CHAPTER VI

MERCURY-CATHODE TUBES

VI-a **Introduction**

In the power rectifiers which we have discussed so far, the electron source was a hot cathode consisting of a coil or strip heated to the emission temperature by passing a current through it from an external source or by means of a heater placed inside the cathode itself. In all such cases, a separate source of current is needed for the heating. As the emission current increases, a point is reached above which, although it may still be possible to construct a suitable cathode, difficulties arise in use. It may be said in general that a hot cathode is usable up to an emission current of 50—100 A. For higher currents, a mercury cathode is used. The *cathode spot,* the emitting region on the surface of the mercury whose formation has already been described in some detail (II-c-3-a), spreads out as the current increases; the maximum permissible tube current is thus still only a fraction of what the cathode could deliver. No external source of current is needed for the heating of the mercury cathode.

The presence of mercury vapour makes it unnecessary to fill the tube specially with gas to carry the discharge. It is no longer necessary to preheat the cathode. Against these simplifications compared to the hot cathode there are a number of disadvantages, of which we may mention first the necessity of having some ignition device to produce the cathode spot. Once the cathode spot has been formed, the instantaneous value of the current must be kept above a certain value, otherwise the discharge will be quenched and it will be necessary to form the cathode spot again. The quenching of the discharge can be prevented by maintaining an auxiliary discharge with a current of at least 5 A (cf. II-c-3-b).

The vapour pressure in the tube depends on the temperature (cf. I-b-2). The amount of mercury which evaporates also increases with the current. It is not only the cathode spot and its direct surroundings which determine the amount of mercury vapour formed per second: as the cathode spot moves over the surface of the mercury, it forms a fine mercury spray. The evaporation of mercury from these droplets is in fact the main source of vapour.

Fig. 164 shows the results of some measurements of the specific evaporation as function of the current [41]. It will be seen that the amount of mercury vapour formed increases more than proportionally with the current. Other measurements have shown that the rate of evaporation from the mercury pool is strongly dependent on the temperature. It is clear that a relatively large mercury surface will produce more mercury vapour; the designer of mercury-cathode tubes must therefore aim at keeping the mercury surface small as well as keeping its temperature low.

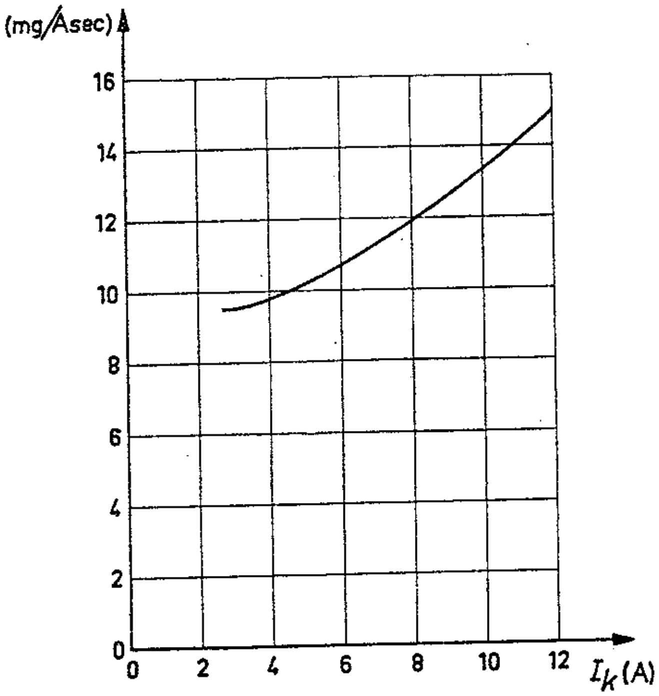


Fig. 164
Specific evaporation of mercury at a cathode spot as a function of the current.

The mercury vapour must return to the liquid state by condensation, and the heat of condensation thus set free must be removed. Water cooling or air cooling may be used. Very large glass tubes may be cooled by natural or forced convection of the surrounding air. Iron tank rectifiers are usually provided with cooling fins past which air is blown; they may however be surrounded by a cooling jacket or a cooling coil through which water flows.

The mercury droplets produced by the motion of the cathode spot must be prevented from reaching the anode by screens. The formation of these droplets may be reduced by means of a "mercury anchor", i.e. a strip of metal projecting out of the mercury: certain metals are wetted by mercury when they are very clean, and the cathode spot tends to stay near to the mercury-metal junction when a mercury anchor made of such a metal is used. When the erratic motion of the cathode spot is stopped in this way, the amount of mercury which vaporizes is considerably reduced [65]. Moreover, the use of a mercury anchor reduces the arc voltage (see VI-e-4).

To sum up, a mercury cathode is simple and indestructible, but a considerable number of incidental factors must be taken into consideration when using it.

As mentioned above (and also in II-c-3-a), the possible ignition devices may be divided into two classes:

a. those for periodic ignition, also at irregular intervals;
b. those in which ignition is only necessary once, the discharge being maintained with the aid of an auxiliary arc.

VI-b **Survey of single-action types of tubes**

There are various types of mercury-cathode tubes with a single anode. We will begin by briefly mentioning the main characteristics of each type before going into details of one or more representatives of each. We may distinguish between:

1. the welding ignitron and the pulse ignitron (a simplified welding ignitron),
2. the ignitron as a rectifier,
3. the excitron,
4. the sendytron.

VI-b-1 THE WELDING IGNITRON

The ignitron used as a fast-acting switch for the transmission of one or more current pulses of defined magnitude in the type of welding known as resistance welding is the simplest mercury-pool tube. Apart from the mercury cathode and a graphite anode it contains a third electrode, the semiconducting ignition rod (cf. II-c-3-a). The cathode spot is formed by an ignition pulse at the start of each period, and moves over the surface of the mercury starting from the line of contact between the mercury surface and the ignition rod. The spot moves 1—2 cm in 1/100 second (half a period). This means that the spot never gets the chance to reach the wall of the tube, since it only moves for half a period at most and the ignition rod is situated at least e.g. 3 cm from the wall. It is clear that it is undesirable for the discharge to reach the junction between the mercury pool and the wall of the tube (see VI-e-3). We shall see below that this situation can arise in other types of mercury-cathode tubes unless special precautions are taken.

The *pulse ignitron* may be regarded as a special simplified model of the welding ignitron. It is used e.g. in thermonuclear research, where current pulses with amplitudes of millions of amperes are sometimes required. Such pulses are obtained by discharging a battery of capacitors charged to several kilovolts, and are used to produce the strong magnetic fields required in such investigations. The pulse ignitron serves as a switch in this process. Although the peak current is so high, the average current is much lower, so that the tube can be air-cooled by natural convection. No cooling jacket is thus needed for the pulse ignitron.

VI-b-2 THE IGNITRON AS RECTIFIER

Special ignitrons are made for rectification purposes, in particular because much greater demands are made on rectifiers as regards commutation (see IV-b-4) and the ability to stand up to high voltages than are made on welding ignitrons. The mercury tube sketched in Fig. 165 may be regarded as a precursor of such tubes. This tube consists of a stainless steel tank sealed on to a glass cap which contains the anode and an auxiliary anode which can be lowered into the mercury and withdrawn again [34]. Such a set-up is not however suited for current-control purposes, since one has no control over the moment of ignition with respect to the sinusoidal variation of the anode voltage with time.

Later rectifier tubes therefore contained, besides the ignition rod which ensures ignition synchronized with the alternating anode voltage, at least an auxiliary anode, a limiting ring for the cathode spot, a splash screen (baffle) and a de-ionizing ring. The significance of all these electrodes will be made clear during the description of various special tubes (see VI-e).

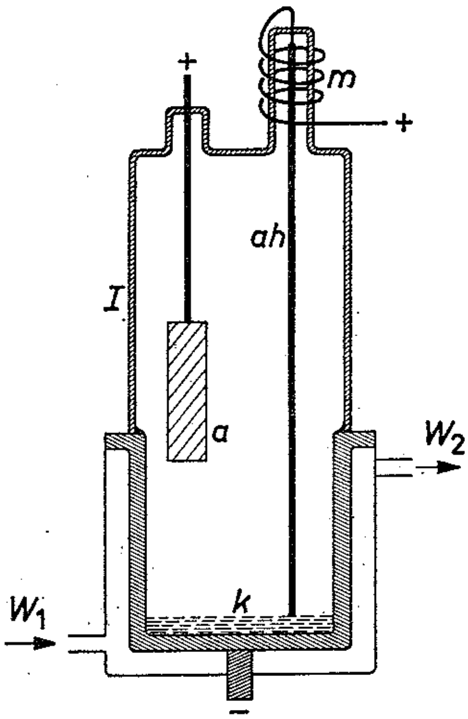


Fig. 165

Schematic section through a sealed-off metal mercury-cathode rectifier tube consisting of a water-cooled stainless steel vessel with a glass cap *I* hermetically sealed on to it. The main anode and the auxiliary anode are sealed into the cap. k = mercury-pool cathode, a = graphite anode block. The auxiliary current flows through the coil of an electromagnet m which draws the auxiliary anode a_h up out of the mercury, thus igniting the auxiliary arc. This auxiliary arc keeps the tube in a permanently ionized state; it is not possible to regulate the moment of ignition periodically.

VI-b-3 THE EXCITRON

The excitron is also a rectifier tube. It differs from the ignitron rectifier in that the cathode spot is formed once only instead of each period. An auxiliary arc is formed between an auxiliary anode (the "exciter"), which 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 semiconductor 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 automobile industry. Various problems which confront the user in this connection deserve further discussion.

VI-c-1 ELECTRODES AND IGNITION

The cathode and the ignition rod

Fig. 166 shows the steel welding ignitron in its simplest form. The cathode *k* consists of a pool of mercury which extends in a thin layer over the bottom of the tube. It is important for regular ignition that the mercury surface should be clean; the meniscus will then be curved downwards.

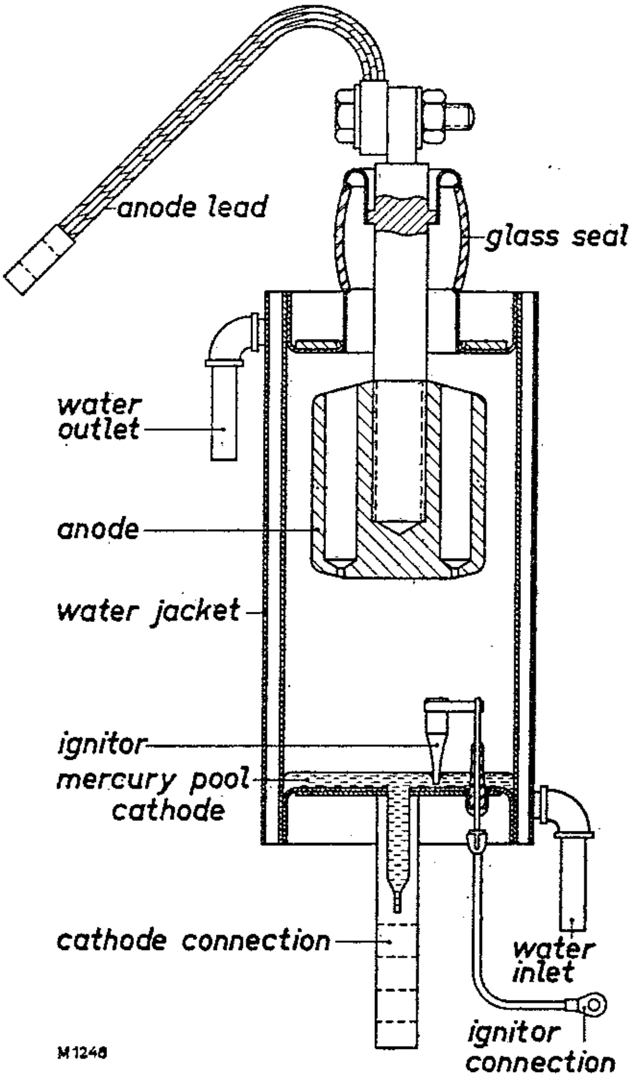


Fig. 166

Construction of a steel ignitron for welding purposes (simplified sketch).

The characteristic component, which also gives the tube its name, is the ignitor *I*, which dips into the pool of mercury. This is a round rod of homogeneous semiconducting material, which consists of a mixture of carbides and various other materials. One end is ground to a specially shaped point. This point is partially immersed in the mercury, which forms a downwardly curved meniscus near the line of contact (Fig. 167).

The resistance of the rod when dipped into the mercury frequently has a value of 30 ohm. This electrode was first used in 1933 by Slepian and Ludwig [44].

The emission mechanism of the ignition spark which is produced between the rod and the mercury has already been discussed in II-c-3. We shall now go into rather greater detail (see Fig. 167).

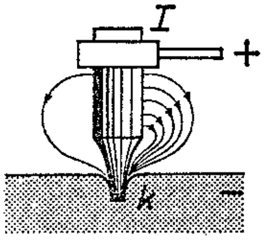


Fig. 167
Ignition rod *I* (positive) of semiconducting material. The specially shaped point dips into the (negative) mercury pool *k*, which forms a downwardly curved meniscus along the line of contact. The lines of force are closer together near the bottom of the slit.

The ignition rod *I* and the mercury *k* originally form a poor contact for the current which is passed through them. The line of contact between the two conductors changes into a spark contact, and a microscopic arc is produced between the positive rod and the negative mercury. (The opposite polarity is bad for the rod.) What circumstances make the formation of an arc possible? In the first place a voltage gradient, and this is present. We are here dealing with two materials of different conductivity. The rod has a much higher resistance than the mercury, so the current passing through it gives rise to a considerable voltage drop. Owing to the form of the space between the rod and the mercury, the lines of force come closer together as the bottom of the slit is approached, so that somewhere near where the mercury and the rod touch each other an arc can be formed between the two; this is the real cathode spot. The voltage gradient along the rod causes this arc to rise into a region of lower field strength, and the discharge comes to rest along a longer line of force, with one end on the rod-holder, which acts as anode, and the other on the cathode spot, which has now moved away from the point of contact. The surface state of the rod is also of importance in the formation of the spark, which appears e.g. from the fact that the mercury may not wet the rod. The interested reader is referred to the literature for further details [70, 71 and 72].

The tube enters its normal state, with a high current, as soon as the main discharge takes over from the auxiliary discharge. Some time is however needed for this; the length of the delay depends on the design and the temperature of the tube. The first few discharges are somewhat slower than subsequent ones.

The anode

The anode consists of a graphite block (Fig. 166), in which some holes are made in order to reduce its weight and to speed up degassing during the manufacturing process. These holes are open at the bottom, so that no mercury can collect in them. The graphite body is screwed on to a steel bar to the top of which an extruded chrome-iron ring is soldered. The edge of this ring is sealed on to a glass insulator.

The anode is heated by the energy given up by electrons on entering it (= current × work function) and by part of the arc losses. About half of the latter is due to the cathode fall, which may be assumed to be at least 8 volts. The total burning-voltage drop depends somewhat on the magnitude of the tube current and the vapour pressure, and lies in the range 13—18 V.

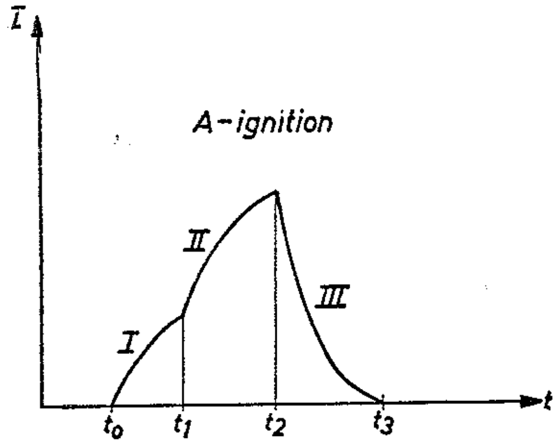


Fig. 168

Variation of the current through the ignition rod in the course of anode ignition.
Period *I*: the current increases from zero. At time t_1 the cathode spot begins to be formed. The current is mainly determined by R_s, R_I and the discharge in *Th* (cf. fig. 170).
Period *II*: after the cathode spot is formed, the current through the rod increases further because the resistance of the rod is partly by-passed by the auxiliary arc. At time t_2 the main anode takes over the discharge from the rod.
Period *III*: after the main anode begins to pass current, the current through the rod decreases gradually to zero (at time t_3), because the main discharge as it were short-circuits the ignition-rod circuit.

The anode temperature must be rather high in order to ensure a low vapour density near it, and to keep mercury from condensing in the anode compartment; both these conditions are necessary to prevent backfire. The vapour density must be low because a small amount of ions can quickly be neutralized at the negative anode, and condensation must be avoided because a drop of mercury on the surface of the anode lowers the work function.

The heat dissipated in the anode is lost by radiation and convection to the nearest parts of the wal, and by conduction along the anode lead.

Anode ignition

The simple and cheap method of "anode ignition" (*A*-ignition) is sufficient for resistance welding (see Fig. 170). In this method, the necessary energy is taken from the main circuit. The second method in general use, that of capacitive ignition, is more complicated, and is especially suitable for polyphase rectification purposes; it can however also be used for welding (cf. VI-e).

In *A*-ignition, the ignition rod *I*, which is in series with a current-limiting resistor R_s, is brought up to the voltage of the main anode by means of a thyratron *Th*. If *Th* is made conducting, a current I_p flows via *I* to *k* during the positive phase, and the cathode spot is formed. The value of I_p is limited by R_s, which is recommended for good operation, and by the resistance of the ignition rod R_I. (2 ohm is sufficient for R_s if the supply voltage is 220 V, and 6 ohm at 600 V.) The main anode immediately takes over the discharge, and the auxiliary discharge is as it were short-circuited by the main arc. The thyratron is cut off, opening the auxiliary-discharge circuit, and the current through the ignition rod stops. The variation of this current is shown in Fig. 168. Apart from the cathode heater of the thyratron, no extra source of power is needed for ignition.

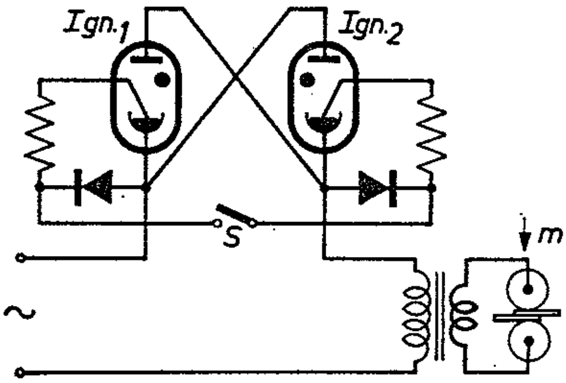


Fig. 169

Simple switching circuit with two ignitrons Ign_1 and Ign_2 connected in anti-parallel for the supply of the welding transformer with seam-welding machine *m*. When the switch *S*, which need not be designed for heavy currents, is closed the main current flows through each of the ignitrons alternately, and further through the primary of the transformer.

Both the above mentioned ignition methods require a rather heavy pulse, but only for a short time: in order to produce the spark, sufficient voltage (200 to 300 V) must be present for e.g. 100 μsec to begin with, and then sufficient current (20 to 30 A) must be delivered. The delay time of the ignition decreases as the pulse voltage is increased.

VI-c-2 OPERATION OF THE TUBES

Resistance welding [36, 45a] includes spot welding and seam welding. In spot welding, a strong current is passed for a short time through the point of contact of two pieces of metal which are pressed together by means of contact electrodes. The Joule heat evolved is nearly sufficient to melt the metal at the point of contact. The electrodes are removed after a short pause for cooling, and the two pieces of metal are now joined to each other. If this treatment is repeated at regular intervals while the pieces to be joined are passed between two rollers which also act as the electrodes, a seam weld is produced. One of the conditions for a good weld is that the right amount of heat should be produced, in other words that the current pulse should have the right amplitude and duration. The welding specialist makes use of a programme which details the electrode pressures and currents as functions of the time.

Some circuits

Current pulses flow through the welding machine for shorter or longer times, as we have seen above. Ignitrons are the indicated switches for the control of these pulses. The control circuit of the ignition unit of these tubes enables the welding transformer, which transforms the mains voltage into the low voltage needed for welding, to be connected with the mains for one or more periods or for a fraction of a period. The simplified circuit of Fig. 169 shows the transformer, served by two ignitrons Ign_1 and Ign_2 in anti-parallel for single-phase welding. The time during which current is passed is controlled by the switch S, which only controls the relatively low ignition current. Each tube passes current pulses of hundreds or thousands of amperes, but the mean current through the tubes is much less than that. Fig. 171 gives an impression of the way in which the ignitrons can be controlled electronically. In this circuit, the mechanical switch S of Fig. 169 is replaced by two thyratrons T_{I} and T_{II}, whose switching grids receive control pulses produced by a pulse generator which is synchronized with the mains voltage. There is also a time-switch circuit, and a phase-control circuit. The thyratrons cannot pass any current in their normal

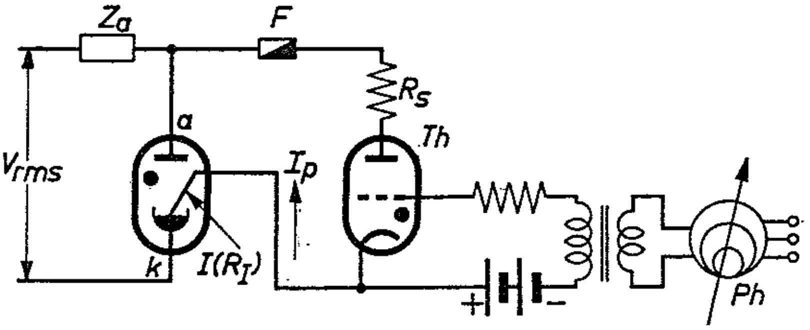


Fig. 170

Circuit for "anode ignition" of an ignitron. When the thyratron Th is made conducting, the ignition current I_p flows (from the source which also supplies the main anode a) through the ignition rod I and the mercury cathode k. The cathode spot is formed, and then a takes the discharge over, Th is quenched and the current through the ignition rod falls to zero.
Z_a = load impedance, F = fuse, R_s = current-limiting resistance,
R_I = resistance of the ignition rod, Ph = phase controller.

state, because of their negative grid bias. Positive control pulses produced by the pulse generator, however, open T_{I} and T_{II} alternately for a specified part of the period. The magnitude of the current through the welding transformer depends on the setting of the pulse generator and the timer. Further factors which influence the quality of the weld, such as the nature of the material to be welded (in particular its thermal conductivity), inductance of the welding transformer, etc., cannot be discussed here. Further details are given in the literature [36].

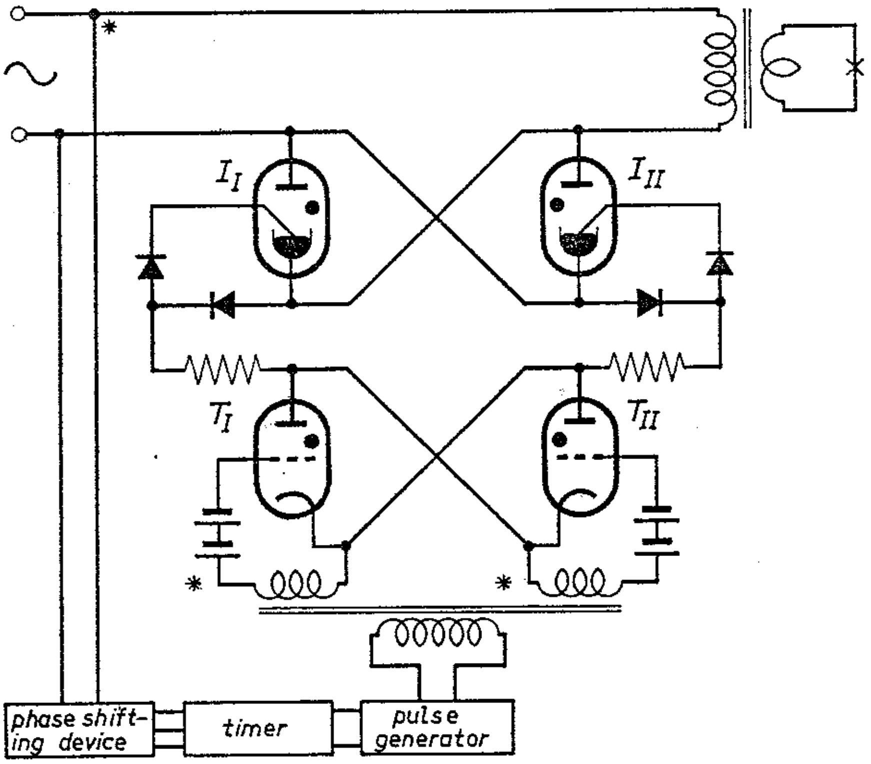


Fig. 171

Anode ignition of the anti-parallel ignitrons I_{I} and I_{II} by electronic means, with the aid of two thyratrons T_{I} and T_{II}. The thyratrons are ignited by grid-voltage pulses. The number of pulses delivered by the pulse generator, and their phase, are controlled by a timer and a phase-shifter respectively.

Loadability of the tubes

Ignitrons are always used in pairs for welding purposes, in an anti-parallel circuit as in Fig. 171. Certain tube specifications should be adhered to in order to prevent overloading. The maximum permissible power, expressed in kVA, is usually given for the pair of tubes; it follows that the rms value of the anode current is of importance. Furthermore, the average tube current I_{av} calculated over a certain maximum time t_{av} determines the losses. The choice of the "duty cycle" is also of importance. We shall now explain these concepts.

Single-phase welding

The simplest example is the single-phase welding circuit. The power of the welding transformer and the mains voltage would together determine I_{rms} for the tubes, if the welding were a continuous operation. The load is however almost always intermittent, so that the tube kVA's for welding can be considerably higher than for continuous operation (e.g. in a rectifying installation).

The "duty cycle" is the percentage of the time during which the tubes pass current in a working period. For example, if the tubes pass current for 4 periods and then remain cut-off for 6 periods the duty cycle is 40 %. The duty cycle would have exactly the same value if the tube passed current for 40 seconds and then rested for 60 seconds; but this is not allowed, as the average tube current I_{av} integrated over a certain averaging time t_{av} must not exceed a certain value, to prevent overheating of the tube (see III-b-1). Fig. 172 shows the loading limits for a pair of welding tubes type 5552 A (see below) which in this case are not thermostatically controlled, at a mains voltage of 250 V_{rms} and for various values of the duty cycle. The loading limit is lower at a mains voltage of 500 V_{rms}. The maximum permissible power is 1200 kVA for two tubes, so the permissible tube current is inversely proportional to the mains voltage. The average

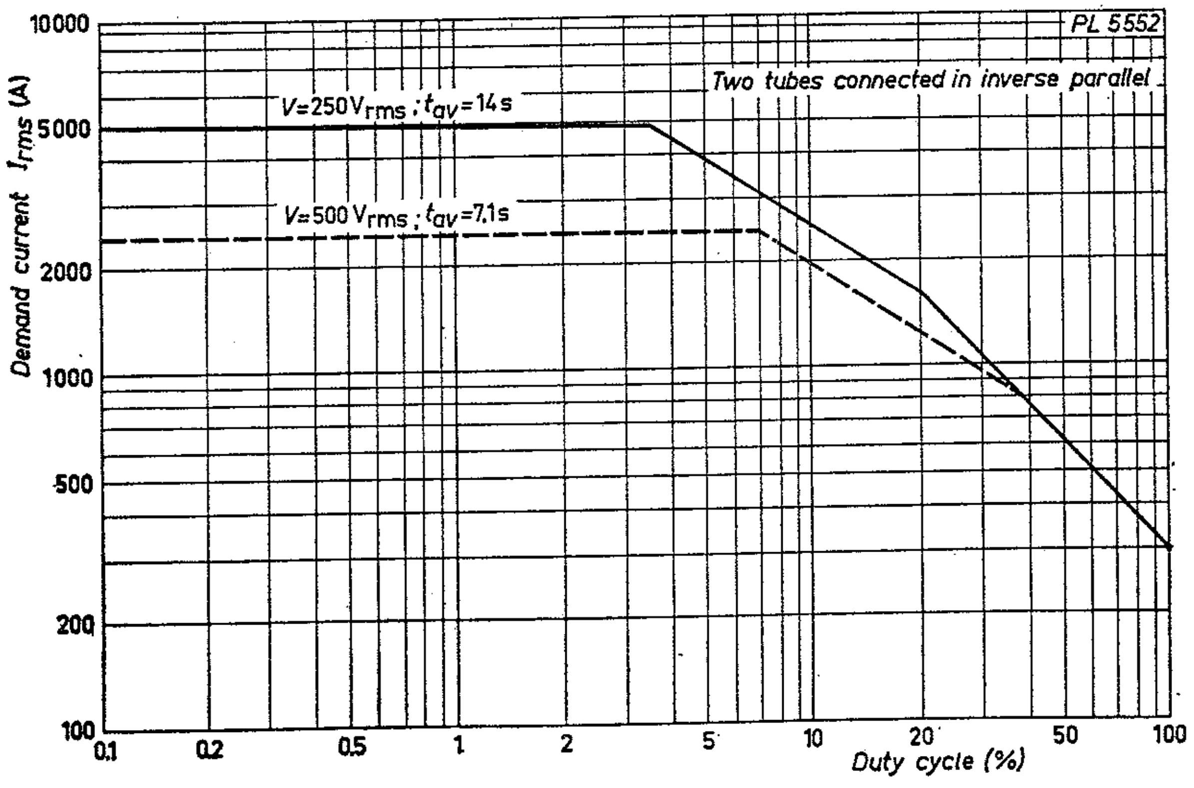


Fig. 172

Loadability of two anti-parallel welding ignitrons type 5552 A (not thermostatically controlled), for two mains voltages.

current per tube, which determines the heating of the tube, may not exceed 75 A. If the power does not exceed 400 kVA, however, I_{av} may be as much as 140 A.

Cooling

The tube is provided with a cooling jacket to conduct off the heat dissipated in it. Both the inner and outer cylinder must be of stainless steel: normal steel corrodes easily, producing hydrogen which can diffuse through the inner wall into the tube.

In order to keep the mercury-vapour pressure within the permissible limits, the inlet temperature of the cooling water must be at least 10° C, and the outlet temperature must not exceed 45° C. The increase in temperature for the stipulated minimum flow rate of cooling water (6 l/min at max. load) is about 6° C, which determines the amount of water needed. Tube 5552 A (see Fig. 166) has a water inlet pipe underneath and a water outlet on top, and a coiled wire, not showed in the figure, is placed between the walls of the cooling jacket to direct the flow of water and make for efficient cooling and economic use of water. The water input is underneath because the cathode side must be kept colder, so that the excess mercury vapour condenses there rather than near the anode. There are moreover other reasons for wishing the anode to be somewhat hotter, as we have seen above (cf. VI-c-1, the anode).

Circulation of the cooling water

There are various standard ways of passing the water through the cooling jackets. The method used in a particular case must be decided having regard to two factors: the tube temperature and the water consumption.

We may distinguish:

I. The open cooling system.
The cooling water is taken from the mains, and is allowed to run down the drain after it has passed through the cooling jacket of the tube.

II. The closed cooling system.
The same water is circulated the whole time with the aid of a pump. This water is cooled at a suitable place in the circuit. The cooling takes place in a radiator, by means of e.g. air, or water which may be of inferior quality, such as sea water.

III. The combined cooling system.
It is also possible to combine methods I and II. A closed cooling system is then used, but cold water is added and warm water removed

as necessary. A contact thermometer, which keeps the temperature of the outlet water e.g. between 25 and 30° C, controls the amount of water which is replenished. The circulating water also passes through a radiator, where it is cooled as in method II.

In each of the above-mentioned methods, the cooling water may pass through a number of tubes in succession (up to 3), or each tube may have its own cooling-water supply.

Each method has its advantages and disadvantages. The most important consideration is the quality and availability of the water, but the operating conditions, including the loading of the tubes, may also be of importance. For example, it may be desired to keep the temperature of the water within narrow limits, in connection with commutation (see IV-b-4). There is a close connection between the maximum and minimum temperatures of the cooling water and the conditions of loading and cooling.

Cooling after end of operation

The tubes are still warm after they are switched off, and thus still contain some mercury vapour, which could condense anywhere if all parts of

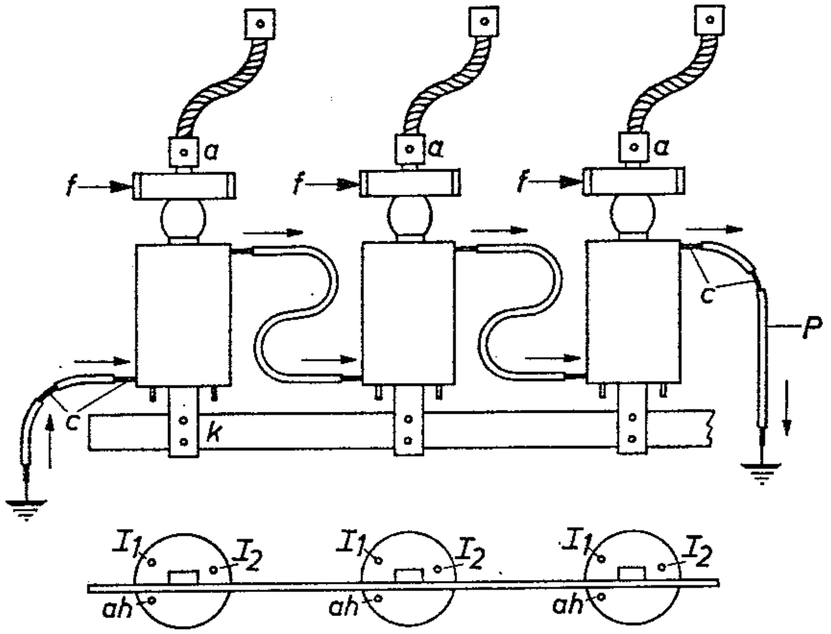


Fig. 173

Cooling of three ignitrons, with the water passing through the tubes in series. In order to prevent electrolytic corrosion of the cooling jacket, a piece of metal tubing connected to the cooling jacket by the copper wire c is inserted in the water pipe P. Corrosion, if any, then attacks this piece of metal tubing, which can easily be replaced.

f = cooling fins
I_1 and I_2 = ignition rod and spare ignition rod } see VI-e
a_h = auxiliary anode

the tube were allowed to attain the same temperature. The anode in particular, on which mercury must under no circumstances condense, cools off very quickly. The cooling water must therefore be left running for about half an hour after switching off, so that all the mercury vapour has the chance to condense in the right parts of the tube.

Electrolysis

The cooling water always has a certain conductivity, which may possibly lead to corrosion of the cooling jacket near the inlet and outlet pipes. This is especially likely if the jacket (which is in electrical contact with the cathode) is not at earth potential. If this is the case, it is advisable to cut the inlet and outlet tubing for the water in two, and to connect the two pieces with a piece of metal pipe which is connected to the cooling jacket by copper wire (see Fig. 173). The corrosion, if any, then attacks the pieces of metal tubing rather than the cooling jacket; if this tubing is seriously corroded, it can easily be replaced.

Quality of the cooling water [35]

All types of water, except for distilled water, contain substances which can have a harmful effect on the metal walls which they must cool; this effect may be chemical or electrolytic in nature. Certain salts may be deposited on the walls, hindering the heat transfer, or the metal may be corroded. A given type of water must thus satisfy certain conditions if it is to be suitable for cooling purposes.

The American Standard for pool-cathode mercury-arc power converters, Jan, 1949 (formerly AIEE report No. 6) makes the following demands on the water for cooling systems without heat exchangers:

1. a neutral or slightly alkaline reaction (pH 7—9);
2. a maximum chloride content of 20 mg/l; maximum content of nitrate and sulphate 10 and 100 mg/l respectively;
3. maximum 250 mg/1 solids;
4. a temporary hardness (as opposed to permanent hardness, the hardness which remains after treatment; temporary hardness is mainly due to calcium carbonate) which must not exceed 10 German degrees (18° French, 12.5° English), which corresponds to 250 ppm (by weight) in the American system;
5. specific resistance at least 2000 ohm.cm.

Mains water usually meets these specifications. If a closed cooling system is used, it is recommended that the cooling water for the heat exchanger should be pre-treated with sodium chromate to hinder corrosion.

Special rules are laid down by the manufacturers for the cleaning of tube walls if they should become covered with a deposit.

Saving water and preventing overloads (with a thermoregulator)

The jacket of the 5552 A, the tube we are specially concerned with here, has a copper plate welded on to it. A thermoregulator can be fastened on to this and can produce a considerable saving of water (Fig. 174). This thermoregulator closes the current circuit containing an electromagnetically operated water valve when the temperature of the cooling jacket reaches its maximum permissible value. Cooling water then begins to flow. As soon as this cooling causes the temperature of the jacket to fall a few degrees, the thermoregulator opens the current circuit so that the cooling water ceases to flow.

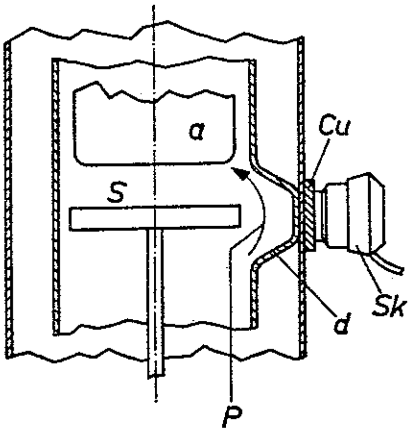


Fig. 174

Thermostatic switch *Sk* mounted on the cooling jacket of an ignitron. The switch controls an electromagnetic tap, which can be used to save water or to protect the tube against overloading.

Cu = copper plate soldered on the outer jacket
d = dip in the inner water jacket
a = anode
S = screen
P = discharge path

The tube can be protected against overloading in a similar way. If we have for example two welding ignitrons working in anti-parallel, which will in general be cooled in series, the first tube is provided with the above-mentioned thermoregulator for controlling the flow of water. The second ignitron is provided with a similar switch which is however set for a higher temperature, and which is connected in the ignition circuits of both tubes; this prevents overloading.

The external cooling coil

The cooling jacket may be replaced by a coiled copper pipe soldered on to the outside of the tube. This stil gives a good thermal contact between the wall of the tube and the cooling water, while it provides a better separation between the evacuated part and the part containing water. Hydrogen gas which may be present in the water can no longer diffuse into the tube. A steel of poorer quality than the usual stainless steel can therefore be used for the wall of the tube. This cooling method is more effective because there is no turbulence and no dead space in a pipe as there is in a cooling jacket.

There is no need to stipulate the minimum flow rate of the cooling water in this case; it is enough to specify the outlet temperature. The cooling coil is not wound with an even pitch over the whole tube: there are more windings on the cathode side than on the anode side, so that the anode side is warmer with a cooling coil than with a cooling jacket.

VI-c-3 THREE-PHASE WELDING (frequency changing)

It is an obvious idea to use a single-phase welding transformer for resistance welding, since the secondary (low-tension) side must consist of a coil closed via the two welding electrodes and the object to be welded. If this method is used, however, the mains is subjected to short but very heavy current pulses; if e.g. the instantaneous power taken is 2000 kVA, the amplitude of the current pulse in a 500 V mains is 4000 A. The effect of these current pulses is most unpleasant for other consumers on the same mains. Moreover, the mains is loaded unsymmetrically (single-phase loading).

A second disadvantage of single-phase welding is due to the high reactance on the secondary side, a result of the self-inductance of the electrode holders, which must be long so that they can be used with large subjects, and which therefore enclose a large area. This self-inductance

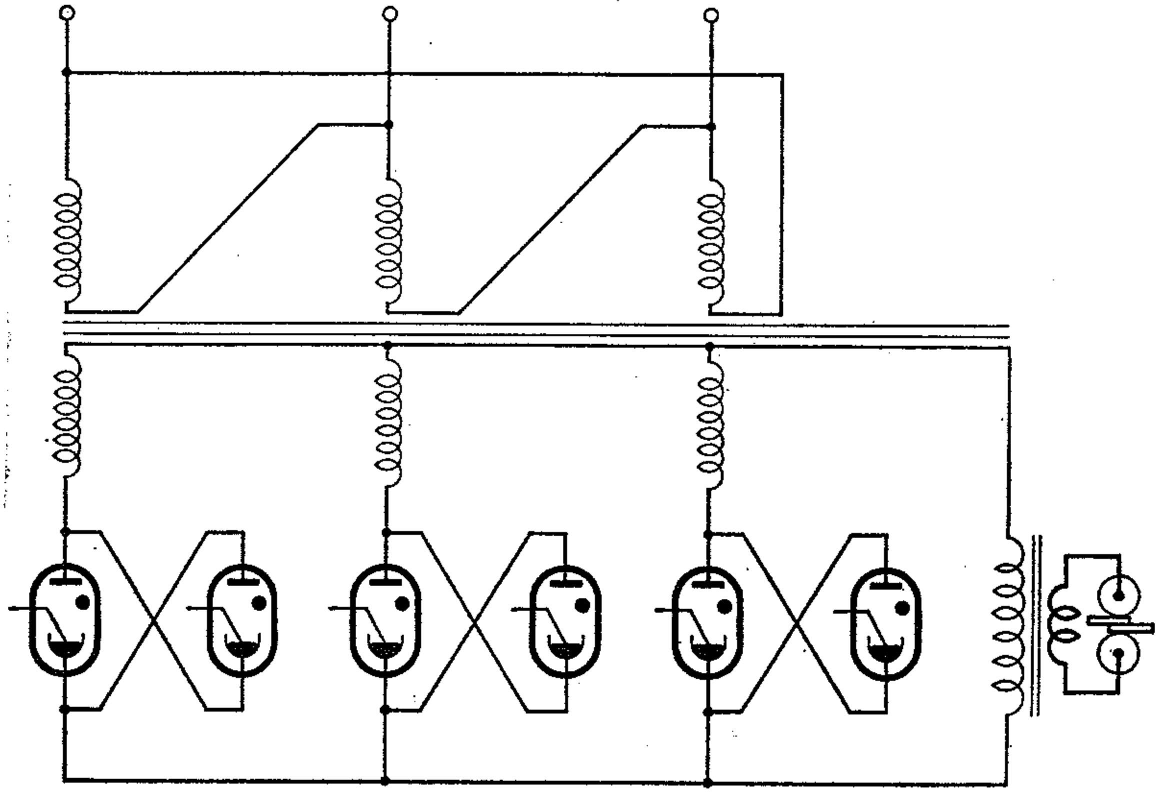


Fig. 175

Circuit for 3-phase welding, using a 3-phase transformer which supplies the single-phase welding transformer via three pairs of anti-parallel ignitrons.

leads to a low cos φ for the set-up; a high secondary voltage is needed to maintain the desired current through the object to be welded, so that the losses are high. One way of solving these problems would be to lower the frequency. This can be done e.g. by using a 3-phase supply, so that the load is distributed evenly over the three phases. The core of the transformer must then however contain more iron, because of the low frequency of the welding current.

There are two main circuits which are used for this purpose: in Fig. 175 the single-phase welding transformer is connected to the mains via three pairs of anti-parallel ignitrons, with or without a three-phase transformer in between, while in Fig. 176 the primary side of the welding transformer consists of three seperate coils, each connected to one phase of the mains in series with two anti-parallel ignitrons. We will consider this latter welding system in somewhat greater detail.

The six ignitrons of Fig. 176 consist of three pairs, each fed by one of the three mains phases *R*, *S* or *T*. The tubes can also be thought to be arranged in two groups of three, viz. R_1–S_1–T_1 and R_2–S_2–T_2. The control of the circuit is always arranged so that first the tubes of group 1 ignite a

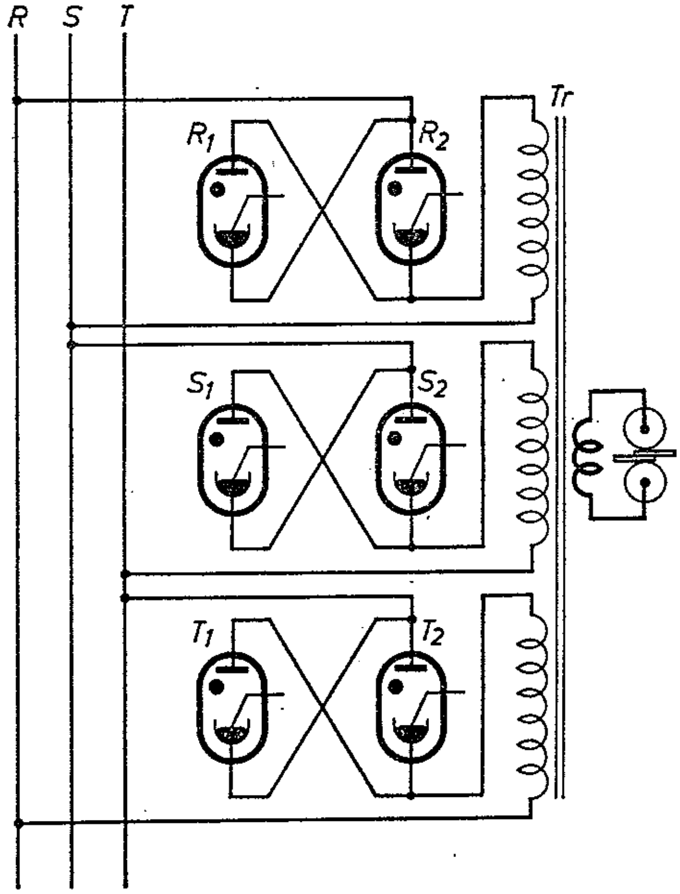


Fig. 176

Circuit for 3-phase welding, with a welding transformer *Tr* whose primary consists of three separate windings on one iron core. Each of the three windings is connected to one phase of the 3-phase mains in series with a pair of anti-parallel ignitrons.

number of times in succession (*a*), and then the tubes of group 2 ignite an equal number of times (*b*). The currents flowing through the three primary windings of the transformer *Tr* are thus rectified, first in the positive sense and then in the negative sense, so that a varying flux flows through the core. Between the two intervals *a* and *b*, and again between *b* and *a*, the primary current is given time to decrease to about zero to avoid undesirable complications, and during these two interpulse times, *c* and *d*, no ignition pulses must be fed to the tubes. The relative lengths of the periods *a*, *b*, *c* and *d* determines the frequency of the welding current, which can be chosen to be e.g. of the order of 10 c/s when the mains frequency is 50 c/s. Fig. 177 gives an example of frequency changing from 50 to $7^1/_7$ c/s [37]. This method of 3-phase welding comes down to the combination of three currents which supply the welding transformer. As against the advantage of the increased value of cos φ and the lower current, which is moreover distributed over three phases, we have as mentioned above the necessity of having a heavier iron core for the welding transformer because of the lower frequency of the welding current.

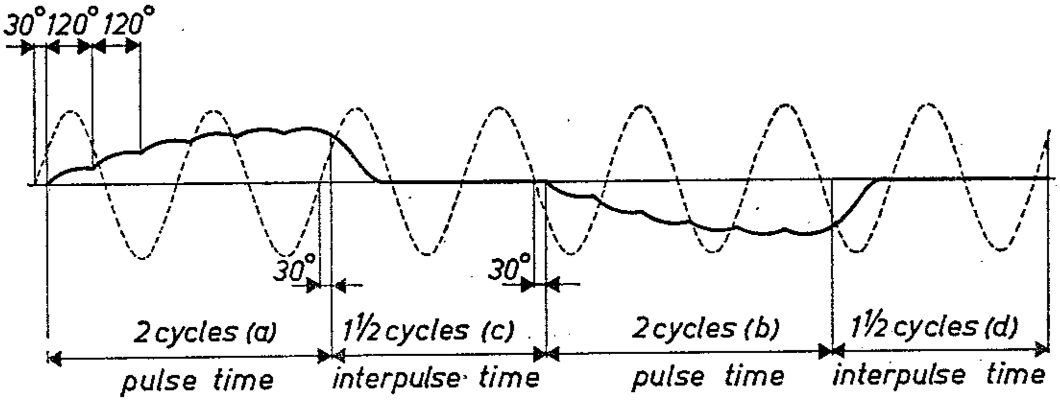


Fig. 177

Oscillogram of the current through the welding transformer when frequency changing is used. Each seven periods of the mains voltage becomes one period of the welding transformer. If the mains frequency is 50 c/s, the frequency of the welding current is thus $7^1/_7$ c/s.

Power control by frequency changing, with or without changing the angle of ignition, gives excellent results; for details we refer to the relevant literature [38].

Special tubes are on the market for three-phase welding, e.g. the 5822, which is made by several ignitron manufacturers. This is a water-cooled tube; because the commutation conditions are more stringent than in single-phase welding, it is provided with a splash screen which keeps drops of mercury away from the anode and also furthers rapid de-ionization in the reverse phase. Six of these tubes can control a power of 860 kVA.

Depending on the value of $i_{ap\,max}$, which may vary in the range 1200 to 1500 A, the tube can withstand a forward or inverse voltage of 1500 to 1200 V. For other operating conditions, see Table XV.

TABLE XV

IGNITRON TYPE 5822

DATA FOR INTERMITTENT RECTIFIER SERVICE OR FREQUENCY-CHANGER RESISTANCE-WELDING SERVICE

$v_{ap\,fwd}$	(V)	1500	1200
$v_{ap\,inv}$	(V)	1500	1200
$i_{ap\,max}$	(A)	1200	1500
$I_{av\,max}$	(A) 1)	16	20
$i_{ap\,max}$	(A) 2)	336	420
$I_{av\,max}$	(A)	56	70
$t_{av\,max}$ (sec)		6.25	6.25
I_{av}/i_{ap} (max) (t_{av} = max. 0.2 sec)		0.166	0.166
$i_{surge\,p}/i_{ap}$ (max) ($t_{i\,surge}$ = max. 0.15 sec)		12.5	12.5

1) max. average current at max. peak current
2) max. peak current at max. average current

VI-d **The pulse ignitron**

We get a good idea of the emission possibilities of a mercury pool if we consider the General Electric ignitron type GL 7171. This tube has a single cylindrical envelope of stainless steel, with an external diameter of about 54 mm. The surface area of the mercury pool will thus be about 20 cm^2. According to the published data, the cathode spot can deliver a current of 35 000 A, if the duration of the pulse does not exceed about 1 μsec. The permissible current decreases with increasing duration, but may e.g. still be 30 000 A at 100 μsec. The mean value however, averaged over at most one discharge cycle, may not be more than 0.1 A. This means that the tube may not be ignited more than once per minute.

It will be clear from these data that the tube can be given a simple construction: there is no need for a cooling jacket, and natural convection cooling by the air is sufficient.

Such currents at tube voltages of some tens of kilovolts are met with when magnetic fields have to be produced very rapidly, e.g. in thermonuclear research. Batteries of capacitors of 1000 μF and more are used, being charged up to 12—20 kV. Such a battery is split into several units, each of which is discharged via an ignitron. The discharge current flows through a common coil within which the desired magnetic field is produced.

This same tube is used for switching off DC circuits. One of the most difficult problems in electrical engineering is to construct a mechanical switch which can switch off a current of about a hundred amperes in a DC mains of thousands of volts. The contacts are likely to be burnt up very quickly, and the arc produced between these contacts is difficult to quench. If an ignitron is shunted across the switch, this tube can be made to ignite at the moment that the contacts begin to open, the changing electrical situation at these contacts being made use of to bring the discharge about. The tube current which then flows short-circuits the arc between the contacts, as it were. The discharge in the tube can be quenched with the aid of a special circuit in which e.g. a counter-voltage is applied to the tube by means of a capacitor.

VI-e **Rectification with the aid of ignitrons** [45b]

High DC powers for rolling mills, traction motors, electrochemical plants and DC mains can be taken from the AC mains with the aid of ignitrons as well as in other ways. The controllability of these tubes makes it possible for the user to control the voltage and/or power of e.g. a motor. Special ignitrons are made for such purposes. Such tubes are generally designed to

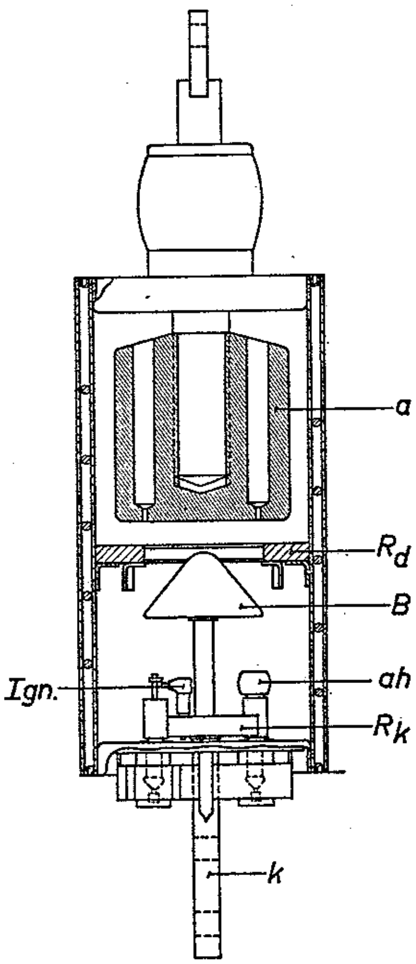


Fig. 178

Cross-section through a tube of type 5555, as an example of an ignitron for rectification purposes, a = anode, k = cathode terminal, I_{gn} is one of the two ignition rods, a_h = auxiliary anode, B = splash baffle, R_k = limiting or anchor ring for the cathode spot, R_d = ring connected to the inner wall of the tube, for reducing the ion bombardment of the anode during commutation.

meet the special requirements of e.g. traction applications. We shall therefore discuss the different kinds of tubes separately. First we shall consider tubes like the 5555, which is made by several firms. The load data are given in Table XVI, and a cross-section of the tube is shown in Fig. 178. If the maximum permissible mean tube current of 200 A is not enough for some purpose, several ignitrons can be used in parallel. The tube is provided with two ignition rods (one of which is kept as a spare), an auxiliary anode, a screen or baffle, a de-ionization ring and an anchor ring. We shall discuss these various auxiliary electrodes below.

TABLE XVI

ELECTRICAL DATA (MAXIMUM VALUES)
of ignitron type 5555

	I	II
$v_{ap\ inv}$	900 V	2100 V
$v_{ap\ fwd}$	900 V	2100 V
i_{ap}	1800 A	1200 A
i_{av}	200 A	150 A

IGNITION ROD

$v_{p\ fwd}$: anode voltage
$v_{p\ inv}$: 5 V
$i_{ign\ p}$: 100 A

AUXILIARY ANODE

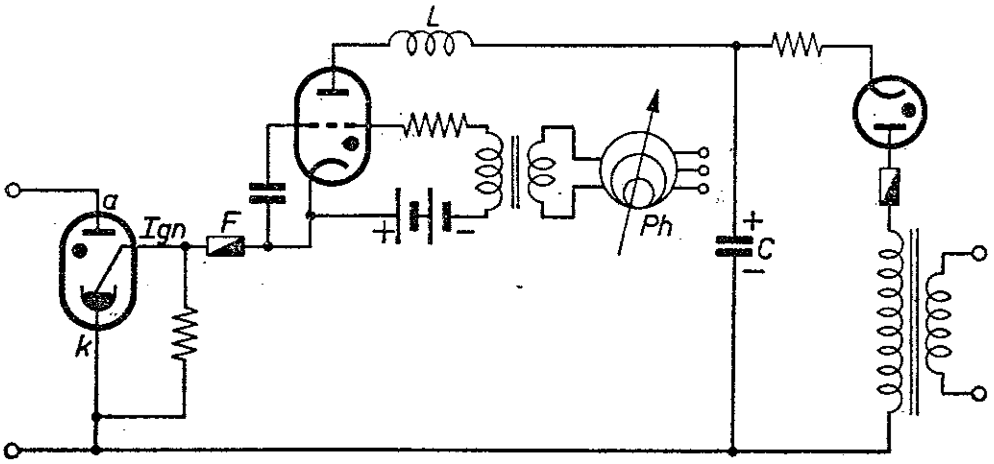
$v_{ah\ p\ inv}$: 25 V (anode conducting)
$v_{ah\ p\ inv}$: 160 V (anode not conducting)
$v_{ah\ p\ fwd}$: 160 V
$i_{ah\ p}$: 20 A
$i_{ah\ av}$: 5 A (t_{av} : max. 10 sec)

THE IGNITION *(capacitive ignition)*

As we have already mentioned, there are two main ways of passing the ignition current through the ignition rod: anode (*A*) ignition and capacitive (*C*) ignition. We have already discussed the first method in connection with welding ignitrons, and we shall now say something about *C*-ignition.

If the ignition rod were fed from the anode in a rectifying circuit, the inverse voltage in the circuit might on occasions be so large that the anode voltage (and thus the ignition-rod voltage) was too low, or the current through the rod was too low to guarantee reliable ignition. *C*-ignition however offers a higher degree of freedom and is therefore more suitable for this application, especially for multi-phase rectification.

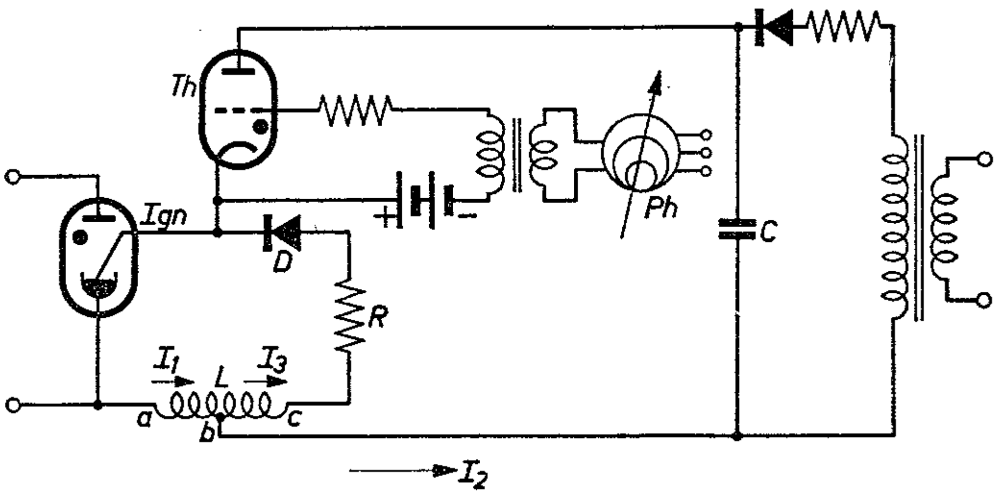
The circuit for C-ignition is shown in Fig. 179a. The principle of operation is explained in the caption. The current-time diagram for the ignition rod is shown in Fig. 180. The ignition cycle may be divided into two periods. In the first, from t_0 to t_1, the variation of the current is determined by the magnitude of L, C and the resistance R_I of the rod. The cathode spot is formed at the instant t_1. The variation of the current in the



Ph = phase controller

Fig. 179a

Conventional circuit for capacitive ignition of an ignitron. The discharge current of the capacitor C flows periodically via the coil L and the thyratron to the ignition rod *Ign* and the mercury cathode k, giving rise to a little spark at the mercury surface. The phase of the ignition moment can be adjusted with the aid of the phase regulator *Ph*. Because of the presence of the coil, C is charged up with opposite polarity, so that the current through the ignition rod becomes zero, whereafter C can be charged up again with the original polarity.
F = fuse.



Ph = phase controller

Fig. 179b

Control circuit for capacitive ignition using a low-power thyratron *Th*, e.g. type 5684. The discharge current flows through *Th* for only a short time: for most of the discharge, the current flows through the whole of the coil L, the current-limiting resistor R and the diode D, so that *Th* is relieved of its load.

second period is determined by L, C and the voltage across the auxiliary arc. The current varies nearly sinusoidally with time in both periods, because the ohmic resistance is low.

The duration of the whole process must be long enough to allow the main discharge to take over from the auxiliary discharge. If we take e.g. $L = 1$ mH, $C = 5\ \mu$F, and neglect the ohmic component, we find
$t_2 - t_0 = \pi\sqrt{LC} = \pi\sqrt{10^{-3}.5\,.\,10^{-6}} = 220 \times 10^{-6}$ sec or 220 μsec.

The variation of the current in the ignition-rod circuit as sketched in Fig. 180 is quite independent of the type of tube and of the main anode circuit. The power consumed by the control circuit for ignitrons is much greater than that for thyratrons. If we assume that the average value of the ignition-rod current I_{av} during an ignition cycle of 200 μ sec (= t) is 10 A (the peak value i_{ap} will be many times higher) and that the mean voltage of the rod $\overline{V}_{av} = 200$ V, we find that the mean ignition power at mains frequency $f = 50$ c/s is:

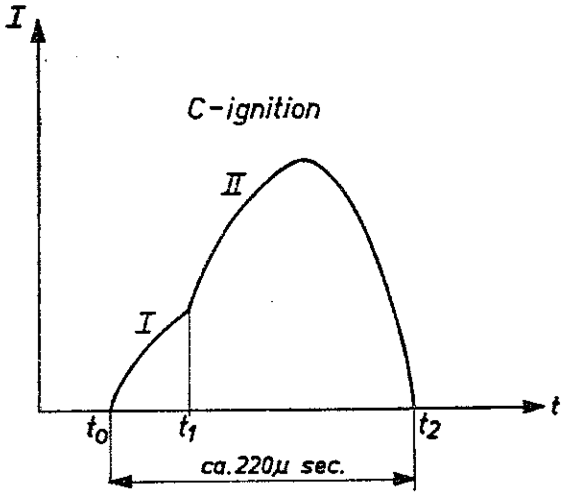


Fig. 180
Current through the ignition rod as a function of time for C ignition. During period *I* there is not yet any cathode spot; this is formed at time t_1. The variation of the current during period *II* is mainly determined by L and C (see Fig. 179a).

$$W_{ign} = f \times t \times V_{av} \times I_{av} = 50 \times 200 \times 10^{-6} \times 200 \times 10 = 20 \text{ watt.}$$

Let us now consider a thyratron with a peak-voltage transformer placed in the switching-grid circuit. We may assume a mean peak voltage V_{av} of 100 V for 1 msec (= t), and a grid current $I_{av} = 3$ mA. The mean power of the grid circuit W_g is then:

$$W_g = f \times t \times V_{av} \times I_{av} = 50 \times 10^{-3} \times 100 \times 3 \times 10^{-3} = 15 \text{ mW.}$$

There are however ignition methods for ignitrons where the power needed is only a fraction of that mentioned above. We shall now mention one important example, beginning with a short introduction.

In general, the following are necessary for reliable ignition:

a. a high current through and a high voltage across the ignition rod, to ensure stable cathode-spot formation;
b. the discharge current must flow through the rod for long enough after

the formation of the cathode spot for the main arc (or the auxiliary arc) to take over the discharge;

c. the formation of the cathode spot must be completed within a certain time.

The simplest way of fulfilling these three demands is to use an *LC*-circuit, a conventional example of which has been discussed above. If such a circuit is designed properly, it meets all three demands. However, such a circuit produces a current lasting for a long time, which also flows through the thyratron which acts as a switch in the ignition circuit. Moreover, at the end of the ignition cycle, the thyratron is subjected to a high and steep inverse-voltage pulse. A sturdy thyratron such as the 105 or 106 is usually necessary for such *LC*-ignition if the thyratron is to have a sufficiently long life.

Fig. 179b shows an ignition circuit for *C*-ignition in which a low-power thyratron such as the 5684 (see Table XVII) is sufficient (Philips have applied for a patent for this method of ignition).

The ignition cycle can be divided into two phases:

1. the time during which the thyratron *Th* passes current,
2. the time during which the diode *D* passes current.

During phase 1, the capacitor *C* is discharged via *Th*, the ignition rod *Ign* and the part *ab* of the self-inductance *L*. The peak value of the current is quickly reached because of the low value of the product *LC* in this phase. As soon as the voltage across the capacitor is zero, the second phase begins. The (maximum) magnetic field strength present in the coil at that moment is not used to charge *C* negative, but causes a current in the circuit *a-b-c-D-Ign* which maintains the discharge along the ignition rod. Since this current now flows through the whole coil, its value is only a fraction of the peak current (the number of ampere-turns remaining constant). This current does not therefore flow through *Th* but through *D*, and rather slowly at that. The result is that the thyratron in this circuit only passes a high current for a short time, and that the inverse voltage across it is not high and moreover increases slowly. A small thyratron may therefore be used and in fact the whole circuit is much lighter than in the more usual *LC*-ignition methods.

TABLE XVII

ELECTRICAL DATA (MAXIMUM VALUES) OF THYRATRON TYPE 5684

$v_{ap\,fwd}$	1000	V	
$v_{ap\,inv}$	1250	V	
$-V_g$	300	V	before conduction
$-V_g$	10	V	during conduction
i_{kp}	30	A	
I_k (t_{av} : 5 sec)	2.5	A	
i_{surge} (max. 0.1 sec)	300	A	
I_g (t_{av} : 1 cycle)	0.1	A	
i_{gp}	0.5	A	
R_g	10—100	kΩ	
t_{amb}	−55/+75	°C	
Commutation factor	0.7	V/μsec × A/μsec	
CAPACITANCES			
C_{ag}	3	pF	
C_{gk}	14	pF	
TYPICAL CHARACTERISTICS			
V_{arc}	10	V	
t_{ion}	10	μsec	
t_{dion}	1000	μsec	

THE AUXILIARY ELECTRODES

1. *The auxiliary discharge*

When the ignitron is used as a rectifier, various circumstances can make it necessary for the cathode spot, once formed, to be maintained no matter what the anode voltage. To ensure this, an auxiliary discharge is maintained between an auxiliary anode and the mercury pool. This auxiliary discharge may be a permanent DC arc, or may carry a pulsed current: the choice between these two is determined by the nature of the load and by the method used to control the ignition. We must remember in this connection that a non-anchored cathode spot (see VI-a) needs an instantaneous current of about 15 A, or an average current of 5 A, for it to be maintained reliably over a period. The following example should help to make these points clear for the case when the auxiliary anode is fed with an alternating voltage. Fig. 181 shows the auxiliary anode a_h connected to a transformer T ($V_{sec} = 50$ V), in series with a current-limiting resistor R of 5 ohm. The auxiliary-current circuit also contains a fuse F and a selenium diode S. The function of the latter is to prevent a_h from being overloaded by any back current which may happen to come from the main discharge. We shall first show that the auxiliary-anode voltage V_{ah} must have a phase lead with respect to the main-anode voltage $V_{a\ rms}$ (see Fig. 182). At full drive and with 3-phase rectification, a given tube will ignite at the instant P

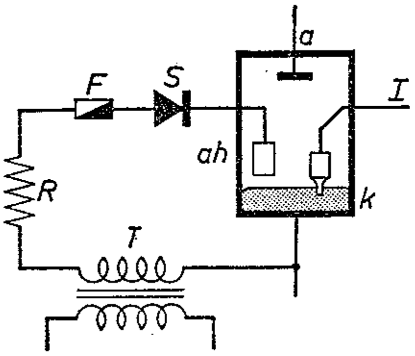


Fig. 181

Auxiliary-anode circuit with AC supply. Selenium diode S blocks any back current from the main discharge. F = fuse.

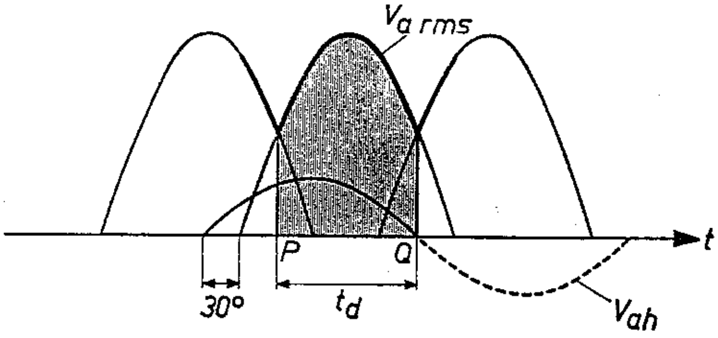


Fig. 182

The phase of the auxiliary-anode voltage V_{ah} during 3-phase rectification without retarded ignition. V_{ah} has a phase lead of 30° over the main-anode voltage $V_{a\ rms}$. At the point Q, where the main discharge is quenched, the auxiliary current becomes zero so that the main anode, which is now becoming negative, cannot be struck by ions from the auxiliary discharge.
t_d = discharge time.

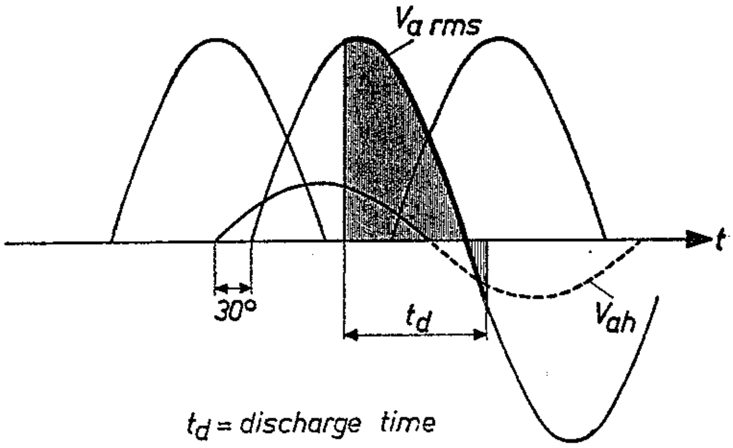


Fig. 183

Three-phase rectification with retarded ignition (discharge time t_d). The auxiliary voltage V_{ah} has a phase lead of 30° over the main-anode voltage $V_{a\ rms}$ as in Fig. 182, so that during the inverse phase the main anode is not bombarded by ions from the auxiliary discharge.

and be quenched again at the instant Q (phase difference 120°). The anode becomes negative after the main discharge is extinguished. Under these conditions, we do not want there to be any ionization as a result of the auxiliary arc, since this would cause ion bombardment of the anode. The auxiliary voltage V_{ah} must therefore go through zero at time Q, i.e. V_{ah} must have a phase lead of 30° with respect to $V_{a\ rms}$. Even if the ignition is retarded, a phase lead of 30° is usual, as may be seen from Fig. 183. V_{ah} must also have a phase lead with respect to $V_{a\ rms}$ in Graetz circuits, as will be explained below. An auxiliary discharge is needed under the following circumstances:

a. *At low anode current* (mean tube current 0 to 10 A), which will be obvious from the above. The next two cases are in fact special cases of this.

b. *At low anode current due to high counter-voltage.*
In this case the positive voltage between the anode and the cathode, and thus the tube current, decreases as the counter voltage V_b increases. (This counter-voltage may be due to a battery load, see Fig. 49).

c. *At full drive.*
Here the moment of ignition is displaced to the region of anode voltages where the lowest instantaneous anode voltage is present. This also causes a low anode current, and makes it possible that the available anode voltage will be too low to form the arc at the ignition moment.

d. *With Graetz circuits.*
Let us take as an example three phase voltages U, V and W which feed six tubes *I—VI* (see Fig. 184a). The direct current has thus a 6-phase ripple. Each tube passes current during 120°, in such a way that e.g. tube *I* is in series with tube *V* for 60°, and with *VI* for the other 60°. In order to keep the ignition circuit simple, each tube receives an ignition pulse once per period from a six-phase pulse generator. If we realize that the "time line" takes up the position *a* to *g* successively, it will be clear that the currents through the various tubes will have the forms shown in Fig. 184b. Tube *I* first passes current in series with tube *V*, as mentioned above; its supply voltage during this period is $\overline{U} + \overline{V}$. Then tube *I* passes current in series with tube *VI*, the supply voltage being $\overline{U} + \overline{W}$. At the end of this period *I* is quenched and, as has been mentioned above, the current through the auxiliary anode must be zero at this moment. It follows that V_{ahI} must

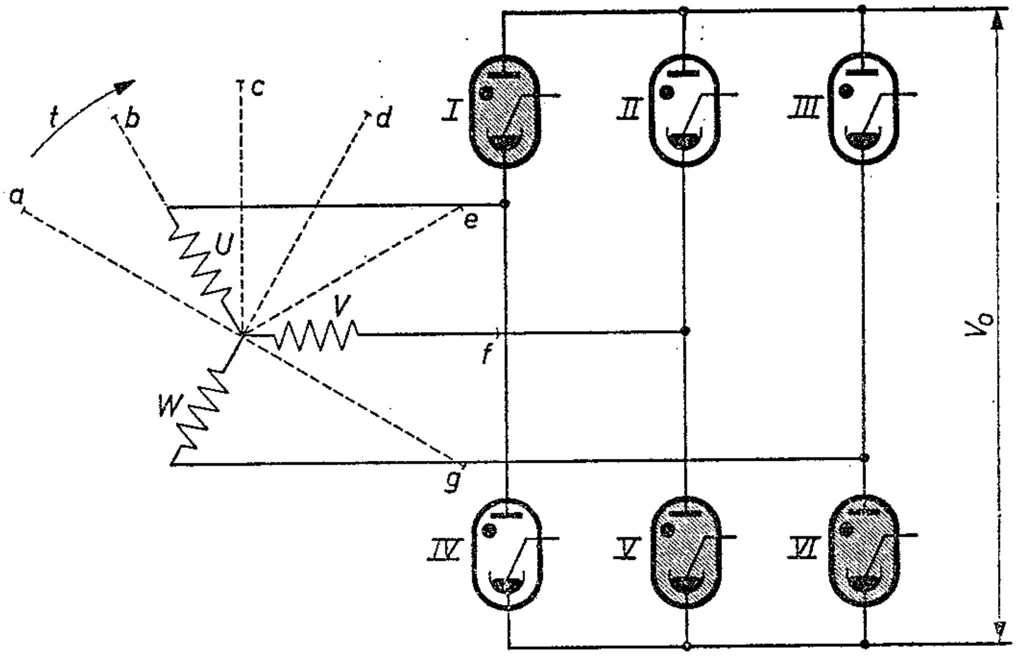


Fig. 184a
Circuit for supply of 6 ignitrons in a Graetz circuit from a 3-phase mains. Each tube passes current for 120°, e.g. *I* first for 60° in series with *V*, then for another 60° in series with *VI*. If the time line is assumed to follow the arrow *t*, taking up the positions *a* to *g* in succession, then if the phase of the auxiliary-anode voltage is suitably chosen the distribution of the current among the tubes is as shown in Fig. 184b.

be in phase with $\overline{U} + \overline{V}$, and have a phase lead of 60° with respect to $\overline{U} + \overline{W}$. This arrangement has another advantage; at the moment when the ignition pulse P_{I} is fed to *I*, the instantaneous auxiliary voltage is sufficiently high, while *I* continues to pass the auxiliary current (and thus to remain ionized) during the rest of the period during which the anode is conducting. Since the ignition pulse is given to two tubes in succession, even though they must pass current simultaneously, the tube which receives the ignition pulse first must remain ionized with the aid of the auxiliary arc until the second has received its ignition pulse too.

The auxiliary current can in principle be omitted if the two tubes which are to work in series receive an ignition pulse *simultaneously* only once, namely when the rectifier is set into operation. After this, the "second" tube will always be able to work together with the "first" tube (which is already passing anode current) at the moment when it receives its ignition pulse. Even if the moment of ignition is retarded, this method still works, as long as the instantaneous value of the total direct current does not become zero. In that case, the double pulse would have to be administered afresh every 60°.

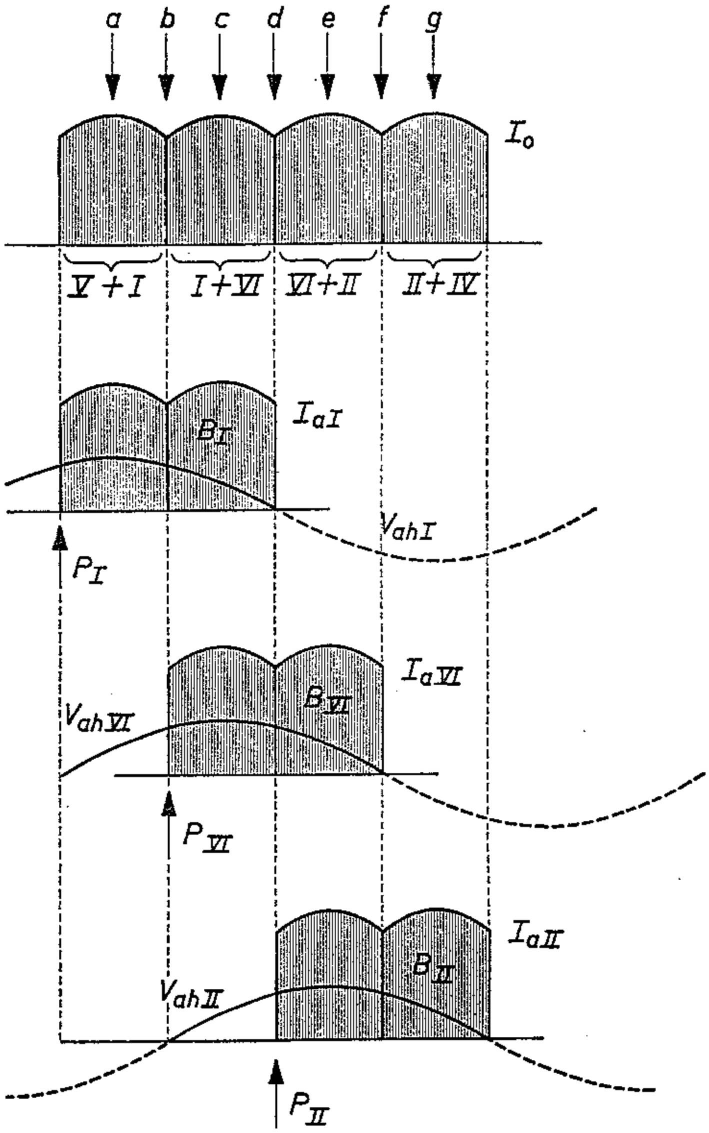


Fig. 184b

Three-phase Graetz circuit with 6 ignitrons. Schematic representation of the phase of the auxiliary anode voltages V_{ah} with respect to the main-anode voltages at the instants *a* to *g* (see Fig. 184a). Thus the auxiliary-anode voltage $V_{ah\mathrm{I}}$ of tube *I* must be in phase with the coupled main-anode voltage *U—V* according to time line *a*, and have a 60° phase lead with respect to the coupled voltage *U—W* according to time line *c*. Tube *I* receives its ignition pulse P_{I} at a moment when the auxiliary-anode voltage is already considerable, and the auxiliary current continues to flow until the end of the conducting period of *I* (B_{I}). I_0 is the total DC current with 6-phase ripple given off by the assembly, $I_{a\mathrm{I}}$ the contribution made to this current by tube *I*, etc.

2. *The splash screen*

The mercury in the cathode spot can evaporate so vigorously that mercury droplets are produced. Some of these would even be capable of reaching the anode, which might give rise to anode emission and thus to back current. This is one of the reasons why the tube 5555 (see Fig. 178) is fitted with a splash screen (baffle) *B*. This screen also hinders exchange between the hot anode and the cold cathode. Its third useful function is to check the diffusion of ions from the plasma to the negative anode in the inverse phase. The baffle is in the form of a mushroom, placed between the cathode and the anode, with a graphite top and a metal stem which is welded on to the cathode cap.

The result of anode emission in multi-phase rectification is more or less equivalent to short-circuiting. In a circuit for single-phase welding, the situation is much more favourable because there is always a current-limiting component in series with the tubes, and because the variation of the inverse voltage on each tube is regular thanks to the parallel arrangement of the tubes. Welding ignitrons do not therefore generally need a baffle.

3. *The de-ionization ring and the limiting ring for the cathode spot.*

The operating conditions of an ignitron when it is used for rectification are less favourable than when it is used for welding, as we have seen above.

The difficulty is connected with the rate at which a current which is flowing falls to zero, i.e. with $-\mathrm{d}i/\mathrm{d}t$. In a welding tube, I always decreases sinusoidally no matter when the moment of ignition is. In rectification, however, $-\mathrm{d}i/\mathrm{d}t$ is greater the more phases are used. Moreover, the inverse voltage increases rapidly, i.e. the commutation conditions are unfavourable (see IV-b-4). The ion bombardment which the anode must endure as a result of this can be reduced by placing a ring R_d near the anode (Fig. 178).

The discharge space is then split in two, as it were, the lower, vapour-rich, part being somewhat cut off from the anode part. The ring, which is connected to the inner wall, also has a local cooling action. Like the baffle, the de-ionization ring also hinders the radiation of heat from the anode towards the cathode.

Especially when the auxiliary anode is fed from a separate DC source, but also when AC is used, the cathode spot gets plenty of chance to reach the wall of the tube, which has the same potential as the mercury pool, in its motion over the mercury surface. This would give rise to local heating of the wall and evolution of gas, and the cathode spot would be able to climb up the wall, which is wetted with drops of mercury. Droplets of mercury from the cathode spot might then even reach the anode between the baffle and the de-ionization ring. A limiting ring, R_k, of e.g. quartz, is therefore placed on the surface of the mercury, with the ignition rods within it. The diameter of the ring is chosen so that the cathode spot can never get so far from the mercury pool that it can "see" the anode.

Another possibility is to make the ring of a suitable metal. It is then known as an anchor ring, and we shall now discuss this in somewhat greater detail.

4. *The anchor ring* [41, 65, 66]

As the cathode spot moves over the surface of the mercury, it always produces more mercury vapour than is needed for keeping the arc discharge going (cf. Fig. 164). We have already mentioned that the excess vapour must be condensed again, which needs extra cooling. Moreover, droplets of mercury are splashed upwards, and must be prevented from reaching the anode. The above-mentioned screens which are provided for this purpose cause the arc to be rather long, which entails a high arc voltage. If the cathode spot could be prevented from moving, this would be a great improvement. A step in this direction has been found in the placing of a metal ring (anchor) in the mercury so that it sticks out above the surface. The spot will prefer to stick to the ring, if only because the current can then follow the way of least resistance. If moreover the metal is given a special treatment so that it is wetted by the mercury, i.e. so that the meniscus is curved upwards, instead of downwards as usual, the amount of mercury evaporated will be minimum. The heat dissipated will be led off by the shortest path, via the anchor ring to the metal cathode tray to which the ring is fixed. The luminous, linear cathode spot spreads out round the anchor ring as the current increases; the thermal resistance thus being kept low. Uniform conduction of heat along the whole length of the ring must be possible. Under these conditions, the arc voltage can be reduced to about 10 V, and the necessary auxiliary-anode current to only a few amperes.

There are only a few metals which come into consideration for the material of the anchor ring. Tungsten is usually used: it is not dissolved or otherwise attacked by the mercury, but continues to present a clean surface.

VI-f **The ignitron with vacuum pump**

The ignitrons we have discussed so far have been contained in a sealed vessel. Demountable tubes are also sometimes used for high powers. They must then be equipped with a vacuum pump which keeps the vacuum sufficiently high in the tubes or in the combination of tubes which forms a multiphase system. Until about 1940, is was usual to use one iron vessel with 6, 12, 18 or 24 anodes in the latter case. We shall discuss this design below (VI-j-2).

There are two types of demountable single-anode tube, viz. the ignitron with periodic ignition and the excitron (see VI-b-3).

As an example of an ignitron with a vacuum pump we shall consider the ignitron used for traction purposes. A large tube of this type is shown in Fig. 185; this is used e.g. for the DC supply of traction motors. A six-phase combination of such tubes is used in a sub-station to transform AC power into 1500 V or 3000 V DC energy for the overhead lead. The strong variation in the amount of current taken and the temporary overloading on the tubes when the trains are started have made it necessary to design railway ignitrons in a way which differs considerably in certain details from the tubes we have dealt with so far. Thanks to the intermittent ignition, it is possible to allow the mercury to make direct contact with the wall of the tube (cf. VI-e-3); this is not possible with the excitron, which we shall discuss below.

A graphite grid in the shape of a bowl is placed around the anode; sometimes there are two such grids. The inner one is connected to e.g. a transformer winding which gives a voltage of such a phase that the grid is positive when the cathode spot is formed and negative when the main anode ceases to pass current. The ignition voltage of the main discharge is thus lowered in the positive phase, and in the negative phase the grid aids the rapid disappearance of the positive space charge around the anode.

The outer grid acts as a switching grid, as in a thyratron. Other details of the construction are mentioned in the caption of the figure.

Single-anode ignitrons have the advantage over the iron vessels with many anodes which we shall discuss below that the operation is very little disturbed if one of the tubes has to be changed, since the rectifying unit can go on working for a short time with one tube less. Fewer spares need then be kept. Moreover the arc voltage is lower.

VI-g **The locomotive rectifier**

Developments in railway traction have of recent years led to the insight that it is possible to combine the economic advantages of the AC overhead net with normal mains frequency and directly coupled to the general electricity supply, with the attractive features of DC motors. Previously, it was usual to use AC commutator motors; but this was only possible at low frequencies, so that a *separate* electricity supply was necessary for the railways, with a frequency of $16^2/_3$ c/s. Mercury-cathode rectifiers placed in the locomotive can now act as the link between the mains and the motor. These may be of the ignitron type, or the excitron type.

a. *The ignitron type*

The problems connected with the mobile installation of tubes, where they

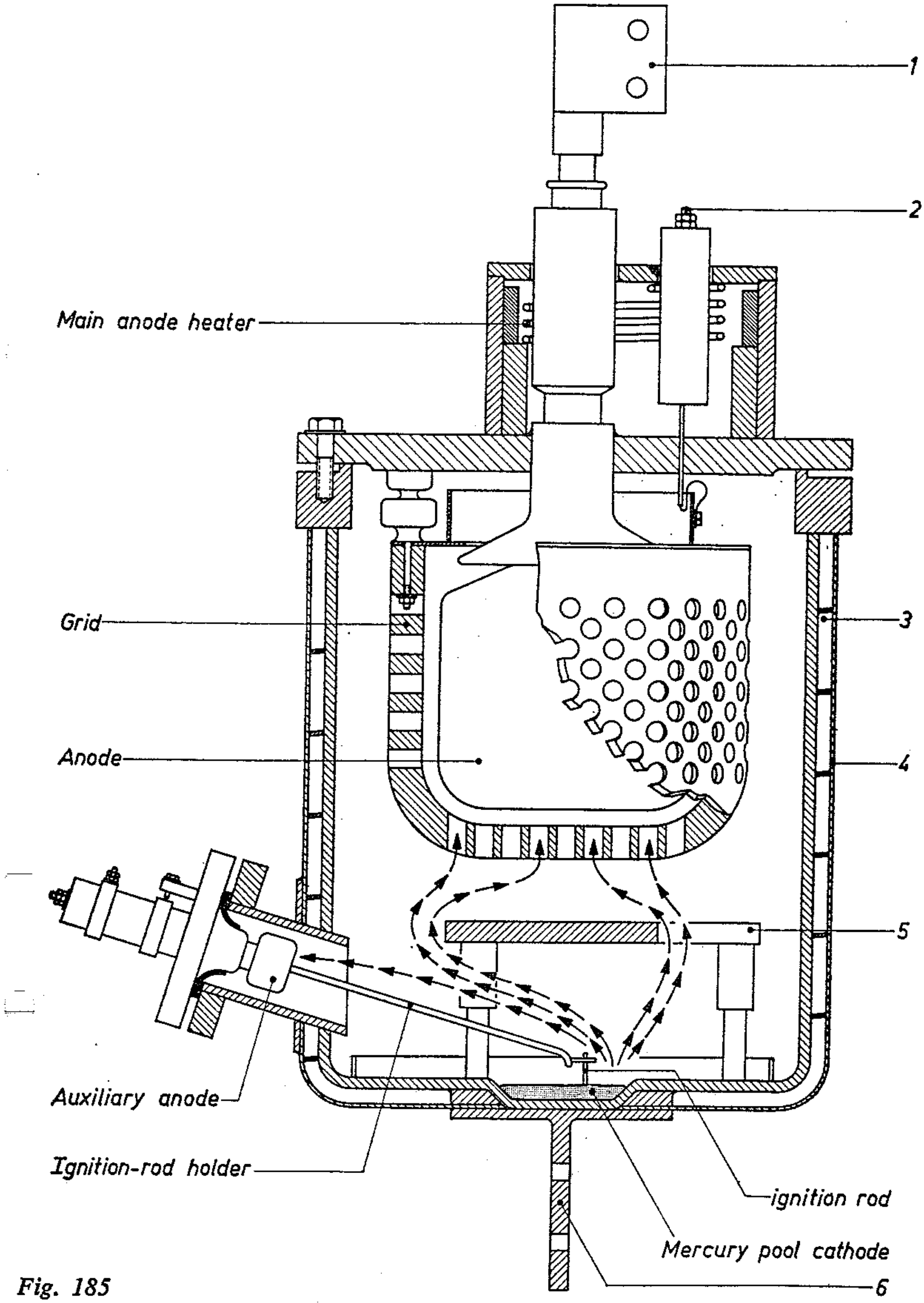


Fig. 185

Demountable ignitron (G.E.C.) with one anode, for installation in sub-stations for traction power. A vacuum pump must be used with this tube, which has a concentric ignition-rod holder and auxiliary anode.

1. main anode terminal	4. cooling jacket
2. grid terminal	5. splash baffle
3. cooling-water space	6. cathode terminal

A heater coil is wound around the anode lead and grid lead, to prevent the condensation of mercury on these electrodes [110].

are subjected to jolts, vibration and oscillation, have been solved by several manufacturers of rectifiers. General Electric's water-cooled, pumpless ignitron type GL 6504 contains a number of features which are developed in answer to these problems (Fig. 186).

The splashing of the mercury is limited by hindering the motion of the mercury pool. This is done by dividing the surface into small regions about one square inch in area by radial molybdenum partitions between two rings which are placed just above the mercury surface. The ignition rods are

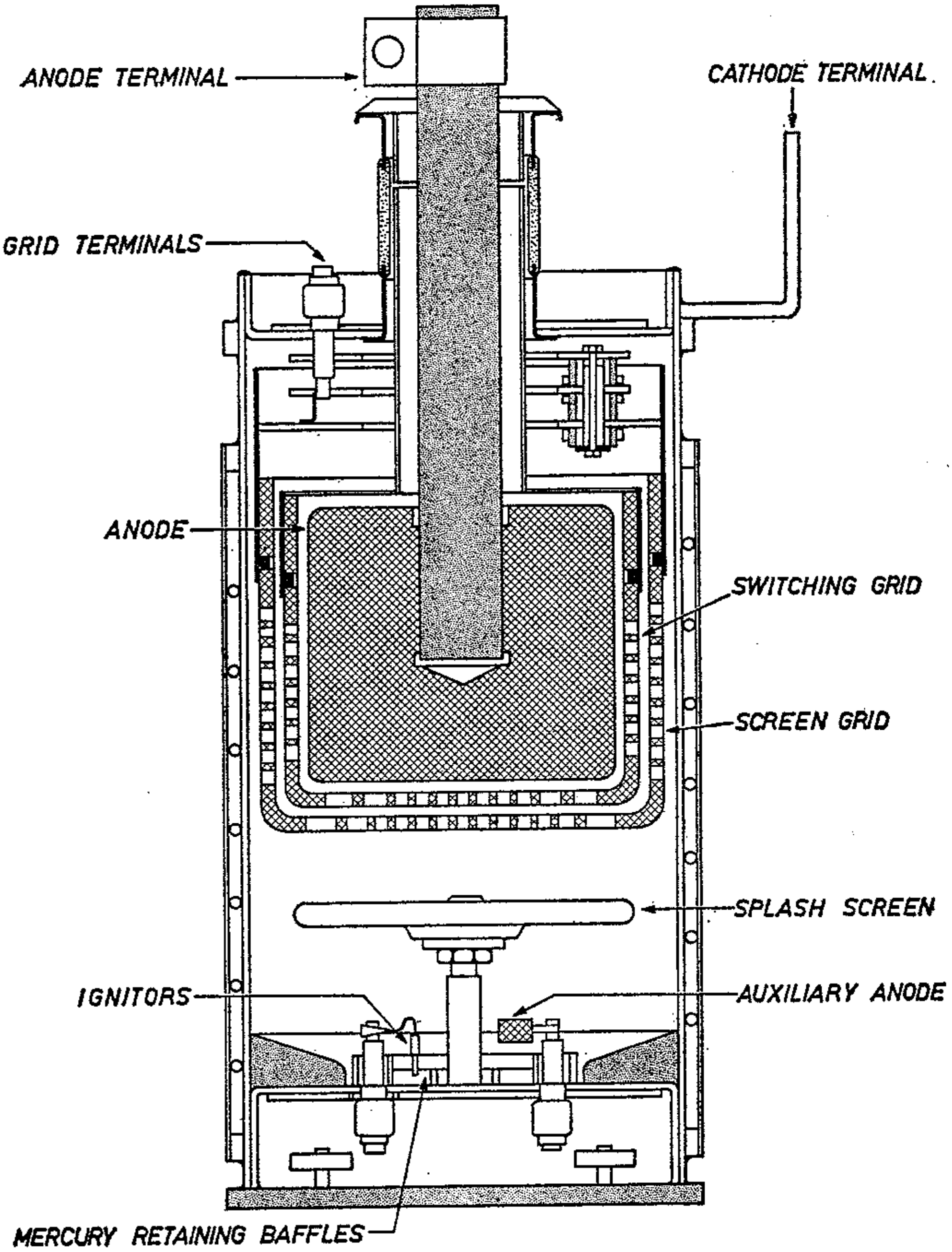


Fig. 186

General Electric pumpless ignitron type GL 6504, for use as a locomotive rectifier. The cross-section shows the grids, the splash screen, the ignitors and the retaining baffles which limit the motion of the mercury pool. The cathode terminal is on top of the can (which acts as a coaxial return lead for the tube current).

placed in compartments near the middle. There is also a splash screen between the cathode and the two graphite grids which are arranged around the anode. The grid nearer to the anode is a switching grid, the other one is a screen grid. The frequent starting and stopping of passenger trains means that the rectifiers must deal with frequent large current peaks. The electromagnetic effect of these current pulses on the discharge in each tube, and in neighbouring tubes, is therefore reduced by leading the cathode current back coaxial with the arc, i.e. via the outer jacket. The external field is thus zero. This construction means that the cathode terminal is on top of the tube, near the anode terminal. Twelve such tubes can serve a 4000-HP locomotive. The peak forward anode voltage must not exceed 4000 V, and the maximum permissible average current is about 700 A; the actual value depends on the duration of the load.

b. *The excitron type* [64]

A locomotive rectifier built according to the excitron principe is e.g. the "Com-pack" mercury-arc rectifier of the G.E.C. Type C7-Mk1 is a

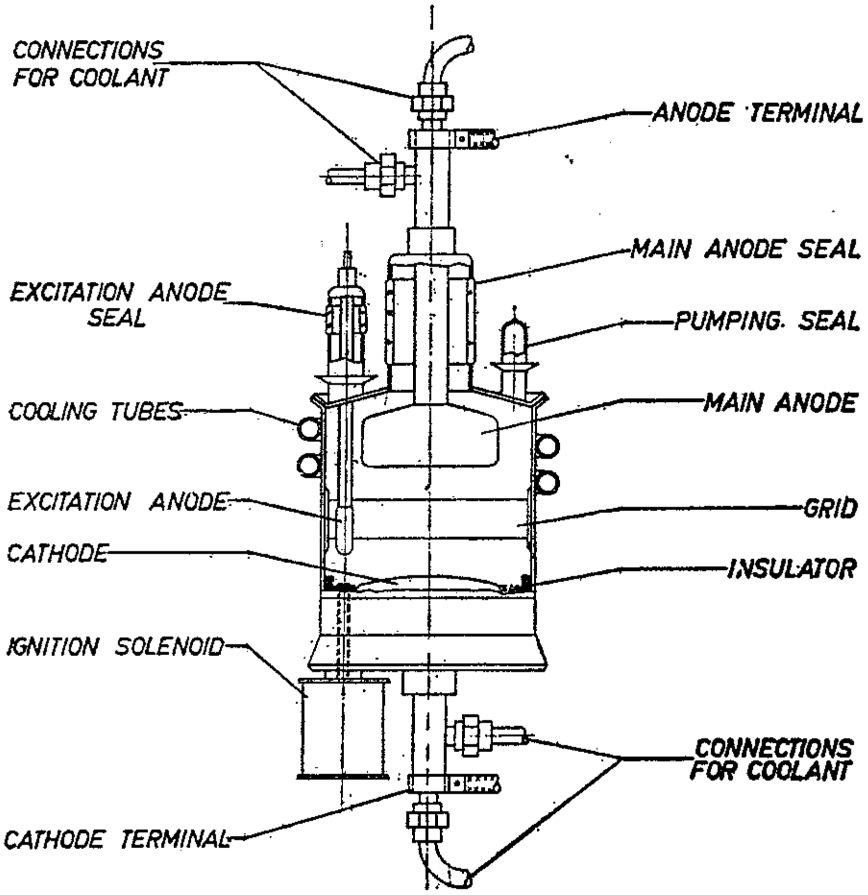


Fig. 187

Pumpless mercury-arc rectifier tube on the excitron principle, for use in a locomotive (General Electric type C7-Mk1). The can is cooled by an external cooling-water spiral. The anode and the anchor ring are cooled by a separate stream of water. The permanent auxiliary arc is produced with the aid of a jet of mercury which impinges on the auxiliary anode [33].

pumpless tube, designed for a continuous current $I_{av} = 120$ A at 1250 V (Fig. 187). The cathode spot is anchored, and the tube is water-cooled (see the caption of this figure). The relatively small size of this tube and its increased resistance to oscillation and jolting make it suitable for use in a train.

VI-h **Ignitrons for high tensions**

Ignitrons for use in high-power rectifiers and inverters, e.g. for the transmission of energy at high DC voltages, must work at voltages of tens of kilovolts. In inverters, tubes are used to convert AC to high-tension DC, which is then transmitted along a cable. When it arrives at its destination, the DC energy is transformed back into AC with the same sort of tubes. One of the difficulties in this application is that special measures must be taken to cut off these valves in the inverse phase: the high inverse voltage must be taken up by a thin ionic layer around the anode, while the rest of the tube is practically field-free. Attempts have been made to reduce the load on this thin layer by distributing the inverse voltage over the whole distance between the anode and the cathode. This has led to the introduction of distribution grids, the voltages between which are determined by connecting them to the tappings of a potentiometer connected between the anode and the cathode. The basic construction of the tube thus becomes as shown in Fig. 188 [39].

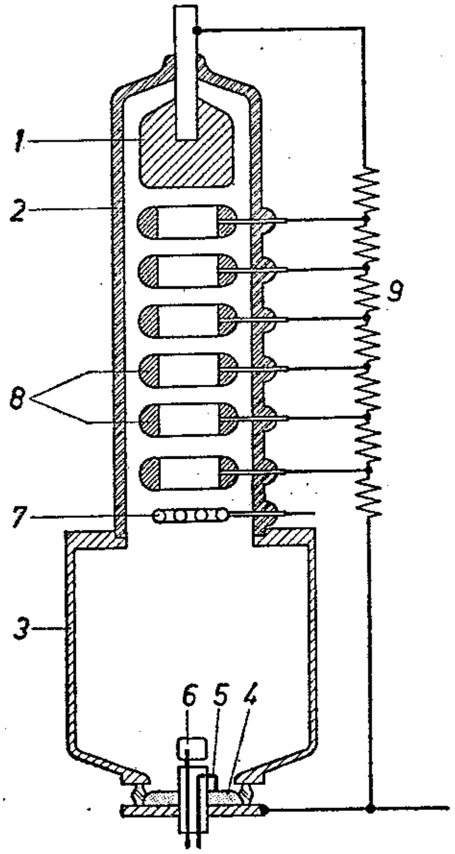


Fig. 188

Sketch of the construction of the ASEA valve for power transmission at high DC voltages.
1. anode, 2. insulator, 3. iron tank, 4. mercury cathode, 5. ignitor, 6. auxiliary anode, 7. switching grid, 8. voltage-dividing grids, 9. voltage-dividing resistor for inverse voltage [39].

The ions thus get much more chance to give up their energy to neutral molecules, or to be neutralized on the walls, during their passage to the anode. The voltage distribution is chosen to match the various ionization densities in the different parts of the tube. The de-ionization is so effective

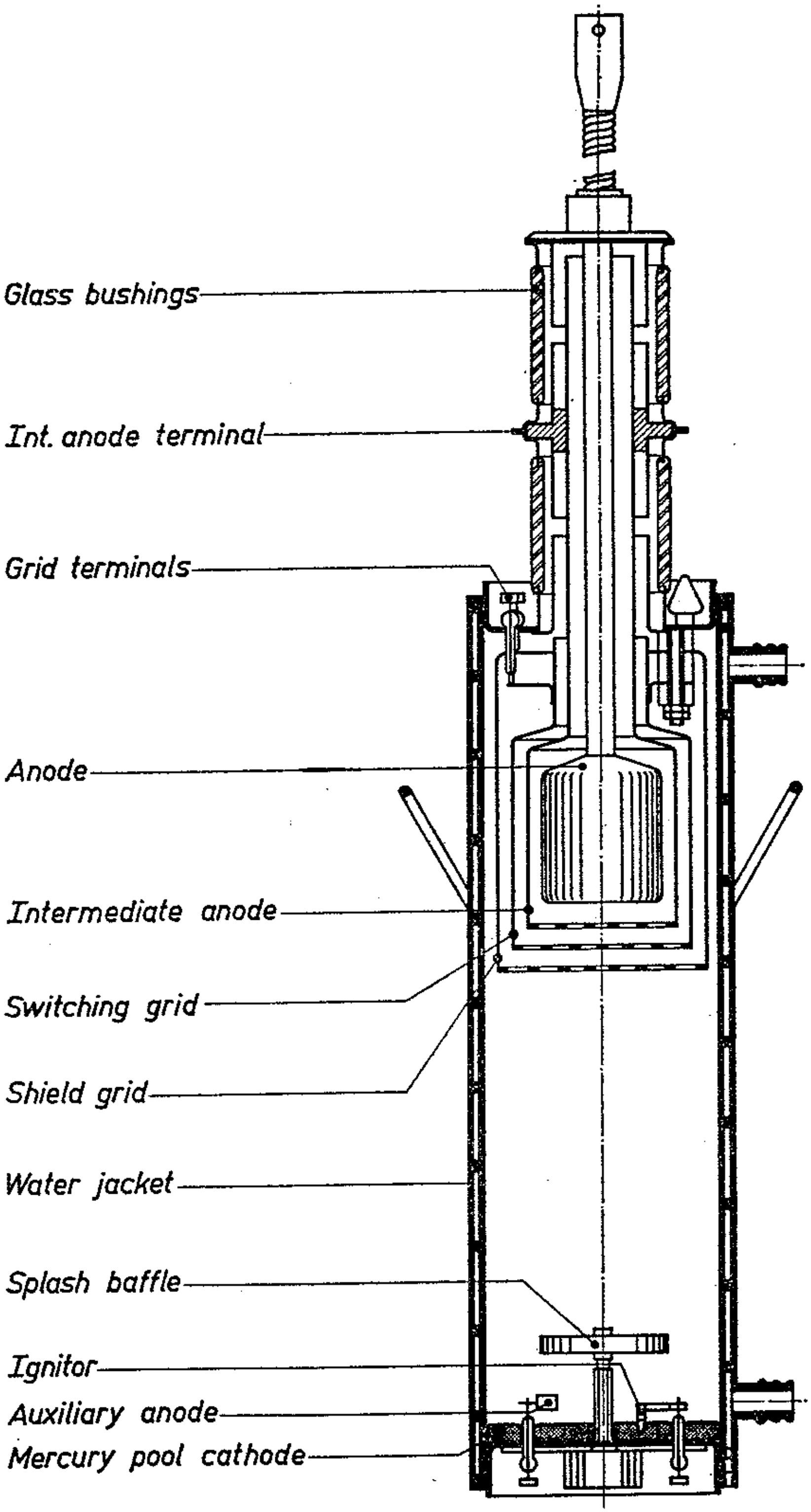


Fig. 189

High-tension ignitron, General Electric type GL 6228/506, with three grids. The supporting ring of the third grid ("intermediate anode") bears small metal cylinders which protect the metal-glass seals of the bushings against discharges which could otherwise be emitted from this electrode. Similar screens are also placed above and below this electrode [33].

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 (or 1 minute)
rate of flow of cooling water	12 1/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}	=	$\leqslant$ 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 $\frac{1}{2}\ CV^2$ = 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.

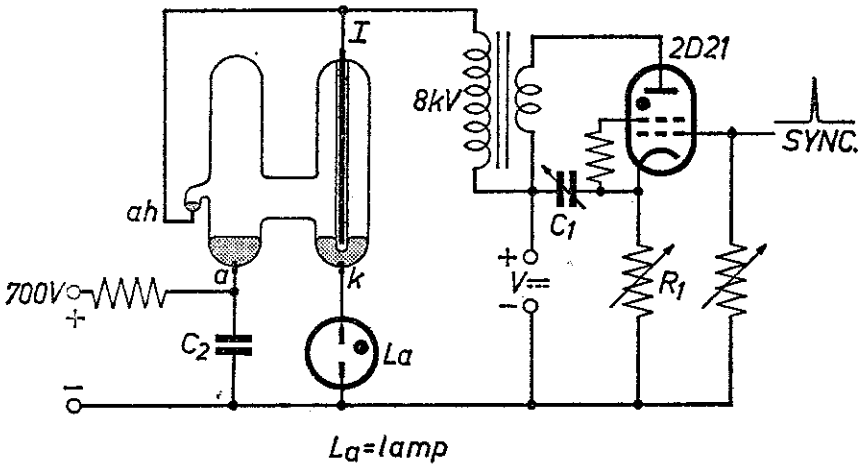


Fig. 190

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 of space is also achieved, because better use is made of the capacious mercury-condensation space present in some tubes to keep the pressure low for the sake of the anode. Just as in tubes with oxide cathodes, however, there is the disadvantage that in the negative phase an anode, acting as a probe in the discharge, is influenced by the ionization produced by the arc current to another anode. Two constructions have proved suitable for tubes of this type: with glass envelopes, each anode being withdrawn in a separate side arm, and with iron envelopes. The latter are mainly used for very high powers.

VI-j-1 GLASS VESSELS

It has already been mentioned in III-b-3 that if the anode is withdrawn in a glass side arm whose diameter is small compared to that of the rest of the discharge space, the discharge becomes of the column type; the ignition voltage is then no longer in the neighbourhood of the ionization voltage of the gas, but considerably higher. The burning voltage also increases. This increase in the ignition voltage is found in the negative phase as well as the positive. Surprisingly enough, the increase of the ignition voltage is greater in the negative phase. This makes the use of long anode arms attractive in rectifier tubes for high anode voltages. The backfire voltage

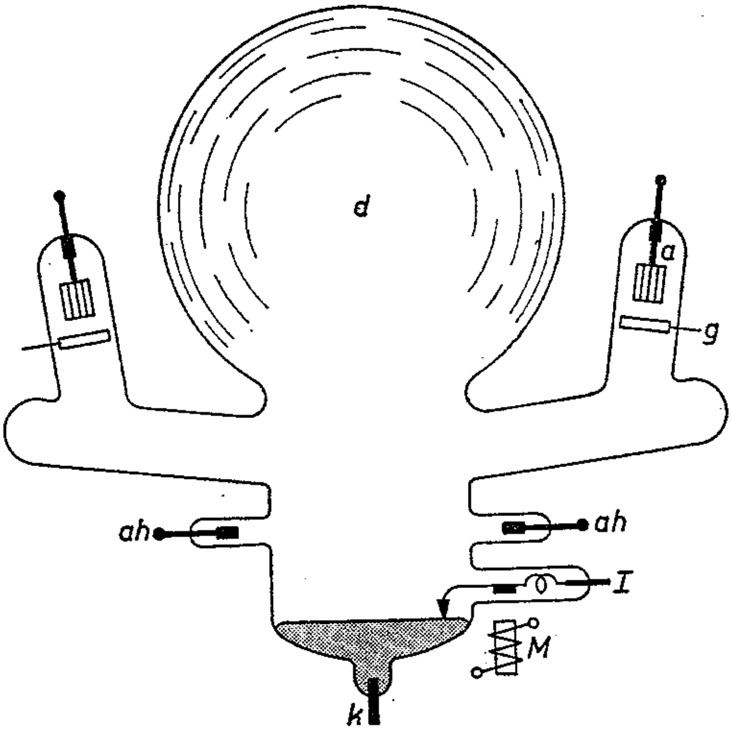


Fig. 191

Pyrex-glass mercury-vapour mutator for use as a rectifier or inverter, with three or six anodes (two drawn), for loads of up to 500 A at 50—750 V. This is a sealed-off air-cooled tube, which requires no pump.

d = condensation compartment, a = anode, a_h = auxiliary anode, k = cathode, I = ignitor (magnetic), M = magnet, g = switching grid [111].

of tubes with long cylindrical arms is directly proportional to the length of the arm and inversely proportional to the diameter.

It must be realized however that when glass side arms are used, the ignition voltage in the positive phase is no longer reproducible. This depend, among other things, on the state of the wall (surface charges, conductivity) and the magnitude of the current in the previous period (residual ions). The discharge can be facilitated by irradiation or by an auxiliary discharge.

The construction described above is used in tubes for 100 to 500 A at 50 to 750 V. Fig. 191 shows such a tube, with a large cooling dome and three (possibly six) sealed-in anode arms (the simplified figure only shows two arms). Despite the fragility of the glass construction, these tubes are rather attractive because they need no vacuum pump because the walls are not porous for hydrogen, as are the iron vessels described below under some circumstances. These tubes are made of pyrex glass, which can stand relatively high temperatures. We recognize the components essential for the ignition and maintenance of the cathode spot. The anodes may be made of tungsten, molybdenum or graphite, and at high currents they are cooled by cooling fins attached to the anode leads.

The temperature of the cooling dome is often kept low enough by natural convection, but above a certain load forced air cooling must be used.

Since these tubes are made of glass, some of the heat evolved is imparted to the surrounding air by radiation. The tubes are controlled with the aid of switching grids, one of which is placed in each arm near the anode.

VI-j-2 IRON VESSELS

Glass rectifiers can no longer be used for currents of the order of 500 to 10 000 A and voltages from 500 to 3000 V, and iron vessels must be used under these conditions. Such tubes are mainly used on the railways and for electrolysis. Multi-anode tubes with iron envelopes are also used for the supply of large transmitters, e.g. for 20 kV/30 A.

The number of anodes is usually 6 or 12, sometimes 18 or 24.

These tubes have a number of features which differ from those of glass tubes. It has already been mentioned that hydrogen produced by electrolysis in the cooling water diffuses through the iron wall. These tubes must therefore be pumped out during operation, the more so because they are made of several separate parts which are clamped together so that the inside can be inspected at intervals. A completely vacuum-tight seal is not possible with such a construction. Rubber-like substances are used as sealing agents, or special mercury seals are used. The water cooling is sometimes replaced by air cooling for this reason, but this brings difficulties at high powers.

Fig. 192 gives an impression of an iron mercury-cathode rectifier. The first thing to strike the eye is the cathode tray, which is separated from the rest of the vessel by a layer of insulation. This prevents cathode spots from being developed on the wall. Further, a quartz limiting cylinder placed in the mercury pool prevents the cathode spot formed inside it from reaching the edge of the tray. The graphite anodes give off their heat via the anode leads, which are cooled with the aid of fins. Each anode has a screen which prevents mercury from splashing on it. An insulated de-

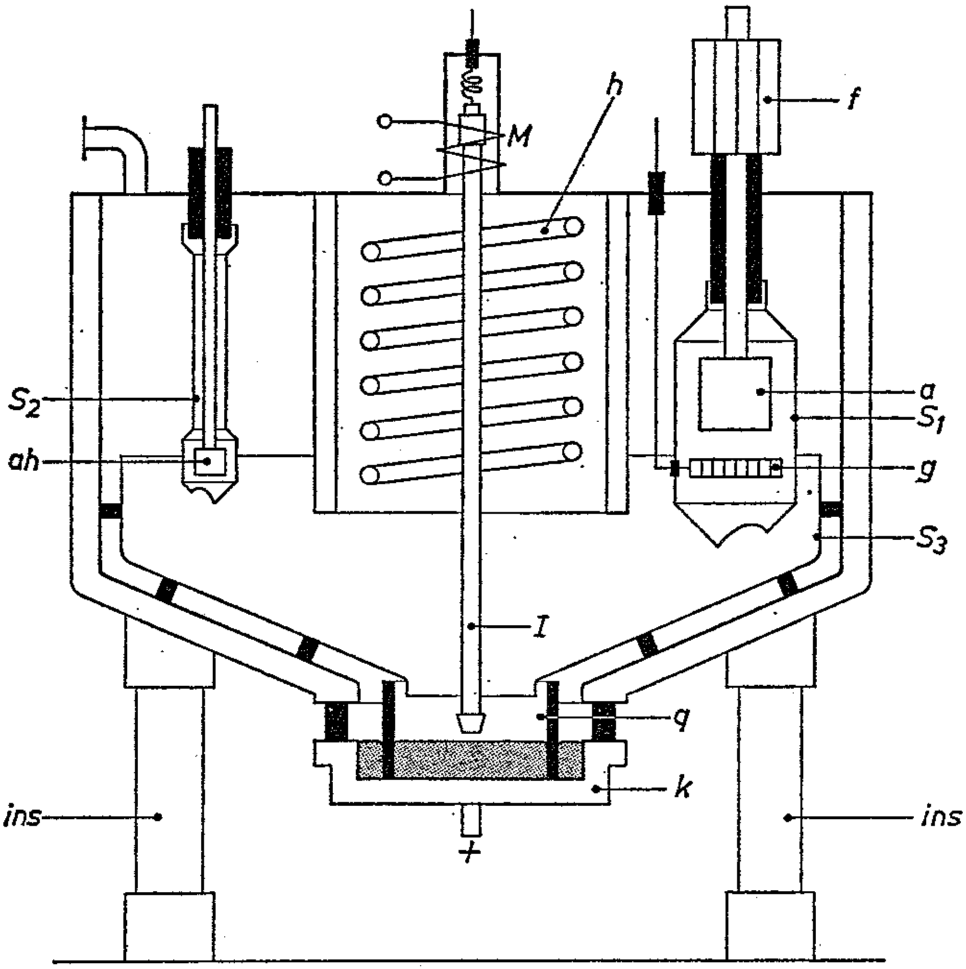


Fig. 192

Main details of a mercury-in-steel rectifier for loads of up to several kilo-amps at several kilo-volts. The rectifier is water-cooled. The cathode tray k is insulated from the cooling jacket. A pre-heater coil h serves to increase the vapour pressure while the rectifier is warming up.
a = main anode, a_h = auxiliary anode, S_1 and S_2 = cylindrical screens against splashes of mercury, g = switching grid (or deionizing grid), I = ignitor with magnet M for pulling it up, S_3 = steel-plate screen for preventing discharge currents through the wall of the vessel, *ins* = insulating support, q = quartz cylinder for limiting the cathode spot, f = cooling fin.

ionization grid is also placed in front of each anode; this also acts as a switching grid. The cathode spot is maintained permanently between the auxiliary anode, which is fed from an auxiliary rectifier, and the mercury. A resistance-ignition rod is not used with tubes of this type. A sufficient reason for this is that these tubes were in use long before ignitrons were thought of; but moreover such an ignition rod could easily be ruined by air leaking in from outside, for which it is very sensitive.

If the rectifier is still cold when it is started up, the mercury-vapour pressure will be very low. The risk of backfire is then greater than at the normal operating temperature. A heating coil is therefore usually built into these tubes; this ensures that the vapour pressure is a bit higher at the start, and hinders vapour from condensing on the anode. On the other hand, these tubes have the advantage that they can stand a considerable temporary overload. The same devices are used for de-ionization and voltage division in high-tension models as in high-tension ignitrons (cf. VI-h).

cathode layer will be impaired. One of the reasons for this is the bombardment by ions, which becomes excessive at high currents.

Since the total current which the photocathode may deliver is only a few microamps, and the sensitivity is usually about 150×10^{-6} A/Lm at $V_a = 100$ V, the maximum premissible luminous intensity is quite low. It can of course be increased to a certain extent if the anode voltage is decreased accordingly.

VARIATIONS IN THE SENSITIVITY

The sensitivity of a photocell usually changes somewhat during the first few dozen hours of operation: it will usually decrease, but may occasionally be found to increase.

It is also normal for the sensitivity to decrease very gradually if the photocell is in continuous use for some considerable time. This decrease is partly of a temporary nature, due to a secondary effect of little importance called cathode fatigue (for further details see Zworykin [48], page 53). When the cell is illuminated intermittently, the cathode has time to recover from this fatigue during the periods of inactivity. In the long run, however, the sensitivity of every photocell does show a permanent decrease which, however, is very slow.

Consequently, if the photocell is used sensibly, i.e. if the user takes care that there is always a suitable margin between the applied voltage and the breakdown voltage and that the illumination is never too great, the photo-emission may be expected to remain practically constant for a long time.

The photocell should be kept in the dark when not in use: even if there is no anode voltage, prolonged exposure to direct sunlight will cause permanent chemical changes in the photosensitive layer which will finally render it completely useless.

VII-d **Inertia and modulation frequency** [52]

The formation, and in particular the decay, of the discharge in a gas-filled photocell takes some time. This may be regarded as a kind of hysteresis: the ions, with their lower velocity, are always a bit behind the electrons. In order to keep this effect within reasonable limits, the gas pressure is chosen rather less than 0.55 mm Hg, which is the optimum value as far as the formation of the ions and electrons by collosion is concerned (cf. VII-b, gas amplification). Reduction of the pressure causes the ions and electrons to move faster, so that the build-up and decay times of the discharge are decreased.

The practical consequence of this inertia is that the depth of modulation