HIGH-VOLTAGE RECTIFIER VALVES FOR X-RAY DIAGNOSTICS

by J. H. van der TUUK.

The high-voltage rectifier valves used in X-ray installations, especially in diagnostic apparatus, have to satisfy in the first place the following requirements: they should be resistant to high voltages, furnish the necessary large peak currents with a reproducible and not too large voltage loss, and should not develop too much heat. In this article it is explained in what way two fundamental types of valves, namely vacuum and gas-filled valves, can satisfy the requirements mentioned. Gas-filled valves are found to possess several properties which are very favourable for the object in view. However, also in the field of vacuum valves constructions have recently been developed which give interesting results, thanks to the use of thoriated tungsten cathodes, and which may supplant entirely or for a large part gas-filled valves because of their universal applicability.

In principle, after being stepped up, the alternating voltage from the mains can be applied directly to an X-ray tube. In the half cycle in which the hot cathode is negative and the anode positive X-rays are excited, while in the other half nothing happens. The fact that in many cases it is, nevertheless, found preferable to apply direct voltage or at least pulsating direct voltage to the X-ray tube has two reasons. In the first place when X-rays are excited in both halves of the cycle, with a given peak value of the tube current, double the X-ray intensity is obtained and, moreover, upon smoothing the rectified voltage X-ray output becomes larger, compared to the heat developed. In the second place, when an X-ray tube works on A.C., sometimes something does happen in the “other” half of the cycle, and what happens is extremely undesirable, viz. the so-called back-lash. This may occur in the half cycle in which the anode is negative and starts to emit electrons, either by becoming too hot (thermal emission) or because the electric field at its surface exceeds a certain value (cold emission) or it is struck by positive ions of gas. Since such a back-lash often leads to the destruction of the tube it must be prevented under all circumstances. When rectified voltage is applied the problem of back-lash, which presents special difficulties in the case of the X-ray tube because of the great heat development on the relatively small focus 1), is transferred to the high-voltage valves, which serve for the rectification. These valves are very similar to the X-ray tube itself: they, too, possess a cathode and an anode in a vacuum-tight envelope. Since, however, in the case of valves the electrons carrying the current in the direction of transmission need not be strongly accelerated and focussed, local intense heating of the anode can be avoided by suitable construction, so that this important source of back-lash is eliminated.

Let us now consider somewhat more closely the requirements demanded of high-voltage rectifier valves. From the above follows the general requirement of voltage reliability, i.e. resistance to the high-voltage in the negative phase without danger of back-lash. In the positive phase, of course, the rectifier valve must be able to pass the current necessary for the X-ray tube. In the case of X-ray tubes for diagnostics it is, at present, a question of short-lived peak currents of 1 to 1.5 A, while maximum voltages up to 125 kV occur. In the case of therapy tubes much smaller currents are used, for instance maximum 40 mA continuously, with, however, considerably higher voltages, viz. 200 to 400 kV.

We shall devote ourselves here especially to the high-voltage rectifier valves used for diagnostics. In this case there are several additional requirements. For easy operation of an apparatus for diagnostics it is desirable that a certain tube voltage always corresponds to a definite position of the voltage regulator; for that purpose the voltage loss depending on the current should be small in all the parts of the high-voltage generator (transformer, valves, connections) and it should be as independent as possible of the circumstances of operation. The valves may; therefore, even at the highest currents, only require a low and reproducible voltage in the direction of transmission. This is especially true when the apparatus is provided with an automatic adjustment for the tube current 2).

In the case of modern apparatus for diagnostics the valves are often housed in the same oil-filled

1) See the discussion of the problem of back-lash in the article J. H. van der Tuuk, Hard-glass X-ray tubes in oil, Philips Techn. Rev. 6, 309, 1941.

2) Such an arrangement, which serves to load up the focus of the X-ray tube automatically to the permissible temperature at every adjustment of tube voltage and loading time, is discussed in detail in: H. A. G. Hazeu and J. M. Ledeboer, A universal apparatus for X-ray diagnosis, Philips Techn. Rev. 6, 12, 1941.
container with oil as the high-voltage transformer, etc. Since, in order to keep the voltage loss (i.e. the copper and iron losses) constant, the whole generator may not become too warm, the additional requirement should be made of the valves that they develop little heat. On the one hand this is already ensured if the valve only takes up a low voltage in the direction of transmission, since the anode dissipation is proportional to it; on the other hand it also makes desirable a high specific emissivity of the cathode, since then only a small filament power is used for the emission of the peak currents.

We shall now examine several old and new valve constructions and ascertain how, in each case, the requirements mentioned can be satisfied.

**Vacuum rectifier valves**

*Fig. 1* shows diagrammatically the construction of the old vacuum rectifiers as they were used for many years in all kinds of high-voltage installations. The envelope of the valve is so far evacuated that no breakdown can be caused by gas ions. The most important factor which should be taken into account to prevent back-lash is therefore the cold emission of the anode. In order to remove any such danger the field strength at all points on the surface of the anode should remain below a certain value, for instance $10^4$ V/cm. For this purpose sufficient distance between the electrodes is necessary. Furthermore, the anode should be properly smooth-finished, in order to avoid local increases in the field strength, which are known to occur wherever there are slight irregularities in the surface. (In this respect also the problem of back-lash is easier to solve in the case of a rectifier valve than in that of an X-ray tube; in the latter case the anode surface at the position of the focus is always rendered slightly rough in the course of time by the intense heating (evaporation.).

As far as the distance between the electrodes is concerned, the larger it is made the greater the influence of the space charge on the variation of the field and the higher the voltages necessary in the direction of transmission to draw the desired current from the hot cathode. Therefore it is clear that the distance between the electrodes will not be made greater than absolutely necessary. For 100—125 kV, for example, a distance of 8—9 mm is sufficient. With a given valve according to *fig. 1* the voltage loss amounted to about 2500 V for a current of 1A.

The small distance between electrodes, arrived at in this way, makes it impossible to use an oxide cathode, for there would be too great a danger of traces of barium from such a cathode striking the anode. Due to the increase in field strength at the unevenness thus formed (and due to the low work function of the barium) such a spot might act as a centre of cold emission in the counter-phase. Therefore in this type of valve tungsten cathodes are always used, where the danger mentioned cannot occur. Tungsten cathodes, however, require a much higher temperature for the same emission and a much higher cathode power than oxide cathodes. In order to supply momentary peak currents of 1—1.5 A, 125—150 W are needed with a tungsten cathode, compared with only about 8 W with an oxide cathode. In this case in valves of the type of *fig. 1* temperatures of the tungsten wire of more than 2350 °C are reached. Since the evaporation of the tungsten is already very appreciable in this region of temperature (the vapour pressure lies in the neighbourhood of $10^{-6}$ mm of mercury) and as a consequence the filament has a lifetime of only a few hundred hours, the filament is often allowed to burn at a temperature of more than 100° lower during fluoroscopy (continuous operation), which already gives a lifetime of a couple of thousand hours, and the heating voltage is only increased to the necessary value for a moment just before each X-ray photographic exposure. Furthermore it is clear that fluctuations in the mains voltage have an unfavourable effect on the lifetime of the filaments when continually working so close to the limits. In order to improve this situation it is necessary to have recourse to the use of a stabilizer for the heating voltage.

The construction sketched in *fig. 1* also presents difficulties as far as the reproducibility of the voltage loss is concerned. Secondary electrons from the anode strike the glass walls of the envelope, which are thereby charged and begin to exert a grid action on the current of electrons between cathode and anode. The potential to which the wall becomes charged depends upon all kinds of factors, for example on the occurrence of corona phenomena.
outside the valve and the like. Although the relation between current transmitted and voltage loss of the valve at low measuring voltages is then often sufficiently reproducible, this is found to be no longer the case for operation under high-voltage. The voltage loss may then vary considerably and may sometimes be so high that the valve itself begins to emit X-rays to an appreciable extent and the anode becomes very hot.

Thus it is obvious that although the simple construction sketched might often answer well in installations for testing materials or for medical therapy and also for simple apparatus for diagnostics, where it is a question of maximum currents of a few hundred mA, it can certainly not be employed in every case in modern apparatus for diagnostics.

Gas-filled rectifier valves

An entirely different type of valve is found to satisfy better the requirements made of diagnostic apparatus. These valves are not highly evacuated but are filled with a gas to such a pressure that after ignition of the valve an arc discharge occurs. The rectifying action in this case is due to the fact that the ignition is initiated by the electron current emitted by the filament: in the half cycle in which the filament becomes positive normally there are not sufficient electrons and the valve does not ignite 3).

Compared with vacuum valves we may conceive the situation during the arc discharge such that the space charge of the electrons emitted by the filament is compensated by positive ions of gas. Due to this, only extremely low voltages are necessary for passing even very large currents, for example 25 V at peak currents of 1.5 A. Such a small voltage loss can be entirely neglected with respect to the voltage on the X-ray tube.

The working voltage of the valve mentioned, in contrast to the case of the vacuum valves, depends little on the distance between the electrodes. Therefore, in constructing the valve there is no objection to have a rather large distance between the electrodes, which is of course desirable in order to avoid trouble from cold emission in the negative phase and to be able to use an oxide cathode.

Incidentally, in the case of gas-filled valves the cold emission is not the main cause of back-lash. Back-lash is more apt to occur due to a breakdown in the gas, resulting in an arc discharge in the wrong direction. The structural measures to be taken in order to avoid breakdown can be deduced from a consideration of the familiar Paschen curve, see fig. 2, which indicates the breakdown voltage $V_d$ as a function of the product of gas pressure $p$ and electrode distance $d$. If a given combination of gas pressure, electrode distance and valve voltage $V$ (highest voltage between the electrodes occurring in the negative phase) corresponds to a point $A$, which lies above the curve, breakdown will occur.

In order to avoid breakdown, when $p$ and $V$ are given the electrode distance should obviously be chosen much larger or much smaller. In practice the first method is out of the question, since then one would arrive at enormous lengths of the tube for the high-voltages required. But the second method brings us into conflict with the requirement that the electrode distance should be large enough to exclude cold emission.

A solution of this dilemma is found in a simple way. Suppose that at point $A$ (fig. 2) cold emission were precluded. The valve is then built up of a number of units in series, each with the same electrode distance as for point $A$, and to each of these compartments only a proportional part of the total voltage is applied 4).

---


Let us now turn to the gas with which the valve is filled. A rare gas cannot be used because of the well-known phenomenon of gradual disappearance of the gas during operation of the valve at high voltage: it is taken up in the cathode and walls; the pressure in the valve falls. Therefore the discharge is made to take place in saturated mercury vapour: a drop of mercury is placed in the valve and from this the mercury vapour which disappears is always supplemented by evaporation. The result, however, is that the vapour pressure in the valve depends upon the temperature of the surroundings.

In this way one arrives at a work point for each separate compartment which, if the subdivision has been carried far enough, lies below the Paschen curve (see fig. 2). Each compartment is then safe as far as breakdown is concerned, and since the field strength $V/d$ (when the voltage is evenly distributed and the field homogeneous) is even smaller for point $B$ than for point $A$, there is also no danger of cold emission. In practice, for example, a division of the valve into three stages is already sufficient. In fig. 3 such a three-stage gas-filled valve is shown diagrammatically, while fig. 4 shows two photographs of it.

We have just spoken of the assumption of a homogeneous field and a uniform distribution of the voltage over the electrodes. In the construction according to fig. 3 the field is not, of course, entirely homogeneous; the intermediate electrodes cannot be constructed as parallel plane plates but should have holes in order to allow the passage of the electrons from the cathode to the anode. In practice they are constructed as cylinders. The greatest field strength now depends also on the shape of these cylinders and it is possible to influence the chance of back-lash, for instance, by the choice of the size of the opening of the cylinders. In order to guarantee a sufficiently uniform distribution of the voltage over the different stages the impedance between all successive intermediate electrodes should be made as nearly equal as possible. To that end condensers of 80 µF are connected in parallel with the intermediate spaces, which condensers have the form of rings lying around the rectifying valve, as may be seen in the photograph of fig. 4b.

Let us now turn to the gas with which the valve is filled. A rare gas cannot be used because of the well-known phenomenon of gradual disappearance of the gas during operation of the valve at high voltage: it is taken up in the cathode and walls; the pressure in the valve falls. Therefore the discharge is made to take place in saturated mercury vapour: a drop of mercury is placed in the valve and from this the mercury vapour which disappears is always supplemented by evaporation. The result, however, is that the vapour pressure in the valve depends upon the temperature of the surroundings.

$^5$ The velocity of this process (called clean-up) increases rapidly with increasing voltage. It is not the same for different gases; for xenon, for instance, it is smaller than for argon.
see fig. 5. Gas-filled valves can therefore only be used in a limited temperature range, which in the case of the Philips high-voltage rectifiers for X-ray purposes lies between about 17 and 40 °C. At too low a temperature the pressure becomes so low that no ignition occurs in the direction of transmission (the chance of formation of gaseous ions is too small); at too high a temperature the pressure becomes so high that breakdown occurs in the negative phase (the valve no longer rectifies). The latter can be seen directly from fig. 2: with increasing pressure the work point $B$ is displaced horizontally to the right and after a certain pressure has been reached it comes to lie above the breakdown curve (unless $B$ lies lower than the minimum of the curve, but in practice such a far-reaching subdivision of the voltage is not possible). The liquid mercury that has to be present in the valve should not come into contact with the anode or the intermediate electrodes, since local increases of the field strength would then occur and these might cause cold emission and thereby back-lash. Therefore the drop of mercury has to be present in the valve should not come into contact with the anode or the intermediate electrodes, since local increases of the field strength would then occur and these might cause cold emission and thereby back-lash. Therefore the drop of mercury is placed in a special compartment, separated from the rest of the valve by a capillary (see fig. 3). Due to its surface tension the drop cannot flow through the capillary, while the mercury vapour is admitted freely to the valve.

Although, according to the above, we arrive at a distance between neighbouring electrodes in the gas-filled valves which is not greater than that in vacuum valves, it is, nevertheless, possible to employ an oxide cathode in gas-filled valves. Since there is no trouble with space charge here the cathode can be mounted behind a screen (the ring $R$ in fig. 3) which prevents any particles shot off the cathode from reaching the neighbouring electrode. At the same time the screen prevents an ion bombardment of the hot cathode and the accompanying sputtering. As already stated, an oxide cathode requires a cathode power of only 8 W for the largest peak currents occurring; thereby the cathode temperature is about 900 °C. At this temperature it is found that even after some time no disturbing evaporation of barium from the oxide cathode occurs, although, remarkably enough, the vapour pressure of pure barium is quite considerable at the temperature mentioned.

**Improved vacuum rectifiers**

Let us return for a moment to the vacuum valves. The construction according to fig. 1 was not practicable for modern diagnostic apparatus. It proved, however, to be capable of improvement in various respects. An important improvement was the alteration of the construction as shown in fig. 6.

![Fig. 5. Vapour pressure of mercury as a function of the temperature.](image)

**Fig. 5.** Vapour pressure of mercury as a function of the temperature.

![Fig. 6. The characteristic of the vacuum rectifiers can be considerably improved by the use of a cup-shaped anode $A$. In this case it forms part of the valve wall ("Metalix" rectifiers) which makes cooling easier.](image)

**Fig. 6.** The characteristic of the vacuum rectifiers can be considerably improved by the use of a cup-shaped anode $A$. In this case it forms part of the valve wall ("Metalix" rectifiers) which makes cooling easier.

Here the anode is not a flat plate at some distance from the cathode, but a cup surrounding the cathode. By this means the electrons having to pass from the filament to the anode are spread over a larger solid angle, the current density becomes smaller and therefore the space charge has less effect. In fig. 7 the characteristic of a valve with

![Fig. 7. Characteristics of vacuum rectifiers at high temperatures of the filament (more than 2350 °C): a) according to the old construction of fig. 1, b) according to the improved construction of fig. 6.](image)

**Fig. 7.** Characteristics of vacuum rectifiers at high temperatures of the filament (more than 2350 °C): a) according to the old construction of fig. 1, b) according to the improved construction of fig. 6.
cup-shaped anode is compared with that of a valve with a plane anode. In order to transmit a current of 1 A the improved valve needs a voltage of only 650 V, compared with 2500 V in the case of the old valve. At the same time the cup shape of the anode, which in this case forms part of the wall of the valve, practically entirely prevents secondary electrons from striking the glass wall and there is no longer any fear of a grid action of varying wall charges.

A practical model of such a valve, the "Metalix" rectifier, to be used in air, is shown in fig. 8. These valves attracted considerable attention and they may still be found in use in existing diagnostic apparatus. Their further development, however, was curtailed by the introduction of the gas-filled valve. We have seen, indeed, that gas-filled valves considerable increase in the electron emission, so that for the same tube current a lower filament temperature is sufficient and a smaller filament power is needed 6). In practice a temperature of about 1750 °C is used. At this temperature the evaporation of the filament is so slight — although here again the vapour pressure of the pure thorium at the temperature in question is by no means low — that even after several thousand hours of operation no appreciable quantity of evaporated material can be detected as a deposit on the valve wall, not to speak of the occurrence of any burning through of the wire. The resulting, much lower, sensitivity to fluctuations of the heating voltage makes the above-described complications (increase of voltage for each exposure, stabilizer) unnecessary. The fila-

Fig. 8. "Metalix" vacuum rectifier valve. Since this valve is not intended for immersion in oil in the generator container, but for use in air, the envelope is made of non-transparent glass, in order not to give a disturbing light in the X-ray room. The anode is provided with cooling fins. The total length is 55 cm.

are able to satisfy the highest requirements in diagnostics. The objection to gas-filled valves, namely the limitation of their useful temperature range of 17-40 °C, makes gas-filled valves unsuitable for use in tropical climates or in apparatus for the macroscopic testing of materials, which have to be used under very divergent conditions of temperature. Thus in any case vacuum rectifiers, which are independent of temperature, still command a certain field of application, and for the sake of having a single type of rectifier of universal applicability further development of vacuum rectifiers, viz. a still better approximation of the requirements made by diagnostics, certainly seemed worthwhile.

In recent years several improvements have proved possible by which vacuum rectifiers, which had remained at the stage of development shown in fig. 6, could be given a new lease of life. Probably the most important improvement is the employment of thoria for the filament. The addition of thorium to the tungsten results in a moment power is reduced from 125—150 W for the pure tungsten cathode to somewhat more than 30 W for the cathode of thoriated tungsten.

The thoriated tungsten filaments are especially sensitive with respect to the vacuum: traces of gas in the valve may reduce the electron emission considerably. Therefore the use of these cathodes is only possible by taking more care for a very good vacuum than in the case of the old vacuum valves. During manufacture the valves are very carefully evacuated. During operation the high vacuum is maintained with the help of a barium getter.

Another modification introduced in the construction of the "Metalix" rectifier valves of fig. 6, which made them more suitable for modern diagnostic apparatus, may be seen in fig. 9. The cup shape of the anode and thus the favourable characteristic

6) Because of the reduction in the filament power required, thoriated tungsten cathodes are also used in some modern transmitting valves. See E. G. Dorgelo, Several technical problems in the development of a new series of transmitting valves, Philips Techn. Rev. 6, 253, 1941.
of fig. 7b is retained, but now the anode no longer forms part of the valve wall. By means of a thin pin of material with a low heat conductivity (molybdenum) it is connected with a metal cap welded to a hard-glass envelope and serving for the current supply. Thanks to this construction the anode can be heated to a higher temperature during degassing, while at the same time the field strengths along the glass are lower. By this means, and because of the fact that the metal cap in question remains relatively cold, it becomes easier — as in the case of the above-described gas-filled valves — to make the valves suitable for operation under oil. This leads to an important reduction in dimensions. The valve for 125 kV now has a length of somewhat more than 20 cm with a diameter of 9 cm (see fig. 10), i.e. about the same dimensions as the three-stage gas-filled valve.

Thanks to the cup shape of the anode in the new construction, practically no secondary electrons can strike the glass wall, and if this does happen the screening of the cathode is an adequate insurance against the occurrence of grid action. For the dissipation of the heat developed on the anode, which in the construction according to fig. 8 took place easily by conduction and convection into the surrounding air, in the new construction use is made of radiation. Because of the large radiating surface of the cup anode, an anode dissipation of 40 to 50 W, as occurs in continuous operation (about 30 mA), offers no difficulties at all, and a peak current of 1 A, at which the anode dissipation amounts to about 600 W, can easily be coped with for a few seconds, since the anode possesses a sufficiently generous heat capacity.

Summarizing, we may say that vacuum rectifier valves in their latest forms give very interesting results and are already beginning to conquer considerable territory. It is possible that ultimately they will again entirely replace gas-filled rectifier valves.

Fig. 9. Diagram of a modern vacuum rectifier. The filament K is made of thoriated tungsten. The cup-shaped anode A no longer forms a part of the (hard-glass) valve wall, which makes it easier to use the valve under oil. G is a getter (barium mirror).

Fig. 10. Modern vacuum rectifier for 125 kV with cup-shaped anode and thoriated tungsten cathode. The valve, more than 20 cm long, is included to be used under oil.