly be used for the dielectric. If a high voltage (about 10 kV) is applied between these two electrodes (mercury negative), a spark which leads to the cathode spot can be produced. This may be due to cold emission (field emission) or possibly also to the motion of the mercury; we do not yet have a clear insight into the mechanism of this capacitive ignition [5, 6, 72].

Once possible form of the ignition circuit is shown in Fig. 190. A charged capacitor C_1 discharges through the primary coil of a small HT transformer (cf. the ignition coil of a car), a small thyratron being used as switch. The high voltage produced across the secondary of this transformer is applied between I and k. As soon as the spark is produced, an auxiliary discharge forms between a_h, which is connected to I, and k. The energy stored in the transformer can now flow off through this arc.



La=lamp

Fig. 190

Ignition circuit for a sendytron used as a switch for a stroboscope. High-voltage pulses, synchronized with the phenomena under investigation, are fed to the ignitor *I*. When the sendytron is ionized, C_2 is discharged via the tube and the flash-lamp *La*.

The ignition energy is low — many times lower than is required for an ignitron. The ignition frequency can be adjusted up to a maximum of 300 c/s, e.g. with the aid of a continuously regulable tone generator which feeds the switching grid of the above-mentioned thyratron. The glass coating will eventually be affected by the sparking, and this determines the life of the tube, as the main electrodes have an unlimited life.

Use [42]

As we have mentioned this tube is used in stroboscopy and for resistance welding. We shall only discuss the first application here.

For the observation or photograpy of rapidly moving objects (the motion may or may not be periodic), strong flashes of light of short duration may be used. (A typical flash lamp gives a flash which lasts for 3–10 μsec, with a luminous intensity of 10^7 lux two metres from the lamp.) This flash may be produced by discharging a capacitor in series with the self-inductance of the (short) connecting wires and the special flash lamp, using a sendytron as switch (see Fig. 190). The mean current through the sendytron is low: for periodic discharging, peak current about 1000 amps, pulse duration 3 μsec and $f = 250$ c/s, I_{av} = about 0.5 A. Some cooling is usually needed to keep the temperature of the mercury cathode within the limits stipulated by the manufacturer. Air cooling produced by a small fan placed under the tube is sufficient. The ignition frequency is synchronized with the frequency of the phenomenon to be observed. The thyratron may receive its pulses from e.g. a relaxation oscillator with regulable pulse frequency.

The evaporation and condensation of the mercury in the anode and cathode compartments are only in equilibrium for one single value of the load. Under other circumstances, special measures (e.g. heating or cooling) must be taken to prevent the situation from getting too far from equilibrium.

We may see Fig. 35 a small tube around the ignition rod, which prevents further ignition as soon as the mercury level of the cathode has risen to the lower end of this tube; the position of the tube is chosen so that the anode contact plate is still covered with mercury when this happens. If on the other hand the mercury level falls on the cathode side and rises on the anode side, ignition will stop as soon as the ignition rod is practically out of the mercury. The tube is also made so that it can be tipped up from time to time, so that any too great difference in the mercury levels can be corrected. This would be unnecessary with a double-action tube, i.e. one with two ignitors. Such tubes are also made as AC switches for welding, and as a replacement of two anti-parallel thyratrons, ignitrons or sendytrons.

VI-j Tubes with more than one anode and a common mercury cathode

The reasons for placing more than one anode in a rectifier tube have already been discussed in Chapter III, during the treatment of hot-cathode rectifier tubes. More or less the same argument holds for mercury-pool rectifiers, if we add one or two extra reasons. The fact that a mercury-cathode tube needs some means of initiating (possibly periodically) or maintaining the discharge means that we simplify matters considerably if we combine several single tubes into one big one with several anodes and only one mercury cathode, since only one ignition circuit is needed for this multiple tube. Another advantage is that the anodes help each other with the ignition: the passage of the arc from one anode to the other is aided by the ionization already established. A considerable saving is fed by a separate rectifier, and the mercury as described in II-c-3-a. Since this auxiliary arc is present the whole time, a switching electrode is needed to control this tube, just as with the thyratron. The advantage of an excitron over an ignitron is that the bulky and complicated ignition circuit required for the periodic supply of the ignition rod is replaced by the simpler and lighter supply equipment for the switching grid. Moreover, the simple transition of the auxiliary discharge into the main arc makes the excitron very reliable. Since however the auxiliary arc is present the whole time, the positive space charge in the region of the main anode is increased. A de-ionizing electrode placed around the anode is therefore often found in these tubes as a second grid (cf. VI-e).

Precautions must be taken to ensure that the cathode spot, always present in the excitron, does not reach the wall of the tube. The mercury pool of high-power tubes is therefore insulated from the wall of the tube. This brings however considerable complications with it, and an attempt has been made to find a simpler solution by placing a cooling coil near the wall but insulated from it. This screens the arc off from the wall. Moreover, the motion of the cathode spot is further restricted by means of a quartz ring which projects above the surface of the mercury.

VI-b-4 THE SENDYTRON

The sendytron makes use of a method of capacitive ignition. This means that the ignition rod which dips into the mercury is not a semi-conductor but has a metal core covered with a layer of hard glass or quartz (cf. II-c-3-a). As long as the mercury is clean (in which case it does not wet the glass), a short voltage pulse of some kilovolts applied between the metal core and the mercury is enough to produce one or more miniature cathode spots in the circular slit between the outside of the ignition rod and the mercury.

The voltage used depends on the thickness and dielectric constant of the insulating layer covering the metal core. The low value of the ignition energy is an advantage, but this is largely balanced by the high voltage needed for ignition. The insulating coating is gradually affected by the high load put on it, and in the end breakdown will occur.

We shall now discuss in somewhat more detail the construction of one tube of each of the above-mentioned types, and shall mention how the special demands made on such tubes in practice can be met.

VI-c The ignitron for resistance welding [43]

By far the most ignitrons are used for welding purposes, e.g. in the