CONTENTS

FOREWORD

A fascinating field of modern science and technology is dealt with in this book. The author has spent almost a lifetime working on gas-filled discharge tubes for industrial and electrical engineering applications – doing research on them, developing them, testing them – and has thus covered the wide field of gas discharges from many angles. He therefore writes with the authority of experience, to the benefit of his readers – especially those who are new to this field.

The explosive expansion of this subject during the past half century has made it impossible for any one person to be an expert in the whole field. This makes it the more important that the author's ample store of practical knowledge and experience (much of which has never been published before) is laid down in this book. The younger generation of workers in this field will find much to interest, and maybe inspire, them, and even the expert will find facts which are new to him. Moreover, those who simply wish to use gas-discharge tubes without going too deeply into the theory of their operation will find this book invaluable.

We of the old brigade in this interesting field of applied science appreciate it highly that the author had the initiative, the energy and the patience to complete this valuable book. We commend it to the readers, and wish it many years of fruitful life.

November 1963 Dr. J. G. W. Mulder

Translated from the Dutch by R. H. Bathgate, Knegsel, The Netherlands

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PREFACE

The extensive periodical literature on electronics contains many articles dealing with gas-discharge tubes, but it will be difficult to find a good review article on this type of tube. This book has been written to fill this gap. It describes the construction and operation of these tubes and the physical principles on which they are based, and gives practical details of typical applications.

Gas-discharge tubes exist for all kinds of purposes, but this book deals only with the most important types as used at present in industry and research, and for traction purposes. Some of the tubes described here have been, or are likely to be, superseded by more modern electronic devices such as semiconductor diodes and transistors; but others, e.g. mercury vapour rectifiers, are still in active development for welding and other heavy-duty applications (e.g. traction, inverter stations and transmitter supply). Other tubes are finding growing application in nuclear research and allied fields (e.g. as radiation counters), where there is still plenty of room for expansion.

Gas-discharge light sources are not dealt with in this book.

The author's aim has been mainly to give the user of gas-discharge tubes sufficient information (including plenty of practical examples) to enable him to deal with any problems which may arise in connection with the application of these tubes. The scientific level of the treatment makes it suitable for a skilled technician (what is known as a "practical engineer" in the U.S.A., or the graduate of a "higher technical school" in Holland).

It is clear that the electronic circuits associated with gas-discharge tubes may take many different forms, depending on the precise problems to be dealt with. These circuits are only described in sufficient detail to explain the different applications of the tubes in question; for further details, the reader is referred to the literature. (References in brackets throughout this book refer to the bibliography at the end of the book.)

Note:

The reader will notice that the characteristics of several types of tubes are given with quite a wide tolerance. Similar characteristics are met with in the operating data supplied by the manufacturers of these tubes. For a given tube, the characteristic can in fact be specified much more closely:

the tolerance indicated is due to the spread in the characteristics of different tubes of the same type. This spread will probably be gradually reduced in the future, as the factors governing the manufacturing process come to be better known. However, the spread does not normally matter in practice, since the operating conditions are usually flexible enough to allow for it.

Acknowledgements

The author received much helpful information during the writing of this book.

In particular he is very indebted to Dr. Ir. J. G. W. Mulder who gave him valuable guidance during his first steps in the field of gas discharges and for so many years thereafter. He acknowledges his constructive criticism. He is also very thankful for the help and many important suggestions received from Dr. Th. P. J. Botden and from Prof. Dr. A. A. Kruithof.

Especially the part concerning radiation counter tubes has been thoroughly revised by Dr. K. van Duuren, for whose help the author is very much obliged.

Moreover he wishes to thank very much Dr. O. Reifenschweiler who gave much constructive assistance in the writing of the section dealing with neutron generators. Prof. Dr. K. S. Knol's kind advice re noise tubes is gratefully acknowledged.

Many thanks are also due to Mr. R. H. Bathgate who translated the Dutch manuscript into English.

Finally he is very grateful to his friends and colleagues who offered their assistance during the preparation of the book, and he wishes to express his gratitude to the firms and individuals who gave their permission to reproduce certain illustrations. The sources are indicated in the captions to the figures in question.

November, 1963. H. L. van der Horst

CHAPTER I

PHYSICAL PRINCIPLES

1-a Introduction

Under normal circumstances, a gas is a nearly perfect insulator: the molecules and atoms are electrically neutral, so that their motion is not affected by electric or magnetic fields. If we are to get an idea of what happens in a gas discharge, we must first realize how a gas can become conducting. In order for this to happen, *free* charged particles must be produced in the gas. These will then move under the influence of the electric field produced between the negative electrode (the cathode) and the positive electrode (the anode), causing an electric current to flow. In this chapter we will first discuss some properties of gases, then some ways in which free electrons can be produced in gases, how their motion is determined and what effects this has on the gas. Finally, those types of discharges which are most important from the point of view of this book will be treated.

1-b The gas

1-b-1 TYPES OF GASES AND VAPOURS

Both inert gases and non-inert gases are used in gas-discharge tubes. The inert gases, helium, neon, argon, krypton and xenon (chemical symbols He, Ne, A, Kr and Xe) have only one atom per molecule and are chemically inactive. Non-inert gases, such as hydrogen, nitrogen, oxygen or carbon dioxide (H_2, N_2, O_2 and CO_2) have more than one atom per molecule, and can take part in chemical reactions.

Vapours (e.g. mercury vapour or alcohol vapour) are sometimes used in gas-discharge tubes instead of gases. We speak of a *saturated* vapour when, at a given temperature, the substance in question exists in the liquid (or sometimes solid) state as well as in the vapour state. At each temperature an equilibrium is established, so that the rate of passage of molecules from the vapour phase to the liquid phase is equal to that in the reverse direction. If the temperature is increased, the pressure of the saturated vapour increases rapidly, causing more and more liquid to evaporate. If the temperature is still increased after all the liquid has evaporated, the vapour is said to be unsaturated; it now behaves more or less like a gas.

I-b-2 GAS PRESSURE AND GAS DENSITY

Not only the nature but also the amount of the gas in the discharge tube is of great importance. This is usually given in terms of pressure, since this can easily be measured. It is however better to use the *density* of the gas, as the density of the gas in an enclosed space is independent of the temperature, while the pressure is not.

The molecules of a gas are in continual rapid motion, and frequently collide with each other. If the temperature is not too high, these collisions are completely elastic, i.e. they only cause changes in the velocity of the molecules, but not in their physical or chemical properties. The molecules merely exchange energy. As long as no energy is lost through the walls of the vessel, the total energy of the gas remains constant and so therefore does its temperature.

If the temperature is increased, the gas molecules move faster. The force with which they collide with the wall of the vessel and the number of collisions will increase correspondingly, in other words the pressure will increase, even if the number of molecules remains constant. The relation between the gas pressure and its density (i.a. the number of molecules per unit volume) is

$$p = n\,k\,T \tag{1}$$

where p = pressure of the gas
n = number of molecules per unit volume = density
k = Boltzmann's constant
T = absolute temperature (in degrees Kelvin, i.e. degrees Centigrade + 273°)

The quantity

$$p_0 = \frac{p\,.\,273}{T} = 273\,n.k \tag{1a}$$

is often used, this is the pressure reduced to 0 °C (= 273 °K). If p_0 is given, it may be seen from (1a) that n is also defined, since 273 k is a constant. For gases and unsaturated vapours, the pressure is proportional to the absolute temperature if the density remains constant.

The pressure of saturated vapours increases much more rapidly than this, as may be seen for mercury vapour in Fig. 1. Since equation (1) still holds, it follows that the number of molecules per unit volume increases with the temperature.

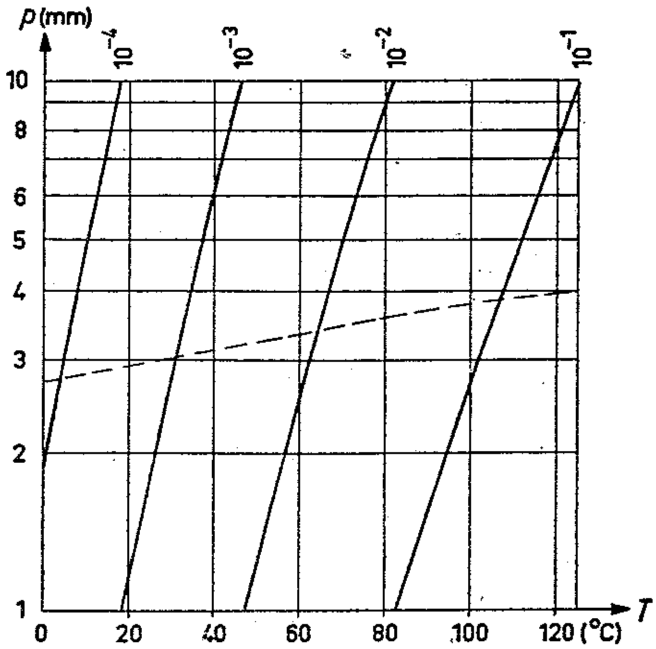


Fig. 1

Vapour pressure p of saturated mercury vapour as a function of the temperature T in degrees centigrade. The broken line represents an increase of the pressure of unsaturated mercury vapour which is proportional to the absolute temperature in degrees Kelvin.

I-b-3 MOLECULES AND ATOMS

The molecules of the gas in a gas-discharge tube occupy very little of the available space at the low pressures which are normal in such tubes. For example, at $p_0 = 1$ mm Hg, although there are about 5×10^{22} molecules per m^3, the average distance between molecules is about 100 times the diameter of a molecule, if we think of it as roughly spherical.

Although monatomic molecules do behave differently from polyatomic ones in a discharge, we will speak of atoms in what follows where these differences are of no vital importance. This is because most discharge tubes contain monatomic gases or mercury vapour, which is also monatomic.

I-c **Electronic emission**

Electrons are minute particles which all carry the same electric charge of about 1.6×10^{-19} coulombs. This charge is often denoted by the letter e.

Under normal conditions, a gas contains very few free electrons, although cosmic rays and other natural phenomena do produce a very small number. A larger number of electrons can enter the gas e.g. from the electrodes or from the walls of the tube. A solid, such as the metal from which an electrode is made, contains a large number of electrons, but it must be treated in some way to make it emit some of these. The three main ways of producing electrons from a substance are to heat it, to apply an electric field to it, and to shine light on to it. These three methods will be discussed in this chapter. Other, less usual, methods such as bombardment with electrons or positive ions will also be mentioned in this chapter in so far as they have an appreciable effect on the mechanism of the discharge. Further methods which have no appreciable effect on the discharge mechanism will not be treated.

I-c-1 THERMIONIC EMISSION [1]

Thermionic emission in vacuo

A metal can emit electrons if it is hot enough. This effect was discovered by Edison in an incandescent lamp in 1883, and is sometimes called the Edison effect. He noticed that a conducting disc in the lamp acquired a negative charge while the lamp was burning. If now an electric field is applied so that the disc is made positive with respect to the filament (i.e. the filament is the cathode and the disc is the anode; see Fig. 2), a stream of electrons will flow from the filament to the disc. It is normal to indicate the direction of flow of the electric current as being in the opposite direction from that of the electrons.

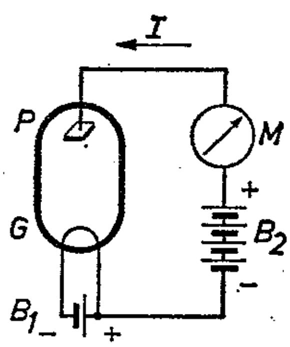


Fig. 2
The Edison effect.
If the voltage of the battery B_2 is applied between the filament G, which acts as the cathode and is heated to incandescence by the battery B_1, and the anode P (i.e. P is positive), electrons move in the tube from G to P. Since the electrons carry a negative charge, the meter M will indicate a current I in the direction shown in the figure.

Richardson's emission equation

The rate of emission of electrons from a thermionically emitting cathode depends on the temperature and the "work function" φ of the metal. This is equal to the potential difference in volts which the electron must overcome before it can leave the metal; in other words, an electron must possess an energy of $e\varphi$ joules before it can leave the metal.

The electron current which leaves the unit surface of a metal at a given temperature is known as the specific emission, and is given by Richardson's equation:

$$I_s = A\,T^2 \varepsilon^{-\frac{e\varphi}{kT}} \tag{2}$$

where I_s = electron current density in A/m^2 = specific emission,
$A \approx 10^6$ $A/m^2.(°K)^2$,
T = absolute temperature in degrees Kelvin,

ε = the base of the natural logarithms ($\sim$2.718),
and k = Boltzmann's constant (1.38×10^{-23} joule/°K).

As may be seen from Table I, each metal has its own value of the work function. However, changes in the state of the metal can have a large effect on the work function. For example, φ is much lower for a thin layer of barium atoms adsorbed on barium oxide (barium on barium oxide, Table I) than for barium metal in bulk. Similarly, thoriated tungsten (a specially prepared mixture of thorium and tungsten) has a lower work function than either thorium or tungsten by itself.

TABLE I

WORK FUNCTION φ IN VOLTS FOR A NUMBER OF METALS, CARBON, AND BARIUM ON BARIUM OXIDE, ARRANGED IN ORDER OF INCREASING MAGNITUDE

Material	φ	Material	φ	Material	φ
Barium on barium oxide	1.1	Thoriated tungsten	2.7	Iron	4.4
Caesium	1.9	Calcium	2.8	Carbon (graphite)	4.4
Potassium	2.1	Thorium (in bulk)	3.3	Mercury	4.5
Sodium	2.3	Magnesium	3.5	Tungsten (in bulk)	4.5
Barium (in bulk)	2.3	Tantalum	4.1	Nickel	4.9
Strontium	2.3	Zirconium	4.2	Platinum	5.3
		Molybdenum	4.3		

The specific emission of tungsten-oxide cathodes

The heater in a vacuum tube is often made of tungsten (symbol *W*), which has a high melting point (3655 °K).

In Table II are given the values of the specific emission I_s of tungsten at various temperatures. The total current emitted by a tungsten wire of diameter d metres and length l metres is thus $I = I_s \times \pi \times d \times l$ A.

TABLE II

SPECIFIC EMISSION I_S OF PURE TUNGSTEN AS A FUNCTION OF THE TEMPERATURE [112]

Temperature (°K)	2000	2200	2400	2600	2800	3000
I_s (A/m^2)	10	133	1160	7170	3.54×10^4	14.15×10^4

The rate of emission of electrons from a heated wire such as tungsten or nickel can be considerably increased by coating it with a suitable oxide, e.g. thorium oxide on tungsten or barium oxide on nickel. If a nickel wire is given such a coating, a very thin layer of barium atoms can be formed on top of the coating (this process is known as "activation"). It may be seen from Table I that these barium atoms have a work function of only 1.1 V. It follows from Equation (2) that the specific emission of such an oxide cathode is 1.5×10^4 A/m^2 at 1100 °K.

Saturation and space charge

If a voltage of e.g. a few tens of volts is applied between the cathode and anode of a vacuum tube, it will be found that the emission current is much less than that calculated from Equation (2).

Richardson's Equation gives the *saturation current,* i.e. the maximum current which the cathode can emit at the temperature in question. The fact that the actual current is much lower than this can be explained as follows: the electrons leaving the cathode build up as it were a negatively charged "cloud" of large density *(space charge)* in neighbourhood thus partly reducing the electric field just in front of the cathode and sometimes even reversing its sign (see Fig. 3, curves 1 and 2). The further emission of electrons from the cathode is thus hindered and many electrons even return to the cathode.

The negative space charge can be diminished by increasing the electric field strength between the cathode and the anode, e.g. by increasing the voltage between them. The emission current at a given cathode temperature will therefore increase as the voltage is raised (see Fig. 4). If the anode voltage is raised far enough, however, the electron emission no longer increases: the saturation current for that temperature has been reached. The field strength at the cathode will then no longer be negative (Fig. 3, curve 3). The voltage above which the current no longer increases is called the saturation voltage.

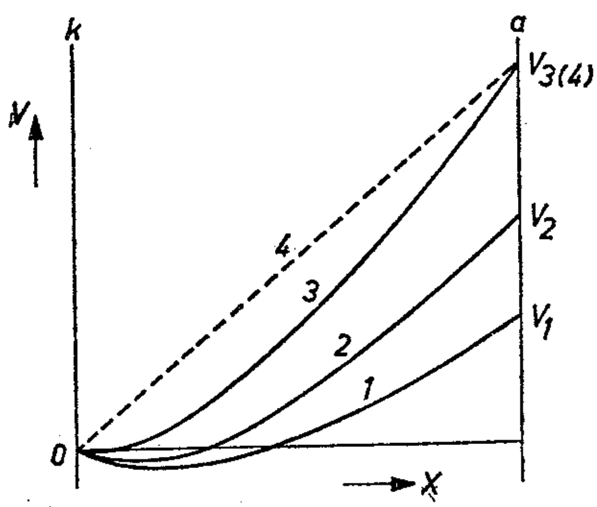


Fig. 3
The potential V as a function of the distance x between the electrodes k (cathode) and a (anode) for three values of the anode voltage: V_1, V_2 and $V_3 = V_4$. Curves *1*, *2* and *3* relate to a cathode which is emitting electrons; curve *4* is without emission. The negative space charge near the cathode causes the potential curves to deviate from the straight line in a downward direction. Curve *3* starts off just horizontal by the cathode. The electrons which leave the cathode do not return, but all go to the anode; the saturation current is just reached for the anode voltage V_3.

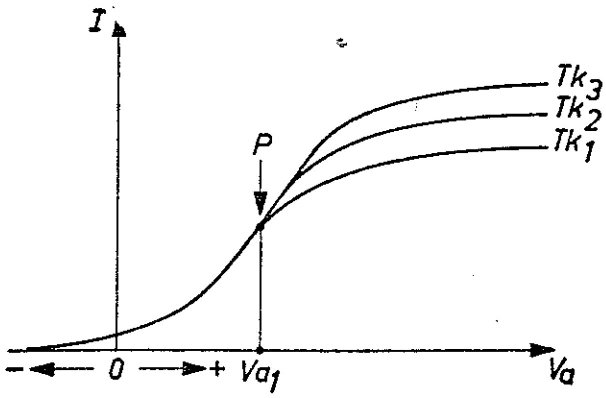


Fig. 4

The emission current I as a function of the anode voltage V_a for three values of the cathode temperture, T_{k1}, T_{k2} and T_{k3}. Up to the point P (anode voltage V_{a1}), the current is determined by the anode voltage alone. If the voltage is increased further, I tends to the saturation current, which is higher the higher the cathode temperature.

If on the other hand the anode voltage is kept constant at a value considerably below the saturation voltage and the cathode temperature is increased (Fig. 5), the emission current will also increase until a temperature is reached at which the negative space charge formed in front of the cathode is so great as to prevent the emission of further electrons. The maximum current then will be far less than the saturation current at that temperature.

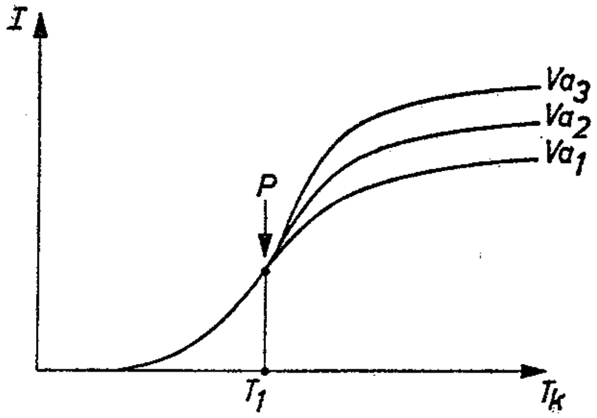


Fig. 5

The emission current I as a function of the cathode temperature T_k for three values of the anode voltage: V_{a1}, V_{a2} and V_{a3}. Up to the point P (cathode temperature T_1), the emission current is saturated and depends only on T_k. If T_k is increased beyond T_1, the anode voltage has an effect on I, and the emission is not saturated.

Thermionic emission in a gas

The saturation voltage of a vacuum tube is very high compared to that in a gas-filled tube. It is reasonable to expect that the number of electrons which a heated filament can emit at a given temperature will not depend on whether there is any gas present. It will be shown in Section 1-g-3. B that in a gas discharge the effect of the space charge in front of the cathode can be annulled under certain conditions, so that the saturation current is reached at a relatively low anode voltage.

I-c-2 FIELD EMISSION

Field emission, otherwise known as cold emission or auto-emission, is the emission of electrons by conductors at very high electric field strengths. A field strength of the order of 10^9 V/m is usually needed for this, although in certain cases 10^7 V/m is enough. The discharge currents measured in the latter case are, however, very small, of the order of thousandths of a μA [82, 83].

I-c-3 PHOTO-EMISSION

If light or some other form of electromagnetic radiation falls on an electrode, electrons will be emitted under certain circumstances. This will be discussed in further detail in Chapter II and VII.

I-d Collisions between electrons and gas atoms

I-d-1 MOTION OF THE ELECTRONS IN THE GAS

Let us imagine a closed vessel containing gas atoms and electrons. There are two reasons why the electrons should move. In the first place they will move from regions where they are concentrated to regions where they are not so concentrated, just like each atomic species in the gas. This type of motion is called *diffusion*. In a gas discharge, diffusion of the electrons will always be found when differences in the electron density occur. Secondly, the electrons will move under the influence of an electric field. If two metal electrodes are sealed into the above-mentioned vessel and a voltage is applied between them, an electric field will be produced in the vessel which will cause the negatively charged electrons to move away from the negative cathode and towards the positive anode. The distance an electron can move before it comes into collision with a gas atom depends on the density and nature of the gas. We speak of the *mean free path* λ_e of

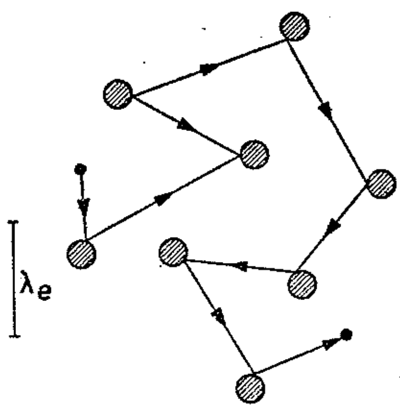


Fig. 6a

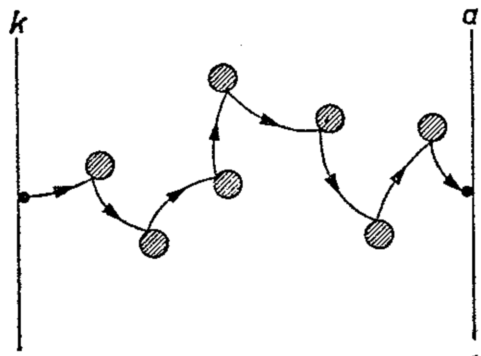


Fig. 6b

Fig. 6a
The path described by an electron in a gas in the absence of an electric field. The electron moves in straight lines between collisions. λ_e = mean free path.

Fig. 6b
The path described by an electron in a gas under the influence of an electric field. The electron moves along curved paths which are concave towards the anode.

the electrons, because the distance moved between two collisions varies because of the irregular distribution of the atoms in space. The value of λ_e is lower the more atoms there are per unit volume, and the larger these atoms are. The connection between these quantities is given by:

$$\lambda_e = \frac{4}{\pi d_a{}^2 n} \tag{3}$$

where d_a = diameter of atoms
and n = number of atoms per unit volume = density of atoms.

It follows from Equation (1) together with Equation (1a) of Section I-b-2 that λ_e is inversely proportional to the reduced pressure p_0.

The motion of diffusing electrons is sketched in Fig. 6a, and that of electrons in an electric field in Fig. 6b.

I-d-2 ELASTIC COLLISIONS

Let us suppose that an electron of mass m, after having obtained a velocity v, and thus an energy $\frac{1}{2}mv^2$, as the result of previous collisions, collides with a gas atom with the much greater mass M. In by far the most collisions, the electron will give up only a small part of its energy to the atom, and will move off in a new direction after collision. The energy transferred to the atom will manifest itself as an increase in the heat of the gas, and not as a change in the state of the atom. Since the atom behaves as a completely elastic body, such collisions are known as *elastic collisions.*

The fraction of the energy of the electron transferred to the atom can be calculated by the methods of classical mechanics, and is found to have an average value of $2\ m/M$ per collision if enough collisions are considered. Now the mass of the electron is about 1/1840 times that of the hydrogen atom, while that of e.g. neon is 20.2 times that of the hydrogen atom, so the electron loses on the average 1/20,000 of its energy at each collision with a neon atom. This means that the energy of the electron is practically unchanged by the collision. The kinetic energy of the electron is thus equal to the potential difference passed through times its charge, $(V_2—V_1)e$ joules, even if it undergoes elastic collisions.

I-d-3 NON-ELASTIC COLLISIONS

As the kinetic energy of the electrons steadily increases under the influence of the electric field, a moment is reached where the energy lost by the electron in some collisions is considerably greater than in the above-mentioned elastic collisions. In order to understand the consequences of these non-elastic collisions, we must briefly consider the structure of the atom.

Structure and excitation of the atom

According to Bohr's theory of the atom (see e.g. [92]), the electrons in an atom move, each in its own orbit, around the positive nucleus. Each orbit corresponds to a certain energy. Depending on the position of their orbit in the atom, the electrons are more or less firmly bound to the nucleus.

In a gas discharge we are almost entirely concerned with the electron in an atom which is most weakly bound, i.e. in one of the outside orbits. Now this electron is free to occupy a number of different, unoccupied orbits, in each of which its energy is different. These different energies are called the energy levels of the atom. If the atom is left alone, the electron in question will end up in the available unoccupied orbit with the lowest energy. The atom is then said to be in the ground state, and this energy level is known as the ground level. All other energy levels are reckoned from the ground level (see Fig. 7).

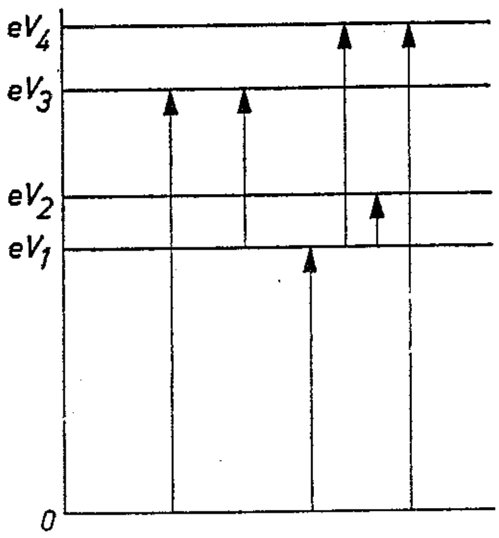


Fig. 7

Sketch of the energy levels of an atom. The ground level is represented by *O*. The energy differences between the first, second, third and fourth excited levels and the ground level are eV_1, eV_2, eV_3 and eV_4 respectively.

If the atom in its ground state is bombarded with electrons of steadily increasing energy, the outer electron will not be able to move to another orbit until the energy eV_1 of the bombarding electron is equal to the energy difference between the ground level and the next higher one. This process of bringing the electron into an orbit with higher energy is known as the excitation of the atom, which is then said to be in an excited state. The voltage V_1 is, therefore, known as the lowest excitation voltage of the atom.

For neon this excitation voltage is 16.55 V. Bombardment with electrons of energy less than 16.55 e joule cannot thus lead to excitation. If the electrons possess a greater energy than this, excitation is possible and will indeed occur in some of the collisions. The excited state can usually only last for a short time (about 10^{-8} second), after which the electron which has been displaced returns to the ground state, emitting radiation in the process.

The energy of the emitted radiation is again exactly eV_1 joule, the energy difference between the (first) excited state and the ground state. The frequency ν of the radiation is now given by Planck's quantum law:

$$eV = h\nu \tag{4}$$

where eV is the energy of the radiation
and h is Planck's constant, 6.625×10^{-34} watt-second².

The atom has many other excited energy levels above the first excited energy level, each with its own energy. If the atom is excited into one of these higher energy levels by a fast electron, it can return to the ground state either directly or via one or more other excited states, each successive one lying closer to the nucleus. Each time the atom passes from one state to a lower one, it emits energy in amounts characteristic of the atom. Since the quantum law always holds for this emission, the radiation emitted by the atom can have a series of sharply defined frequencies, each one corresponding to a line in the spectrum, which are also characteristic of the atom. In other words, if light is emitted by a gas in a gas discharge, the spectral lines in the emitted light indicate the nature of the gas. Often the colour alone is enough to show which gas is used in the tube.

On the other hand, a quantum of radiation coming from outside can be absorbed by the atom and excite it if it is of the right size (e.g. eV_1 for the first excited level).

Metastable states

In some excited states of the atom, the excited electron can remain in its orbit for much longer than 10^{-8} second — up to e.g. more than 0.1 second.

The atom is then said to be in a *metastable* excited state. According to the quantum theory, this is because the atom in such a state cannot return to the ground state simply by emitting radiation, but must lose some or all of its energy by collision with other atoms or with the wall of the tube. It can also happen that the atom collides with another fast electron, which excites it to a still higher state from which it can easily return to the ground state.

Ionization

If an electron which collides with an atom in the ground state has enough energy (at least eV_i joule), it can free the outermost electron completely from the atom. The minimum energy necessary is known as the ionization energy, and the corresponding voltage V_i, as the ionization voltage. After this collision, the atom has become a positively charged *ion*, since it has lost an electron, while we now have two free electrons instead of one. This process is called ionization by collision. For neon the bombarding electron must have a kinetic energy of at least 21,5e joule for this to be possible.

If metastable atoms with an excitation energy of eV_a' are produced in a discharge, the bombarding electrons only need to have the energy eV_i—eV_a' to ionize the atom. In this case, we speak of cumulative ionization.

As we have already seen, an ion is a charge carrier, in contrast with an excited atom or an atom in a metastable state, which is electrically neutral.

Now it can happen — but only with non-inert gases — that one or more free electrons tack on to an originally neutral gas atom, thus forming a negatively charged ion. In the tubes we are going to consider, however, only the positive ions are of importance.

An atom can be ionized in other ways than by collision with an electron: by collision with a positive ion, by quanta of radiation of energy $h\nu \geqslant eV_i$ joule or by collision with fastmoving neutral atoms at high temperatures. These other possibilities are also negligible compared to ionization due to electrons in all the gas discharge tubes discussed in this book, so we will not consider them any further.

Ionization probability and excitation probability

Let us consider an electron moving through a gas under the influence of an electric field. In the beginning, when its velocity, and thus its energy, is low, it will only undergo elastic collisions. The atoms are not changed by the collision, and the energy of the electrons increases steadily. When this energy exceeds eV_a joule, there is a chance at each collision that the atom will be excited, although most of the collisions will still be elastic. Finally, when the energy exceeds eV_i joule, there is a chance that the atom will be ionized, besides the chance that it will be excited. If it is ionized, we then have two free electrons instead of one.

Both of these electrons have a low energy, and the process just described repeats itself. A kind of chain reaction is thus produced, which may result in a "avalanche" of electrons.

Let us now consider a stream of electrons moving in an electric field through a gas. At every spot we will find some electrons with a low energy and some with a high energy. Those with a low energy will only undergo elastic collisions, while those with high energies may also excite or even ionize the atoms of the gas.

It has been found for a discharge in neon between two plane electrodes a large distance apart, where the ratio of the field strength F to the reduced pressure p_0 of the gas is $F/p_0 = 10^4$ V/m . mm Hg, that 32 % of the energy which the electrons gain from the field is used for ionizations, 44 % for excitation and 24 % heats the anode; the energy transferred to the gas by elastic collisions is less than 1 %. The corresponding percentages for other values of F/p_0 are shown in Fig. 8.

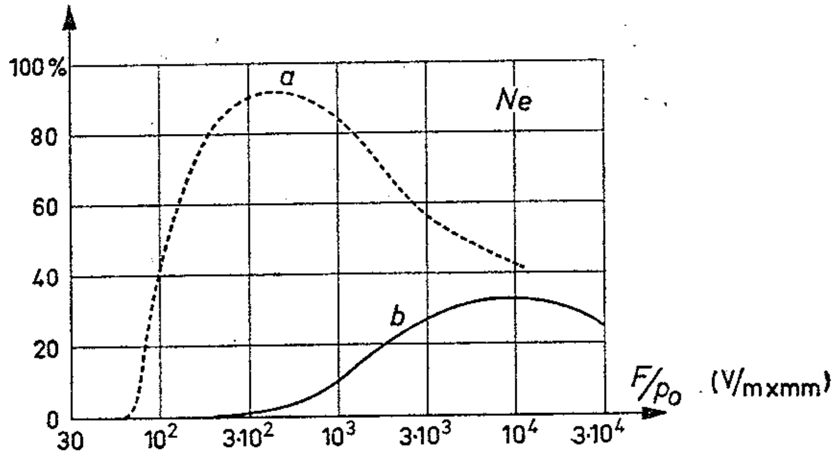


Fig. 8

The percentage of the energy which the electrons gain from the electric field (which is a function of F/p_0), used for:
a = excitation of the atoms,
b = ionization,
F = electric field strength,
p_0 = reduced pressure of the gas [67].

The ionization coefficient

If a stream of electrons passes through the gas in a homogeneous electric field, the number of newly formed electrons is proportional to the electron current, so that the percentage increase per volt potential difference passed through is constant. This percentage also depends on the increase in the velocity of the electrons per mean free path caused by the field. This increase is proportional to the electrical field strength F and to the mean free path $\lambda_e = 4/\pi d_a^2 n$ (see I-d-1 (3)), i.e. inversely proportional to n or to p_0 (see I-b-2 (1a)).

The increase in the velocity of the electrons is thus proportional to F/p_0; and the relative increase in the electron current per volt potential difference passed through, which is called the ionization coefficient (per volt) η, also depends on the ratio F/p_0.

Another ionization coefficient, $\alpha = \eta \times F$, is sometimes used. Since, in a homogeneous field, F is the potential difference per metre, α represents the relative increase of the electron current per metre passed through. The ionization coefficient was introduced by Townsend. We may now write $\alpha/p_0 = \eta\ (F/p_0) \times F/p_0$. It thus follows that α/p_0, like η, is a function of F/p_0.

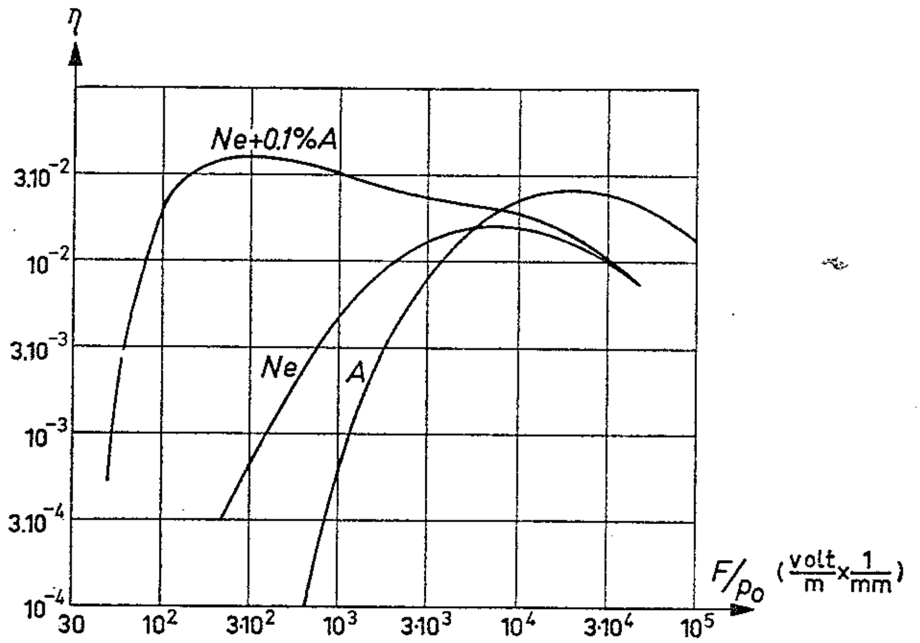


Fig. 9

The ionization coefficient η per volt potential difference passed through, as a function of the ratio of the field strength to the reduced pressure, F/p_0, for neon, argon and neon + 0.1 % argon.

Fig. 9 shows η as a function of F/p_0 for neon, argon, and the mixture neon + 0.1 % argon. The ionization coefficient η for pure gases shows a definite maximum at a certain value of F/p_0. As the value of F/p_0 decreases from this value, the excitation probability and the energy loss of the electrons with elastic collisions respectively will increase considerably at the expense of the ionizations; as F/p_0 increases the number of collisions decreases considerably, so that more energy is transferred to the anode and thus lost for ionization. It may also be seen from the figure that the ionization increases considerably if a little argon is mixed with the neon. Especially at low values of F/p_0, a large number of neon atoms are excited. Among these will be quite a large number of metastable neon atoms with $V_a' = 16.55$ V. These last for a relatively long time, and thus have quite a fair chance of losing their energy by collision with an argon atom. Since the ionization voltage of argon is only 15.7 V, the argon atom may be ionized by such a colission. This phenomenon is known as the *Penning effect*. It can also occur if other gases than argon are added to the neon, as long as they have an ionization voltage of less than 16.55 V. As metastable atoms have a relatively long life, they are capable of undergoing many collisions before they lose their energy, so only a very small percentage of e.g. argon need be added to increase η considerably.

I-e **Ignition and extinction of the discharge**

While the current in a resistor or a capacitor starts to flow as soon as a potential difference is applied, this it not so with a gas discharge. It takes some time for the current to reach its full value. Similarly, some time is necessary for the conducting state to disappear when the current is cut off. The times which characterize these phenomena are of importance in many circuits. We shall therefore consider them in some detail.

I-e-1 STATISTICAL DELAY TIME AND BUILD-UP TIME

We must make a distinction between the statistical delay time and the build-up time of a discharge. The former is only of importance with discharges which have no source of electrons such as a hot cathode or a photocathode. A number of electrons must then be formed by e.g. cosmic radiation before ionization can begin. Since it is a matter of chance whether a quantum of cosmic radiation enters the tube, the formation of these first electrons is governed by statistical laws. Each free electron thus formed can give rise to an avalanche of electrons, and each electron in the avalanche can give rise to a further avalanche. It is these avalanches which serve to ignite the discharge. The formation of the first avalanches is also governed by statistical laws, and together with the formation of the first electrons determines the *statistical delay time.*

Apart from this, all gas discharges need a certain time for the desired discharge current to be built up. This is the *build-up time.* Before the electron current can reach its final value, the ions formed must have time to spread throughout the tube, especially in order to neutralize the negative space charge near the cathode. The ions, which are much heavier than the electrons, move relatively slowly towards the cathode, so that it takes a certain time before the final state is reached. This time is shorter as the anode voltage is raised, as the ions then move faster. The build-up time of discharges in rare gases may be of the order of a microsecond under favourable circumstances.

I-e-2 THE DISAPPEARANCE OF THE CHARGE CARRIERS

When the anode voltage is removed from a discharge, the current naturally stops immediately; but the charge carriers do not disappear at once. In general the ions and electrons in a discharge can disappear in two ways: by recombination in the gas or by diffusion to the walls or the electrodes and recombination there.

Recombination in the gas

In pure inert gases or metal vapours at low pressures, such as are found in most of the gas-discharge tubes discussed in this book, the recombination of positive ions with electrons in the gas is a most unlikely process. According to the laws of mechanics, such recombination can only occur if another particle is involved in the collision, which is thus called a "three-body collision". The number of such collisions at the low pressures normally found in gas-discharge tubes is negligibly small.
Recombination in the gas is however possible in non-inert gases such as hydrogen, which can form molecular ions.

Recombination at the walls

In pure inert gases or metal vapours, the disappearance of electrons and ions only occurs by means of collisions of these with the walls of the tube or the electrodes, which thus as it were play the role of the "third body". For this to be possible, the charged particles must diffuse to the walls. Ions diffuse slowly, because each collision with neutral atoms causes them to lose much of their energy, while their velocities are naturally low as a result of their large masses. The electrons, which acquire much higher velocities because of their low mass, initially arrive at the walls in large numbers, giving them a negative charge. This causes the electrons remaining in the gas to be retarded and the ions to be attracted and the build-up of the wall charge proceeds more slowly, until finally in the steady state as many ions as electrons reach the walls per second. The energy released by the recombination is taken up by the walls as heat.

Recombination after the discharge is stopped

When the discharge is stopped, the recombination on the walls and electrodes continues, and the number of free electrons and ions in the tube gradually decreases.

The diffusion of the ions to the walls or electrodes can be considerably increased by giving them a negative electrical potential so that they attract the ions. Even if the optimum value of this voltage is chosen, the complete disappearance of ions and electrons from a mercury discharge takes a millisecond or more.

I-f The discharge plasma [3, 4, 67, 78 and 79]

The concentrations of positively and negatively charged particles in a space containing the atoms, electrons and ions of a gas discharge will not be the same at all points. In some places, there will be more electrons than ions, and at other places the reverse will be true.

Where there is an excess of negative charges, we speak of a negative space charge, and where positive charges are in the majority of a positive space charge. In the special case that the negative charges completely neutralize the positive charges of the ions, or very nearly do so, we speak of a *(discharge) plasma.* We will meet a number of discharge plasmas in the various types of discharges discussed below, e.g. the dark part F of the glow discharge between two plane electrodes, which occurs next to the glow itself (cf. Fig. 10) and the positive column in a long cylindrical tube.

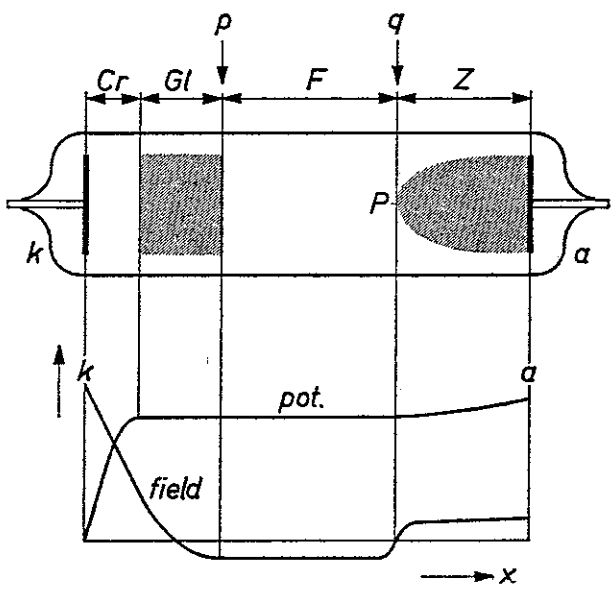


Fig. 10

Light effects in a tube with two flat electrodes.

Cr = Crookes dark space.
Gl = negative glow.
F = Faraday dark space.
Z = positive column.
p = boundary between negative glow and Faraday dark space.
q, P = start of the positive column.
x = distance from k.

The variation of the potential and the field between the electrodes are also shown.

There is practically no electric field in a plasma, because of the neutralization of the space charge. The particles are in continual motion, which is mainly random and only slight in any given direction. Each type of particles, the gas atoms, the electrons and the ions, has its own velocity distribution; if the current in the discharge is not too low, this is a "Max-

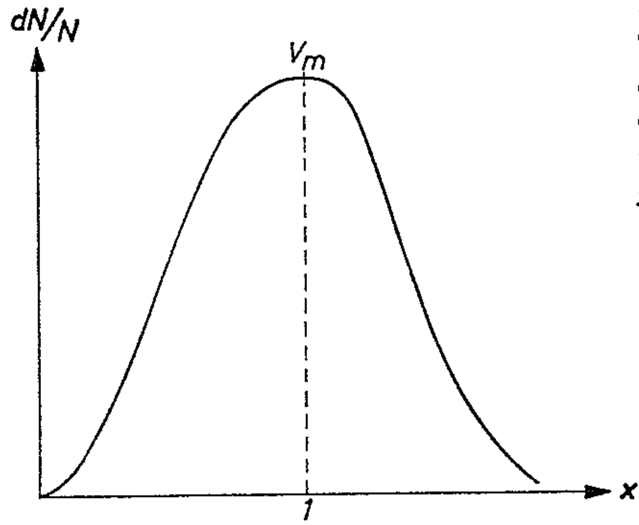


Fig. 11
The Maxwell distribution of velocities. dN/N = fraction of the total number of particles,
v_m = most probable velocity,
$x = v/v_m$, where v = actual velocity.

well" distribution for each one. Such a distribution is sketched in Fig. 11. It may be described by the equation

$$\frac{\mathrm{d}N}{N} = \frac{4}{\sqrt{\pi}}\, x^2\, \varepsilon^{-x^2}\, dx \qquad (5)$$

where $\mathrm{d}N/N$ is the fraction of the total number N of particles which have a velocity between v and $v + d\,v$, while $x = \dfrac{v}{v_m}$. We call v_m "the most probable velocity"; it is equal to 0.81 times the root mean square velocity $\sqrt{\overline{v^2}}$ (see Fig. 11). The only variable parameter which determines the precise form of the Maxwell distribution for a given case is v_m, which is closely related to the temperature of the "gas" (which may be a real gas, or an electron gas or ion gas) in question.

The mean kinetic energy W_m of the gas particles is equal to $\frac{1}{2}\, m\overline{v^2}$ and is proportional to the absolute temperature T:

$$W_m = \tfrac{1}{2}\, m\overline{v^2} = \tfrac{3}{2}\, k\, T \qquad (6)$$

where k is Boltzmann's constant, 1.38×10^{-23} joule/°K.

The electron temperature [4]

If we apply the equation $W_m = \frac{3}{2}\, kT$ to the "electron gas" we obtain a certain temperature. We have already mentioned in I-d-2 that the free electrons in the plasma lose very little energy to the atoms when the collisions are elastic. The energy transfer in a discharge at low pressures does not become appreciable until the electrons have acquired so much energy from the field that they can excite the atoms. The mean energy of the electrons in the discharge will thus be much higher than that of the atoms. It is, for example, quite normal for the mean kinetic energy of the electrons to be about $2e$ joule. The corresponding temperature derived from the above equation is about 15000 °K, this means that if the electrons acquired all their energy from the heat of the whole system instead of from the electric field, the temperature would have to be about 15000 °K to give them the same energy. The electron temperature is then said to be 15000 °K. The atoms in the plasma of a low-pressure discharge have a temperature of only a few hundred degrees Kelvin (about 300 to 400 °K), and that of the ions is not much different.

Noise

An important property of the plasma is that the electron density at a given point continually varies about the mean. The space charge, therefore, also varies continually, and with it the voltage across the discharge. If these voltage variations, which are known as noise, are analyzed, it is found that they consist of a mixture of variations of all possible frequencies (up to a certain very high maximum frequency).

Another example of noise is the thermal noise in resistors and oscillating circuits. The density variations in the plasma are however much greater than in a resistor at the same temperature as the gas, since they are determined by the electron temperature and not by the much lower temperature of the gas itself. According to Nyquist, the maximum noise energy which the electrons can produce in any part of a circuit in a frequency band of width Δf is equal to $kT_e \Delta f$, where T_e is the electron temperature. The electrons in the plasma not only undergo density variations, but also velocity variations which are associated with the emission of electromagnetic radiation. If this radiation is taken up by a receiver, the maximum amount of energy thus transmitted in a frequency band Δf is also equal to $kT_e \Delta f$.

I-g **Types of discharges**

Gas-discharge tubes can be divided into three main groups according to the form of the electrodes, especially the cathode. In the first group we have those tubes with a plane cathode, the anode being e.g. another flat plate parallel to the cathode. In the second group the cathode is a heated filament which emits electrons, and in the third group the cathode is a mercury pool. We will begin by discussing the first group which contains a considerable number of different tubes.

We will then see how the discharges in tubes of the second group, are related to that in tubes of the first group, whereafter we will discuss the second group in some greater detail. The arc discharge which is produced at a mercury-pool cathode does not have a discharge of one of the first two types as precursor. The first stage in such a discharge, the production of an electron-emitting spot on the cathode surface, is discussed in Chapters II and VI. This type of discharge will not be mentioned further in this chapter.

I-g-1 DISCHARGES BETWEEN TWO FLAT PLATES, GLOW DISCHARGES

Non-self-sustaining discharges

We have seen in I-d-3 how an electron avalanche is produced under the influence of an electric field between two flat plates. We mentioned in this connection Townsend's ionization coefficient α, the relative increase of the electron current per metre passed through. If we start off with n electrons, a number $dn = n.\alpha.dx$ of new electrons will be formed in the distance dx. Solving this differential equation, we find that n_0 electrons which move through a distance x in a field F will increase to $n = n_0\, \varepsilon^{\alpha x}$, and $n_0\, (\varepsilon^{\alpha x} - 1)$ ions will be formed. Since the tube we are considering only contains two electrodes a distance d apart, all the $n = n_0\, \varepsilon^{\alpha d}$ electrons will end up on the anode, and will then not be able to cause any more ionizations, while the ions will move in the opposite direction, and end up on the cathode. The discharge will then be over.

It can only continue for an appreciable length of time if electrons are emitted from the cathode owing to some external cause such as irradiation with light. Such a discharge is said to be *non-self-sustaining*. Now various processes are known whereby apart from the above-mentioned "primary" electrons "secondary" electrons can be produced in the gas.

As an example we shall consider the formation of free electrons by the ions which move to the cathode. If each ion produces on the average γ electrons when it strikes the cathode, the above mentioned $n_0\, (\varepsilon^{\alpha d} - 1)$ ions will produce a total of $n_0\, \gamma\, (\varepsilon^{\alpha d} - 1)$ secondary electrons. The ionization coefficient γ depends on the cathode material, and on the ratio F/p_0 which we have already mentioned in connection with the ionization coefficients η and α This type of emission is known as the *gamma effect*, or secondary emission by positive ions.

The mean number of secondary electrons formed from one primary electron by all possible emission processes is denoted by q, and called the *multiplication factor*. We see that for the gamma effect

$$q = \gamma\, (\varepsilon^{\alpha d} - 1)\ .$$

If the voltage between the electrodes is increased, α and γ will in general increase, and q with them.

Self-sustaining discharges

When q is equal to 1, one secondary electron is formed from each primary one. The discharge is then self-sustaining. The value of the current under these conditions can vary from less than 10^{-10} to more than 10^{+4} A. If q becomes greater than 1, the current keeps on increasing until it is limited by the resistance in the circuit.

Breakdown, Paschen's Law

In what follows we will only consider the production of secondary electrons by ions. If other mechanisms also play a part, our conclusions will still be basically valid. If the voltage between the electrodes is increased until the multiplication factor is one, i.e.

$$q = \gamma\,(\varepsilon^{\alpha d}-1) = \gamma\,(\varepsilon^{\eta V_d}-1) = 1 \tag{7}$$

we say that *breakdown* has occured; the voltage V_d at which this occurs is called the *breakdown voltage.*

It follows from Eq. (7) that

$$\varepsilon^{\eta V_d} = 1 + \frac{1}{\gamma} \text{ or } \eta\, V_d = \ln\left(1+\frac{1}{\gamma}\right) \text{ or } V_d = \frac{1}{\eta}\ln\left(1+\frac{1}{\gamma}\right) \tag{8}$$

Since the logarithm of a number increases much more slowly than the number itself, we see from these equations that the value of the breakdown voltage depends mainly on η and not so much on γ. If we recall moreover that both η and γ are functions of F/p_0 (see I-d-3), it is clear that V_d will also be a function of this variable, and will to a first approximation be inversely proportional to η.

We can thus write

$$V_d = \mathrm{f}\,(F/p_0) \tag{9}$$

while the field strength between the two flat plates at the moment of breakdown is given by:

$$F = V_d/d \tag{10}$$

where d = distance between the plates.

It follows that

$$V_d = \mathrm{f}\left(\frac{V_d}{p_0 \times d}\right) \tag{11}$$

This can be regarded as an equation in V_d and $(p_0 \times d)$, which can be solved to give

$$V_d = \mathrm{g}\,(p_0 \times d) \tag{12}$$

In other words the breakdown voltage between two flat plates depends on the product of the pressure of the gas reduced to 0 °C (see I-b-2), and the distance between the electrodes. If p_0 and d both vary so that their product remains constant, V_d also remains constant. This is *Paschen's law* for the breakdown voltage, which is illustrated in Fig. 12 and 13. The physical significance of this law can be seen by substituting the Equations (1a) and (3) in (9).

This gives
$$V_d = \mathrm{f}\left(F \times \lambda_e \times \frac{\pi d_a^2}{4 \times 273\, k}\right) = \mathrm{f}\,(K \times \lambda_e \times F) \qquad (13)$$

Since the factor K contains nothing but constants for a given gas, we see that V_d is a function of $\lambda_e \times F$, the potential difference in the gas per mean free path. On the other hand, if we substitute the above expressions (1a) and (3) for p_0 and λ_e into the Equation (12), we find

$$V_d = \mathrm{g}\left(d/\lambda_e \times \frac{1}{K}\right),$$

i.e. V_d depends on the number of mean free paths between the two elektrodes.

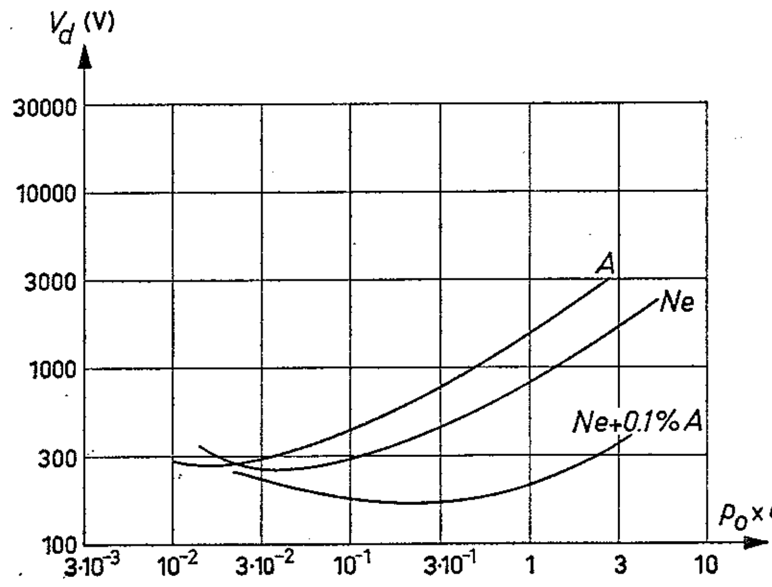


Fig. 12

Breakdown voltage V_d as a function of the product of the reduced pressure of the gas and the distance between the electrodes ($p_o \times d$) for neon (Ne), argon (A) and neon + 0.1 % argon.

We have already seen above that the breakdown voltage decreases as η increases. We are now in a position to understand that the breakdown of neon should be lowered by adding a small amount of argon. We have already seen in I-d-3 that this addition causes the value of η for neon to increase considerably. Fig. 12 shows the Paschen curves giving V_d as a function of $p_0 \times d$ for neon, argon, and a mixture of these two gases. The curves for the pure gases show a decided minimum, which is what we would expect since we have seen that V_d for a given gas is approximately inversely proportional to η, while η has a maximum at a certain value of F/p_0 (see I-d-3).

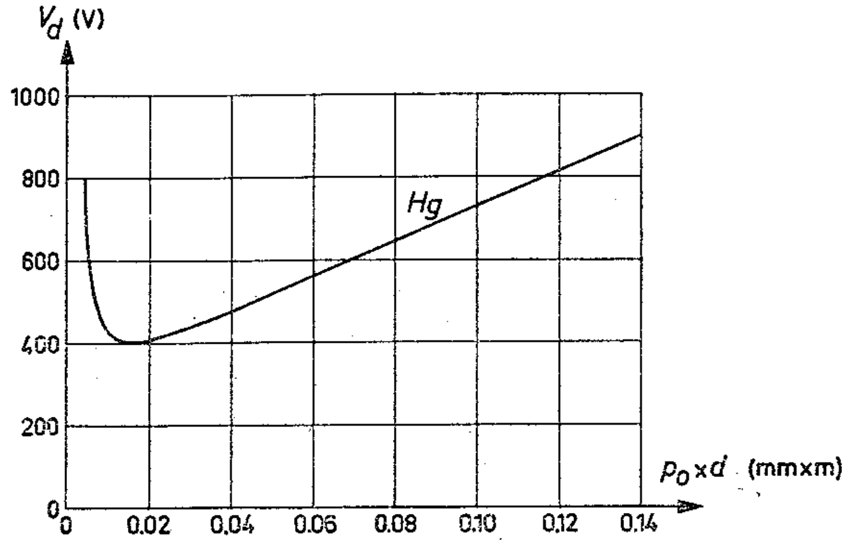


Fig. 13

Breakdown voltage V_d as a function of the product of the reduced pressure of the gas and the distance between the electrodes ($p_o \times d$) for mercury vapour [46].

The current-voltage characteristic

Now that we have seen how the current through a tube is initiated, let us examine how the voltage across the discharge varies as we increase the current, i.e. let us have a look at the current-voltage characteristic of the discharge. This is sketched in Fig. 14. It may be seen that this curve can be divided into six portions, the most important of which will be discussed below. Directly after the breakdown follows the region of *Townsend* discharge, with currents up to about 10^{-6} A. The voltage across the tube in this region is practically constant and equal to the breakdown voltage V_d.

If the current becomes greater than about 10^{-6} A, the discharge becomes unstable and contracts to a small region near the cathode. The voltage thus drops while the current increases (the transition region *C-D* in Fig. 14).

This decrease of the voltage stops at 10^{-4} to 10^{-3} A. The discharge is then concentrated in a small spot on the cathode, called the *cathode spot.* As the current increases further this spot extends to cover the whole cathode, the burning voltage remaining constant. This is the region *D-E* of the characteristic, the *normal glow discharge.* At the point *E* the discharge covers the whole cathode.

If the current is increased even further, the burning voltage increases in the region *E-F,* called the region of *anomalous* glow discharge. The amount of heat dissipated at the cathode gradually increases, until at F thermionic emission begins to play a part.

This causes the burning voltage to decrease again until at G this voltage is low enough for an arc to be formed. After G we have thus an *arc discharge* and the burning voltage then is called an arc voltage.

The arc discharge is formed very easily when the cathode is hot and emits a large number of electrons. We will discuss this discharge in greater detail below.

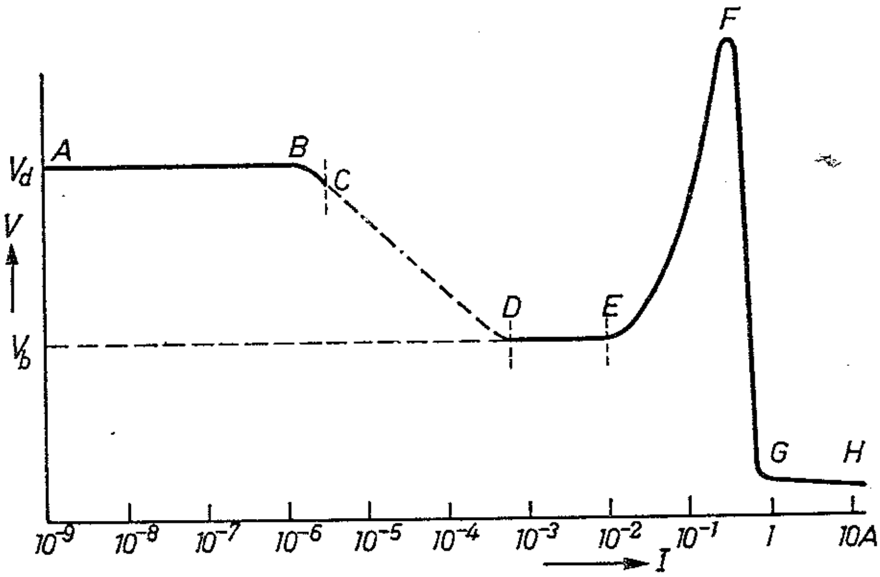


Fig. 14

The current-voltage characteristic for a discharge between two flat plates.
V = voltage, I = current.
V_d = breakdown voltage.
V_b = burning voltage of the glow discharge.
AB = characteristic of the Townsend discharge.
CD = unstable region.
DE = characteristic of the normal glow discharge.
EF = characteristic of the anomalous glow discharge.
FG = transition to the arc discharge.
GH = characteristic of the arc discharge.

The glow discharge

When the discharge is concentrated in a small spot on the cathode (see point D, Fig. 14), the current density is so great that a considerable positive space charge forms just in front of the cathode. The anode is thus, as it were, shifted to near the cathode, and the whole potential difference across the tube is concentrated near the cathode (see Fig. 15 curve 3). In the strong field thus produced, the electrons leaving the cathode rapidly gain enough energy to cause excitation and ionization. The *negative glow,* to which this discharge owes its name, is thus produced a slight distance in front of the cathode. The current density depends mainly on the nature and pressure of the gas in the tube, and is only a few tens of amps per m^2, so that the cathode remains cold. For further details see Chapter V, voltage stabilizing tubes.

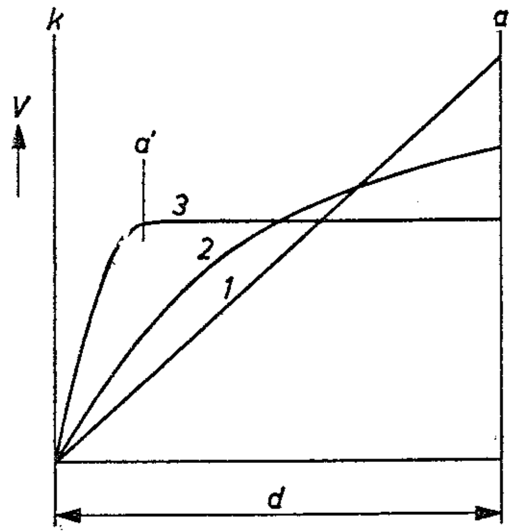


Fig. 15

Potential distribution in the glow discharge between two flat plates.
k = cathode, a = anode, d = distance between cathode and anode.
a' = apparent position of anode in the glow discharge.
1 = electrostatic potential distribution at zero current.
2 = unstable transition state.
3 = potential distribution in the glow discharge.

As we have seen, the burning voltage of the normal glow discharge is independent of the current. It depends on the nature of the cathode material, and of the gas in the tube, and is called the *cathode fall.*
On closer study, it is found that the variations of the intensity of the light in the tube are more complicated than described above.

Fig. 10 gives a more complete impression of these variations. The potential and electric field strength at the various points of the tube are also indicated in this figure. Right in front of the cathode is a relatively dark space (*Cr*), the *Crookes dark space.* The electric field is very large in this space, and the potential difference across it is nearly equal to the cathode fall. Although not much light is emitted here, ionization does take place. Next comes the glow (*Gl*) to which we have already referred, where the field is slight so that the electrons are no longer accelerated so much, but with the energy they gained in the Crookes dark space they are able to cause appreciable excitation, giving rise to the emission of light, and strong ionization. Next we see the second dark space, the *Faraday dark space (F).* There is no field here, i.e. the potential is constant. The electrons move so slowly that they can no longer cause excitation or ionization. This space contains a *discharge plasma* (see I-f). Each volume element contains just as many electrons as ions, on the average.

I-g-2 ANODE FALL AND POSITIVE COLUMN

It was assumed in the above that the flat plates acting as the cathode k and and anode a for the discharge were fairly close together. If we increase the distance between these two plates, we find a new glow of light near the anode, which is accompanied by changes in the potential distribution in this region. If the electrodes are separated even further, we finally obtain the *positive column* (Fig. 10 region *Z*).

We have already seen that the Faraday dark space contains a discharge plasma. The density of this plasma decreases with increasing distance from the cathode. If an anode, i.e. a metal plate with a positive potential, is placed in this plasma, the electrons will be attracted to it, and the ions repelled from it. At the beginning of the dark space (i.e. the end nearest the cathode), enough ions will be able to diffuse towards the anode, despite this repulsion, to compensate the space charge produced by the electrons, which must carry the whole discharge current in the neighbourhood of the anode. The potential of the anode is thus not much greater than that of the surrounding plasma.

If the anode is moved further away from the cathode, the concentration of the plasma near it decreases, and the number of ions which can reach the anode by diffusion is soon not enough to compensate the space charge of the electrons completely. There is thus a net negative space charge near the anode, which gives rise to an electric field. The potential of the anode will then be higher than that of the plasma. The potential difference between the anode and the plasma is called the *anode fall*. If the anode fall becomes equal to the ionization voltage of the gas, positive ions are produced at the surface of the anode. These hinder any further increase of the anode fall, since they compensate the negative space charge. This ionization is accompanied by excitation of the gas atoms, so that the anode is covered by a luminous film, the *anode light*. As a result of the anode fall, the losses at the anode increase so that this becomes warmer.

If the distance between the electrodes is increased even further, this luminous film changes into one or more balls of light, and finally the *positive column* is produced. The discharge then consists of three parts:

a. one part near the cathode, the cathode fall

b. a homogeneously illuminated region, the positive column

c. a part near the anode, the anode fall.

The start of the positive column (*P* in Fig. 10) is also the end of the Faraday dark space.

There are various kinds of positive column. We are, however, only interested in the homogeneous column, which is produced at low gas pressures. In such a column, the state of the discharge in different cross-sections is the same. If the distance between the electrodes is increased under these conditions, the voltage across the tube will increase linearly with the distance, the rate of increase being equal to the electric field strength or gradient in the column. This constant gradient depends on the nature of the gas, its pressure, and the diameter of the tube. Although the positive and negative space charges in the column do not cancel out completely, they very nearly do so, so we can regard the column as being a special sort of discharge plasma (see I-f).

The wall of the tube surrounding the column plays an important role. We have already mentioned (I-e-2) that electrons and ions recombine on the wall to form neutral atoms. The concentration of charge carriers at the wall is thus very small, so that they diffuse from the middle of the discharge to the walls.

The fast electrons initially cause a negative space charge near the wall, which gives rise to a radial field. The positive ions are accelerated in this field, so that finally ions and electrons arrive at the wall at equal rates. This combined diffusion of both sorts of charge carriers is called *ambipolar diffusion.*

This loss of charge carriers by ambipolar diffussion must be made up by ionizations in the column. The column can thus only remain in existence if enough fast electrons are produced in it to cause the necessary ionization. This condition is the reason for the electric field along the axis of the column, which gives the electrons just enough energy for the ionization which is needed.

In discharges in mercury vapour, the pressure is often very low. The mean free path of the electrons, λ_e, is then much greater than the radius of the tube. We will return to this in Chapter VI, in connection with the prevention of backfire. The above mentioned column discharges are used e.g. in gas-discharge lamps and in the so-called noise tubes (see Chapter VIII).

The presence of the above-mentioned glow discharge near the cathode is not essential to the existence of the column discharge. The glow discharge may under certain conditions be replaced by an arc discharge without destroying the column discharge in the rest of the tube. We will therefore now discuss the arc discharge in more detail.

I-g-3 THE ARC DISCHARGE

The arc discharge is produced when the anomalous glow discharge (I-g-1) changes into a thermionic discharge from the cathode via the unstable region *FG* (Fig. 14). Such a discharge is a typical self-sustaining discharge. Thermionic emission from the cathode can also be produced by heating the cathode by external means, e.g. by means of a heated filament. The arc discharge produced then is not self-sustaining. The burning voltage V_{arc} of an arc discharge without positive column is very nearly equal to the ionization voltage of the gas in which the discharge occurs, and decreases as the current increases. The arc discharge thus has a negative characteristic. The value of the current can be hundreds of amperes.

The name "arc" is derived from the shape of the discharge produced between two pointed carbon rods in gas (e.g. air) under about one atmosphere pressure. The upward flow of air due to convection gives rise to the typical arc form (the Davy arc lamp).

A. *The self-sustaining arc discharge*

An arc arises from the anomalous glow discharge as soon as the heat developed by the ion bombardment makes the cathode hot enough to emit the electrons needed to carry the discharge current. The surface of the cathode is usually inhomogeneous, so that the arc only takes up a part of this surface, finally occupying only a small point on the cathode. This type of discharge is much used in gas-discharge lamps, but not in gas-discharge tubes. We will, therefore, not discuss it any further.

B. *The non-self-sustaining arc or low-tension arc*

If the cathode of a gas-discharge tube is heated by external means until it emits electrons strongly, a discharge of high current density and even lower burning voltage than the ionization voltage of the gas can arise. Such a discharge, which can usually only exist if heat is continually supplied from outside, is called the *low-tension arc*. The cathode should be prepared in a special way if it is desired to obtain the low-tension arc easily (see I-c-1 and II-c-1). Let us examine this discharge rather more closely, in order to see what its typical characteristics are.

As we saw in I-c-1, a neon-filled gas-discharge tube with a hot cathode which gives strong thermionic emission of electrons and e.g. a flat anode will have a strong negative space charge due to electrons near the cathode. At an anode voltage of zero, the potential will show a minimum just in front of the cathode, so that very few electrons will be able to reach the anode. If the anode voltage is increased to 15 V (which is still below the ionization voltage, $V_i = 21.5$ V for neon), the depth of the minimum will decrease somewhat (see curve I, Fig. 16) and the electron current will increase, but will still not reach any very great value. As soon as the anode voltage exceeds V_i, the first ions will be formed near the anode, and will move under the influence of the electric field to the cathode where they will neutralize the negative space charge. The minimum in the potential curve thus disappears suddenly, and the anode current rises to the saturation current of the cathode, or to the greatest value permitted by the external circuit.

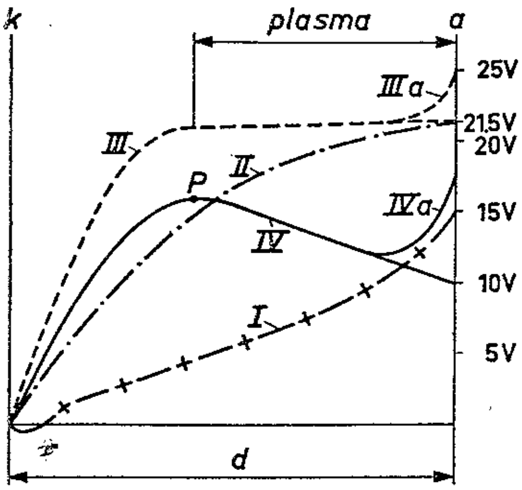


Fig. 16

Potential distributions occuring during the ignition of a low-tension discharge in neon. k = cathode, a = anode, d = distance between cathode and anode.

I. Potential distribution at anode voltage of 15 V tube not ignited.
II. Anode voltage 21.5 V, tube ignited, relatively small current.
III. Potential distribution at higher current.
IIIa. Anode fall.
IV. Potential distribution at even higher current than in III.
IVa. Anode fall.

This process is known as the *ignition* (or breakdown) of the discharge. If the external circuit only allows a relatively small current to pass, the potential varies as shown by curve II of Fig. 16. If the current is increased, the electric field shifts towards the cathode so that one would expect the potential distribution to be as shown by curve III of Fig. 16 (curve IIIa shows what happens if there is an anode fall). The concentration of metastable neon atoms in the discharge has, however, increased so much in the meantime that the large number of electrons present can ionize these metastable atoms. Only 16.6 eV is then in fact needed for the formation of ions. The burning voltage falls to about this value, and the potential distribution is as shown by curve IV of Fig. 16, with IVa representing the situation when anode fall is present.

We see from the above that the ignition voltage of the low-tension arc is always at least equal to the ionization voltage of the gas in the tube. The burning voltage is often considerably lower, in which case it is of the order of the first excitation voltage.

I-g-4 THE CORONA DISCHARGE [3, 67, 79]

The self-sustaining discharge in the inhomogeneous electric field between a thin wire and a coaxial cylinder is called a *corona discharge*. This name is descriptive of the light effects found if the voltage is several kilovolts and the gas pressure is high (e.g. in the atmosphere). The gas pressure need not be high for the discharge to occur, but at low pressure the corona is not visible.

The luminous part of the discharge is usually restricted to a region close to the wire, which may be positive or negative with respect to the cylinder.

Such discharges are found:

1. between the wires of a high-tension transmission system (above ground); here the atmosphere acts as the second electrode.
2. in certain forms of Geiger-Müller radiation tubes (see V-d-6).
3. as the primer discharge in certain trigger tubes (see V-f), and in certain other applications of cold-cathode tubes.

One distinguishes between positive and negative coronas, depending on the voltage of the central electrode. The positive corona consists of a *luminous film* on the wire, and the negative corona of a series of *luminous balls.*

The negative corona discharge

The ions which are formed in the strong field near the negative wire move towards the wire, and free so many electrons from it that the discharge is self-sustaining. Outside this ionization region, the electrons are practically the only charge carriers for the discharge current.

Fig. 17 shows the effect of the space charge on this corona discharge. The increase of the field caused by the ions near the wire can be clearly seen.

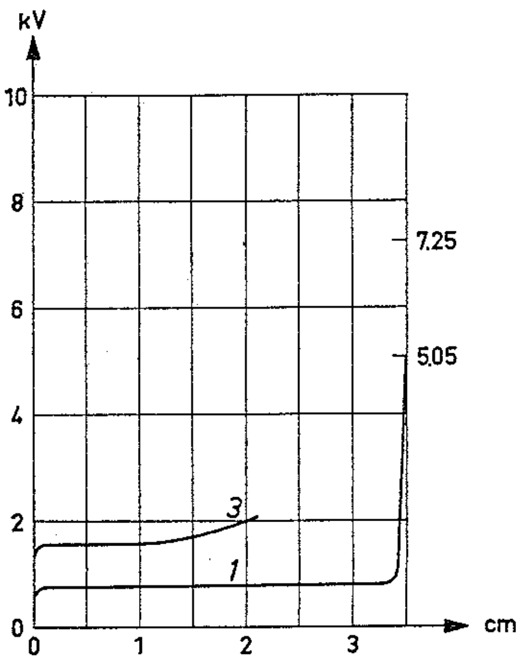


Fig. 17

Potential distribution in the negative corona discharge.
The anode is on the left of the figure, and the cathode on the right. The potential difference with respect to the anode is plotted upwards. The current corresponding to curve *3* is three times that for curve *1* [81].

The positive corona discharge

The positive corona discharge is more important than the negative one for the tubes discussed in this book. A number of electrons are first formed by radiation coming from outside the tube. These will then move

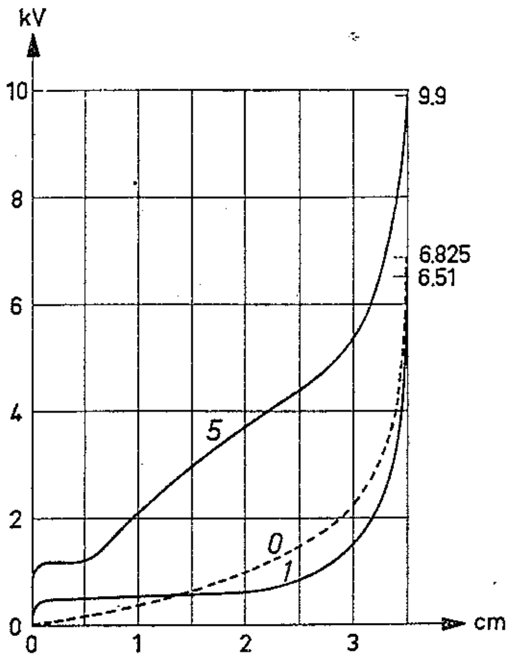


Fig. 18

Potential distribution in the positive corona discharge. The cathode is on the left of the figure, and the anode on the right.
Curve *0*, the electrostatic potential distribution at zero current.
Curves *1* and *5* correspond to two currents differing by a factor of five [81].

towards the positive wire where the field strength is high, and avalanches will be formed from these primary electrons, giving rise to a short current pulse. The ions move away from the wire to the cylindrical cathode. Since the field strength near the cathode is weak, nearly all the current is carried by the ions in this stage. The discharge becomes self-sustaining when so many ions, light quanta or metastable atoms fall on the cylinder that sufficient secondary electrons are produced. The current-voltage characteristic, which is positive at low currents (about 10^{-8} A) and high pressures (about 1 atm), becomes negative at high currents (about 1 mA), and the corona degenerates into a glow discharge. At low pressures, e.g. 30 mm Hg, the ionization is not restricted to the neighbourhood of the wire. The current-voltage characteristic then becomes negative. We will show how use can be made of this discharge in the discussion of the Geiger-Müller counter tube in Chapter V. The change in the potential distribution as a result of the space charge is shown in Fig. 18. The broken line represents the electrostatic potential distribution at zero current.

CHAPTER II

THE CONSTRUCTION OF A GAS-DISCHARGE TUBE

II-a **Introduction**

As often happens in modern technology, there is rather less confusion about how to make and use gas-discharge tubes than about what to call them: recent reference books on electronics talk of gas tubes, gas-filled tubes, gas-discharge tubes and gaseous discharge tubes; and the word "tube" is often replaced by "valve" in English, rather than in American literature. In this book the name "gas-discharge tube" will be used.

Another aspect of nomenclature which might lead to confusion is the name given to the electrodes. Most discharge tubes contain two or more electrodes, and the main current generally flows between two of them. When one of the two is always positive with respect to the other, it is called the anode and the other the cathode, but in many cases their polarity is periodically reversed. However, it usually happens that much more current flows when one of the electrodes is positive. This one is then called the anode, and the other the cathode, no matter what their polarity at any given moment.

In this chapter a general discussion is given of *the gas filling, the electrodes* and *the envelope* of a gas-discharge tube. The details of construction and characteristics of the various gas-discharge tubes are discussed in the following chapters.

II-b **The gas filling**

While care must be taken to remove all the free and absorbed gas from a vacuum tube, the presence of a certain amount of gas is essential in order to give a gas-discharge tube its special characteristics.

We will discuss here the various types of gas and the reason for using them, their pressure and the purity of the gas.

II-b-1 THE GASES USED

Most gas-discharge tubes are filled with an inert gas (He, Ne, A, Kr, Xe) or a mixture of inert gases. These have the great advantage that they do not react chemically and they also give better reproducibility of the tube characteristics than do non-inert gases.

Hydrogen and nitrogen are also sometimes used for filling the tubes.

Finally, a *vapour* filling may sometimes be used, viz. mercury vapour or a mixture of mercury vapour and an inert gas, or a halogen or an alcohol. The choice of the type of gas mainly depends on the demands made on the tube.

Pure inert gas may be used to fill tubes where the difference between the burning voltage and the breakdown or ignition voltage must be large, e.g. in trigger tubes. The reason for preferring a pure inert gas in this case can be made clear with the aid of the Paschen curves (Fig. 19). The choice of a sufficiently high value of p_0d gives a high breakdown voltage, while the burning voltage does not depend very strongly on p_0d. (A very low value of p_0d also gives a high breakdown voltage, but this part of the Paschen curve is difficult to realize in practice). The values of p_0 and d needed to give this high breakdown voltage can be achieved in practice with pure inert gases better than with inert-gas mixtures.

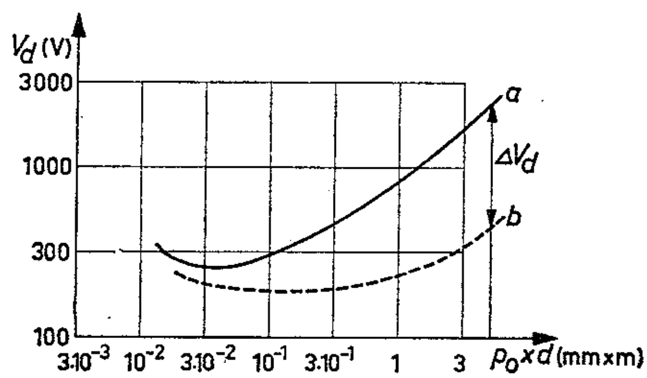


Fig. 19

Typical Paschen curves, showing the breakdown voltage as a function of the product of pressure and interelectrode distance for
a. neon,
b. neon + 0.1 % argon.

The addition of a small percentage of another inert gas, with an ionization voltage lower than the excitation voltage of the metastable state of the main gas, makes the Paschen curve appreciably flatter and its minimum lower (curve *b* Fig. 19, cf. Penning effect, Chapter I-d-3). Such a gas mixture is used e.g. for a voltage-stabilizing tube, where the breakdown voltage V_{ign} for the glow discharge should only be slightly greater than the burning voltage V_{br}. It is then possible to use a lower supply voltage and a smaller resistance in series with the tube than would be necessary if $V_{ign} - V_{br}$ were large.

Mercury vapour may be mixed with the inert gas when the energy lost in the tube should be low, and the life of the tube long. This combination gives for instance a low V_{ign} and V_{arc} in a hot-cathode tube, so the transformer voltage for a rectifier may also be low (this is used in e.g. an LT accumulator charger).

Industrial rectifier tubes for a few hundred volts contain saturated mercury vapour and a little inert gas. Since the anode voltage is quite high, the pressure of the inert gas must be relatively low in connection with the backfire voltage. Nevertheless it helps to support the discharge when the mercury temperature is still too low, while the tube is warming up. After the tube has been warmed up, the mercury vapour takes over most of the discharge. The result is that such a tube can be started cold (as soon as the cathode has been warmed up); moreover, the mercury ensures a long life which would not be obtained if the tubes were only filled with inert gas at a low pressure.

If however the anode voltage of such a tube should be some kilovolts (as in an HT rectifier), then the permissible gas pressure is so low that the inert gas would be cleaned up very quickly (see II-b-2); so only saturated mercury vapour can be used here. The vapour pressure of the mercury (which depends on the temperature) must also be low, so these tubes are specially designed not to get too hot. The reserve of liquid mercury ensures a long life for the tube despite the low vapour pressure, since the vapour is replenished as fast as it is used up during the operation of the tube.

Sometimes unsaturated mercury vapour is used in a mixture, but then the life of the tube is not so long, since the vapour can no longer be replaced as it gradually disappears.

Hydrogen gas is used in e.g. radar thyratrons where a current pulse with very steep flanks is desired, since in hydrogen the build-up and the recovery time (see I-e-2 and IV-b-4) are much shorter than in other gases.

Nitrogen at rather high pressures is sometimes used in surge arresters because of the short build-up time, which allows the tube to respond rapidly to rapid increases in the voltage.

We may finally mention the use of halogens and alcohols. Their strong electron affinity and absorption of the UV light produced by the discharge ensure that the discharge is quickly damped. These substances, mixed with inert gases, are therefore used in e.g. some radiation counting tubes.

II-b-2 THE GAS PRESSURE

After the sort of gas to be used has been decided, the pressure to be used must also be fixed. We have seen in Chapter I that in order to give a clear understanding of the phenomena occurring in a gas-discharge tube, the amount of gas present can best be expressed as the gas *density*, but that it is simpler in practice to use the gas *pressure* at a given temperature; p_0 will be used here for the pressure reduced to 0 °C.

The gas pressure or density has an effect on:

1. the breakdown or ignition voltage
2. the current density
3. the operating voltage
4. the backfire voltage
5. the life of the tube
6. cathode sputtering.

In each particular case the designer of a tube has to decide which of these factors is most important. We will now give some examples of the considerations used to fix the pressure in a gas-discharge tube.

The relationship between the pressure p_0 and the current density j in a glow discharge is given to a good approximation by the equation

$$V_a = \mathrm{f}\,(j/p_0{}^2)$$

This means that the anode voltage V_a remains practically constant if j is varied in proportion to the square of p_0. Under these circumstances, however, an increase in the current density leads to an increase in the heating of the cathode surface. If p_0 is increased too much, the cathode begins to emit thermally, and the discharge changes into an arc, the anode voltage decreasing sharply to the arc voltage V_{arc}. In hot-cathode tubes, the value of V_{arc} increases as the pressure is increased, owing to collision losses; and it also increases as the pressure is decreased to very low values, where the supply of ions is very small. The plot of V_{arc} against p_0 for argon (Fig. 20) shows a minimum at a pressure of about 6 mm Hg (with an inter-electrode distance of about 10 mm).

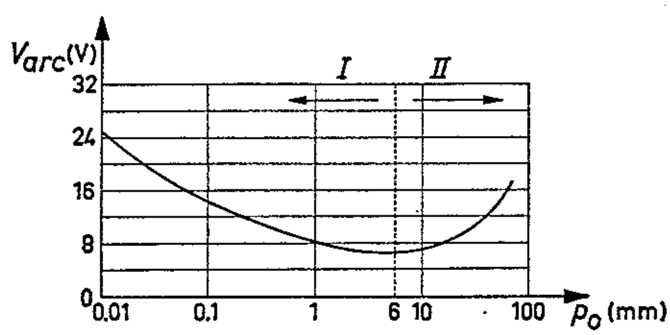


Fig. 20

Influence of the gas pressure p_0 on the burning voltage V_{arc} of an arc discharge. The curve has a minimum at $p_0 \approx 6$ mm.

The current in the glow discharge occurring at the anode of a rectifier tube during the negative phase must be kept as low as possible, since it interferes with the rectification effect. If the pressure is high enough and if the resistance of the circuit belonging to the reversed discharge is low enough, this glow discharge may degenerate into an arc. The inverse current then increases so much that the rectification effect is lost. The ignition voltage for this arc discharge at a given pressure is called the *backfire voltage*. Its value varies considerably from tube to tube of the same type. Tube specifications include a maximum permissible value of the inverse voltage, below which no backfire will occur.

Let us now consider the relationship between the pressure and the life of the tube. At low pressures, the ions pass through a large voltage difference between two collisions, so that the cathode bombardment becomes vigorous with the result that heavy cathode sputtering occurs, limiting the life of the tube. At high pressures the ions strike the cathode with lower velocities, but there are many more of them. However, many of the atoms knocked out of the cathode collide with gas atoms and return to the cathode, so sputtering (and evaporation) is considerably reduced at high pressures. A good example of this effect is to be found in the "Tungar" rectifier tube. The tungsten cathode of such a tube must be at a high temperature in order to give the required emission (cf. I-c-1 and III-b-1); but at these high temperatures the evaporation of the material reaches considerable proportions. The evaporation is however kept within reasonable limits by the high pressure in the tube (10—15 cm Hg).

The material removed from the cathode by sputtering is also deposited on other parts of the tube, where it may lead to short-circuits. This is another reason for having the gas pressure on the high side.

Cathode sputtering is not the only thing which determines the life of a tube, gas may also disappear during the discharge, for a number of reasons. This phenomenon is known as *cleanup*.

The first phase of this cleanup consists in an adsorption of gas atoms on the walls or the electrodes. This gas is thus lost from circulation and the gas pressure decreases. Furthermore, e.g. in high-voltage tubes, which are normally filled with gases at low pressures, the high voltage give rise to *fast* gas ions which can easily penetrate into the surfaces mentioned. This decrease in pressure may determine the life of the tube.

A second phase consists in the trapping of gas during the deposition on the walls of the tube of material released from the electrodes by the discharge (sputtering). The amount of sputtering depends on the energy of the ions, their nature, the gas pressure, the sort of electrode material used and its surface condition (oxidized surface, etc.).

The ion bombardment does not only affect the cathode. The metal particles sputtered from the other electrodes also pick up gas atoms on their way to the walls, thus decreasing the pressure.

Moreover, cleanup may occur by the adsorption of gas on these metallic layers deposited on the walls of the tube. We may also mention for the sake of completeness the tendency of certain gases to react chemically with materials in the tube. This may sometimes be a serious problem with non-inert gases, which can even be activated by the discharge.

One of the great advantages of the use of saturated vapours, such as mercury vapour, in filling tubes is that as long as there is liquid mercury present in the tube, the vapour pressure will not be affected by cleanup, since the losses due to adsorption are made up by replacement from the liquid. This does not hold for unsaturated vapours, of course.

Another way of keeping the gas pressure constant during the life of the tube is the use of a *replenisher*. Materials which under suitable conditions can adsorb large quantities of certain gases *(getters)* are discussed in the next section; a replenisher is a getter acting in reverse. If a metal wire covered with such a material is heated in a glass bulb, the adsorbed gas is released, and on cooling the gas is adsorbed again. The gas pressure may thus be controlled by means of the temperature of the wire. As we will see later on (IV-b-6), this is used in hydrogen thyratrons.

To sum up what we have said above, if certain conditions must be imposed on e.g. the ignition voltage, inverse voltage and/or operating voltage in the design of a tube, these often impose contradictory limitations on the value of the gas pressure. It is therefore necessary to make a compromise. If we think of the relation between the mean free path and the pressure, it is clear that the distances between the electrodes and/or their distance to the wall must be chosen to correspond to the pressure chosen: as a rule the mean free path must be small compared with these dimensions, so that ionizing collisions can occur.

The gas pressure chosen for a gas-discharge tube will be somewhere between 10^{-3} and 10^{3} mm Hg, though the most usual range is from 1 to 10 mm Hg.

II-b-3 THE PURITY OF THE GAS, GETTERS

The inert gas in a tube must be kept pure. The presence of impurities, even in very small amounts, can have a considerable effect on the ignition and operating voltages. These voltages are generally increased by the presence of non-inert gases, since electrons which collide with such molecules lose their velocity or may even be trapped. Their presence may easily be detected from the colour of the discharge. Each pure gas gives a typical colour in a low-pressure discharge (see table III). The same gas may give different colours in discharges of different kinds (e.g. a high-pressure arc).

TABLE III

THE COLOUR OF THE INERT GASES, AND OF A NEON-ARGON MIXTURE, HYDROGEN AND MERCURY VAPOUR IN LOW-PRESSURE DISCHARGE

helium	yellowish pink (green at very low pressures)
neon	orange-red
argon	violet
neon-argon	yellow-orange
krypton	pale lilac
xenon	blue
hydrogen	reddish violet
mercury vapour	blue-green

The colour changes slightly as soon as another gas or vapour is added. Traces of mercury vapour generally give a blue colour which masks the colour of the main component. If some air has leaked into a tube the colour of the discharge will usually be pale, milky or sometimes reddish. Magnesium vapour gives a clear green colour.

There are three conditions for the purity of the gas filling:

a. thorough degassing of the tube
b. filling with pure gas and
c. purifying the gas again, once the tube is sealed.

a. Before a tube is filled with inert gas at the pump, the walls and electrodes (and the getter) must be freed as well as possible from the gases which they contain. This is done by heating the whole tube to as high a temperature as possible and at the same time pumping out until a vacuum of 10^{-5} to 10^{-6} mm Hg or better is obtained. The electrodes are also heated separately by placing them in an HF field. A hot cathode may be heated by passing the heater current for some time.

TABLE IV

SPECIFIC EVAPORATION OF SOME METALS IN KG/M²/SEC AT VARIOUS TEMPERATURES [9]

	700 °K	800 °K	900 °K	1000 °K	1200 °K
W	—	—	—	—	3.22×10^{-26}
Mo	—	—	—	1.37×10^{-23}	2.44×10^{-18}
Ni	8.41×10^{-20}	2.35×10^{-16}	1.08×10^{-13}	1.42×10^{-11}	2.00×10^{-8}
Ba	1.7×10^{-7}	9.1×10^{-6}	2.0×10^{-4}	2.5×10^{-3}	1.0×10^{-1}

The vapour pressure of the electrode materials is still low at temperatures sufficient for degassing [9]. The table below gives some data on the specific evaporation of tungsten, molybdenum, nickel or barium at various high temperatures.

High-quality tubes must be degassed with great care in order to reduce the residual pressure of gaseous contaminations in the sealed tube to as low a value as possible. For example, a residual pressure of 10^{-8} mm of oxygen is enough to cover the metal electrodes with a monomolecular oxide layer in a few hours.

b. Various methods can be used for filling a tube with pure gas from a reservoir so that the amount of other gases or vapours introduced is kept to a minimum. A detailed description of these methods is beyond the scope of this book.

c. Once the gas has been put into the tube and the tube sealed off, the gas may still be purified by means of *getters* [8] in order to remove impurities introduced into the gas filling during and after sealing. Getters are substances which can adsorb or react with non-inert gases. The getter material is placed in the tube in a getter holder; when required for use, it may be evaporated from this holder (evaporating getter) or it may remain in the holder (non-evaporating getter). The alkaline earth metals, especially barium, are mainly used as evaporating getters, while zirconium is the usual choice for a non-evaporating getter. Sputtered layers can also be used as getters.

Evaporating getters

A certain amount of the getter, either as the pure element or in combination with other substances, is placed in a holder on a little rod inside the tube, and the holder can be heated by an external HF field as described above. When it is thus heated to a high temperature, the getter material evaporates and is deposited as a thin film over the cooler parts of the tube. It is thus given a very large surface area, which is as we will see essential for the purification of the gas.

Before evaporating, the getter must be degassed at a temperature low enough to prevent appreciable evaporation, so that it is initially as free from gas as possible. Some getter materials, e.g. barium, are placed in a sealed holder which is designed to open when heated to a temperature higher than the degassing temperature of the tube. Such getters cannot naturally be degassed *in situ*.

The non-inert gases are not only taken up during the time when the getter is evaporated, but also after: the thin getter layer, or mirror, which is deposited on the cooler parts of the tube is also able to combine chemically with reactive gases. A good layer is formed if the evaporation occurs through a gas, and not in vacuo, since then it is given a spongy structure and thus a great surface area, which is essential for strong and fast gettering. If a getter mirror is present it is thus able to trap impurities which may be released from the electrodes or walls of the tube during operation.

Non-evaporating getters

Some substances, such as zirconium and titanium, are very active not only as a layer formed by evaporation or sputtering, but also in the form of pellets, wires, etc. They adsorb selectively as a function of temperature; so e.g. zirconium can be used as a getter at various temperatures. At low temperatures (below 200 of 300 °C) zirconium getters are in particular able to adsorb oxygen and nitrogen [11]. When used in the high-temperature range (at about 900 °C), it can adsorb e.g. oxygen and nitrogen, or hydrocarbons and carbon monoxide. When the tube is constructed in

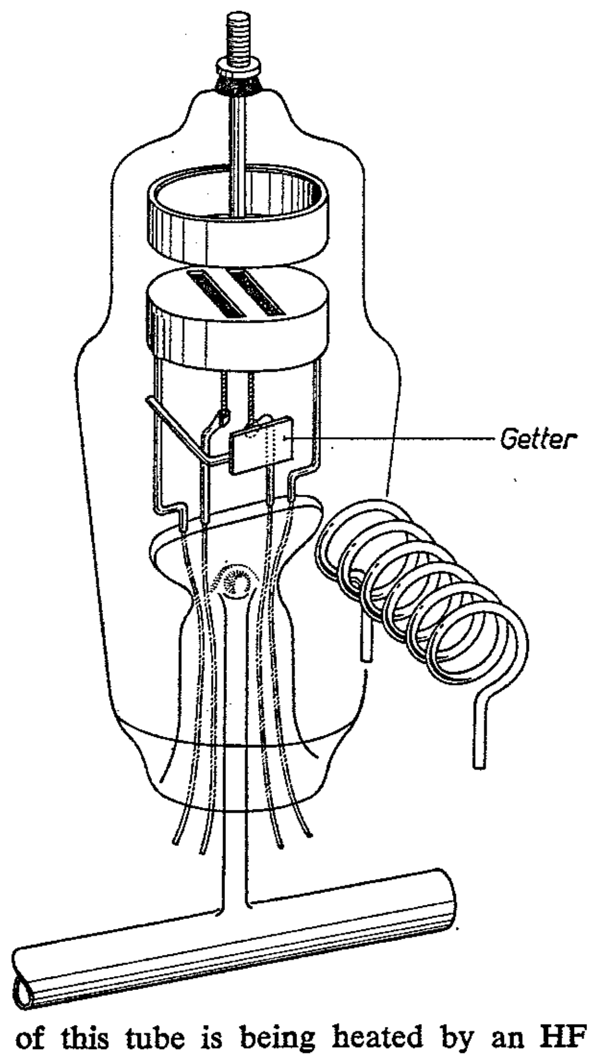


Fig. 21

The zirconium getter of this tube is being heated by an HF field while the tube is pumped out by a vacuum pump.

such a way that different parts of the getter operate at different temperatures, zirconium can therefore adsorb all the above-mentioned gases. A specially prepared Zr getter or a sputtered Zr layer can also adsorb all these gases at a single temperature. Since zirconium does not amalgamate with mercury, it can be used in mercury-vapour rectifiers [8], which is not the case with e.g. a Ba getter.

We will not give any details of gettering speed and the like, which are of importance for the manufacturer but not for the user. Interested readers can find various studies of these points in the literature [10]. We will, however, say something about the getter holder.

The active getter must often not be exposed to the air, to prevent saturation with atmospheric gases which would make it useless for purifying the gas in the tube.

Chemical substances which can release the getter are therefore often enclosed in nickel boxes, which are pinched together at the edges to keep out the air. When such a box is heated in an HF field in vacuo (see Fig. 21), the metal is released by a chemical reaction. When the vapour pressure in the box is high enough to force it open slightly, the vapour is "squirted" out. Care must be taken that the getter lands on the right places, and not where it can hinder the proper functioning of the tube. The getter mirror must not, for example, cause short-circuits between the electrodes. The position of the box must therefore be chosen very carefully.

The getter holder need not however always be closed. Fig. 22 shows some examples of open ones.

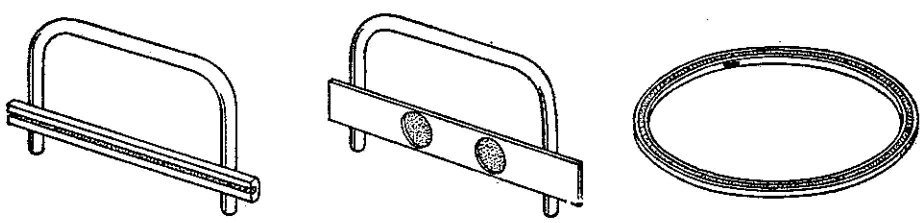


Fig. 22

Various types of open getter holders. In contrast with the type described in the text, these getter holders do not completely enclose the getter-producing substance, which is indicated by dotted areas. The first two types are provided with a metal loop, which is needed to form a closed circuit for the HF current.

Sputtered layers

Another method of forming a getter layer is by means of sputtering, where a discharge is used to eject metallic particles from the cathode by ionic bombardment, after which the particles are again deposited on the walls of the tube.

Atoms of the contaminating gas can be trapped by the metallic particles during sputtering, and deposited with them on the walls of the tube. The sputtered layer can also act as a getter.

For example, in some glow-discharge tubes (e.g. reference tubes, see V-a-2) a molybdenum cathode is sputtered in order to keep the inert gas filling pure.

II-c The cathode

A hot cathode or a cold cathode may be used as the electron source in a gas-discharge tube. Such cathodes are commonly made of metals, which may or may not be oxide-coated. The work functions may have various values (see Table I, Chapter I). A list of the various types of cathode in use is given below.

1. Hot cathode (directly or indirectly heated)	Uncoated (Bright emitters)	Tungsten Thoriated tungsten
	Coated (Dull emitters)	Tungsten or nickel or mixtures of the two coated with alkaline earth oxides
2. Cold cathode	Uncoated	Nickel Graphite Iron Molybdenum Zirconium
	Coated	Nickel or iron coated with barium oxide
3. Mercury-pool cathode		
4. Photo-cathode	caesium-caesium oxide caesium-antimony	

II-c-1 HOT CATHODES

The most obvious way of creating a source of electrons — and this is what the cathode in a gas-discharge tube is — is to heat a metal.

According to the Richardson formula (Chapter I-c-1) the electron emission is proportional to $T^2 \cdot \varepsilon^{-e\varphi/kT}$. The work function φ of a metal is high, so a high temperature is needed to give enough emission, and this leads to considerable evaporation. This method is therefore only used in special cases. Another method is to deposit a layer of a substance with a low φ on the metal. The same emission can then be achieved at a lower temperature, and less energy need be supplied because the heat losses are smaller.

Uncoated cathodes

The use of uncoated tungsten is now practically restricted to some vacuum tubes. A filament temperature of about 2250 °C is normal. As far as gas tubes are concerned, thoriated tungsten wire is used in low-voltage rectifiers. This alloy contains a low percentage of thorium. The spirally wound cathode wire is heated to about 1900 °C, which causes a layer of thorium atoms to be formed on the surface. It is not certain whether thorium oxide as well as thorium is present in this outer layer. The thorium, which disappears from the surface during operation, is replenished from within. The life of the tube is thus determined by the supply of thorium. The high temperature is necessary to give an emission of 10 to 20×10^4 A/m^2. The evaporation at this temperature is limited by a relatively high gas pressure (a few centimetres of mercury). An emission current of about 0.3 A per watt filament power can be obtained.

Coated cathodes

It is possible to increase the emission from the cathode by using a core of tungsten coated with a layer of alkaline earth oxide so formed as to give a spongy structure. Most gas-discharge tubes contain cathodes of this type. The emission temperature is much lower than for uncoated cathodes, being in the range 800—850 °C (about 1100 °K), because the low work function of the oxyde layer means that a sufficient emission is produced at such temperatures (see I-c-1). The attainable current density is 0.5 to 2.5×10^4 A/m^2, and can rise to as much as 100×10^4 A/m^2 during pulse operation (saturation) [12]. The emission current per watt filament power is about 0.6 A.

Fig. 23 compares the emissive power of four types of cathodes. The variable actually plotted is the specific saturation current I_{sat} in A/m^2.

The life of the cathode will be discussed below; but we will mention here that the main causes of deterioration of the cathode are evaporation and sputtering. A well-designed coated cathode will give very slight evaporation and sputtering, as long as the current remains below the saturation current. If the tube is operated under suitable conditions, both these causes of deterioration can be neglected.

The emission due to the γ effect (emission of electrons due to bombardment by positive ions, see Chapter I-g-1) is small as long as the current remains below I_{sat}. If the current exceeds this value, the γ effect increases considerably, and so does cathode sputtering.

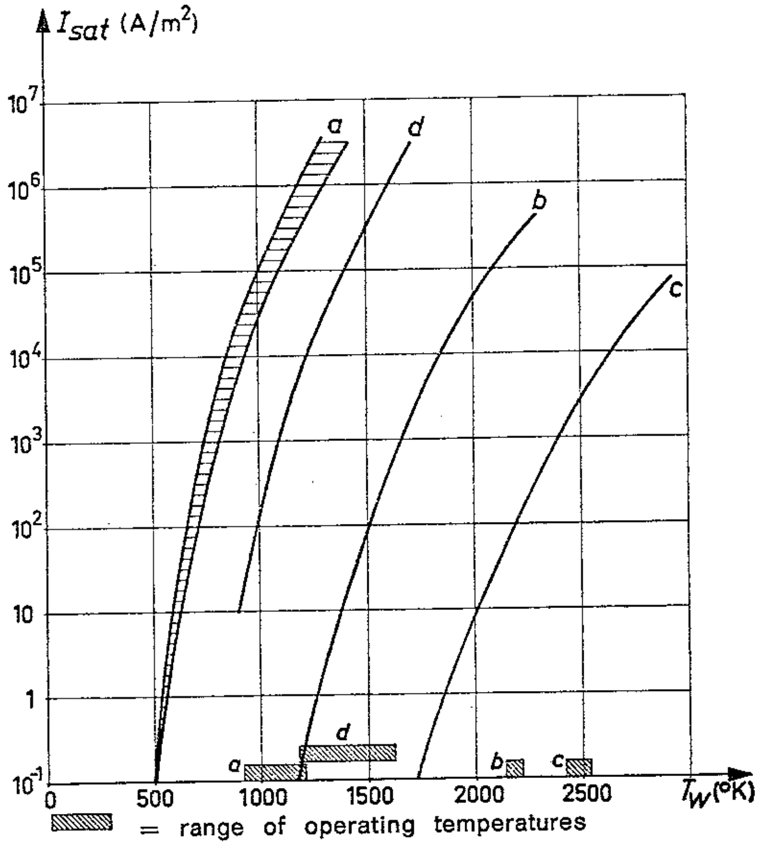


Fig. 23

Saturation current density I_{sat} as a function of the true temperature T_w of the cathode for:
a. oxide-coated cathode, (Ba, Sr)O,
b. thoriated tungsten cathode,
c. tungsten cathode,
d. *L* cathode,
(after Herrmann and Wagener [1]).
The range of operating temperatures is shown by hatched blocks.

As the emission current is increased from zero, a time comes when the saturating emission current is exceeded, i.e. more electrons are produced than can come from thermionic emission. The remainder are obtained by means of the γ effect, as the number of ions bombarding the cathode increases. An increase in the tube voltage will then be observed; this is needed to produce more ions. The ions will strike the cathode with a higher kinetic energy, and this increase in the number and energy of the ions will lead to a sharp increase in the sputtering.

II-c-1-a. *Some phenomena peculiar to the oxide-coated cathode*

The emitting layer

Careful investigation of a tube with an oxide-coated cathode during operation over a long period will help us to understand the working of such a cathode. The cathode is first heated to incandescence by the heating current through the cathode. As soon as a discharge current passes through the tube, the cathode will be seen to heat up. It is true that the energy needed to free the electrons from the oxide layer (equal to $I\ \varphi$, the product of the current and the work function) will have a cooling effect on the cathode, but against this we have the heat supplied by the bombardment by ions and the joule heating by the flow of current in the cathode [1]. In general, the heating effects predominate, so that the cathode temperature increases.

The cathode is prepared by applying a mixture of carbonates, e.g. $BaCO_3$, $SrCO_3$ and $CaCO_3$ (triple carbonate) to a wire which forms the core. A nickel wire may be used, for example. The cathode is first heated in vacuum to about 800 °C to degas it; the carbonates also decompose to the oxides and carbon dioxide is evolved at this temperature. Then the heater current is increased so that the temperature rises to about 1000 °C and is kept at this value for some minutes. This whole process is known as activation of the cathode. Some of the barium oxide at the surface of the nickel is reduced to metallic barium, thus giving a mixture of Ba and BaO. The low work function is maintained as long as both BaO and Ba are present at the surface. When Ba atoms disappear from the surface, they may be replaced from within the oxide layer, by the migration of Ba along the surface of pores, etc. The low value of φ (1.2 e.V) means that considerable thermionic emission occurs even at 850 °C (cf. Chapter I-c-1).

Evaporation of Ba from the monatomic layer is slight at low temperatures, but increases strongly with the temperature above 800 °. The oxide itself evaporates much less, whereas the evaporation of the (nickel) core wire can be neglected. This means that at 800—850 °C the cathode may have a very long life.

Sputtering

The name sputtering includes not only the detaching of atoms from the cathode, but also the detaching of macroscopic particles from this electrode. As the emission current is increased until the current density reaches considerably too high values, the latter form of sputtering gradually begins to predominate. The same thing happens if the cathode temperature is too low, or at high current density as occurs at high gas pressures. The brittle oxide layer becomes locally overheated, and chips jump off.

The same result can also be produced if the filament current of the oxide cathode is reduced to zero during normal operation. The discharge does not normally cease under these circumstances; the arc current becomes concentrated on the windings at that end of the cathode spiral which is most negative with respect to the anode. Thus even if the energy involved is slight, a very large temperature increase is produced locally. Depending on the value of the current density, the emission is accompanied by abnormally strong evaporation of the barium, by strong sputtering of atoms, or in the worst case by the detaching of particles. The latter form of sputtering can quickly lead to destruction of the cathode.

A special case of sputtering is found if the anode voltage and the filament are switched on simultaneously when the cathode is cold. An arc discharge may start before the cathode has reached its normal emission temperature. Sputtering then occurs until the filament reaches the temperature needed for the desired emission current. This way of starting the arc reduces the life of the cathode. It is therefore desirable not to switch on the anode voltage in gas tubes with oxide cathodes until the filament voltage has been applied and the cathode has been given time to reach the right temperature.

II-c-1-b. *The life of the hot cathode*

As has been mentioned, a hot cathode is damaged by evaporation and sputtering. One might ask how long a hot cathode is able to carry out its task, and whether the life of the cathode can be increased by good design of the tube. It has been found possible to design tubes which satisfy the required conditions of voltage, current, etc., and which also have a very long life. The way in which this may be done varies from tube to tube, according to conditions of gas pressure and electrode configuration, as will be shown by the examples given below.

An HT rectifier tube must in general have a low gas pressure, so a mercury-vapour filling is the obvious choice. It is sometimes preferable to have the anode in a region of low pressure and the cathode in a region of high pressure. This can be achieved by having a separate anode and cathode space, linked by narrow channels, with the cathode space at high temperature, resulting in a high mercury vapour pressure. Such a construction is shown in Fig. 24; this has a condensation space *C*, connected on both sides by metal tubes to the anode space *a*, and the cathode space *k*. A pressure ratio of 1 : 20 has been realized in practice. The life of the cathode is then practically unlimited.

In the Philips "1800" series of tubes (115 V series), the cathode is surrounded by a sort of maze of overlapping shields (see Fig. 56). This arrangement makes the positive ions undergo several collisions with the screens before reaching the cathode, thus losing a considerable part of their energy.

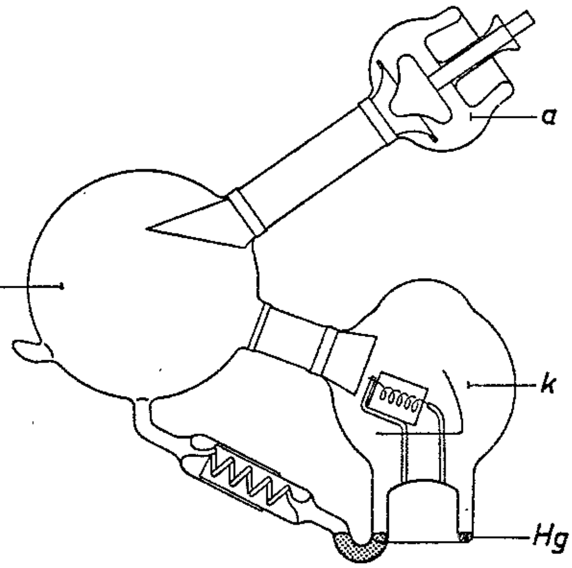


Fig. 24

An obsolete type of mercury-filled high-voltage rectifier tube. The condensation space C is connected to the anode space a and the cathode space k by narrow tubes, which allows the pressure in k during operation to be up to 20 times that in a. This increases the life of the cathode very considerably.

In a last example (Fig. 25) the coated cathode is made hollow, so that some of the material which leaves the cathode as a result of evaporation or sputtering is deposited on another part of the cathode, thus increasing its life.

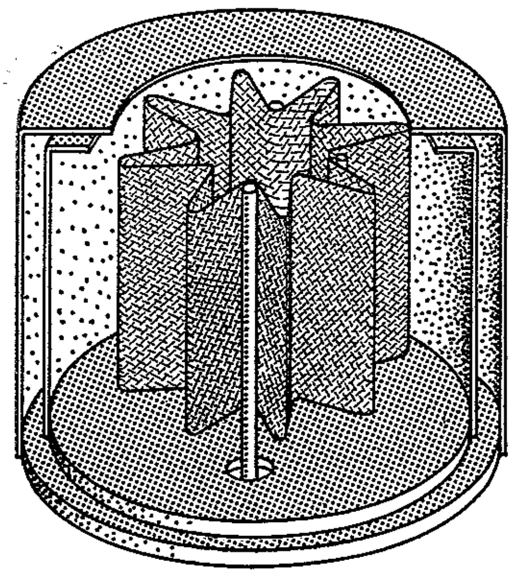


Fig. 25

A hollow cathode of large surface area, made of nickel gauze bent in the form of a star and surrounded by a double screen to reduce heat losses.

These examples, and similar ones which could be brought forward, show that it is certainly possible to design tubes so that the life of the cathode is practically unlimited. But in practice, demands are often made on the tubes which make it necessary to deviate from the ideal design. Requests from the user concerning size, heating time, operation under certain conditions of temperature, price, etc., often force the designer to a compromise which has an adverse effect on the life of the cathode.

The designer should in any case bear the following factors in mind, in order to make the life of the cathode as long as possible:

a. the influence of the magnitude of the variation of V_f (the filament voltage) due to variations in the mains voltage. If this is large, V_f should be stabilized; in general a tolerance of $\pm$ 5 % is permissible.
b. The choice of the gas pressure,
c. the specific cathode load (see section II-c-1-c),
d. the phase relationship between $V_{f\ rms}$ and $V_{a\ rms}$.

By suitable manipulations of these degrees of freedom, the designer will be able to achieve satisfactory results.

It should be remarked finally that the life of the tube need not be limited by that of the cathode.

II-c-1-c. *Construction*

The cathode construction needed to allow the required electron current to be emitted from its surface depends on several factors, such as the emitting material, the wire core which supports the former, and the way of heating.

A certain emitting area is necessary for a given emission current. The specific emission must not be too high, in order to reduce evaporation and sputtering and thus to increase the life of the cathode. 2 to 4×10^4 A/m^2 is a suitable value for directly heated cathodes at a few mm gas pressure.

The loss of cathode material can be further reduced by:

a. making the coated cathode hollow (see Fig. 25 and 29), so that most of the material leaving the cathode by evaporation and sputtering is deposited on another part of the cathode, thus reducing the loss.
b. by continually supplying material with a low φ at the surface of the cathode as it is used up. (See the L cathode, page 52).

The cathode may be directly or indirectly heated. The difference between the two methods of heating is that in a directly heated cathode the heating and the emission are carried out by the same body, while the two functions are carried out by different parts in the indirectly heated cathode.

We mentioned previously that the attainable emission current per watt filament power (i.e. the specific load) is about 0.6 A/watt. It must be remembered that under various circumstances other values may hold. The gas pressure at the cathode must be taken into account, and a cathode rated at 0.6 A/watt can under certain circumstances have a long life at twice that load. Directly heated cathodes can in general have slightly higher specific loads: 1.3 A/watt may be possible. This is the value in the absence of a discharge; the effective value during the operation of the tube will be somewhat lower, because the discharge also contributes to the filament power. Similarly, the filament current I_f is quoted as the current in the absence of a discharge. It is thus possible for the emission current I_e to be greater than I_f.

Directly heated cathodes

The filament current in a directly heated cathode must be high, since the voltage V_f is restricted. The voltage between the ends of the cathode must not be large, to prevent an arc from being struck between the two ends. It is therefore necessary to make V_f less than the breakdown voltage V_d for this arc discharge (when using a.c. $V_f < \dfrac{V_d}{\sqrt{2}}$).

If V_f is made too small, I_f will become so large that the losses in the leads and in the cathode poles will increase considerably. A further restriction is imposed by the emission current I_e, which must also flow through the wire. If this is large, the wire could be destroyed by the extra temperature increase. In order to keep this within limits, I_e must therefore be less than I_f most of the time. The ratio I_e/I_f thus also determines the choice of the filament.

In short, the voltage must be low, and the heater current high.

In vacuum tubes, the emitter is usually in the form of a straight wire, but the cathode of a gas tube may have any of a number of forms, thanks to the presence of ions. The ions together with the electrons form the conducting plasma, which allows the electric field to penetrate even into cavities. The ions also serve to neutralize the space charge of the electrons. Some possible forms for the cathode are shown in Fig. 25, 26 and 27.

The simplest possibility is to coil the tungsten wire core into a spiral. Fig. 26 shows a cathode in which a nickel wire is wound around a tungsten core, which is then coiled into a spiral. Even better is the double-spiral arrangement shown in fig. 27. This method gives one big emitting surface, in effect. The coiling of the wire improves the heat balance: the adjacent windings and the parts inside the cavity irradiate each other, and thus save radiant energy. The temperature of these W-Ni cathodes is 850—900 °C. In the arrangement shown in Fig. 25, tungsten is no longer used as the heater: the oxide film coats a strip of nickel gauze folded into a star, which is heated by the passage of current.

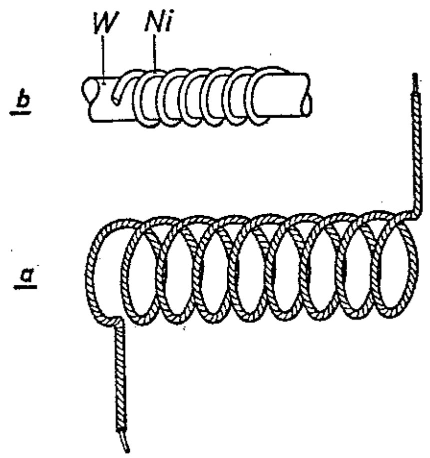


Fig. 26

a. Directly heated cathode consisting of a helical tungsten core with nickel wire wound around it.

b. Magnified view of part of the cathode shown in *a.*

For high currents, a number of spirals could in principle be connected in parallel. This would however involve the use of disproportionally large amounts of metal, since the surface of a wire is proportional to $l \cdot d$ (l = length, d = diameter) and the volume to $l \cdot d^2$. Other cathode constructions have therefore been developed.

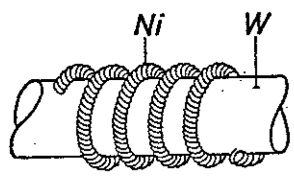


Fig. 27

Magnified view of part of a cathode with a "coiled-coil" configuration.

Such a construction is the "flower" or "star" cathode. This is formed of a number of uniform elements, the precise number used depending on the desired emission. Such an element consists of a tungsten wire core in the form of a sine wave, surrounded by a nickel winding (Fig. 28). These elements are connected in parallel to give a symmetrical many-sided flower or star shape. Such a parallel connection of the cathodes is possible if the cooling due to emission exceeds the heating: otherwise there would be a tendency for all the emission to come from one cathode, because higher emission would cause the temperature to rise, thus increasing the emission even further. The equipotential points on the axis of the system are connected with each other, giving sections with a low V_f and easy mutual heat exchange which prevents extreme heating of any one part. This construction is cheap in mass production, applicable for cathodes of all sizes, and thermally efficient.

The indirectly heated cathode is however sometimes used for higher currents, for reasons which will be mentioned below.

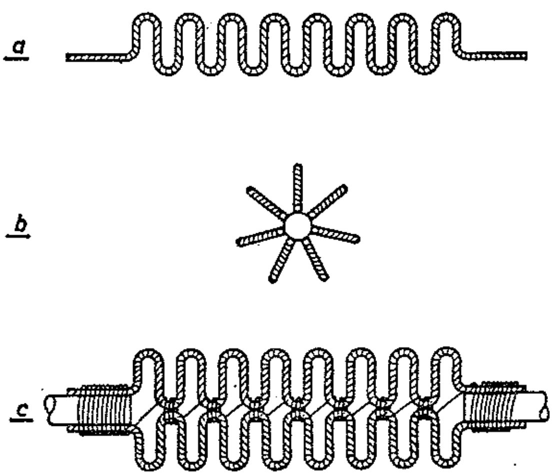


Fig. 28

Diagram of a "flower" or "star" cathode.
a. One element of the cathode.
b. The assembly of the various elements.
c. The connection between two elements, shown in detail. The equipotential points on the axis are joined by means of wire.

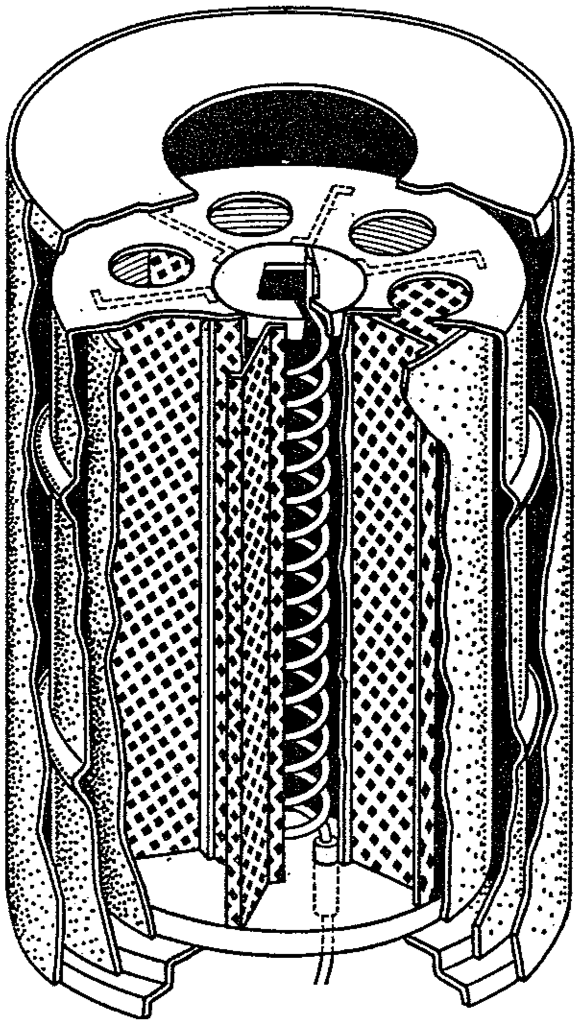


Fig. 29

An indirectly heated cathode.
The heater spiral is surrounded by oxide-coated gauze strips, and radiation losses are reduced by the double metal screen.

Indirectly heated cathodes

If the heating element does not at the same time perform the emission, we speak of an indirectly heated cathode, of which a typical construction is shown in Fig. 29. The heater spiral, which is heated to a temperature of about 1200 °C, is placed within a metal envelope on which the emitting material is applied. The emitting surface is increased still further by connecting the inner cylinder with an outer cylinder by means of radial partitions. This also has the advantage of keeping the emitting material in the enclosed space if sputtering occurs. The surface thus obtained may be compared to a number of cathodes in parallel, and can only be used at low gas pressure, since at high pressures there is a tendency for the discharge to concentrate in one of the cathode spaces, which may lead to damage of this part of the cathode.

The leads of the filament must be shielded to prevent a discharge occurring between them, if V_f is too high. A double or three-fold screen is usually placed around the outer cylinder, in order to reduce radiation losses.

It may be seen from this example that indirect heating has the following advantages:

1. the useful emitting area can be large
2. the potential of the surface does not vary from place to place (equipotential cathode)
3. the choice of V_f can be wider than with direct heating, if the heating filament and its supports are properly shielded. This makes it possible to obtain I_e larger than I_f.

The disadvantages are:

1. the more complicated construction
2. the longer heating-up time, due to the large heat capacity of the whole cathode construction.

An indirectly heated cathode is usually more easily overloaded than the directly heated type, since the latter is designed to carry a current $I_f + I_e$, and the former only carries I_e. An increase in the emission current will therefore do more harm to the indirectly heated cathode.

We will mention here another example of indirectly heated cathodes, although this has so far not found much application in gas-discharge tubes. This is the L cathode [13], which is a typical example of a dispenser cathode, and which is shown in Fig. 30a and 30b.

This cathode allows emission current densities of many millions of amps per m^2 to be produced for short periods of time (pulse emission). It is made of porous tungsten containing Ba and BaO in the pores and on the surface. The Ba at the emitting surface can be replenished from a supply of Ba which is contained in a space behind the porous tungsten wall, the Ba atoms migrating along the surface of the pores. For the rest, the emission is like that of other indirectly heated cathodes. The temperature of the L cathode lies between that of the oxide cathode and the W-Th, and may vary between 900 and 1200 °C. The corresponding saturating emission naturally also varies considerably, from about 3×10^4 A/m^2 to 10^6 A/m^2, while the life becomes shorter as the temperature increases.

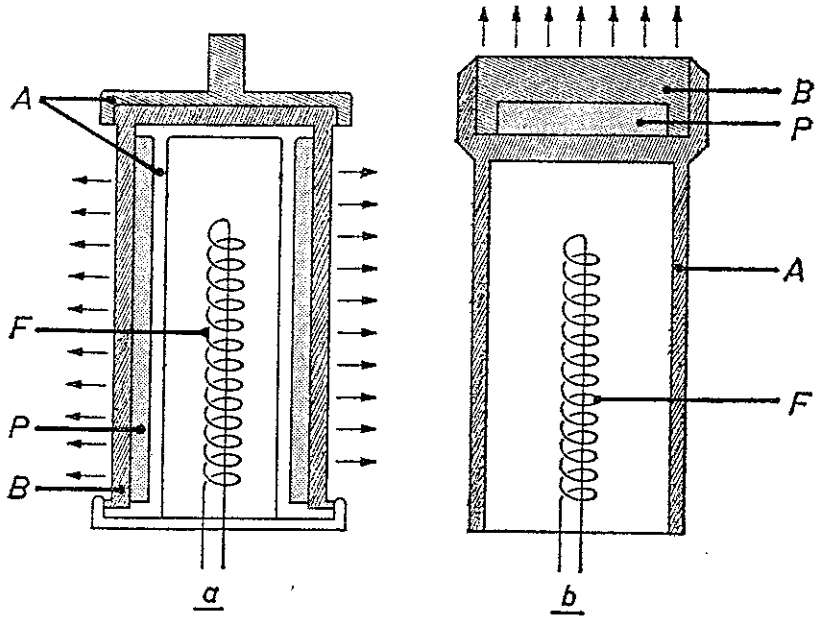


Fig. 30

Sectional views of the two basic types of *L* cathode [13].
a. with cylindrical emitter, b. with flat emitter.
A = molybdenum wall, *B* = porous tungsten wall,
P = (Ba, Sr)O paste, *F* = filament.

II-c-2 COLD CATHODES

II-c-2-a. *Emission mechanism and discharge characteristic*

A hot cathode emits electrons spontaneously as a result of its high temperature. Under certain circumstances, a cold cathode can also emit electrons. We have already seen in Chapter I (see I-g-1) that the electron emission in a glow discharge is mainly due to the bombardment of the cathode by positive ions. The current density depends mainly on the gas used and its pressure, and is of the order of tens of amperes per m^2 of the cathode surface at a pressure of 10 mm. The cathode fall (which is usually approximately equal to the burning voltage) is 100—200 V, so the energy dissipated at the cathode is of the order of thousands watt per m^2. The cathode temperature therefore in general remains so low that thermal emission is out of the question; we thus have a *cold cathode.*

In order to give a large current with a normal cathode fall, the surface area of the cathode must be large; or the pressure must be large. But in the latter case the temperature will become too high, and the glow discharge may change into an arc discharge (see Chapter I-g-3).

A cold cathode is usually made of uncoated metal, though in certain cases it may be coated e.g. by an oxide layer. A cold mercury cathode is also possible.

II-c-2-b. *Uncoated metal cathodes*

An important factor in connection with a metal cathode is the burning voltage, V_{br}, obtainable with it. In most applications the burning voltage is practically equal to the cathode fall, and we will neglect the difference between the two here.

The burning voltage is mainly determined by the cathode material and the nature of the gas; the pressure is not of great importance. For a given gas, the lower the work function of the cathode material, the lower will be V_{br}.

The following table gives an impression of the influence of these factors.

TABLE V

THE CATHODE FALL (IN VOLTS) OF A GLOW DISCHARGE WITH VARIOUS CATHODE MATERIALS AND GASES

	helium	neon	argon	neon + 1% argon	krypton	xenon
nickel	159	**136** (at 40 mm)	181	114	—	—
iron	**150**	**129**	—	95	—	—
molybdenum	**109.5** (at 42 mm)	**107.1** (at 40 mm)	**103.4** (at 20 mm)	**83** (at 40 mm)	**114.8** (at 13 mm)	**133.6** (at 13 mm)
zirconium	—	**105.4** (at 40 mm)	**92.1** (at 10.2 mm)	—	—	—

NOTE: The most reliable values, which have been determined on clean surfaces, are printed in bold type. The other values are uncertain, because they were determined on insufficiently cleaned surfaces. The pressure at which the determination was carried out is given in brackets as far as known.

To get a constant cathode fall, the surface of an uncoated cathode should be very clean, because slight traces of impurities can have a considerable effect on the work function. Since the area occupied by the glow discharge on the cathode surface increases as the current increases, the operating voltage will only remain constant in the normal cathode-fall range if the cathode surface is homogeneous. This normally requires careful laboratory work, but methods have been worked out for achieving this in mass production, e.g. in the manufacture of voltage-stabilizing tubes.

The breakdown voltage (as well as the burning voltage) may be of importance in determining the choice of the cathode material. This voltage is determined by the cathode material, the nature and pressure of the gas, and the distance between the electrodes (Paschen's law, see I-g-4).

The characteristic form of the curves of the breakdown voltage V_d against $p_0 \times d$ is shown in Fig. 31 [67, 107]. The cathode material has a strong influence on V_d near the minimum, but in the right-hand converging branches the influence of the gas predominates.

It is to be expected that the life of the cathode is limited by sputtering, which removes atoms gradually from the surface; but when the proper cathode material, gas and pressure are chosen, and the tube is burning in the normal glow-discharge region, then a cold cathode can have an almost unlimited life [7].

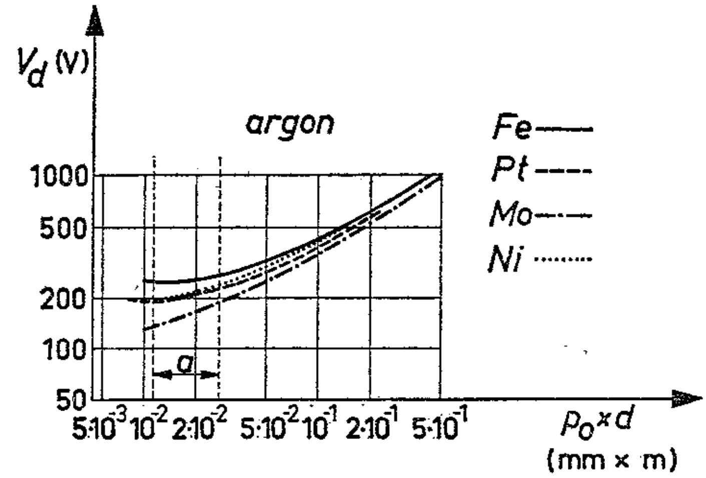


Fig. 31

Paschen curves for a discharge in argon between parallel plate electrodes of Fe, Ni, Pt [67] and Mo [107]. The influence of the cathode material is strongest in the region *a*.

One example of a well designed tube is the voltage-stabilizing tube, Philips type No. 85 A2, which will be discussed in greater detail in Chapter V. The life of this tube may be said to be practically infinite. A case is reported in England where the quality of such a tube was unchanged after operating for 120 000 hours under favourable conditions.

II-c-2-c. *Coated cathodes*

The metal cathode is sometimes coated, in order to reduce the work function. This coating almost always consists of barium oxide, which has a low φ. As with the hot cathode, a certain amount of free barium is produced during the processing of the cathode. This is then gradually used up during the discharge.

The oxide layer makes the coated cathode much more sensitive to wear than the uncoated cathode.

As the barium disappears, φ increases. Sputtering is linked with adsorption of gas and gradual alteration of the electrical properties of the tube. The extent to which this occurs depends on the type of gas used; for example, neon is not so good in this respect as argon.

As with hot cathodes (cf. II-c-1-a and b), the manufacturer is often forced to alter the design to meet the needs of the user. If for example the tube must be small, the cathode surface area may be so small with respect to the rated current that the tube operates in the anomalous discharge region. Some glow-discharge tubes are made with a small cathode to increase the intensity of the light produced, but a black film is rapidly formed on the inside of the envelope, and the cathode is finally destroyed.

II-c-3 THE MERCURY CATHODE

A third type of cathode, which differs considerably from the two types mentioned above, is the mercury-pool cathode. If mercury is used as the cathode, then it follows, in contrast to the other types of cathode, that mercury vapour which can carry the gas discharge must be present also. Both a glow discharge and an arc discharge are possible with a mercury cathode. The glow discharge will occur with low current densities. As the current is increased to a certain value, the discharge may change to the arc type, with a much higher current density. The discharge will then be associated with only a small spot on the surface of the mercury pool, called the cathode spot.

Many tentative explanations of the *emission mechanism* at the mercury cathode during an arc discharge have been put forward, but the last word has certainly not been spoken on this subject yet.

Ecker [31] distinguishes four possibilities:

1. thermal emission (T)
2. field emission (F)
3. combined T and F emission
4. emission due to individual field components (I-F).

Thermal emission cannot be the answer. It has been found that the temperature of the cathode spot is 200—300 °C, which is much too low to account for the observed emission of 10^{10}—10^{11} A/m^2 [32].

The idea behind the field-emission hypothesis is that the field due to a layer of ions near the cathode is so large that it gives rise to the emission of electrons. This would necessitate a field strength of at least 10^9 V/m, while calculations have shown that the actual field strength cannot be expected to be more than 10^7 V/m. And while deformation of the mercury surface can increase the field strength, this increase is still not enough to account for the observed phenomena.

Calculations involving the assumptions that the mercury surface is somewhat rough and that the work function of the mercury is decreased by impurities or by the presence of the gas have shown that the combination of the thermal and field effects could lead to the production of the observed current densities. However, these assumptions have been definitely proved wrong in a number of cases.

Ecker and Müller brought forward the fourth theory, that of I-F emission (individual-field emission). They assume that the field at the surface of the cathode is characterized by a probability distribution, because the individual charge carriers, the ions, are distributed at random over the space-charge zone. The field at any given point of the surface will fluctuate with time as a result of the random fluctuations in the space charge, and a large electron emission may be produced when the field fluctuations are sufficiently large. By the influence of this individual field component, Ecker and Müller explained the emission mechanism without further assumptions.

The influence of various factors such as oxide layers, impurities, and surface roughness is still uncertain. We may in short conclude from the above that there is still no generally acceptable explanation for the electron emission at the cathode spot.

During the arc discharge, the spot moves erratically over the mercury surface owing to asymmetrical evaporation of mercury around the spot. Magnetic fields may also effect the motion of the spot. It is however possible to fix the cathode spot in a given position, e.g. by means of a nickel or platinum "anchor" (see Chapter VI).

II-c-3-a. *Initiation of the discharge*

The difficulty in starting an arc discharge between the anode and a mercury-pool cathode lies in the formation of the cathode spot. Once the spot has been developed, it is easy to increase the arc current and the size of the spot. A cathode spot always appears when a contact between the anode and the mercury pool is broken, but it is not easy to get the same result merely by applying a voltage between the two electrodes. The discharge in a tube with a mercury cathode must therefore be triggered; there are various standard methods of doing this, all of which are based on the production of a suitable auxiliary discharge which can trigger the arc discharge.

In the most usual case, where the anode is fed with an alternating voltage, the discharge must often be initiated periodically in time with the mains frequency. Some of the methods described below are suitable for periodic operation, but some are too slow-acting.

We may distinguish:

a. *the immersion electrode,* which is a springy conductor which comes to just above the mercury surface when it is at rest. It can be briefly immersed in the mercury by means of an external electromagnet. As the contact is broken, a small arc discharge arises between the positive immersion electrode and the negative mercury. This method is generally not suitable for fast periodic operation.

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

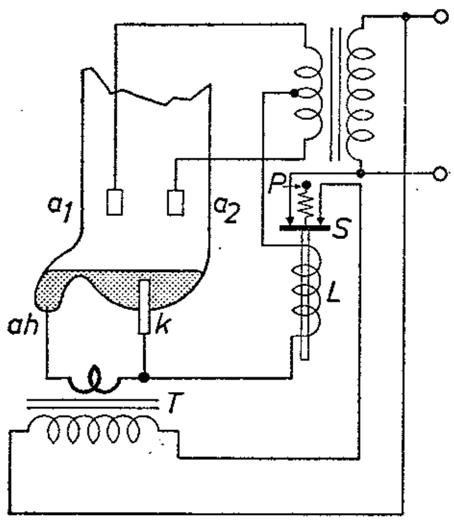


Fig. 32
Production of the cathode spot by breaking a thread of mercury. If there is no discharge between a_1 or a_2 and k, the coil L is unloaded and the switch S is closed by the spring P. The secondary of transformer T then passes a heavy current through the thread of mercury joining the auxiliary anode a_h to k. The mercury thread breaks under the action of the field produced by the current passing through it, and a spark appears across the gap. This spark initiates the main discharge, and the iron core of L is pulled down, opening S.

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

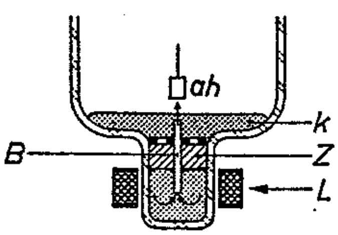


Fig. 33
Production of the cathode spot by means of a jet of mercury. When the coil L is energized the plunger Z is pulled downwards, forcing a jet of mercury upwards through tube B. This jet strikes the auxiliary anode a_h, thus making contact between this electrode and the mercury cathode k. When the current through L is stopped, the mercury jet is broken off and an auxiliary discharge is initiated between a_h and k. This auxiliary discharge forms the cathode spot, thus allowing the ignition of the main discharge.

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

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

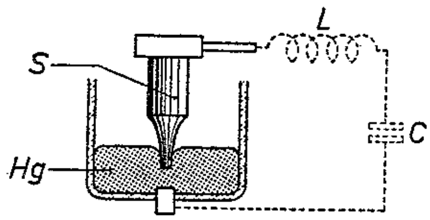
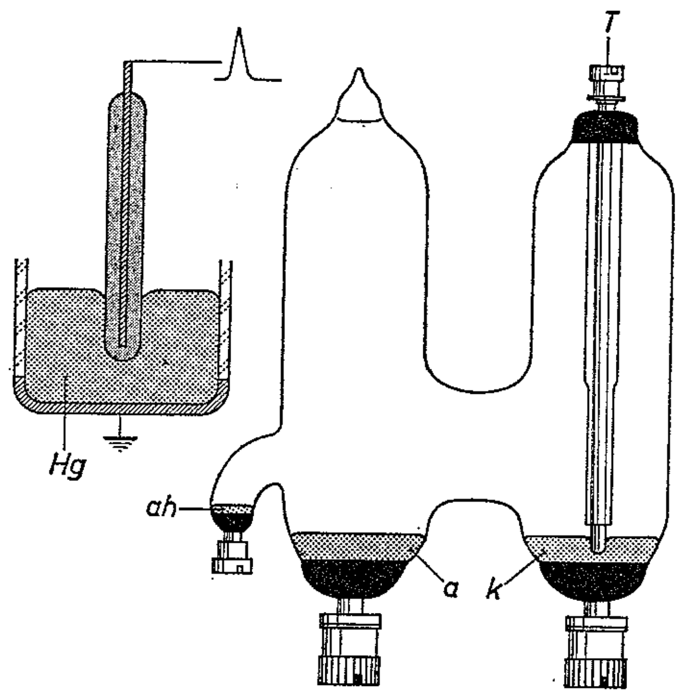


Fig. 34

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

a



b

Fig. 35a

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

Fig. 35b

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

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

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

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

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

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

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

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

II-c-4 THE PHOTO-CATHODE

The last type of cathode we will mention here is the photo-cathode, a light-sensitive cathode used in gas-filled photo-cells. Since the photoelectric effect has already been discussed in Chapter I, we will only give some practical details here.

The typical characteristic of a cathode which emits owing to irradiation by light quanta is its low work function. The current density of a photo-cathode is much smaller than that of the other cathodes mentioned above. For most photo-electric cells it is limited to a few μA.

In complete darkness, a very slight emission current can still be measured. This is due to thermal emission, and at room temperature is about 10^{-6} A/m^2. The sensitivity of a photo-cathode in vacuo hardly decreases at all with time, but in a gas-filled photo-tube the bombardment by ions does cause the sensitivity to fall off gradually. A specific load of 0.5 mA/m^2 cathode surface is permissible for both types, but with this load the sensitivity of a gas-filled cell may fall to about 60 % after 1000 hours' operation. By judicious treatment, in particular by ensuring that the maximum anode voltage is never exceeded, i.e. that the breakdown voltage of the gas is never reached, the life of the gas-filled photo-cell can be extended to several thousand hours.

Some other properties of the photo-cathode will be discussed in Chapter VII.

II-d **The anode**

The influence of the anode on the discharge is much less than that of the cathode. Care must however be taken that the anode temperature does not become too high or it will emit electrons, and the anode material may even evaporate.

As long as the anode is only fed with a d.c. voltage (e.g. in voltage stabilizing tubes), the emission is of no importance. If, however, the anode is sometimes negative with respect to the cathode, as in e.g. rectifier tubes, then the emissivity of the anode does matter. In order to ensure that the tube passes no current in the reverse direction, the emission from the anode must be kept to a minimum: this means that the work function must be large and the temperature not too high. The temperature of the anode depends on the balance between the heat dissipated in it and the removal of the heat, and thus also on its dimensions.

II-d-1 HEAT DISSIPATION IN THE ANODE

We will consider the factors which lead to the dissipation of heat in the anode. These are:

1. the electron velocity, sometimes increased by the anode fall
2. the electron affinity of the anode
3. the ohmic losses in the anode

$\Bigg\}$ anode positive

4. the glow current when the anode is negative.

The current-carrying electrons strike the anode with a certain velocity. When the electron temperature in the plasma is of the order of 10,000 °K, the electrons reach the anode with an energy of about 1 eV. If there is any anode fall, however, in other words if the anode is somewhere outside the dark space, then the voltage increases considerably, e.g. to 10—20 V, so that the electrons have considerably more energy when they reach the anode. This energy is dissipated in the anode as heat.

We have already (Chapter I-c-1) seen that some work must be done to free the electrons from the cathode, this work being measured by the work function of the cathode material. Conversely, when electrons enter the anode they do work at a rate equal to $I\varphi$, where I is the electron current and φ is the work function of the anode material (also called the electron affinity) which is between 4 and 5 V in most cases. This work is also mainly in the form of heat.

Thirdly, the passage of current through the anode gives heat losses equal to RI^2 where I is the current and R is the resistance of the anode, during the positive phase. These ohmic losses are however only a small part of the total heat dissipated.

The fourth cause of heat production is only found in the negative phase. The conditions under which a glow discharge will be formed have already been discussed in I-g-2. If the tube voltage is sufficiently high, the ion bombardment on the anode — which is now the cathode as far as the glow discharge is considered — is considerable because of the large "cathode" fall, but the current is much smaller than when the anode is positive.

In tubes with more than one anode, e.g. two-phase rectifiers (Chapter III-b-2), the one anode is negative with respect to the other in a part of each cycle, and it then behaves like a probe. This means that ions are extracted from the plasma, also giving rise to heat dissipation in the anode. The heat generated by this probe current and by the glow current can in some cases be as large as that due to the first and second factors.

II-d-2 COOLING

If the factors mentioned above determine the amount of heat dissipated in the anode, the final temperature of the anode will also be influenced by the rate at which it gives up heat to its surroundings. This depends on the conduction via the anode lead, the convection via the gas filling, and to a lesser extent on the radiation. With graphite anodes the radiation does count, especially at temperatures above about 800 °C. The blackening of nickel anodes will also improve the radiation to a certain extent. But in general the temperature is mainly determined by conduction and convection. The final temperature is reached when the heating and the cooling are in equilibrium. Forced cooling is not generally used, though the cooling surface of the anode lead is sometimes increased by means of fins (see Fig. 173). The size of the anode itself is also increased in tubes which take large currents, in order to keep the temperature within proper limits.

II-d-3 ANODE MATERIAL

The anode material is only a problem when the polarity of the tube is subject to change, as in a rectifier. The most important requirements are then a high work function, purity, slight sputtering, ease of treatment (working, degassing), and good heat conduction.

Nickel, iron and graphite are the usual materials. The choice between them is sometimes difficult, and depends largely on the specific demands made on the tube in question.

The work function of nickel lies between 3.7 and 4.9 eV, and that of graphite between 4.3 and 4.8 eV. At low current densities, nickel is quite satisfactory; it is easy to work, and can be well degassed. If the current is high, graphite is often better. It has a low density (1.9—2.3), and is not affected by high temperature, it is backfire-proof, i.e. it does not melt if there is a short-circuit or a backfire, and it is a good radiator of heat because it is black. One disadvantage is that it has to be degassed for a long time.

In certain cases, it is necessary to use other materials for the anode. We will only mention the sendytron (Fig. 35 b) in this connection: it has a mercury anode. This tube is meant for large current pulses of short duration, and the reason for choosing a mercury anode is to minimize the contamination of the cathode surface by particles from the anode.

We will have occasion to discuss other anode materials in the detailed descriptions of various tubes.

II-e **Other electrodes**

So far, we have been talking about tubes with only two electrodes, the cathode and the anode. Many tubes have more than two electrodes, however.

The extra electrodes can be divided into the following groups:

a. auxiliary anodes;
b. switching electrodes;
c. screens.

II-e-1 AUXILIARY ANODES

Where it is necessary to keep a plasma in existence or to facilitate re-ignition, an auxiliary discharge is generally maintained. This is struck between an auxiliary anode and the cathode. These auxiliary discharges make ignition easier. The dependence of the ignition voltage on the current of the auxiliary discharge is illustrated in Fig. 36 for a hot-cathode diode and in Fig. 150 for a cold-cathode tube.

An auxiliary discharge is also used to prevent delay in the ignition of the main discharge.

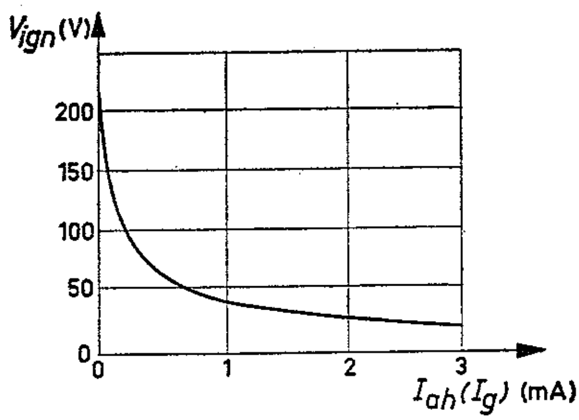


Fig. 36
Dependence of the ignition voltage V_{ign} of a hot-cathode diode on the current I_{ah} of the auxiliary discharge (grid current I_g).

II-e-2 SWITCHING ELECTRODES

While it is quite common to control the current in vacuum tubes by altering the heater voltage of the cathode, this method is not effective in gas-filled tubes, and leads to sputtering (cf. II-c-1-a). A separate electrode is needed to control the average current in a gas-filled tube, as is indeed often used in a vacuum tube. The effect of the control electrode is however completely different in vacuum tubes and gas tubes. In a vacuum tube this electrode is called the control grid as the anode current is controlled by variation of the grid voltage. This name would give the wrong idea if applied to the corresponding electrode in a gas tube. We will talk here of a *switching grid* (cf. IV-a), which indicates its mode of operation rather better. This grid is used to prevent the ignition of the discharge up to the desired moment, so that the tube acts as a switch in the circuit. The value of the discharge current is not however influenced by the grid, which is also not capable of quenching the discharge. The working of the grid can be described as follows: if it has a negative potential with respect to the cathode, it can prevent the ignition of discharge; a suitable positive voltage applied to the grid will ignite the discharge at the desired moment. By choosing the moment at which this happens, the duration of the discharge in each half period can be controlled. The grid control will be described in greater detail in the chapter on thyratrons. Other control methods (trigger electrode, external electrode, etc.) will be discussed under the accounts of the tubes in which they occur.

II-e-2-a. *Temperature of the grid*

Grid emission is most undesirable in controlled tubes, since it may give rise to an unwanted discharge where the grid acts as a cathode; the tube will then no longer be under control. Grid emission may be caused by the deposition of oxide particles from the cathode, if the grid temperature becomes too high. The user should therefore take care that the grid load does not exceed that laid down in the tube specifications, in order to keep the temperature within proper limits. Similarly, the cathode must be prevented from evaporating too much, which might lead to the deposition of a mixture of barium and barium oxide on the grid.

The heat dissipation in the anode is largely caused by the current through the tube (kinetic energy of electrons), but the current going to the grid is very small because of the high resistance usually placed in series with it. The source of heat here is rather the plasma of the main discharge, together with radiation from the anode and cathode. Electrons and ions which land on the grid owing to diffusion can transfer energy to the grid by means of collisions and recombination. The collision yields heat owing to loss of kinetic energy. The recombinations of ions and electrons leads to the formation of slow atoms, and the ionization energy released can be given up to the grid. Heat can also be conducted through the hot gas of the discharge; but this contribution is normally only of secondary importance.

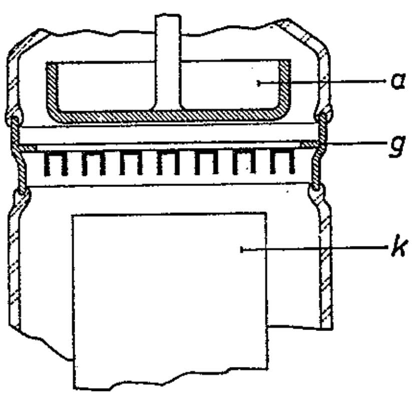


Fig. 37

A sectional view of part of a thyratron. The switching grid *g* consists of rods of prepared nickel or iron, of *U*-shaped cross-section, welded on to a ring of chrome iron. The ring is sealed directly into the glass envelope. This construction gives a large area of contact between *g* and the surrounding air, thus allowing effective cooling.

The grid must also get rid of its heat. It can be made larger than otherwise necessary, in order to aid the cooling, or it may be artificially cooled.

It is an advantage if the tube can be so constructed that a cold stream of gas inside or outside the tube can contribute to the cooling. The external grid is an example of this (see Fig. 37, 91 and Photo 4).

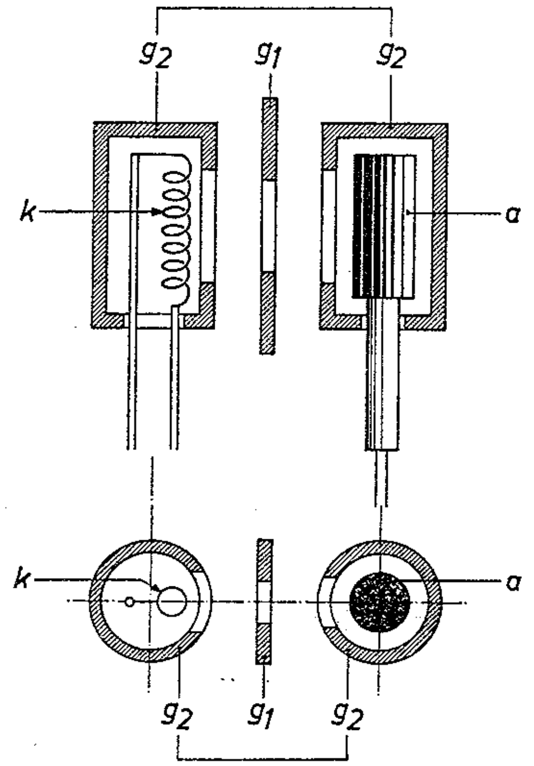


Fig. 38

The arrangement of the grids in a low-power tetrode. The cathode k and the anode a are surrounded by slotted cylindrical screen grids g_2. A switching grid g_1 consisting of a metal plate with a rectangular hole in it is placed between k and a.

Although the temperature range in question is not high enough for thermal radiation to be very important, it may be helpful to blacken the grid, or to coat it with suitable fine granular material: this both increases the heat radiated away from the grid and helps to prevent a lowering of the work function due to deposition of cathode material.

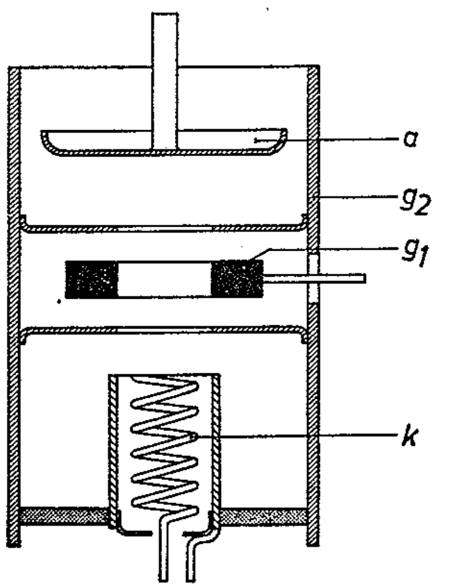


Fig. 39

The arrangement of the grids in high-power tetrode cf. Fig. 99 and Photo 7. The switching grid g_1 is a graphite ring.

Grids may be made of graphite as well as metal. The reasons governing the choice are similar to those already mentioned for anodes (II-d-3). The grid must have a large heat capacity and sturdy construction when large powers are involved. The forms usually used are cylinders, rings and the like or discs with relatively wide openings in the form of slits or holes. Figures 37 to 40 give some examples of possible constructions.

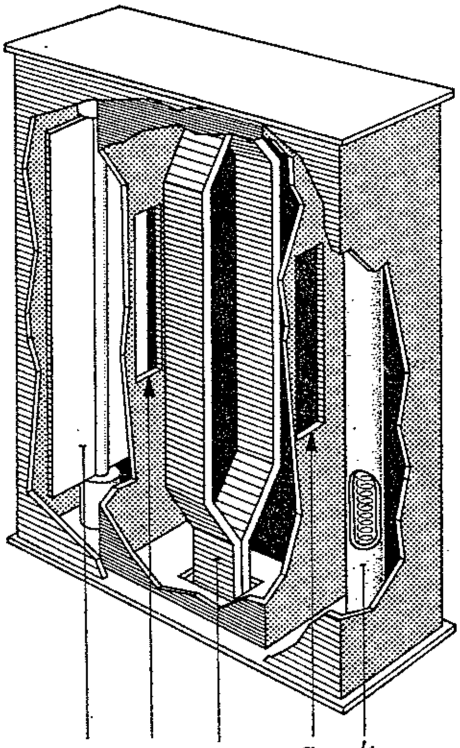


Fig. 40

Cut-away view of the electrodes in the tetrode thyratron PL 2D21. Comparison with Fig. 38 makes further explanation unnecessary.

II-e-3 SCREENS

The four electrodes mentioned so far (cathode, anode, auxiliary anode and switching grid) can carry out the most important functions of any gas tube. Of subsidiary importance are further conductors or insulators which are normally placed in the discharge space and are called screens. They are needed to:

1. prevent solid particles from being deposited on certain places;
2. keep the discharge away from places where it is not wanted;
3. shield certain parts from radiation of heat;
4. reduce electrode capacitances.

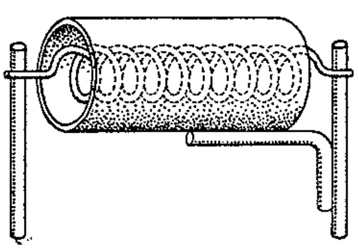


Fig. 41

A helical hot cathode surrounded by a cylindrical nickel screen. Oxide particles sputtered from the cathode are caught by the screen, to that they cannot reach the anode where they might give rise to backfire. The oxide layer deposited on the screen can also emit electrons, since the screen is heated by radiation from the cathode; after the tube has been in use for some time, this emission current will make up an appreciable part of the whole.

The most important screens may be described as cathode screens and anode screens.

A simple example of point 1 is shown in Fig. 41. The screen here consists of a metal cylinder placed concentrically with the cathode spiral. This reduces the deposition of cathode material on the anode, since most of the sputtered or evaporated particles of the cathode will land on the screen. It also helps to improve the heat economy by reducing the power lost as radiation, but this function is of secondary importance.

Figures 42 to 44 illustrate point 2: little glass tubes round the glass-metal seal where leads enter the tube prevent a discharge on the leads near the

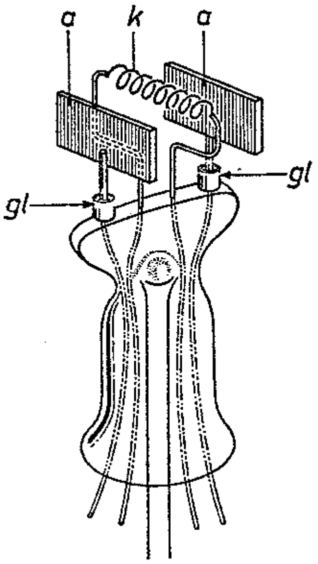


Fig. 42

Electrode assembly of a two-phase rectifier tube. The anode leads are fitted with small glass collars (*gl*), which help to keep the metal-glass seals intact by preventing discharges and the deposition of sputtered material near them and also improve the insulation of the leads by increasing the length along the surface of the insulation.

seal, which might cause cracks, and also prevent the deposition of sputtered material near the leads which might cause electric leaks. Moreover the screen *S* in Fig. 43 prevents the ignition of a discharge between the two anodes.

An example of the third function is the metal screen *S* placed between

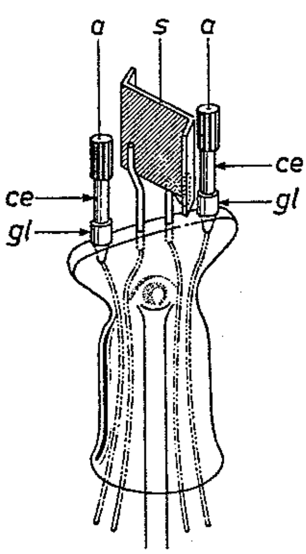


Fig. 43

Anode assembly of a two-phase rectifier tube with a hot cathode. The two graphite anodes *a* are separated by a screen *S*, which prevents any discharge between them. Discharge between the anode leads is prevented by the closely fitting ceramic tubes *ce* and the glass collars *gl*.

the incandescent cathode and the condensation space in a high-tension mercury-vapour rectifier tube (Fig. 45). This keeps the mercury condensate at the bottom of the tube cool.

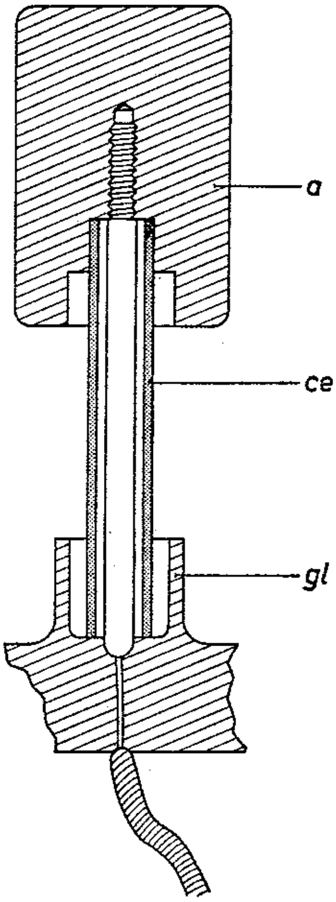


Fig. 44

Detail of the assembly of Fig. 43, showing the "labyrinth" holes at both ends of the anode lead, which prevent the deposition of sputtered material near the seals.

Finally, an example of the fourth type is the screen grid. This electrode is important as an electrostatic screen between the switching grid and the anode, reducing the capacitance between these electrodes (cf. IV-c), and also having some effect according to points 1 and 3.

More examples will be met later on in the book.

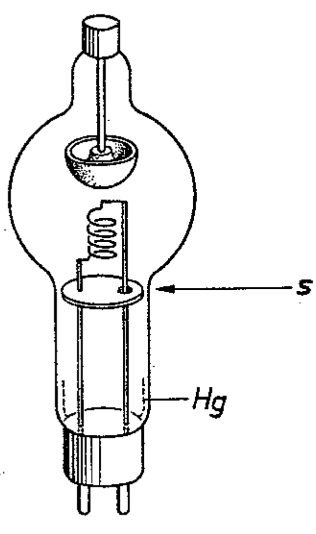


Fig. 45

High-voltage mercury-filled rectifier tube. The lower part of the envelope must be kept cool so that the mercury can condense there; it is therefore shielded against radiation of heat from the hot parts of the tube by the metal screen S.

II-f The envelope

The envelop of a gas-discharge tube may be made of glass or metal, depending on the amount of heat to be dissipated.

Glass can still be used up to currents of about 500 A and arc voltages of 20 V (10 kW dissipation). The tube losses can in such cases still be transmitted through the glass walls to the outside air, if necessary with the aid of forced air cooling. If the energy dissipation is higher than about 10 kW the glass envelope needed would be impractically large, so a metal envelope is necessary. The maximum permissible temperature can then be higher, and better cooling is possible, if necessary with the aid of air or water. The better cooling possibilities also enable the designer to make metal tubes smaller than the corresponding glass ones would be. Since glass envelopes are cheaper, however, most gas-discharge tubes are made with glass.

It is also sometimes possible to use envelopes made partly of metal, and partly of glass. At very high powers, however, the envelope must be made entirely of metal, except that glass (or ceramics) is needed to insulate the various electrodes. In any case, the envelope must allow the electrodes, etc., to be firmly fixed in place in the proper positions relative to each other, and the whole gas space to be properly sealed off without leaks.

In high-voltage tubes, the electrodes must be placed far enough apart to prevent breakdown at undesirable places, or "creep" discharges along the walls. Although it has proved possible to use ceramic envelopes, which can stand high temperatures, no gas-discharge tubes with ceramic envelopes are yet on the market.

II-f-1 MATERIALS

The above-mentioned demands made on the envelope mean that all the component parts, conducting as well as insulating, must come up to very special requirements.

When glass is used as the insulating material, a suitable metal must be used in combination with it. Many types of glass-metal seals are used, among which we may name hard glass with tungsten, copper or Fernico (an alloy of iron, nickel and cobalt); and soft glass with copper, molybdenum-nickel or chrome-iron. The choice is determined by the demands to be made on the tube, by the ease of working, the maximum permissible temperature, etc.

It is also possible to make ceramic-metal and ceramic-glass seals, which are free from vacuum leaks and heat resistant. These techniques are however not yet used much in making gas-discharge tubes.

Finally, mica is used in various tubes for insulation and other functions and even as the window in radiation-counter tubes (see Chapter V-d-10). It has been found that mica can give vacuum-tight joints with chrome steel.

II-f-2 TYPICAL CONSTRUCTIONS

We will briefly illustrate what has been said above about the envelopes by some examples. Fig. 42 shows a "pinch" seal for a two-phase rectifier tube. The leads, with a bit of glass tubing round each one, are heated in the gas flame and the semi-molten glass and the leads are pressed together to a solid whole with a pair of tongs. The flanged glass edge is later sealed into a cylindrical glass bulb.

Photo 1 shows how the leads, arranged in a ring, are placed in a special jig and surrounded by powdered glass, which is then pressed around the leads with the application of heat to give a vacuum-tight seal (pressed-glass seal).

When large currents are involved, the construction shown in Photo 2 for a tube with two anodes can be used. The anode leads are soldered on to little cups of chrome steel, which are then sealed into a specially shaped piece of pressed glass. This construction is short-circuit-proof and has a good mechanical strength. A similar construction is used for cathode poles.

Other constructions will be met with in the descriptions of the various types of tubes in the following chapters.

CHAPTER III

HOT-CATHODE RECTIFIER TUBES

III-a **Introduction**

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

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

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

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

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

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

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

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

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

III-b Low-voltage tubes

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

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

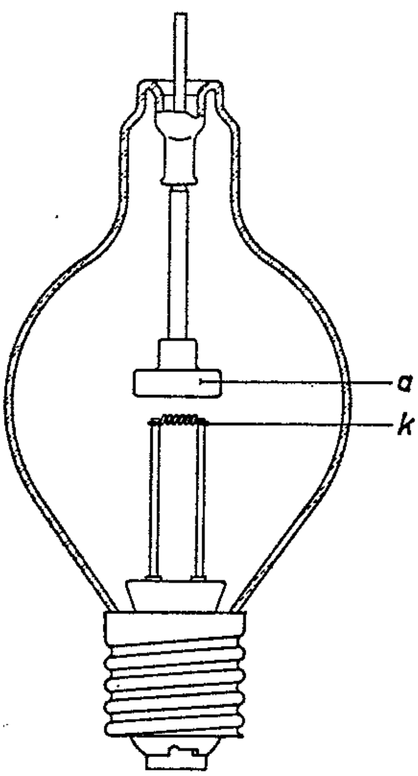


Fig. 46

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

III-b-1 TUBES WITH A SINGLE ANODE

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

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

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

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

The most important data of this tube are:

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

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

Operation of a single-phase rectifier tube

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

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

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

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

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

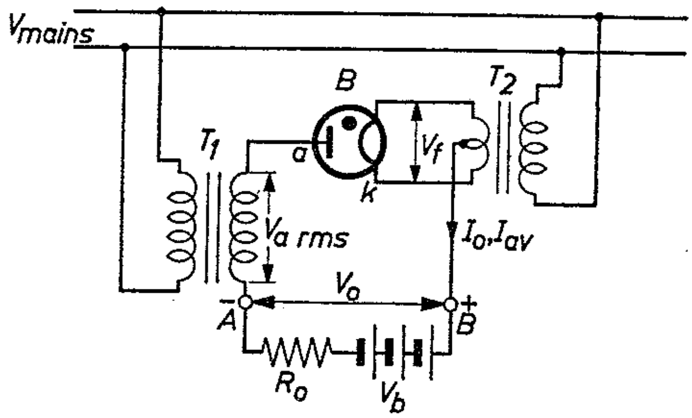


Fig. 47

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

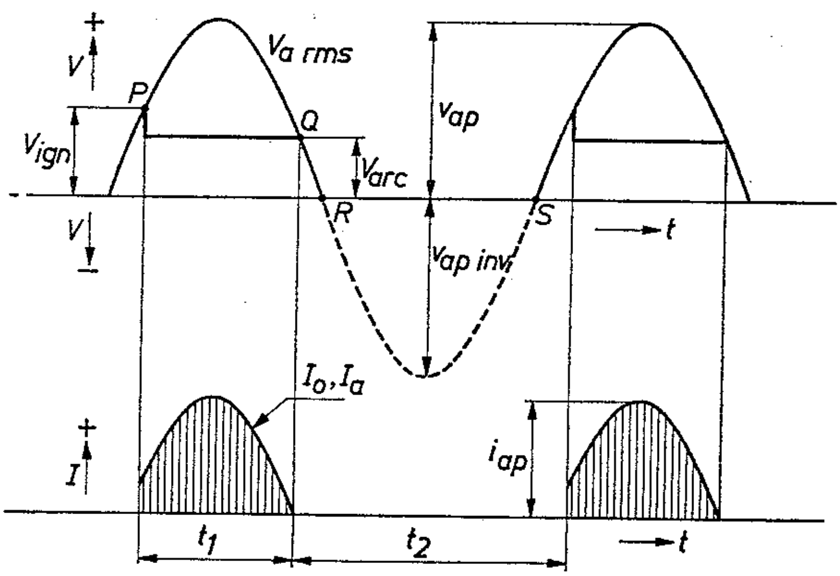


Fig. 48a

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

Fig. 48b

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

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

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

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

The initial value of the current is

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

(ignoring the resistance of the transformer).

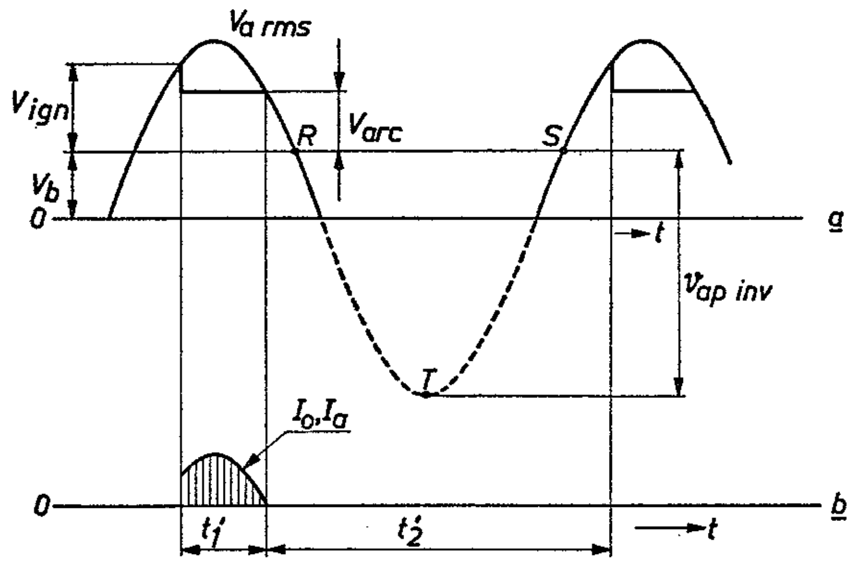


Fig. 49a

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

Fig. 49b

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

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

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

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

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

Inverse current

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

It follows from what we have said above that:

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

Tube efficiency

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

$$\eta = \frac{W_o}{W_o + W_f + W_{arc}} \qquad (3)$$

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

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

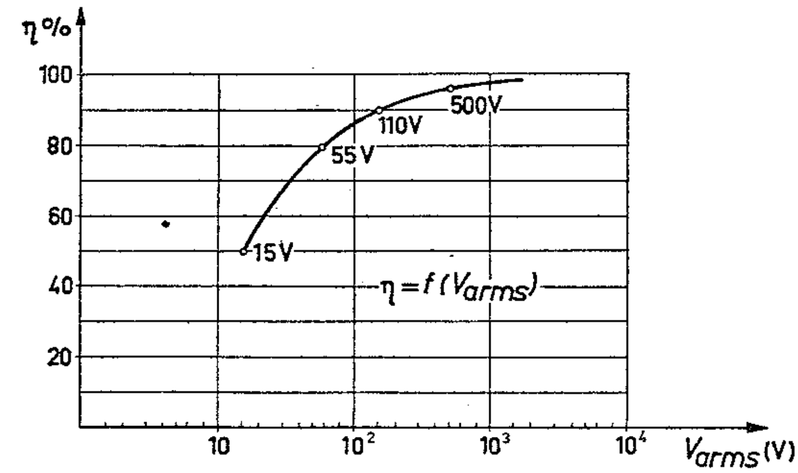


Fig. 50
Tube efficiency η as a function of the AC anode voltage $V_{a\ rms}$.

Inverse voltage

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

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

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

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

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

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

Peak current and average current

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

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

while for charging a battery of inverse voltage V_b we have

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

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

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

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

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

where $t = t_1 + t_2$.

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

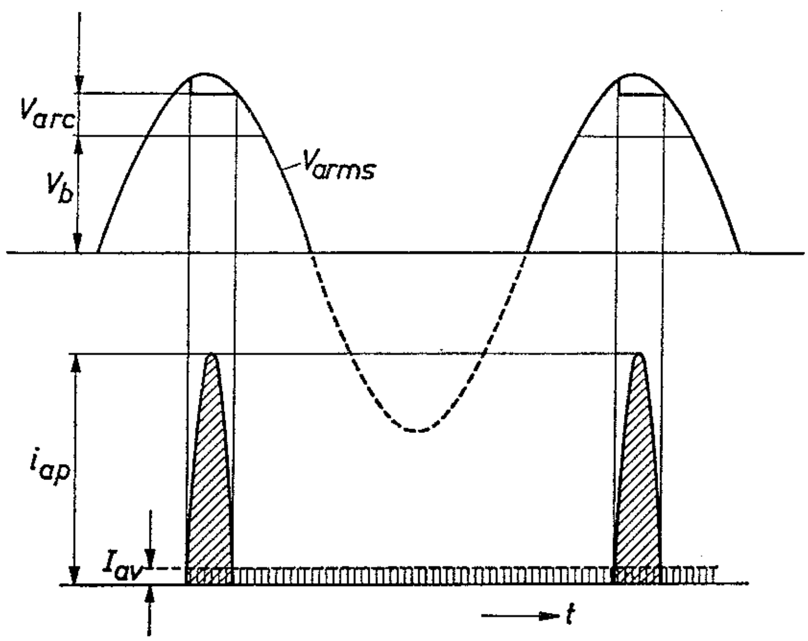


Fig. 51

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

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

Averaging time

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

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

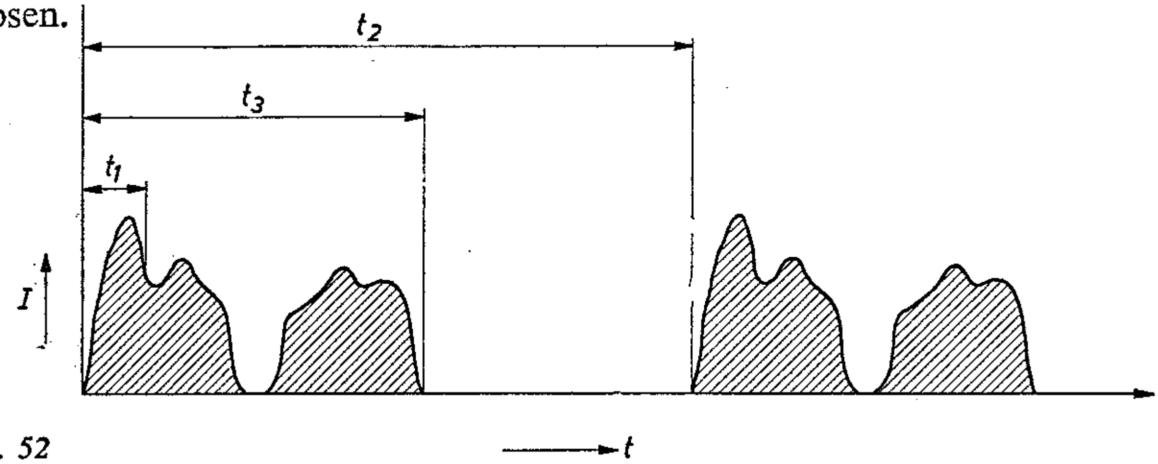


Fig. 52

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

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

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

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

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

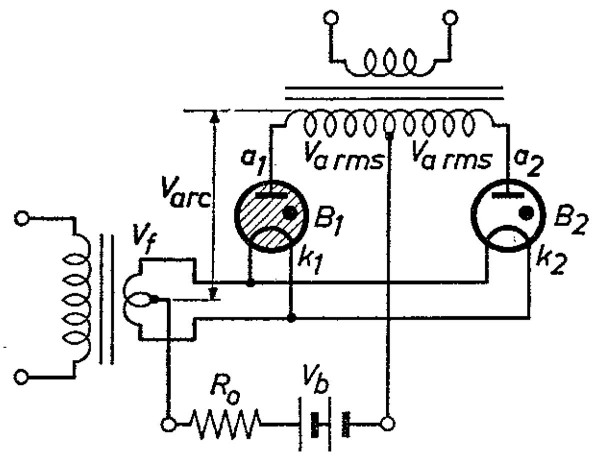


Fig. 53a

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

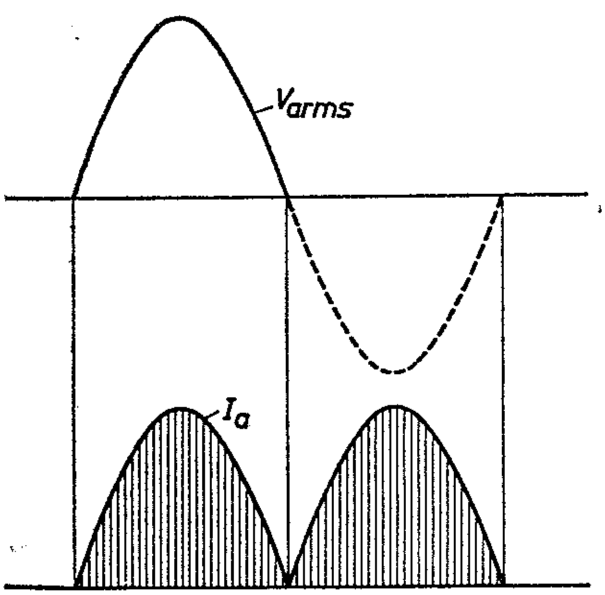


Fig. 53b

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

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

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

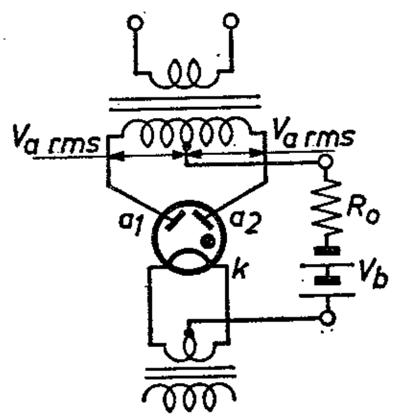


Fig. 54
Circuit for two-phase rectification, using one tube which contains two anodes and a single cathode.

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

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

TABLE VI

OPERATING DATA OF THE PHILIPS TUBES 367 AND 1859

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

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

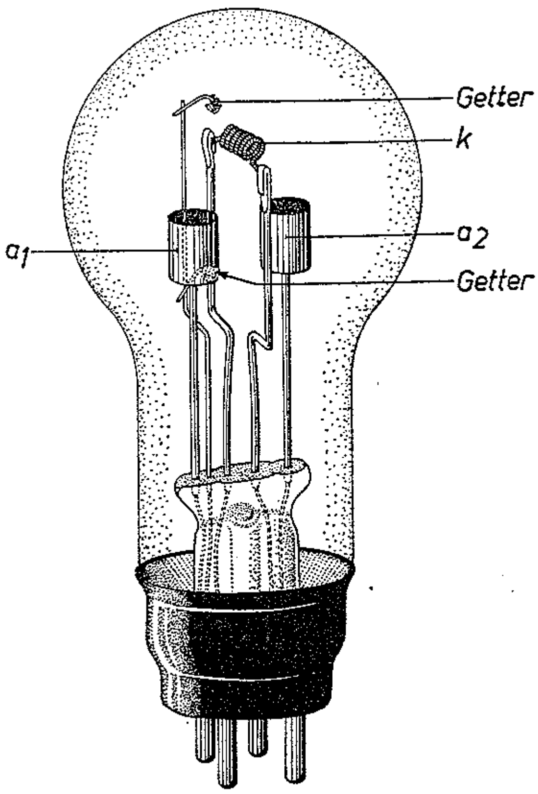


Fig. 55

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

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

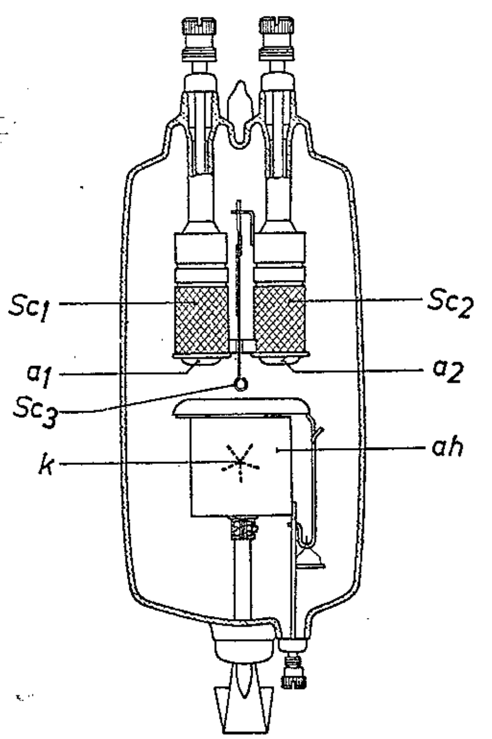


Fig. 56

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

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

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

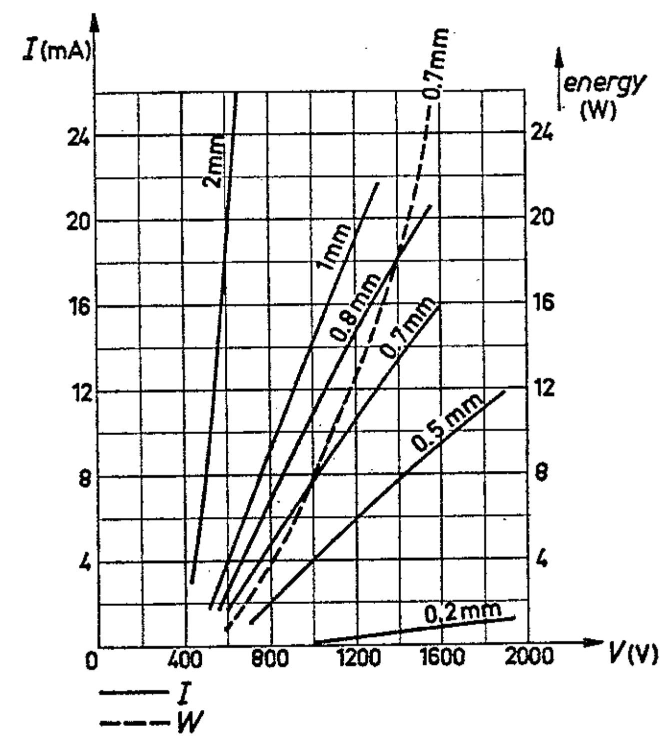


Fig. 57

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

the anode lead. Convection plays hardly any part in these tubes with their low gas pressure. Fig. 58 shows the influence of this screen on the glow-discharge current and power for an anode of surface area 14.38 cm². When these figures are compared with those in Fig. 57 for an unscreened anode of half the size, the improvement is striking.

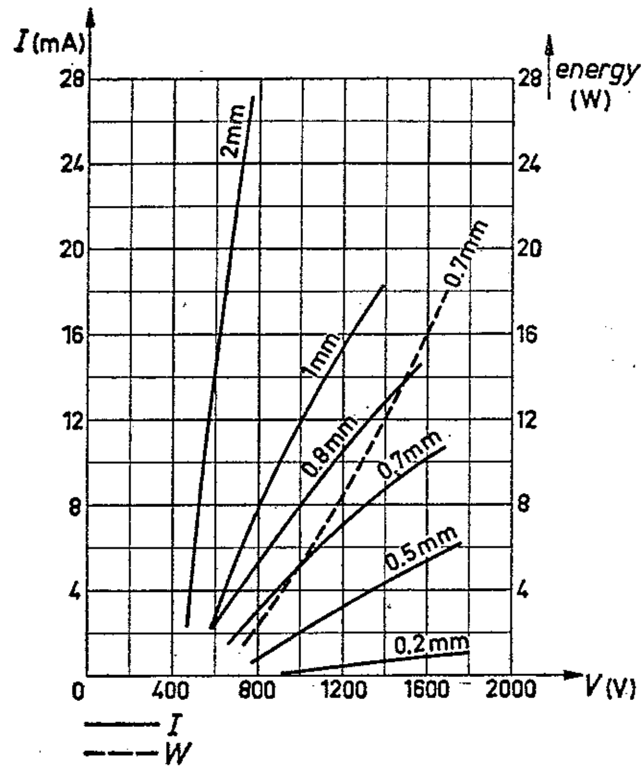


Fig. 58

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

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

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

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

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

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

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

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

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

Surge loading and damping

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

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

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

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

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

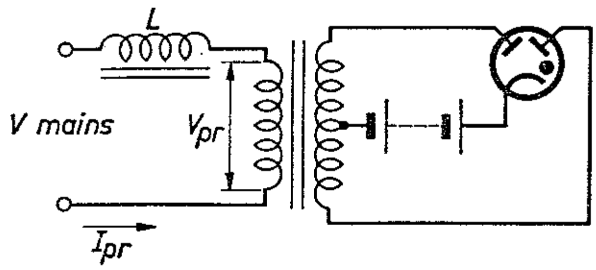


Fig. 59

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

Three-phase and six-phase rectification

If high powers have to be dealt with, or if it is desired to keep the DC ripple small, it is advantageous to feed the rectifier from a three-phase mains and to use tubes with e.g. three anodes in one envelope. Rectification with three single-phase tubes is also possible, but will not be discussed here. The construction of a three-phase tube does not differ in principle from that of a two-phase tube: it just has one anode more. The ripple can be reduced even further with the aid of a 6-phase circuit, which makes use of

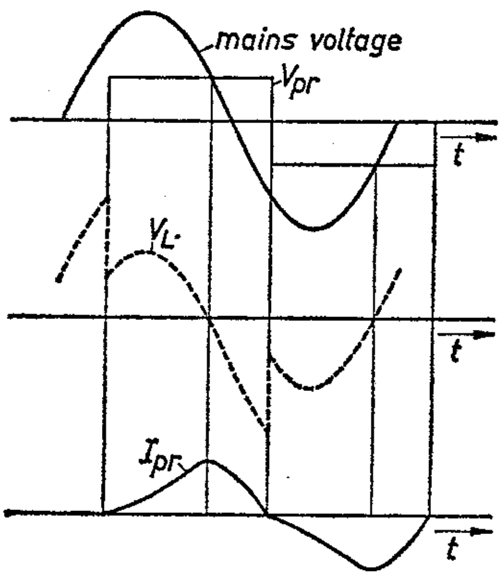


Fig. 60

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

six single-phase, three 2-phase or two 3-phase tubes (or even one six-phase vessel, in big mercury-vapour rectifiers). Fig. 61a and 61b show some switching diagrams, of which a large variety exists. One of the attractive points of 3-phase or 6-phase rectification is that in certain cases the anode-voltage transformer can be completely omitted, and the tubes fed directly from the three-phase mains. Fig. 62 shows a 3-phase system fed from a three-phase mains with neutral lead, and Fig. 63 shows a similar circuit without neutral lead (bridge circuit). It may be seen that in the latter case the direct current produced has a six-phase ripple. The further advantages of this much-used circuit come under the heading of circuit theory, and will not be discussed further in this book.

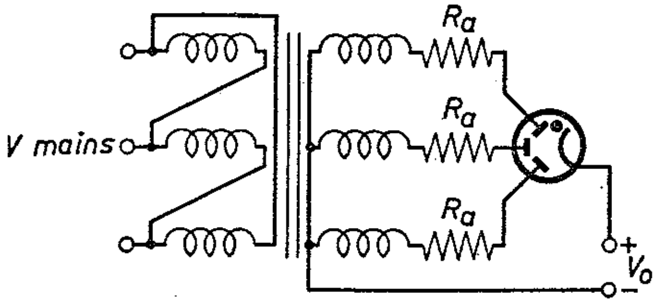


Fig. 61a

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

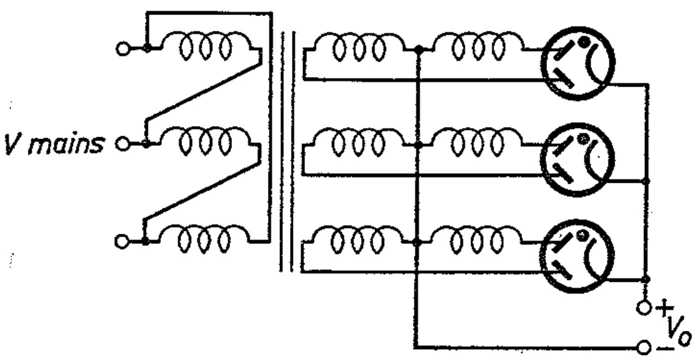


Fig. 61b

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

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

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

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

where V_o is the output DC voltage.

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

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

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

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

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

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

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

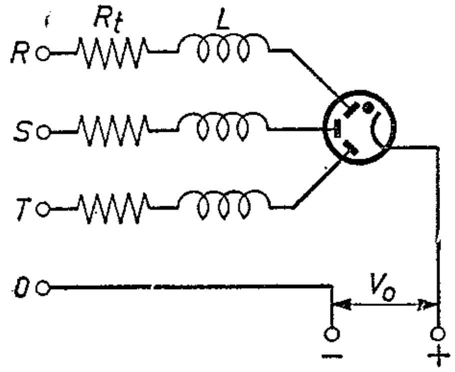


Fig. 62

Three-phase rectification with the aid of a tube with three anodes. The anode-voltage transformer is omitted, and the anodes are supplied directly from a three-phase mains with neutral lead.
R_t = total ohmic resistance in circuit for one anode,
L = inductive component in circuit for one anode.

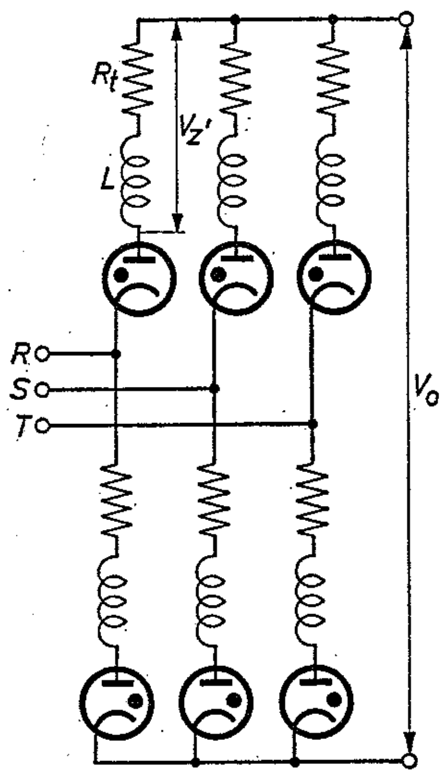


Fig. 63

Rectifier circuit using six tubes each with a single anode, directly fed from a three-phase mains without neutral lead (bridge circuit). The DC output voltage V_o has a six-phase ripple. It is possible to replace the three lower tubes by one tube with three anodes, because all three cathodes have the same potential.
Since there is no anode-voltage transformer, it is advisable to include some damping (R_t + L) in the circuit.

III-b-3 TUBES WITH ANODE SIDE ARMS

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

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

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

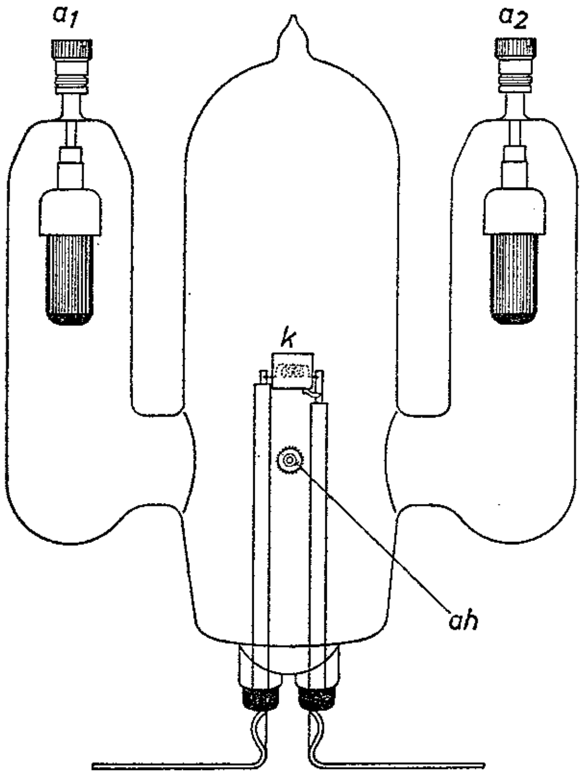


Fig. 64

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

INTRODUCTION

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

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

III-c-1 DEALING WITH THE INVERSE VOLTAGE

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

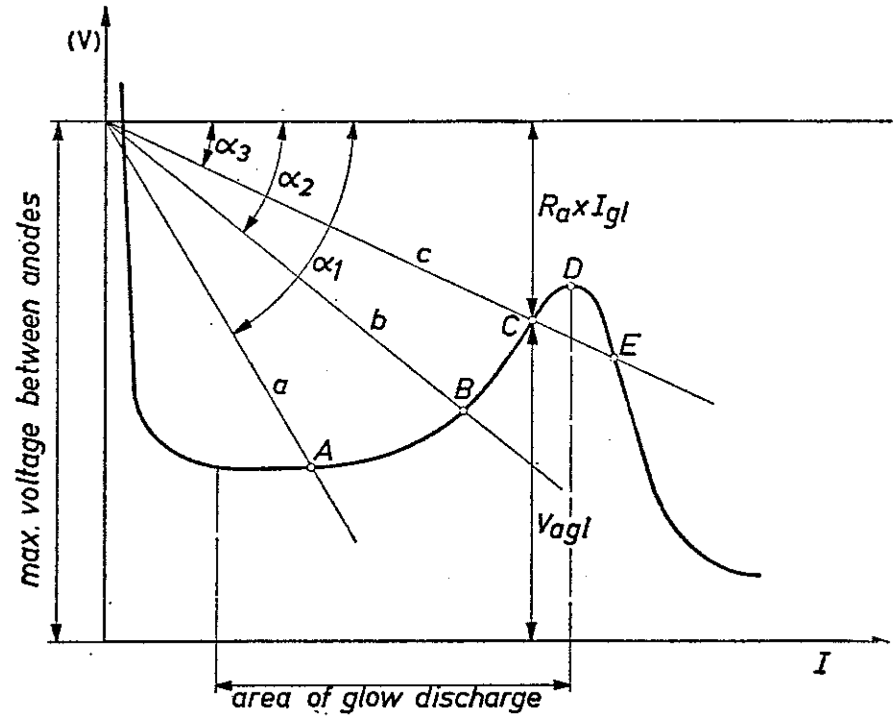


Fig. 65
Blondel diagram.
The thick curved line is the current-voltage characteristic of a gas discharge between two electrodes, e.g. between the two anodes of a two-phase rectifier tube. The glow-discharge region is indicated by the horizontal line. R_a is the resistance in series with an anode. The straight lines *a*, *b* and *c* are "load lines" corresponding to different values of R_a, with slopes α_1, α_2 and α_3 respectively; all the load lines pass through the point on the voltage axis corresponding to the maximum value v_{ap} of the voltage between the anodes. In the glow-discharge region, $v_{ap} = R_a \times I_{gl} + V_{agl}$, where I_{gl} is the glow current and V_{agl} the glow voltage. The operating point of the discharge is the point of intersection of the load line in question and the current-voltage characteristic.

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

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

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

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

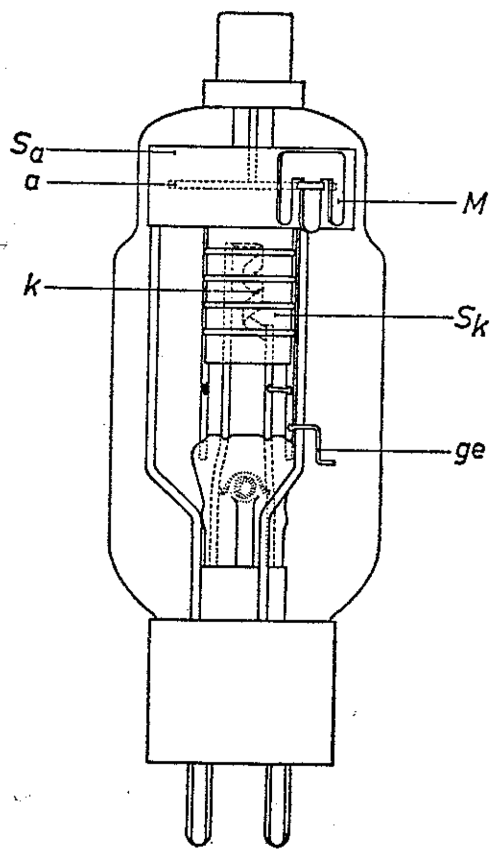


Fig. 66

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

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

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

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

Mercury filling

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

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

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

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

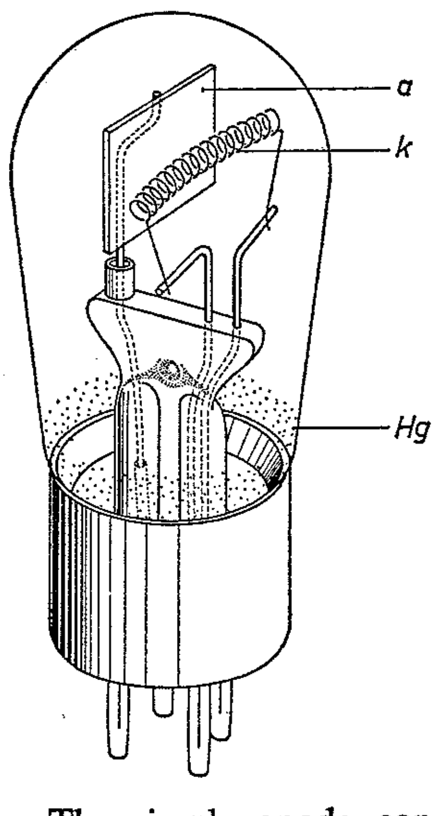


Fig. 67
Example of a simply constructed high-voltage tube filled with saturated mercury vapour. (Philips type DCG 1/250).
Maximum inverse voltage 3 kV, a = vertical anode plate, k = spiral cathode, Hg = spot where mercury condenses.
Because of the relatively low voltage between a and k, the leads of both of these electrodes can be included in the same pinch seal.

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

III-c-2 THE CATHODE

The cathode of a high-voltage tube must be heavier than that of a low-voltage tube for the same current. Since we are obliged to keep the gas pressure low, we must also accept a relatively high cathode sputtering, since in the positive phase the field is closely concentrated around the

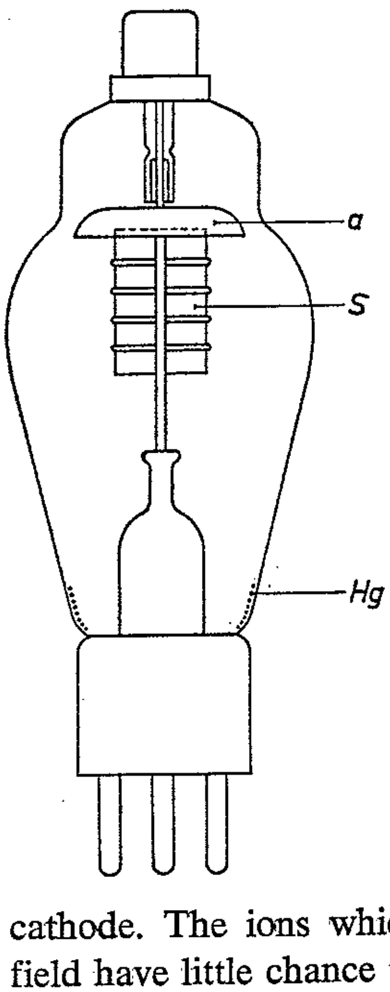


Fig. 68
Rectifier tube with mercury-vapour filling for an inverse voltage of 10 kV. Because of the relatively high anode voltage, the lead of the disc-shaped nickel anode must be led out through the top of the tube, so as to be as far as possible from the cathode lead. S = cathode screen, Hg = mercury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

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

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

Some high-voltage mercury tubes are made with various compartments at different pressures, according to the principle shown in Fig. 69. In the lowest compartment K we find the cathode k and liquid mercury, which is heated by the cathode losses. The middle compartment C acts as a condenser for the mercury vapour, and the upper compartment A contains

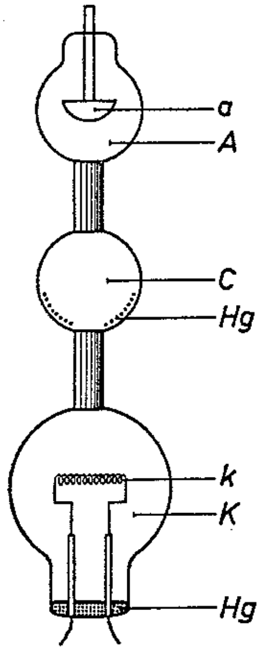


Fig. 69

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

the anode a. The various compartments are connected by narrow metal pipes. This construction makes it possible in a single tube that the relatively small cathode emits amidst a high pressure, and thus does not suffer much from sputtering, while the anode is in a low-pressure region so that high voltages can be tolerated. The pressure in K can be as much as 20 times that in A. Such tubes last a long time, but they are also expensive to make [46].

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

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

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

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

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

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

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

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

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

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

TABLE VII

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

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

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

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

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

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

If the tube has not been in use for some time, all parts will be at room temperature and the mercury may be expected anywhere in the tube. When the tube is switched on again, the mercury vapour may condense at the top of the tube as well as at the bottom. To reduce the

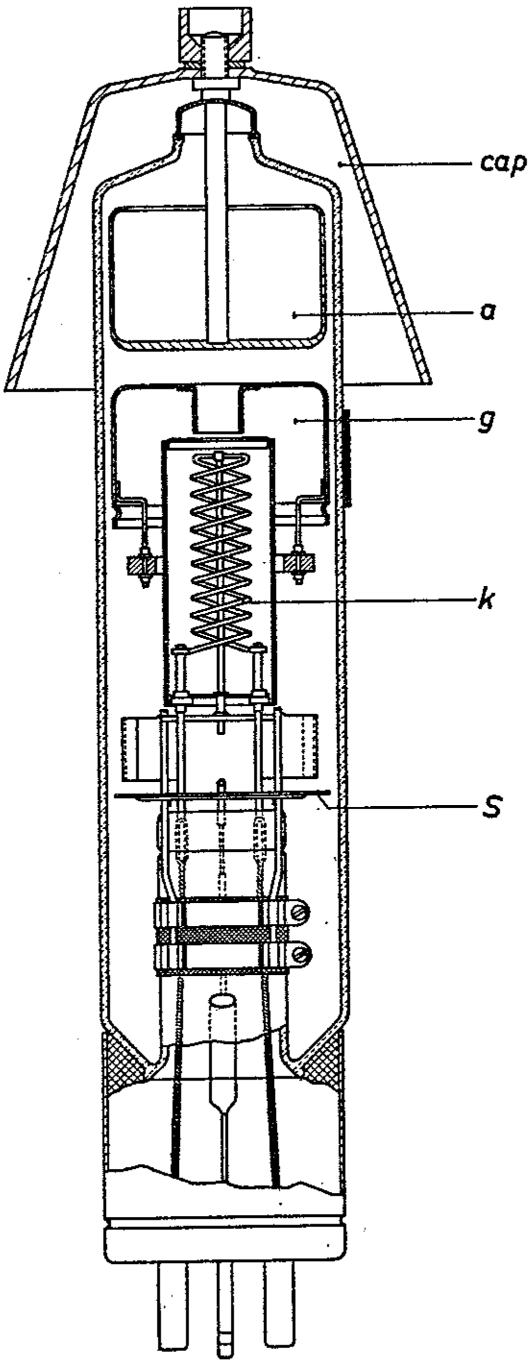


Fig. 70
Controlled high-voltage rectifier tube (Philips type DCG 12/30) with mercury-vapour filling. The short distance between the flat bottom of the anode a and the switching grid g is striking. The latter electrode is practically at cathode potential. The high inverse voltage (27 kV) must be taken up between a and g.
cap is a cap of a thermal insulator around the anode part of the tube. This traps ascending warm air so that, even if there is no anode current flowing, this part of the tube always remains somewhat warmer than the lowest part where the mercury vapour condenses. S is a screen which keeps the heat radiated by the hot cathode k from the lowest part of the tube, so that the temperature of the mercury there, and thus the vapour pressure, remains low.

chance of backfiring, the condensed mercury should be allowed to evaporate from the anode side of the tube before the anode voltage is applied. Tubes of this type are usually specially designed to shorten this warming-up time. For example, some tubes contain an *anode cap* which surrounds the upper part of the envelope. The warm air rising round the tube is thus trapped, and will help to evaporate any mercury condensate which may be there.

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

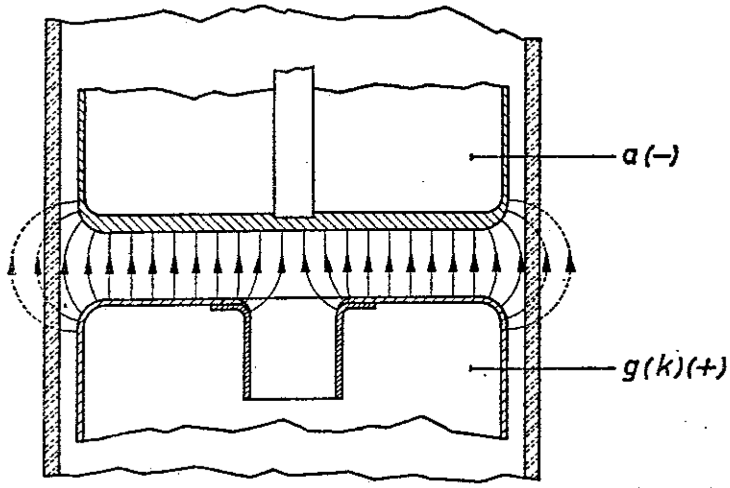


Fig. 71

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

III-c-4 THE MERCURY TEMPERATURE

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

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

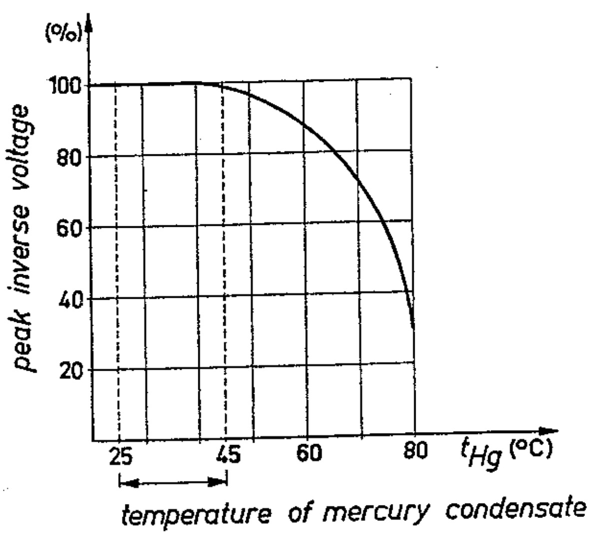


Fig. 72

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

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

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

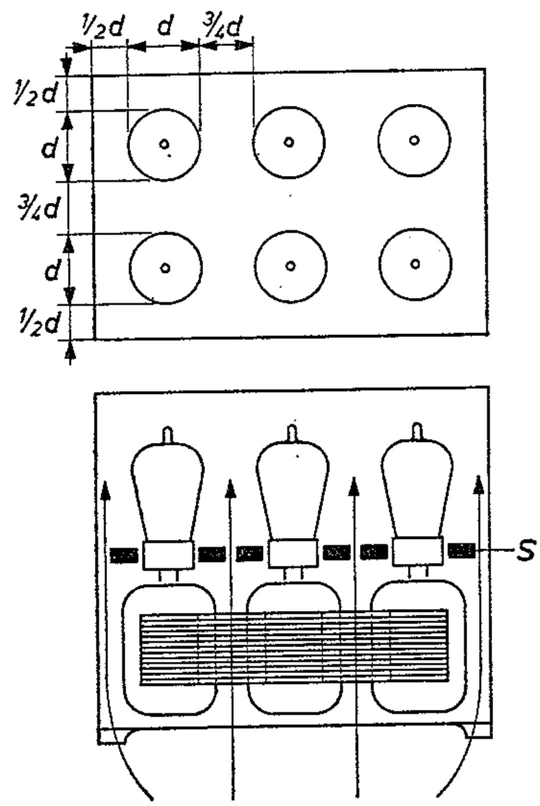


Fig. 73
Sensible arrangement of six tubes in a cabinet with regard to the tube temperature. The heat screen S is slotted so that a natural flow of air occurs in the direction of the arrows. On the one hand the power transformer, which is situated under the tubes, is cooled by the circulating air, while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

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

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

First of all, the ambient temperature t_{amb}. For part of the year, t_{amb} will be lower than 15 °C. It is then usually inadvisable to start the discharge in a mercury tube without special precautions. The simplest way to regain the desired temperature of 15 °C is to make use of the heat dissipated in the hot cathode. It is then necessary to wait a certain length of time, until the temperature of the mercury condensate has risen sufficiently, before applying the anode voltage. Now if the tube has been designed properly, the mercury condensate will be found somewhere near the bottom. This is the obvious place for it, since if the tube is cooled by natural convection the air round it will be warmed up and therefore rise, to be replaced by a fresh supply of cold air at the

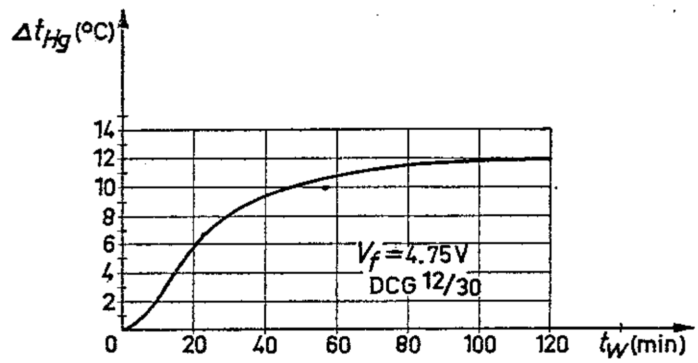


Fig. 74

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

bottom ("chimney effect"). Moreover, if the mercury vapour condenses somewhere in the upper part of the tube, the droplets formed there might fall to the bottom, coming into contact with hot parts of the tube on the way. This could give rise to sudden, though temporary, increases in the vapour pressure which might lead to backfiring. In order to ensure that the lower part of the tube is not much influenced by the warmer upper part, the tube may be made long and thin. This means of course, however, that it will be a long time before the mercury condensate reaches the desired temperature of 15 °C. The warming-up time t_w can be reduced by supplying radiant heat from outside (from an incandescent lamp or small radiator). The direction of the radiation should then be from top to bottom of the tube, so that parts where no condensation should occur are warmed up first. Figure 74 and 75 give some further information about t_w for the DCG 12/30. Fig. 74 shows how fast the temperature of the mercury condensate rises above the ambient temperature (Δt_{Hg}) after V_f has been switched on.

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

Another possibility which must be taken into consideration is that the ambient temperature is too high. The tube will in general be designed to give a temperature distribution along the tube which guarantees that the temperature of the condensate does not exceed the maximum permissible value, even if the tube is fully loaded, as long as the ambient temperature remains within limits which are included in the operating data. This

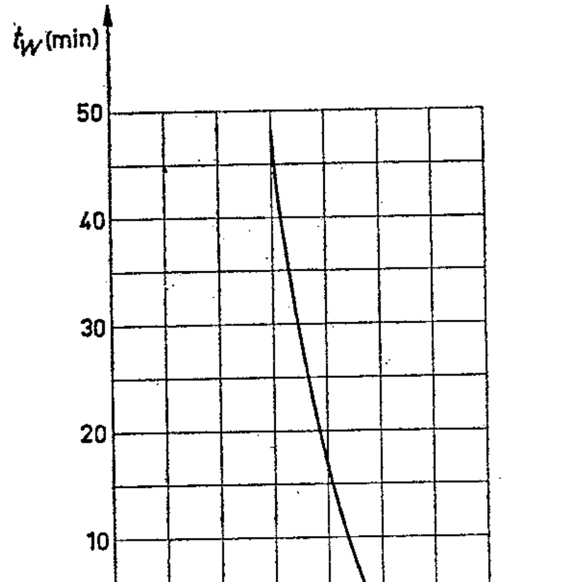


Fig. 75
Influence of the ambient temperature t_{amb} on the time t_w which must elapse before the anode voltage of the DCG 12/30 is switched on. The mercury temperature must be at least 25° C before the anode voltage is applied. If $t_{amb} \geqslant 25°$ C, it is sufficient to wait 1½ minutes after switching on V_f, by which time the cathode will be up to temperature. When $t_{amb} < 25°$ C, one must wait longer.

entails that, if the tubes are used for polyphase rectification, they should not be placed right next to one another. A separation equal to ¾ of the maximum diameter of the tube is sufficient. The distance between the tube and the surrounding wall should also not be too small. Cooling by natural convection should not be hindered (see Fig. 73). A good rule of thumb is that the distance between tubes and wall should be at least half the maximum diameter of the tube. This suggestion, and the rule that the tube should be placed with the anode on top and the cathode underneath, holds for mercury tubes in general.

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

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

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

CHAPTER IV

THYRATRONS

IV-a **Introduction**

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

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

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

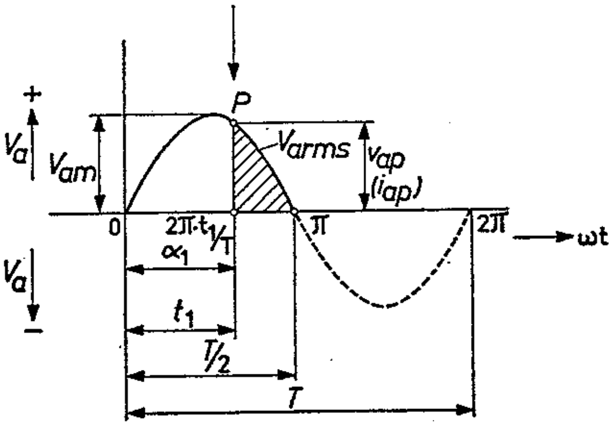


Fig. 76

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

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

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

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

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

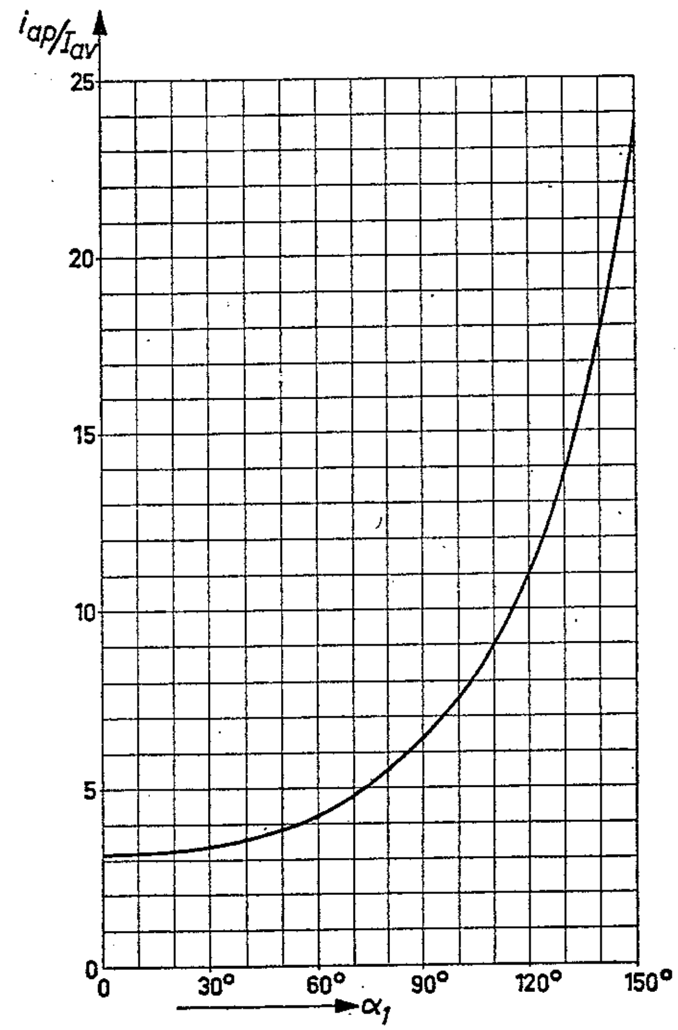


Fig. 77

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

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

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

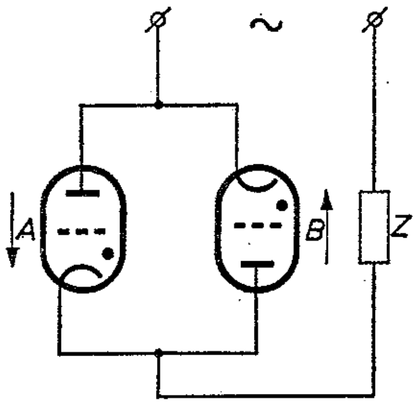


Fig. 78

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

IV-b Triodes

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

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

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

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

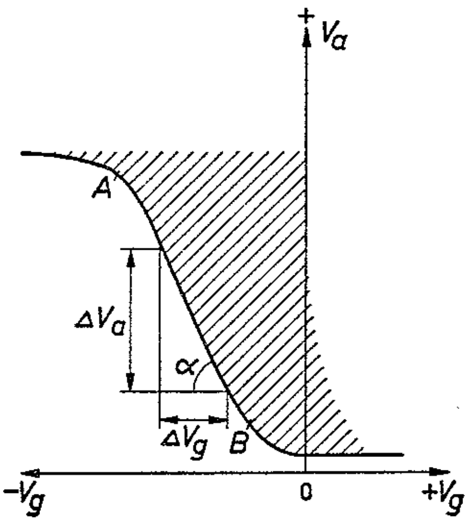


Fig. 79

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

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

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

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

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

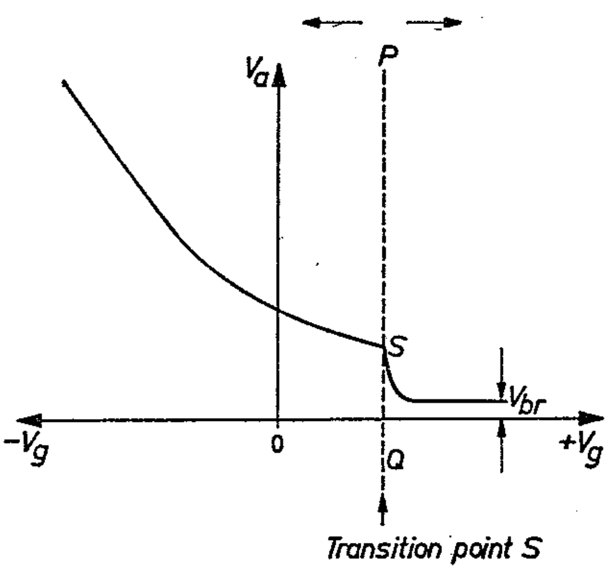


Fig. 80
The control characteristic of a thyratron generally consists of two parts: the (grid) voltage characteristic to the left of the line *PQ* and the (grid) current characteristic to the right. The grid voltage corresponding to *PQ* may be either positive or negative, depending on the construction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

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

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

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

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

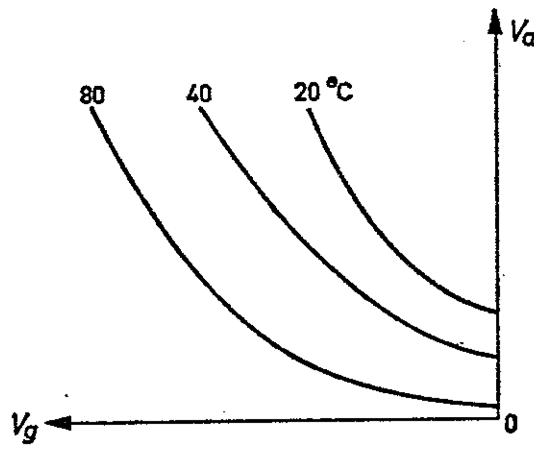


Fig. 81

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

IV-b-2 CONTROL

Control with an alternating voltage in the anode circuit

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

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

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

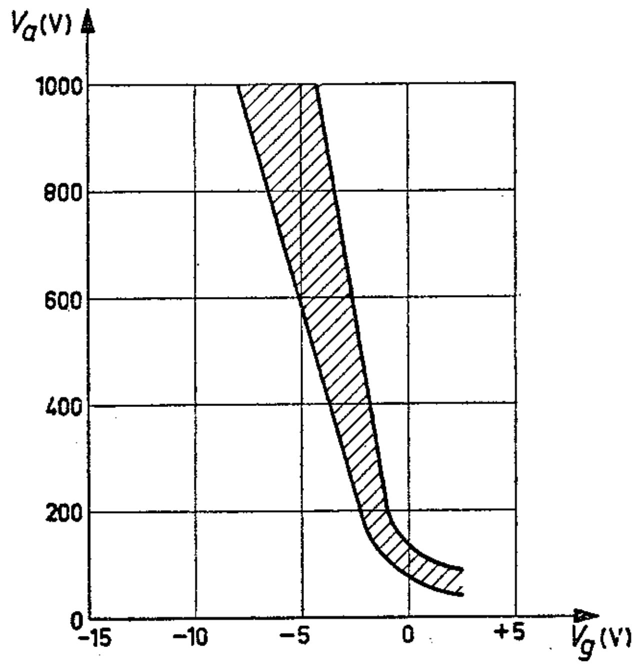


Fig. 82
Spread of the control characteristics of a certain type of thyratron.

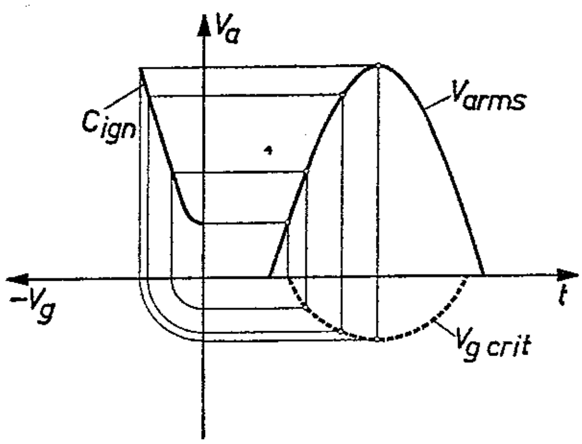


Fig. 83
The dotted line is the critical grid-voltage curve $V_{g\ crit}$ for a sinusoidal anode voltage $V_{a\ rms}$. The construction of the dotted line from the control characteristic C_{ign} and the anode voltage is shown in the figure.

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

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

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

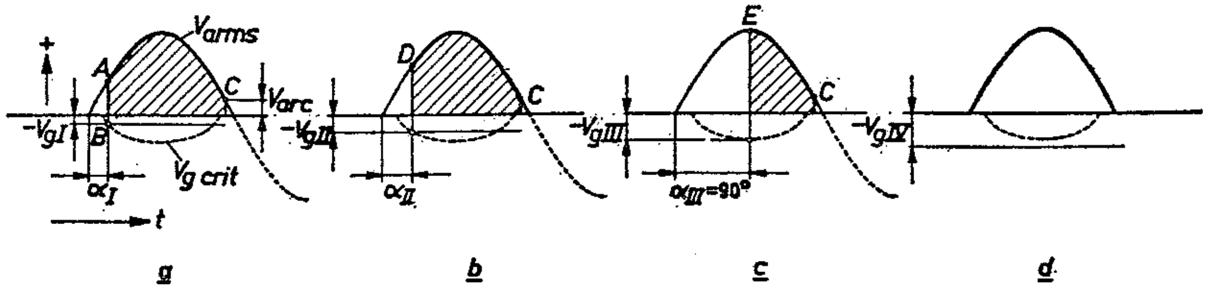


Fig. 84

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

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

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

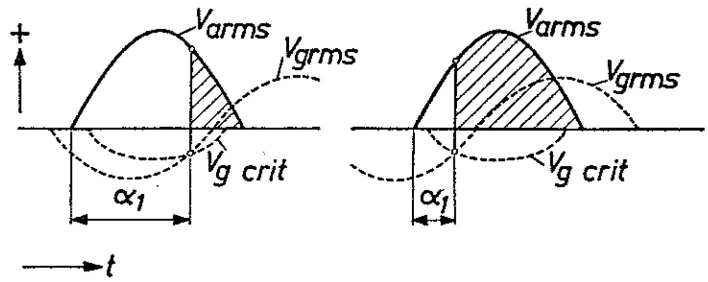


Fig. 85

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

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

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

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

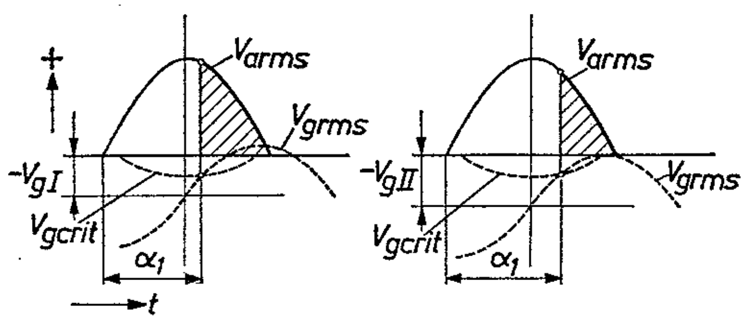


Fig. 86

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

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

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

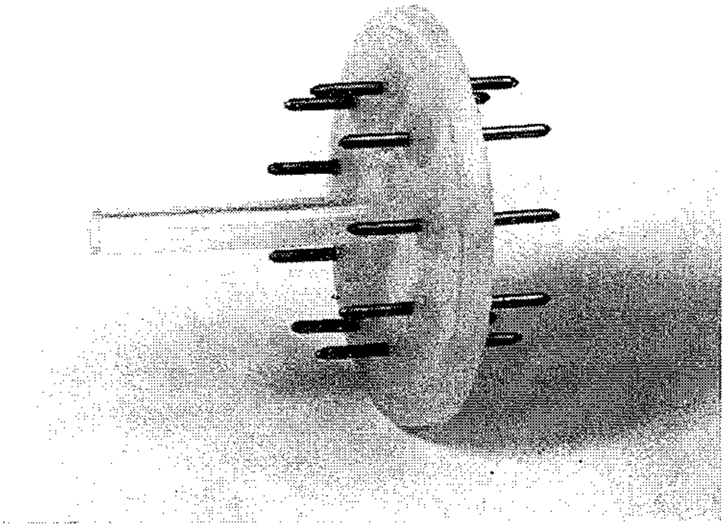


Photo 1

Pressed-glass seal with leads arranged in a ring.

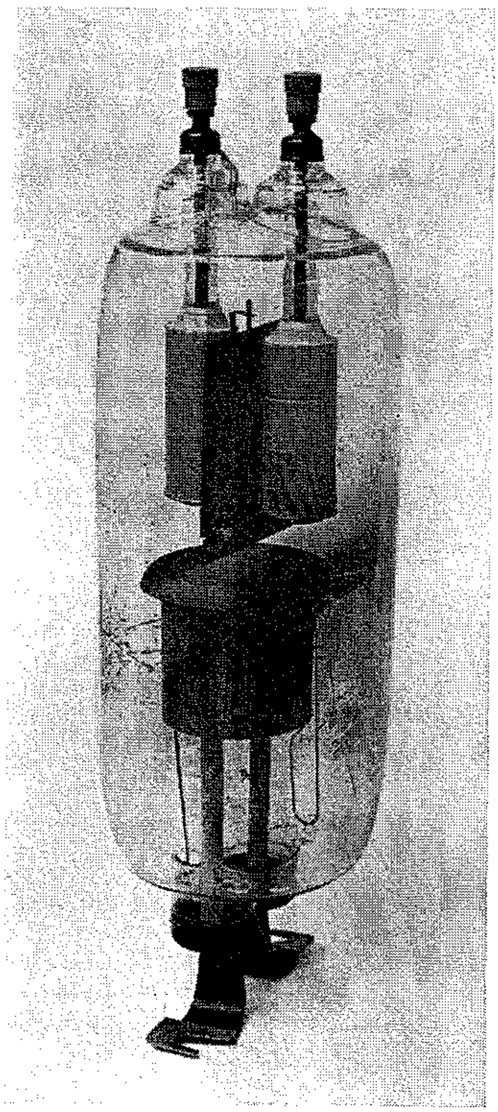


Photo 2

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

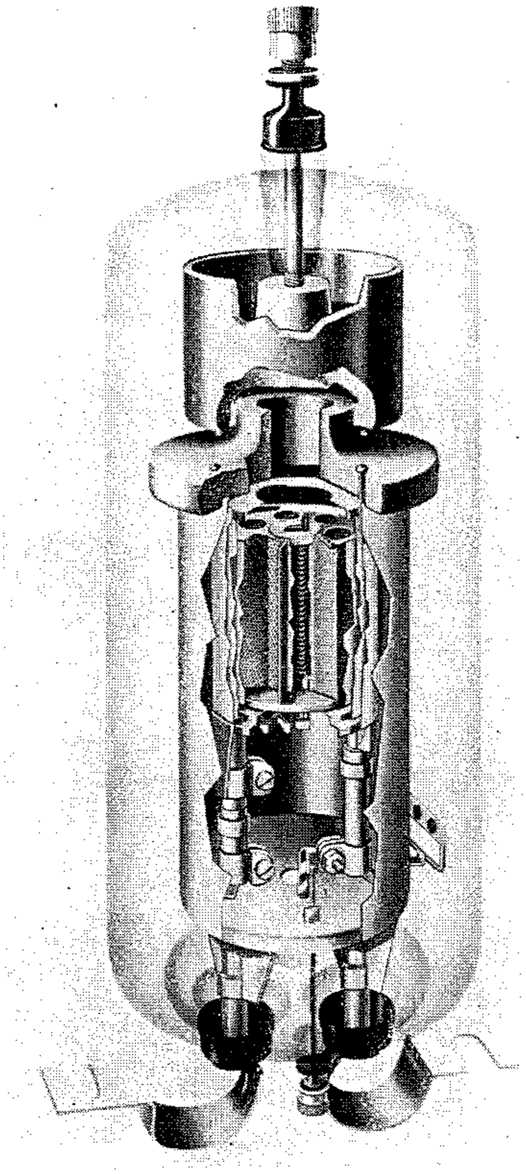


Photo 3

Partly sectional view of mercury vapour thyratron PL 260.

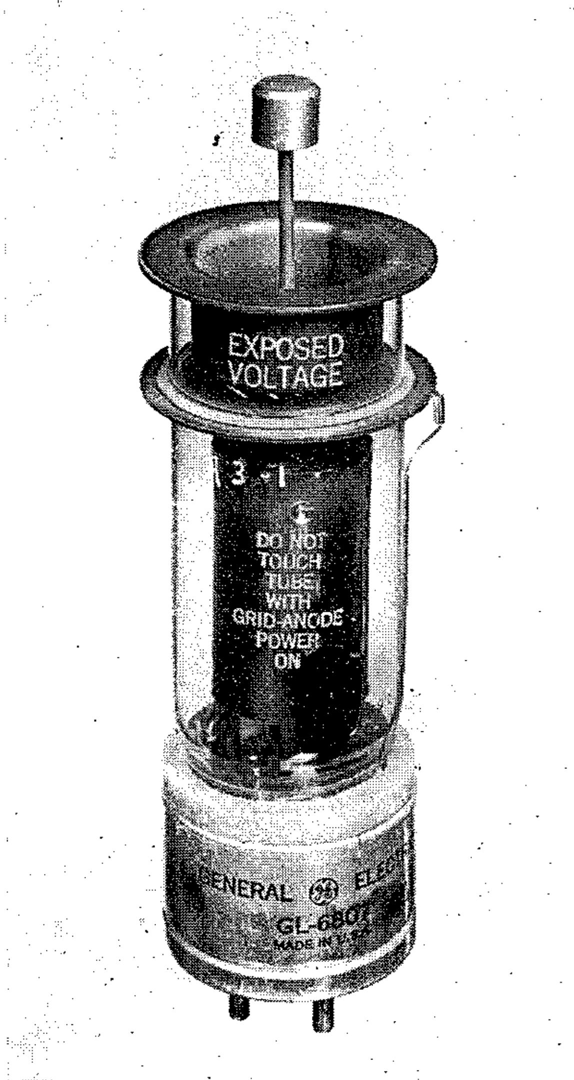


Photo 4

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

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

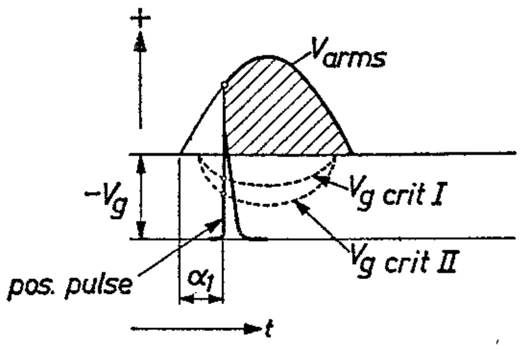


Fig. 87

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

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

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

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

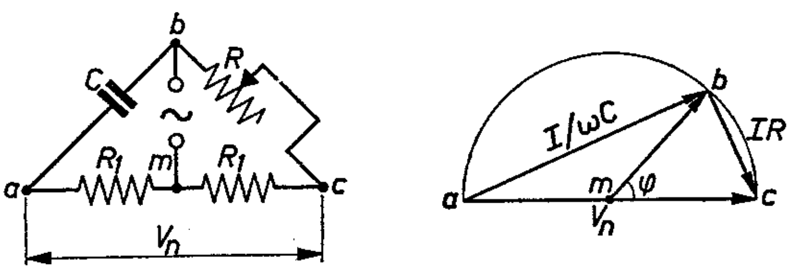


Fig. 88

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

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

Control with a DC anode voltage

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

The resistance in series with the grid

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

Minimum value of the series resistance

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

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

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

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

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

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

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

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

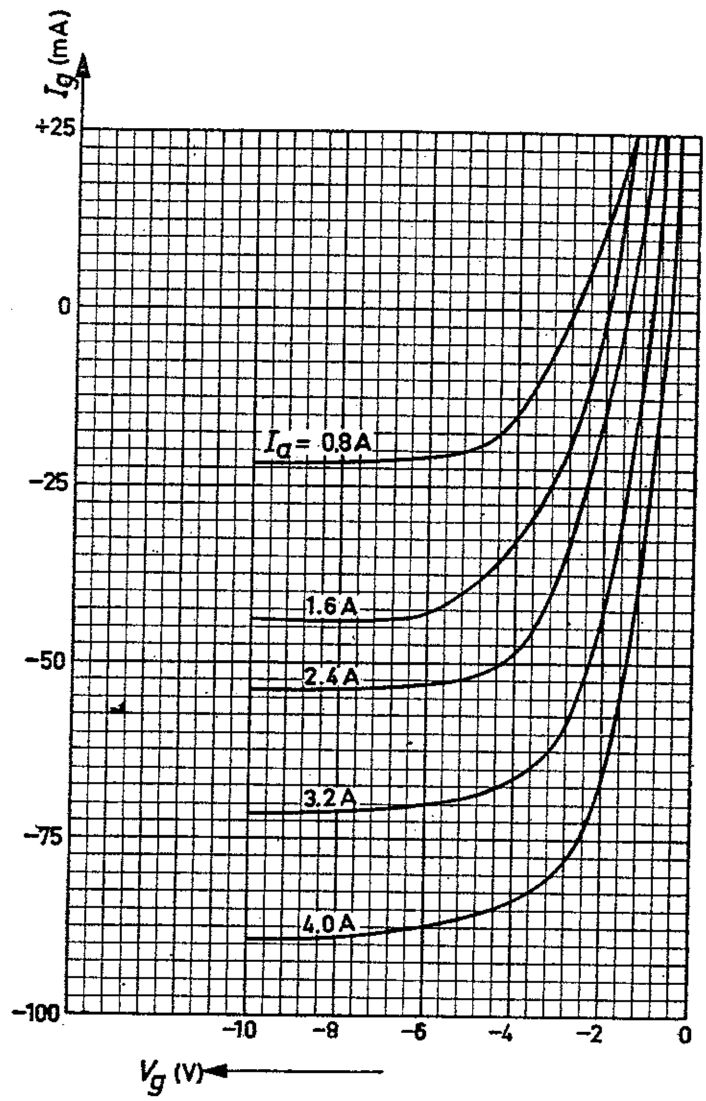


Fig. 89

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

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

Maximum value of the grid series resistance

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

Spread in the ignition characteristics

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

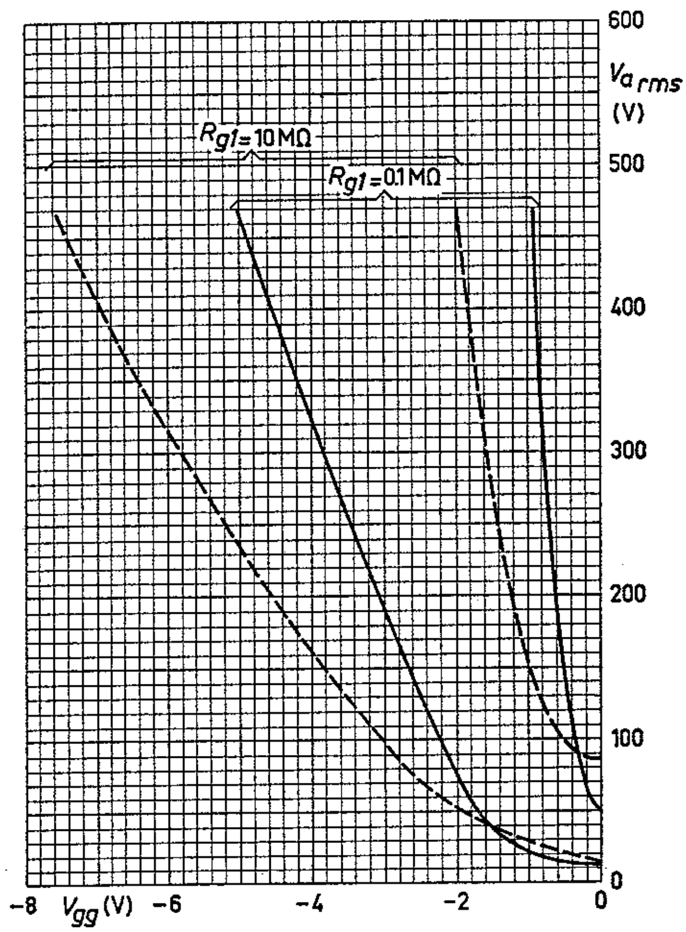


Fig. 90

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

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

Grid emission

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

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

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

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

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

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

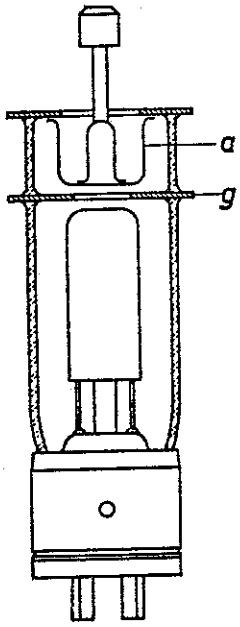


Fig. 91

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

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

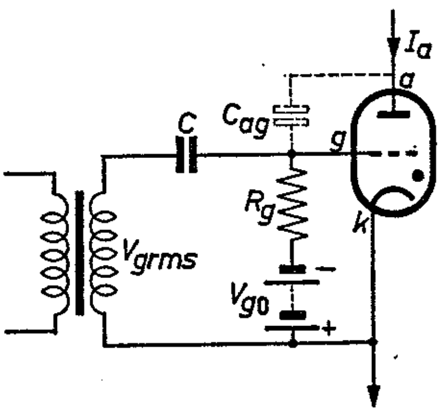


Fig. 92

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

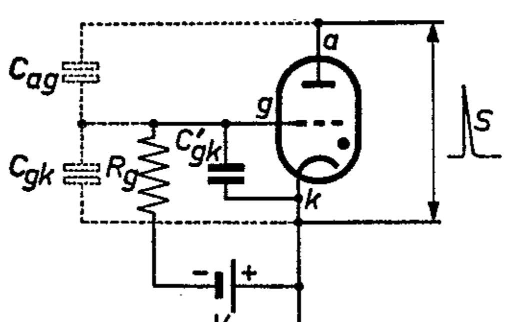


Fig. 93

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

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

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

The grid insulation

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

Example of grid-current characteristic

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

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

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

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

IV-b-3 EXTINGUISHING THE DISCHARGE

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

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

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

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

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

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

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

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

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

The main factors which influence the recovery time are:

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

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

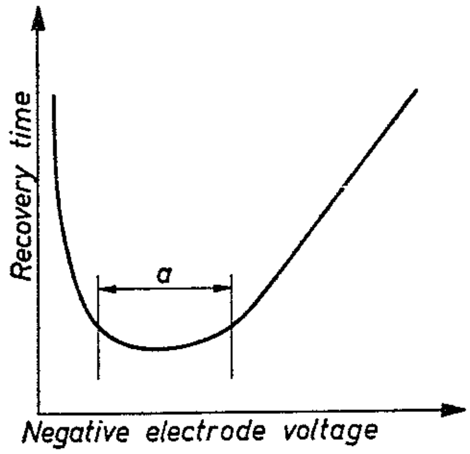


Fig. 94
Recovery time of a thyratron as a function of the negative electrode voltage. If the frequency of the anode voltage is relatively high the best region for operation is *a*.

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

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

Commutation.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

IV-b-5 THE HYDROGEN THYRATRON

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

The gas in the hydrogen thyratron

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

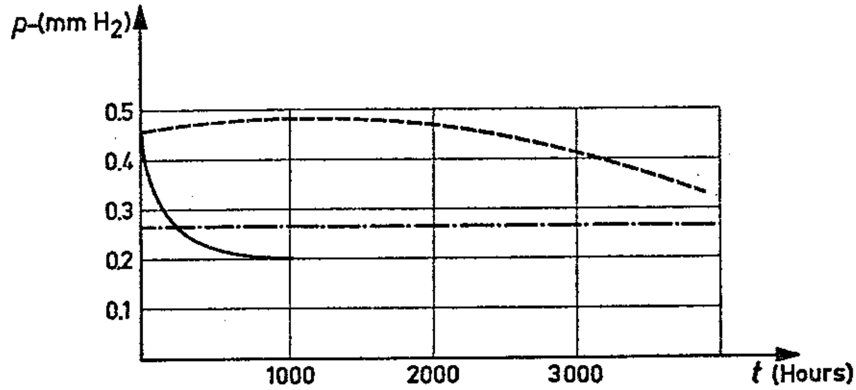


Fig. 95

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

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

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

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

Before 1945 the hydrogen thyratron was practically only used in military

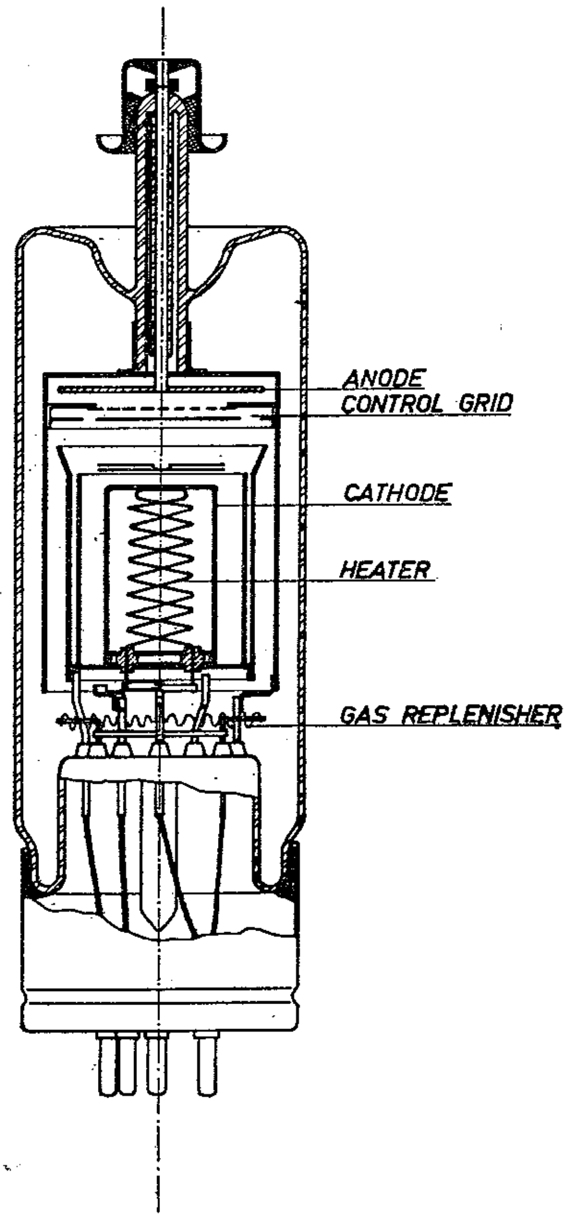


Fig. 96

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

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

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

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

Construction and some data of a hydrogen thyratron

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

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

Ignition properties of a hydrogen thyratron

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

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

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

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

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

IV-c **Tetrodes**

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

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

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

IV-c-1 SMALL SWITCHING-GRID CURRENTS

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

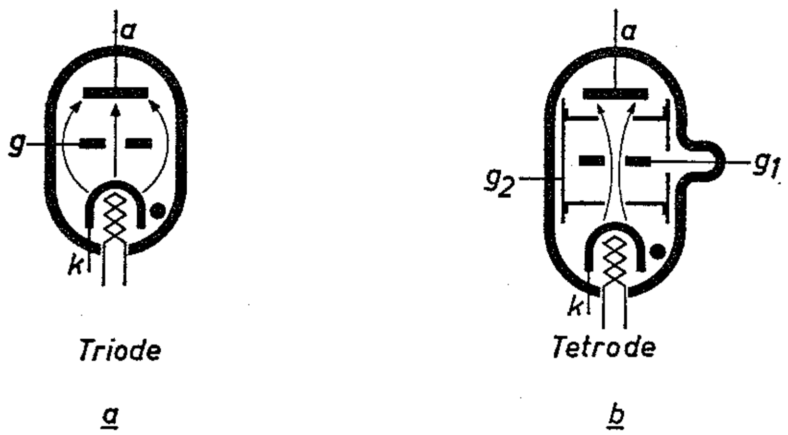


Fig. 97

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

IV-c-2 CAPACITIVE SCREENING

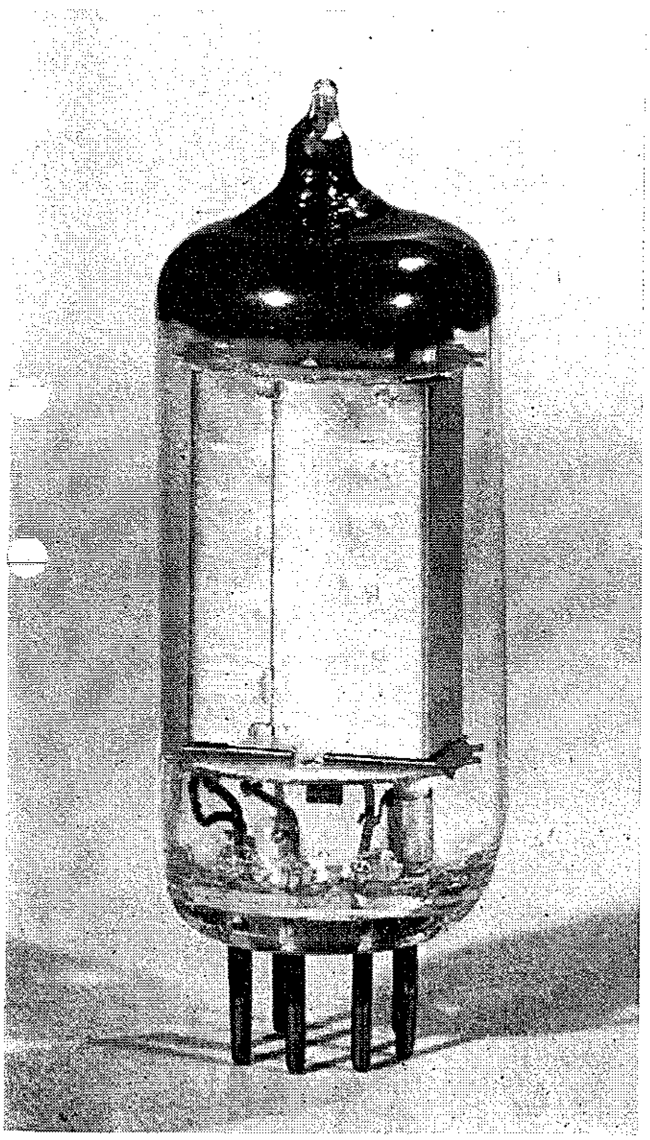
It has been shown in IV-b-2 to be important that the capacitance C_{ag1} between the anode and the switching grid should be low, in order to prevent unwanted ignitions. The effect of the comparatively large value of C_{ag1} for a triode may be corrected by increasing the grid-cathode capacitance C_{g1k},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

IV-c-3 POSSIBILITY OF SHIFTNG THE IGNITION CHARACTERISTIC

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

Photo 5

Photograph of the Philips hydrogen thyratron PL 522.



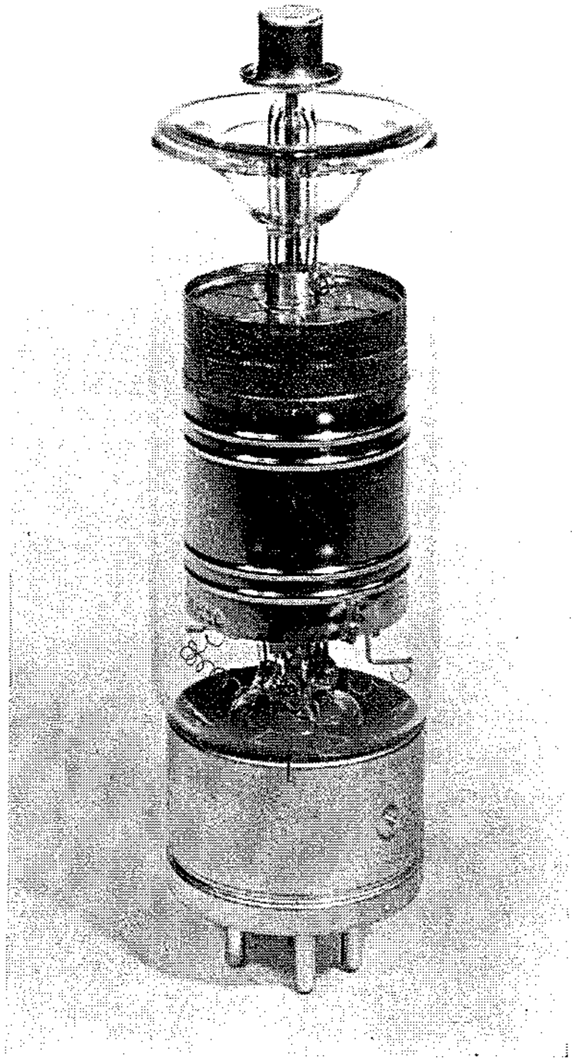


Photo 6

Photograph of tetrode thyratron type PL 2D 21.

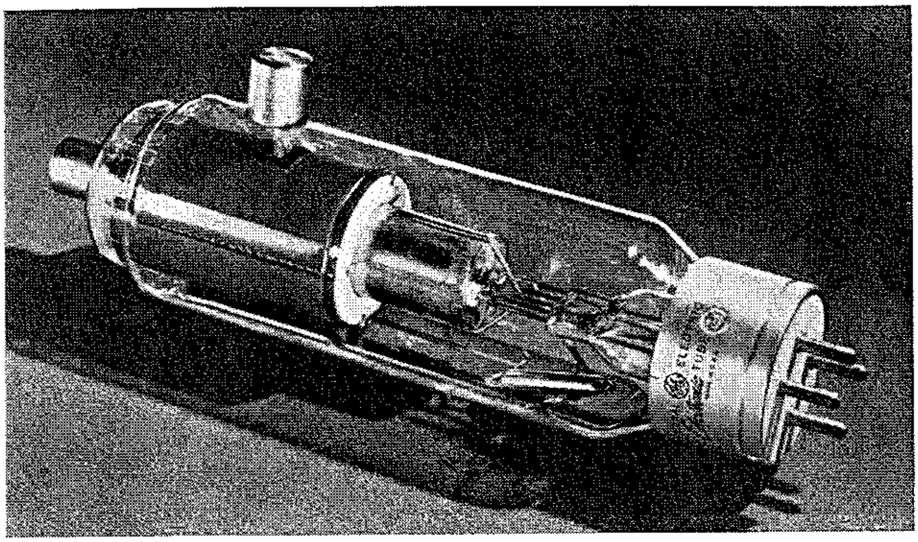
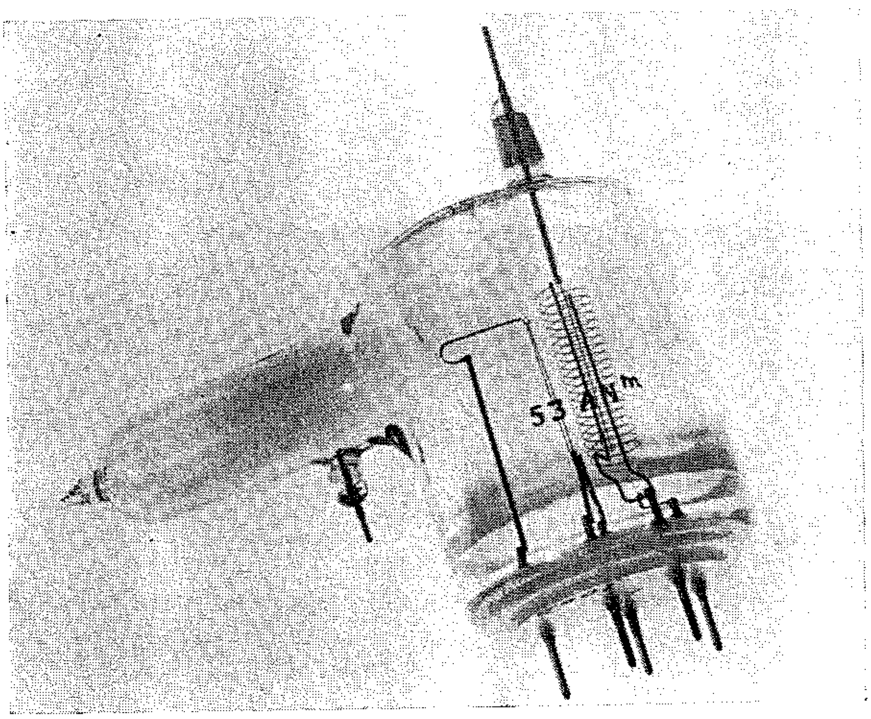


Photo 7

Photograph of tetrode thyratron type FG 105.

Photo 8

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



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

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

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

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

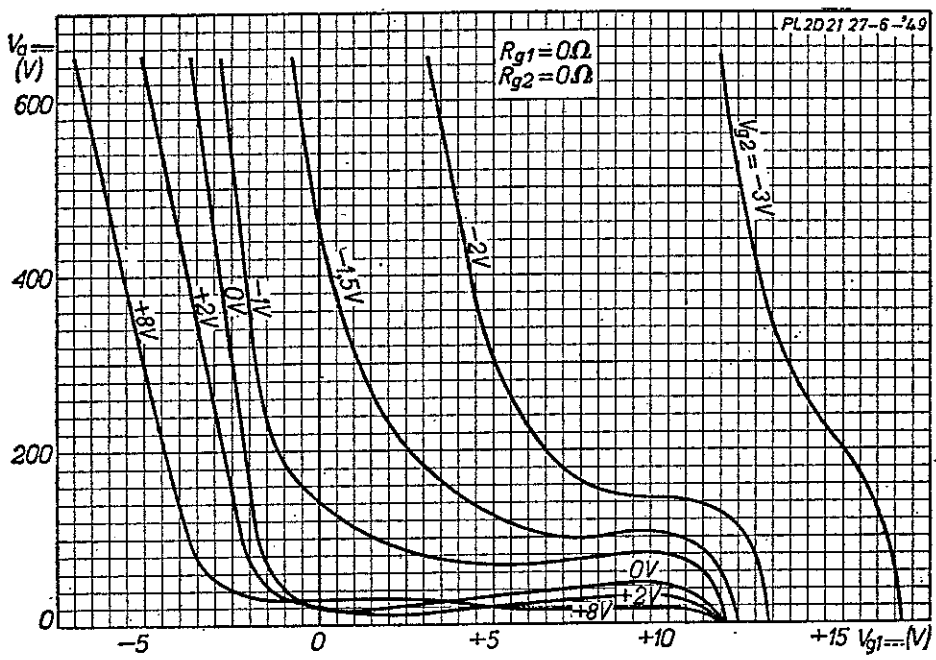


Fig. 98

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

IV-c-4 IMPROVEMENT OF RELIABILITY OF THE IGNITION

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

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

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

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

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

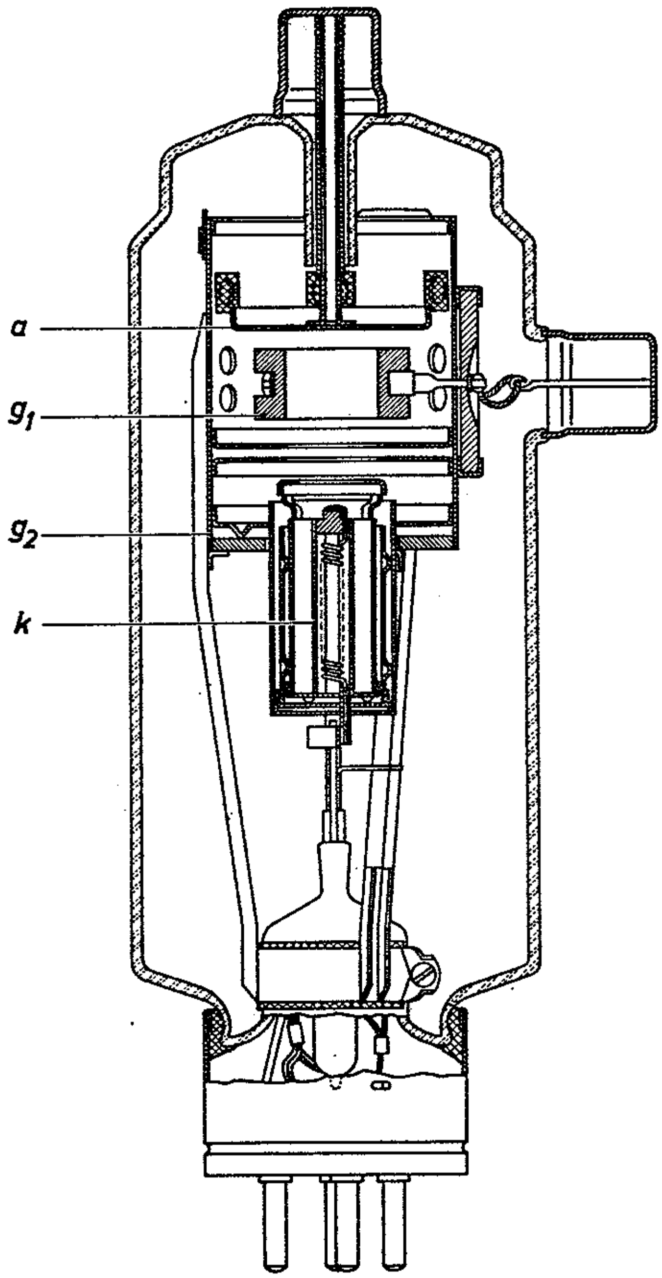


Fig. 99

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

IV-c-7 EXAMPLES OF THE TETRODE THYRATRON

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

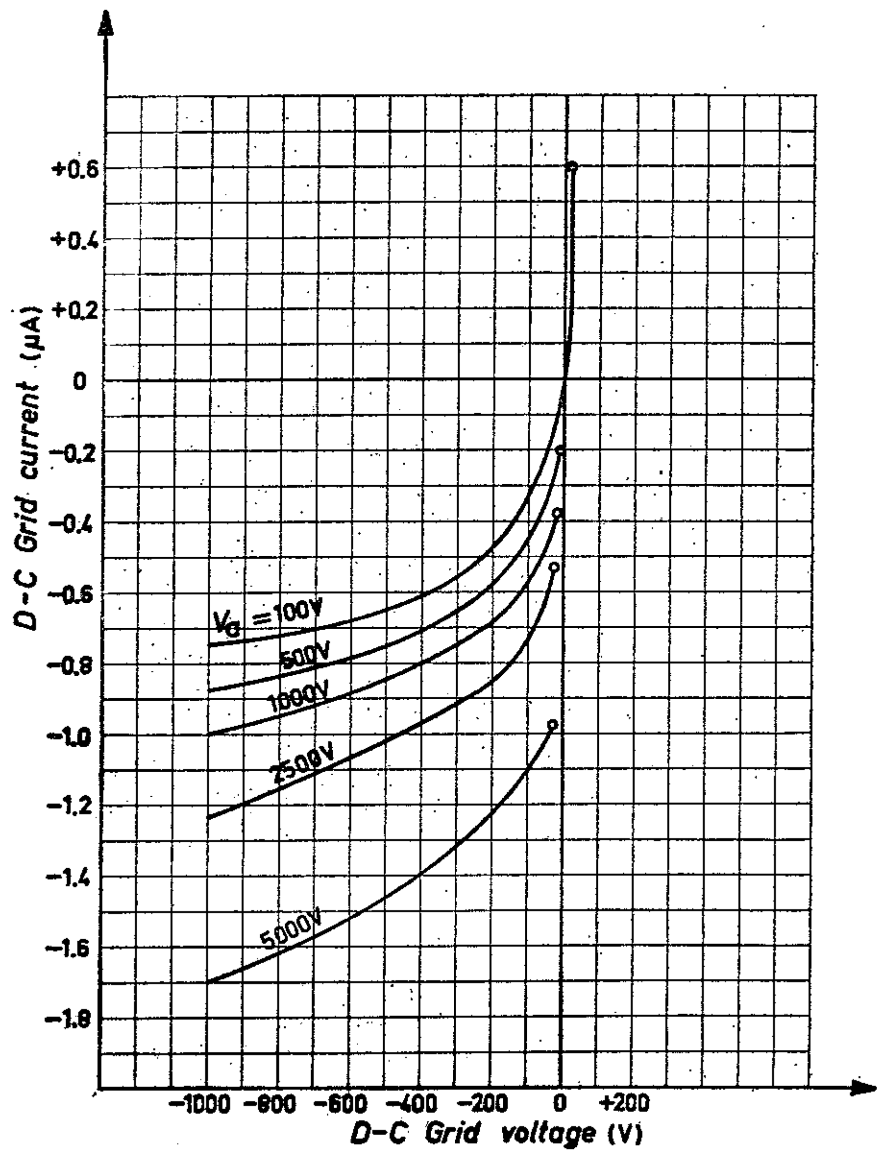


Fig. 100

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

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

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

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

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

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

TABLE VIII

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

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

TABLE IX

OPERATING DATA OF SOME THYRATRONS

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

TABLE IX (continued)

OPERATING DATA OF SOME THYRATRONS

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

APPENDIX

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

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

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

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

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

CHAPTER V

COLD-CATHODE TUBES

Introduction

The gas-discharge tubes treated in the last two chapters contain a cathode which can be heated to incandescence by means of a separate voltage supply, and which then emits electrons. The various types of discharges which can then be produced belong to the class of non-self-sustaining discharges.

As we have already seen in Chapter I, a cathode can also emit electrons in the cold state, in a glow discharge and a corona discharge. Such discharges are self-sustaining. Here no separate source of energy is needed to heat up the cathode, and there is thus no heating-up time necessary for the cathode. It is therefore possible for the discharge to be ignited without any delay.

Whereas the discharge current in hot-cathode tubes can amount to many amperes, that in most cold-cathode tubes is restricted to some tens of milliamperes. If the current becomes much more than this, the cathode temperature rises so much that thermionic emission begins and the discharge can turn into a self-sustaining arc discharge.

As regards the number of electrodes, the simplest form of cold-cathode tube is the diode just as with the hot-cathode tubes, while we will also meet triodes and tetrodes, in which the current through the tube can be controlled. The way in which the current is controlled differs however from what we have met in hot-cathode tubes.

V-a **Diodes; voltage-stabilizing tubes, reference tubes**

There are several types of cold-cathode diodes, each with its own function to perform.

In the course of the treatment of the demands made on *voltage-stabilizing tubes,* we will find an opportunity to learn several of the problems and peculiarities which are also connected with other glow-discharge diodes. Moreover, this type of tube plays an important role in modern electronic apparatus. We will therefore discuss it first.

V-a-1 THE VOLTAGE-STABILIZING TUBE

In many applications of electronics, it is necessary to keep a DC voltage constant irrespective of variations in the mains voltage, the load, etc. Voltage stabilization is often needed in amplifiers, control circuits, generators, etc., in order to be able to comply with the demands made on the constancy of the quantity to be supplied (e.g. current, pulse, frequency).

Since the tube current in the glow-discharge tubes used for this purpose may not exceed some tens of milliamps with the available models, in connection with the maximum permissible cathode load of some mA per cm^2 of cathode surface, the glow-discharge stabilizing tube only comes into consideration for circuits in which the current is low.

The applied tube voltage must exceed the burning voltage V_{br} for the discharge to be ignited. It is useful if the ignition voltage V_{ign} is only slightly more than the burning voltage, so that the supply voltage can also be kept low. In any case, the difference between the supply voltage and V_{br} must be taken up by a resistor in series with the tube.

The gas mixture neon$+1\%$ argon is normally used, if this is compatible with the other demands made on the tube, in order to make the difference between V_{ign} and V_{br} as small as possible. We have already seen (I-d-3) that the rather high breakdown voltage of neon is considerably lowered by the addition of a little argon.

When a tube is completely screened off from the light, ignition is often found to be delayed somewhat; this delay may amount to as much as a few seconds. The tube should therefore in general be illuminated to a certain extent in order to prevent this delay. An increase in the supply voltage can also have the same effect. A little radioactive material is sometimes placed in the tube for the same reason.

The discharge in a voltage-stabilizing tube corresponds to a point on the horizontal part of the current-voltage characteristic of a gas discharge (cf. I-g-1 and Fig. 14). This is the glow-discharge region with normal cathode fall. In other words, the voltage V_{br} across the tube remains practically constant while the current varies within wide limits. The cathode fall of the various types of tubes has a value of between 60 and 160 V. If the pressure in the tube is high and the distance between the electrodes large, *anode fall* amounting to 10 or 20 V may also be present. In such cases, a luminous film or ball will be seen at the anode. The burning voltage is then no longer equal to the cathode fall, but to the cathode fall plus the anode fall.

It should be mentioned that the presence of an anode fall sometimes gives rise to undesired oscillations of the burning voltage.

The potential distribution between the cathode and anode of a stabilizing tube is sketched in Fig. 101. The potential difference between the cathode

k and the glow gl (the cathode fall V_k) is nearly equal to the tube voltage. If the current is increased, the glow spreads out over the surface of the cathode, and the tube voltage remains practically constant until the whole surface of the cathode is covered by the glow. The voltage then increases strongly, as shown by the current-voltage characteristic of Fig. 102 [20].

We have various means at our disposal to obtain a given value of V_{br}: we can choose the composition of the gas and of the cathode material, and we can choose the shape of the electrodes. Table V in section II-c-2-b showed values of the cathode fall for various gases and cathode materials.

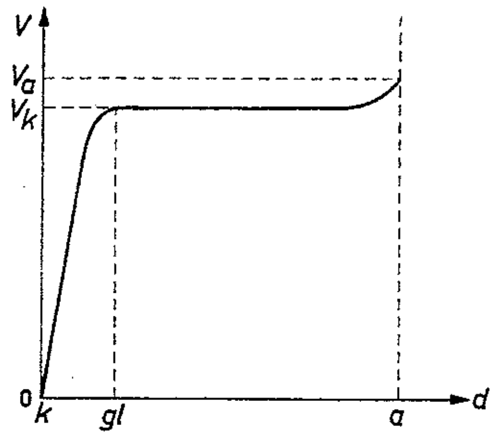


Fig. 101

Potential distribution between the anode k and the anode a of a voltage-stabilizing tube. Most of the tube voltage (the cathode fall V_k) lies between k and the glow gl. V_a is the tube voltage.

A very low tube voltage, e.g. 60 V, can be obtained with a nickel cathode coated with a layer of barium oxide. Another metal which can be used for the cathode is zirconium, with $V_k = 75$ V, and a third is molydenum ($V_k = 85$ V). As we shall see below, molybdenum has some very attractive properties when it is a question of obtaining a very constant burning voltage, if it is treated carefully during the manufacture of the tube. In some tubes, the cathode is made of iron coated with barium or magnesium. V_k then amounts to about 100 V (see Table X in section V-a-2).

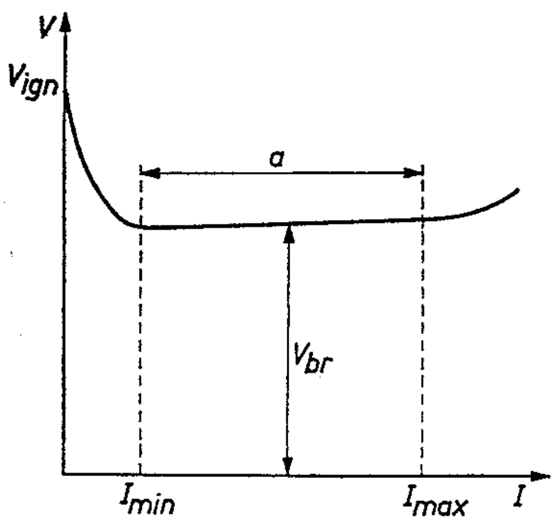


Fig. 102

Current-voltage characteristic of a voltage-stabilizing tube. a is the region of normal glow discharge.

If the stabilizing tube is to do what is expected of it, V_{br} should remain as good as constant while the current increases in the region of normal cathode fall. In other words, it is of prime importance that the impedance or AC resistance R_i of the discharge (i.e. the differential resistance dV_{br}/dI) should be small. This entails that the surface of the cathode should be very clean, since impurities can change the value of φ. If the glow discharge spreads out over such a dirty spot, a relatively large change in V_{br} will be produced. This variation of V_{br} usually takes place in jumps rather than continuously as the current varies. A clean cathode results in a low R_i. Moreover, a carefully prepared cathode may be expected to give a V_{br} which remains constant during the life of the tube and which varies little from tube to tube.

This is especially so for *reference tubes.*

V-a-2 REFERENCE TUBES

Reference tubes are voltage-stabilizing tubes which are used to provide a constant comparison voltage; they are thus rather like standard cells, and are made much use of in control circuits. While care must be taken in the use of standard cells that they do not pass any current, and it is also usual to keep them in a thermostat, the operating conditions for a reference tube are not so strict. On the other hand, the voltage across the latter is only accurate to about 0.1 %, while that of a standard cell is accurate to 0.01 to 0.001 %.

An example of this type of tube is the Philips reference tube type 85 A 2 (1 to 10 mA, 85 V). Fig. 103 shows a sketch of the inside of type 85 A 1, a precursor of the 85 A 2, in which the arrangement of the electrodes can be clearly seen (sealed-off tube, not yet sputtered). The cathode consists of a molybdenum plate, whose surface is cleaned by a special treatment (sputtering). During the cathode sputtering, the walls of the tube become covered with a layer of finely divided molybdenum, which plays an important role in the operation of the tube: not only does it take up impurities which are present in the gas, but it hinders gaseous impurities from being desorbed from the walls.

This molybdenum-sputtering technique enables tubes to be made with a burning voltage which does not vary by more than 0.1 V in 1000 hours of operation. The tubes as manufactured may however show a rather higher variation: the value published in the tube data is a few tenths of a volt. The spread in the value of V_{br} between different specimens of the same type is $\pm$ 1 V to $\pm$ 2 V. Tubes made in other ways may be expected to show a variation of the burning voltage during the life of the tube of about 10 V; the spread in V_{br} will have about the same value. These variations in V_{br} are due not only to impurities in the gas and on the surface of the cathode but also to the polycrystalline structure of the cathode. Recent experiments with monocrystalline cathodes [55] have shown that the spread in V_{br} can be reduced to a few tenths of a volt in this way.

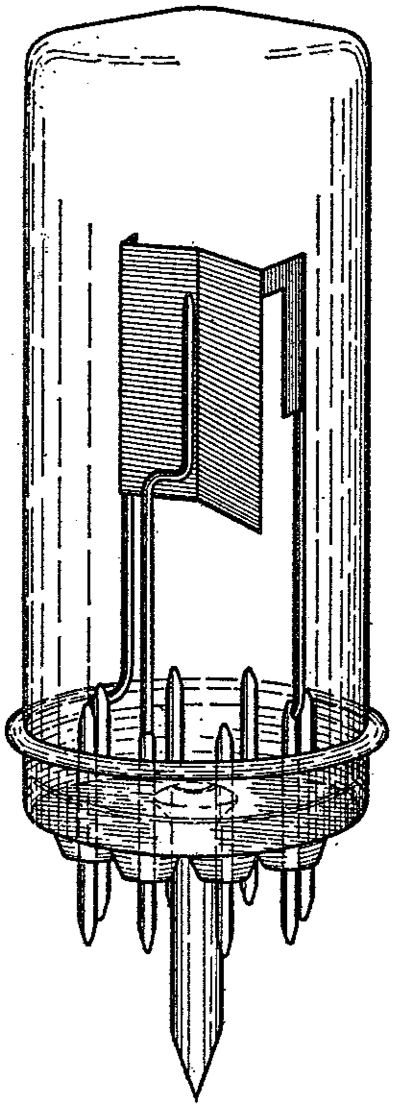


Fig. 103
Electrode arrangement of the (obsolete) Philips reference tube type 85 A 1. The rod -shaped anode is placed near the molybdenum cathode plate. Cathode sputtering has not yet taken place (the envelope is still transparent). Sputtering cleans the surface of the cathode and covers the wall of the tube, with an opaque layer of finely divided molybdenum, which acts as a getter for the gas [19].

Since the sputtering technique makes for a pure gas, the variation of V_{br} with the ambient temperature is also reduced in these tubes. While other stabilizing tubes are quoted as having variations of 20 to 30 mV per degree centigrade, a temperature coefficient of $-$ 4 mV/°C can be reckoned with for the 85 A 2. (The temperature coefficient is negative in tubes where the anode fall is absent.)

It was originally thought that the value of the normal cathode fall was to a first approximation independent of the density of the gas, and thus of the ambient temperature. More accurate investigations of ten years ago have however shown that this is not so [19]. It has however been shown that tubes with molybdenum cathodes can have a very constant and reversible value of the temperature coefficient, which makes it possible to compensate for the variation of V_{br} with the temperature by suitable additions to the circuit.

Fig. 104 shows the miniature model of the 85 A 2. The interior of the tube is in fact hardly visible because of the deposit of molybdenum on the walls.

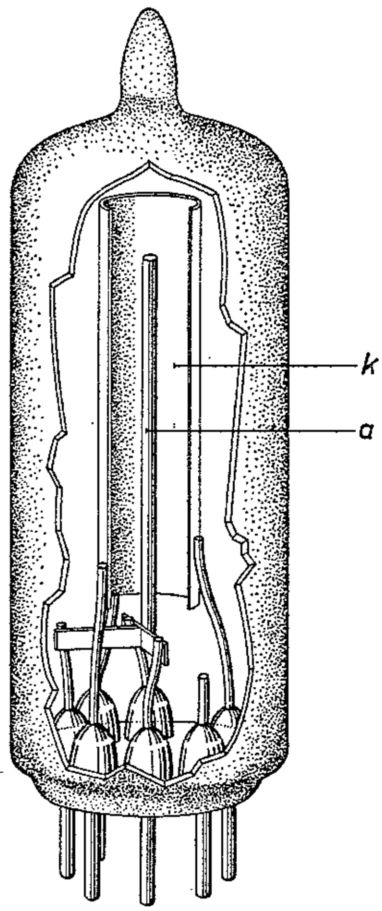


Fig. 104
Cut-away view of the modern reference tube type 85 A 2 with anode rod and coaxial cylindrical cathode.

Another example of a voltage-stabilizing tube is the Philips type 100 E 1, with a nominal voltage of 100 V. This tube is filled with a mixture of helium and argon. The extreme values of V_{br}, as published in the tube data, are 90 and 105 V; but the actual value found for a given tube will usually be much nearer 100 V than this. The current may be from 50 to 200 mA. This relatively high value is made possible by the large surface area of the electrodes (see Fig. 105). The cylindrical coated cathode is surrounded by an anode cylinder on the inside as well as on the outside. The cathode is thus covered with a glow on both sides, giving a low internal resistance.

It may be seen from the figure that the anode cylinders are not coaxial with the cathode. This ensures that the discharge always begins at the same spot, which gives a constant ignition voltage. Moreover, as the current increases the glow spreads evenly across the surface of the cathode, and always in the same way. The probability of voltage jumps is thus reduced.

The internal resistance of a voltage-stabilizing tube is governed by the walls of the tube, among other things. If these are too close to the glow, V_k and R_i may be increased owing to the recombination of positive and negative charge carriers on the walls. This effect is not found with the 100 E 1, because of the screened anode construction.

We may finally mention that there are tubes on the market with burning voltages of up to about 150 V (see table X on p. 148).

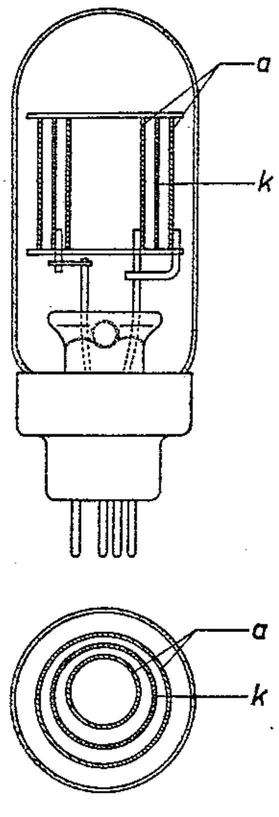


Fig. 105

Voltage-stabilizing tube type 100 E1. The voltage at which tube is stabilized is 100 V, the range of currents from 50 to 200 mA. The cathode cylinder is placed excentrically between the two anode cylinders, so that as the current increases the glow discharge spreads over the cathode in an orderly manner.

Circuits using stabilizing tubes

The principle of the design of a voltage-stabilizing circuit is illustrated in Fig. 106, which shows the simplest circuit of this kind. The voltage V_{aa} feeds both the stabilizing tube B and the load resistance R_o via the series resistance R_s. If e.g. the total current I alters as a result of changes in V_{aa}, the difference current ΔI will flow through B at constant voltage as long as the cathode is not completely covered by the glow. The variation in the voltage, $\Delta V_{aa} = \Delta I \times R_s$, is taken up by R_s.

Under normal conditions R_s is chosen so that the current has the value which corresponds to the middle of the horizontal part of the current-voltage characteristic.

Parallel combination of stabilizing tubes is not possible. The current will always pass through only one of the tubes, because of the negative current-voltage characteristic. If the tube current happens to be so large that it falls outside the stabilization region, a sturdier type of tube must be used.

Series combination is however possible. One example of this is shown in Fig. 107. If it is wished to have a stabilized voltage of 300 V, this can be achieved by three 100-volt tubes, or a suitable combination of tubes with different nominal voltages, in series with the ballast resistance R_s. In order to ensure the ignition of the individual tubes, one or possibly two of the tubes must be provided with a shunt resistance R_{sh} of e.g. 0.5 M Ω. The tube without shunt resistance ignites first, and the remaining voltage is then able to ignite the others.

Table X shows the data of a number of glow-discharge stabilizing tubes.

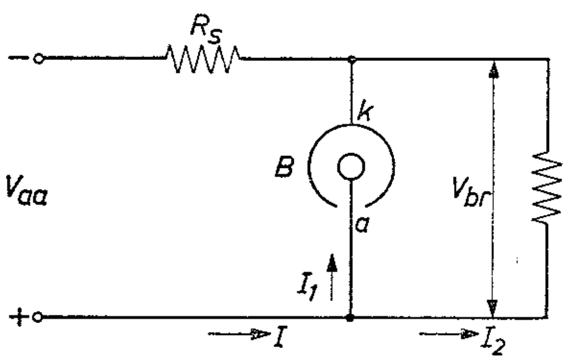


Fig. 106

Circuit for stabilizing the voltage across the load resistance R_O. The difference between the varying supply voltage V_{aa} and the constant tube voltage V_{br} is taken up by the ballast resistance R_s.

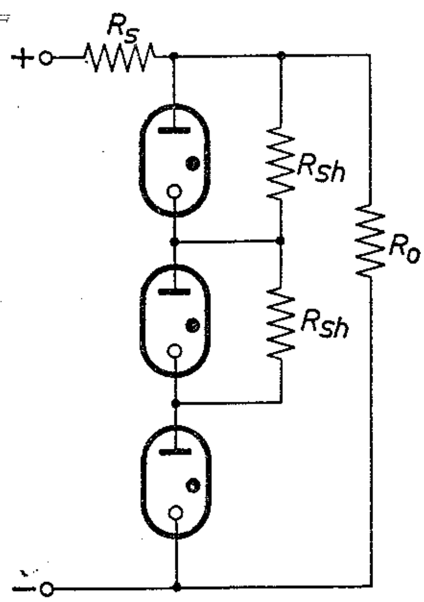


Fig. 107

Stabilizing circuit as in Fig. 106, but for higher voltages. Three tubes are used in series, with one or two shunt resistances R_{sh} (of e.g. 0.5 Mohm) to ensure reliable ignition.

TABLE X

OPERATING DATA OF SOME VOLTAGE-STABILIZING TUBES

TUBE TYPE	85A2 *)	90C1	100E1	OB2	150B2	OA2
nominal burning voltage (volt)	85	90	100	108	150	150
limits of the burning voltage [1]) (volt)	83–87	86–94	90-105	106–111	146–154	144–164
recommended quiescent current (mA)	6	20	125	17.5	10	17.5
max. ignition voltage, in light/in darkness [2]) (volt)	125/160	125/160	125/–	133/210	180/225	180/225
max. internal resistance (ohm)	450	350	30	140	500	240
range of currents (mA)	1–10	1–40	50–200	5–30	5–15	5–30
maximum variation in burning voltage [3]) (volt)	4	14	4	3.5	5	6
max. variation in burning voltage (%) in first 1000 hours at the rated current	0.2 to 0.3 (5.5mA)	± 1 (20mA)	—	± 2 (17.5mA)	± 1 (10mA)	± 2 (17.5mA)
Ambient temperature (°C)	–55/+90	–55/+90	—	–55/+90	–55/+90	–55/+90
Temperature coefficient (mV/°C)	–2.7	—	—	—	10	—

V-a-3 CORONA STABILIZING TUBES

The corona stabilizing tube is very suitable for the stabilization of voltages higher than a few hundred volts at currents of less than 1 mA. Such loads are found e.g. in the control of the intensity of the cathode ray or of the accelerating voltage in oscilloscopes. Much use is also made of such tubes for obtaining a constant voltage in the range from 350 to 700 V at currents of 10 to 100 μA in equipment for measuring radioactivity.

Such a tube consists of a thin anode wire *a* of diameter $Ø_a$ (e.g. some

*) reference tube
1) spread in the burning voltage from tube to tube at the rated operating current
2) during the life of the tube
3) over the whole range of currents

tenths of a millimetre) arranged along the axis of a cylindrical cathode k of length l and diameter $\varnothing_k$ (see Fig. 108). It can be shown that if $\varnothing_k/\varnothing_a$ and $l/\varnothing_k$ are given suitable values, a favourable control characteristic and a low differential resistance R_i (low for corona discharges, that is) can be obtained [67, 85]. The value obtained for R_i may be about 0.2 megohm.

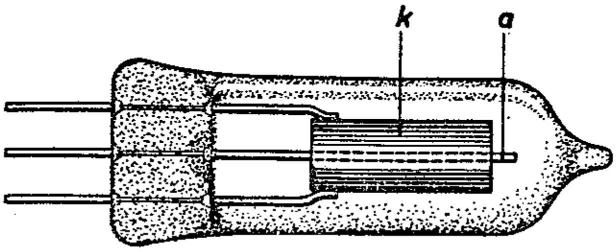


Fig. 108

Corona stabilizing tube. The control region depends on the relative dimensions of the anode wire a and the cathode cylinder k.

The gas filling often consists of hydrogen or a mixture of hydrogen and helium, with a pressure of about 50 mm Hg. As an example, Fig. 109 shows the current-voltage characteristic of an experimental corona stabilizing tube which is filled with hydrogen. The curve usually shifts to somewhat lower voltages during the life of the tube. Under favourable conditions, the voltage decrease is only a few percent in 1000 hours.

V-a-4 HOLLOW-CATHODE STABILIZING TUBE

Another possible basis for the production of a stabilizing tube is the hollow-cathode discharge [68]. A cylindrical hole is bored in a metal block which acts as the cathode. The anode is placed opposite this hole (see

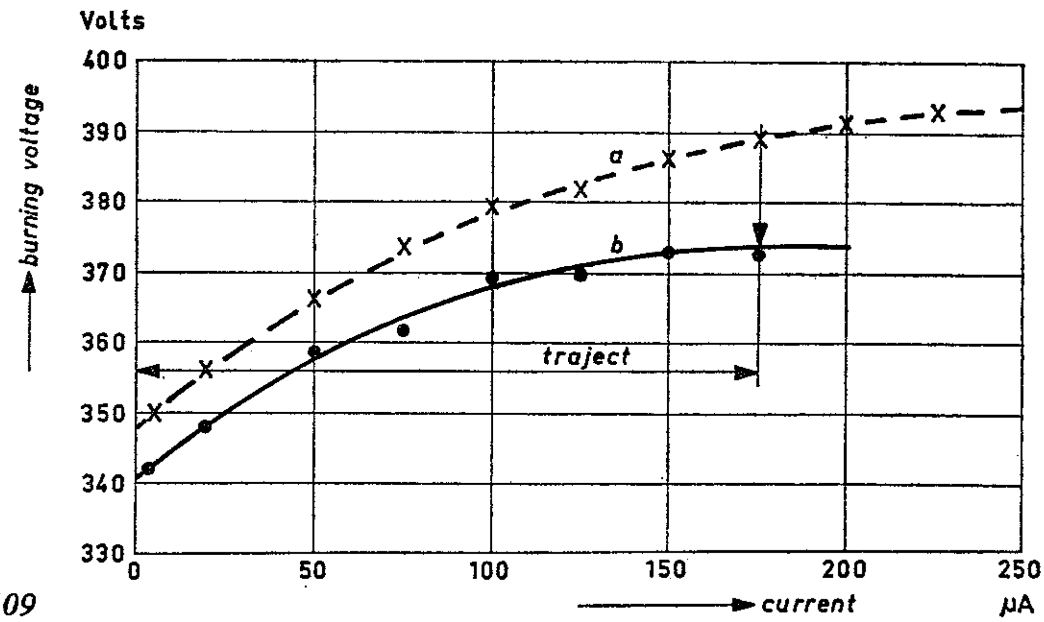


Fig. 109

Current-voltage characteristic of an experimental, hydrogen-filled corona stabilizing tube.
curve a at 0 hours
curve b after 350 hours
"traject" = region between $I = 0$ and I at maximum burning voltage.

Fig. 110 and 111). If the dimensions of the electrodes and the value of the gas pressure are suitably chosen, when a voltage is applied between the anode and the cathode the discharge produced will burn inside the hole, which will gradually change from a cylindrical to a spherical shape as a result of sputtering. The material which is removed from the wall of the hole in some places, causing a widening of the hole, is deposited on other parts of the inner wall. Once the hole becomes spherical, it does not change its shape any more. Gas is absorbed during sputtering. Once the spherical shape has been reached, the gas pressure remains stationary, and the discharge is stable as long as the operating point lies on the horizontal part of the current-voltage characteristic (Fig. 14). This set-up is thus perfectly suitable for use as a voltage-stabilizing tube or reference tube.

The current density can be much higher than at a flat cathode: a current of 50 mA can be obtained inside a spherical hole of about ½ mm radius. Apart from applications in telecommunication, hollow-cathode

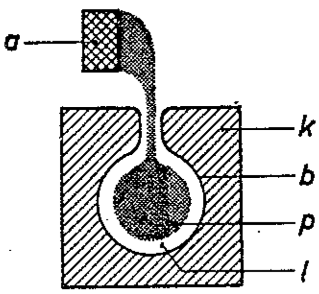


Fig. 110

Principle of the discharge in a hollow-cathode stabilizing tube. a = anode, k = cathode, b = spherical hole, p = plasma, l = ion space-charge layer [68].

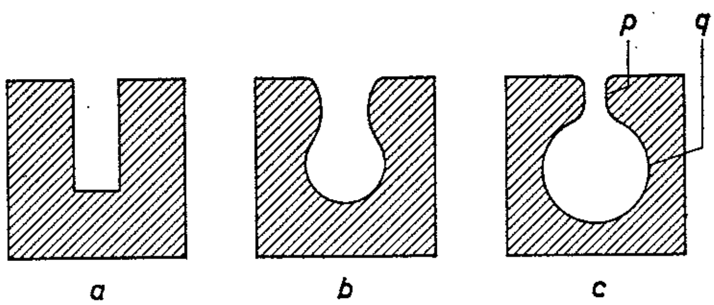


Fig. 111

Formation of the spherical discharge space.

a. Original state with cylindrical bore hole.
b. Intermediate state: the hole is widened by the discharge both at its mouth and in the middle of the cathode block.
c. Stable final state: the mouth of the hole has become narrower, owing to deposition of material removed from the sperical central space [68].

discharges are widely used for experimental work. For example, the very bright light emitted by the discharge during sputtering is characteristic of the metal used for the cathode, and can be used in spectroscopy.

A construction in which this discharge can be approximated to makes use of a cathode consisting of plate bent into the shape of a U (Fig. 112). If the distance d is less than twice the thickness of the glow, the emitted electrons can be efficiently used for the ionization [67]. The fact that the hole is not entirely spherical means however that the cathode material will be attacked, so that sooner or later a hole will appear in it.

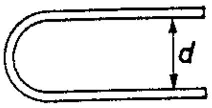


Fig. 112
Construction which gives an approximation to a hollow cathode: a U-shaped cathode plate is used, the distance d between the two limbs of the U being less than twice the thickness of the glow layer.

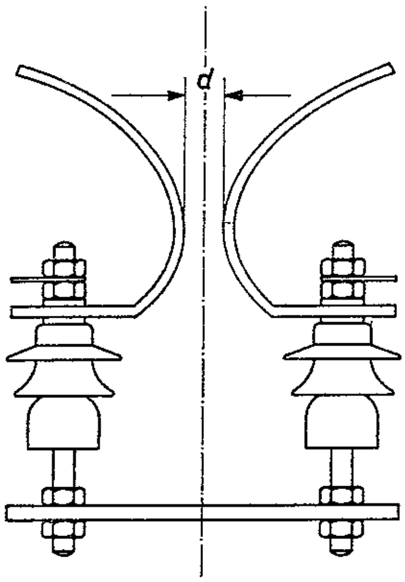


Fig. 113
A spark gap as an example of a conventional surge arrester; this type is known as a "horn arrester".
The shortest distance d between the horns determines the voltage at which the surge energy passes as a spark from one horn to the other.
The arc thus formed between the horns tends to rise because of the heat developed and because of the magnetic field due to the arc current itself; the arc thus becomes longer, and is finally extinguished.

V-b **Surge arresters**

Electrical equipment and mains must be protected against too high voltages or voltage pulses. The insulation between conductors can be broken down by voltage pulses caused by switching operations or atmospheric discharges. Among the classical means of limiting such overvoltages or of leading the excess energy to earth is the spark gap, with or without *horn arresters* for quenching the discharge (see Fig. 113). This does not however work as well as could be wished under some circumstances, e.g. at low voltages. Gas-discharge tubes, usually filled with rare gas, are also used for this purpose. Such tubes are called *surge arresters* [21] or *rare gas cartridges*.

The most important property which such a tube must possess is the ability to ignite with the minimum delay when the voltage exceeds the permissible value. Once it becomes conducting, it must conduct the excess charge away rapidly; and when the voltage falls again to a permissible value, the discharge must be quenched. These properties must not be appreciably altered by the passage of a charge which would be harmful to the equipment which the surge arrester is used to protect, because the arrester must be able to work properly when the next overvoltage comes along. This means, among other things, that the heat capacity of the electrodes is of importance.

Ignition

The *dynamic* ignition voltage of a surge arrester is often more important than the *static* ignition voltage (Fig. 114). A voltage surge is characterized by the duration of its leading and trailing edges, usually expressed in microseconds. The total voltage increase divided by the duration of the leading edge is approximately equal to the *slope of the leading edge* (expressed in kV/μsec), and this quantity determines the dynamic ignition voltage. We have already seen (I-e-1) that a certain time is needed for the discharge to build up between the electrodes of a gas-discharge tube; the dynamic ignition voltage will thus always be greater than the static.

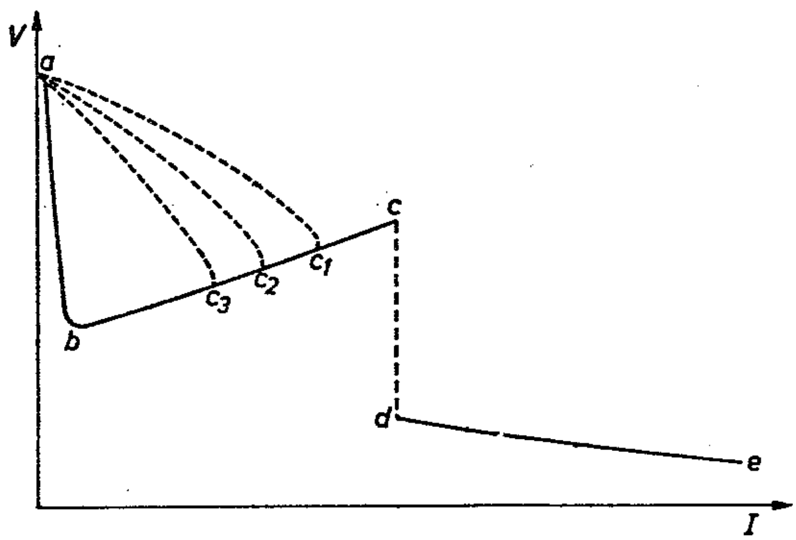


Fig. 114

Current-voltage characteristic of a surge arrester. After breakdown (point *a*), the tube voltage drops to the value corresponding to the point *b*. As the current increases, the positive glow-discharge region *b-c* is traversed. At *c* the discharge changes into an arc with a much lower burning voltage (*d-e*). If the current never reaches value *c*, the discharge will be quenched when the current has decreased to *b* again. In fact, in the very short time during which a discharge is produced, the relationship between current and voltage will not follow the static characteristic *a-b-c*, but one of the dynamic characteristics ac_1b, ac_2b, ac_3b, etc.

However, the breakdown of the insulation material to be protected also requires a certain time. What really matters therefore is that the dynamic ignition voltage of the surge arrester should be less than the dynamic breakdown voltage of the insulation material in parallel with it.

Now all sorts of overvoltages occur in nature, each with its characteristic form. A *standard wave* has therefore been defined, which can be produced by a pulse generator and used to test surge arresters. The form of this artificial voltage surge is shown in Fig. 115, together with the definitions of the quantities which characterize it. It may be mentioned that in atmospheric discharges, which are much more common than direct hits by lightning, the leading edge lasts 1 to 10 μsec., and the trailing edge 5 to 100 μsec. The current-voltage characteristic of the surge arrester is determined with the aid of the pulse generator and an oscilloscope, and the dynamic ignition voltage read off from this curve.

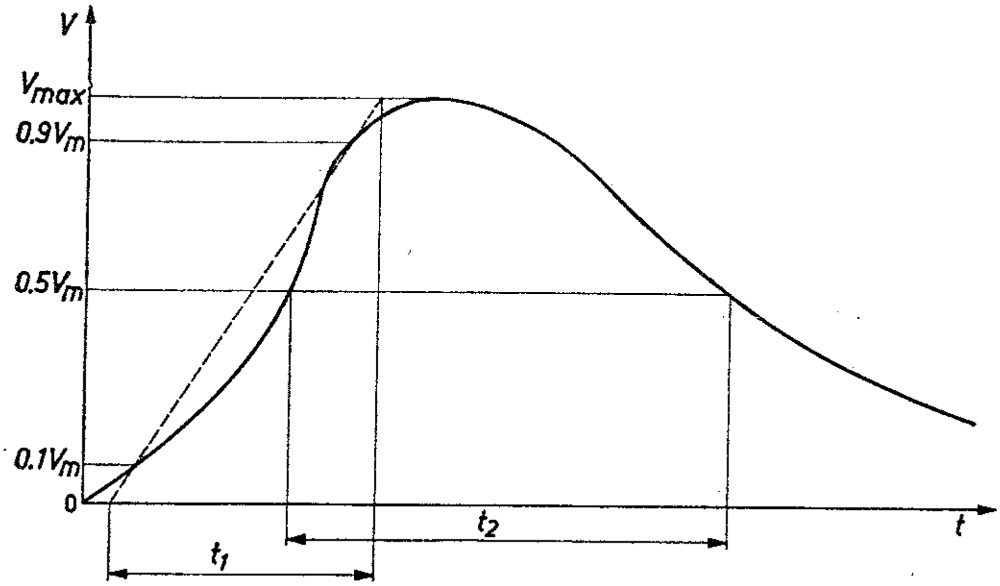


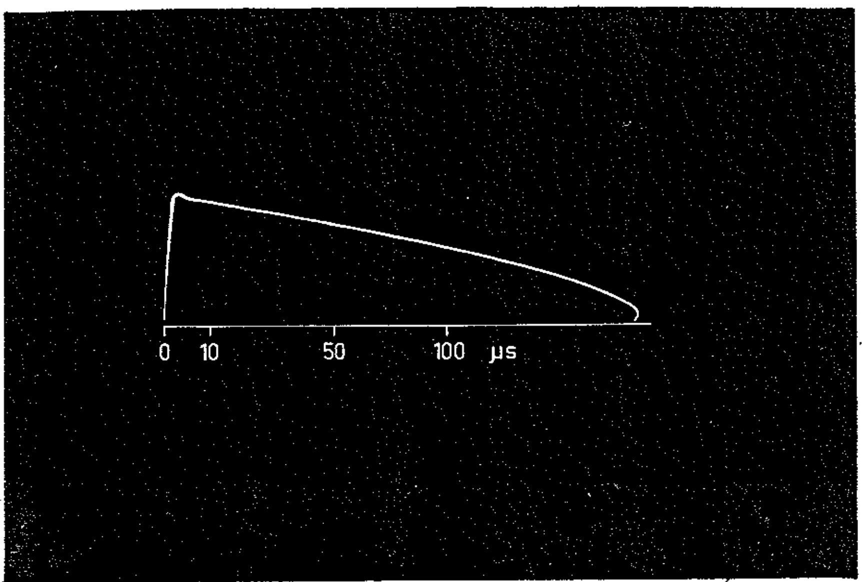
Fig. 115

Form of a "standard wave" (surge-voltage wave) for testing inert-gas surge arresters. The definitions of the front length, t_1, the front slope, V_m/t_1, and the rear length t_2 are made clear in the figure.

The behaviour of a surge arrester during a test is illustrated by the oscillogram of Fig. 116 [22]. The delay in ignition which can be seen here must be made as small as possible. Illumination of the surge arrester with weak daylight or artificial light is usually sufficient to ensure this; sometimes a small amount of some radioactive substance is placed in the tube for the same purpose. The electrodes are usually coated with a layer of material with a low φ, e.g. a calcium compound, in order to give a low ignition voltage.

Quenching

The discharge must cease at a voltage which is sufficiently far above the voltage of the mains to be protected, and the discharge must be quenched quickly. The composition and pressure of the gas in the tube are of importance in this respect; e.g. nitrogen at high pressure may be used. A special series resistance is often made use of too, to make certain that the discharge will be quenched properly. This resistance must not be ohmic, as it would then hinder the rapid removal of the energy of the a



b

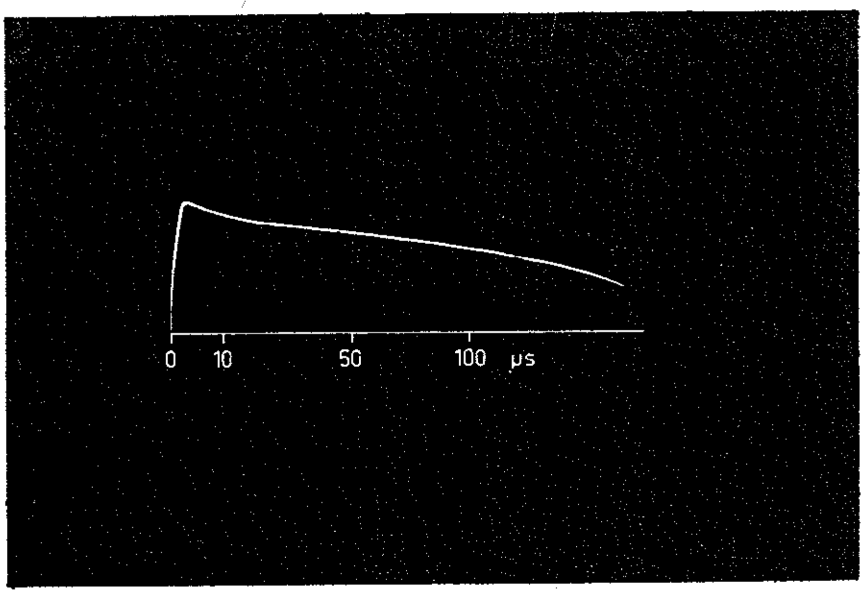


Fig. 116
a current, *b* voltage of a Philips surge arrester type 4394 as a function of time for an overload surge of 300 A. The maximum current is 300 A, the maximum voltage 1320 V. The front slope of the surge is 30 kV/μsec [22].

voltage surge. Voltage-dependent resistors (VDR) are used for this purpose; they are made of a sort of semiconducting material like silicon carbide. The relation between the voltage and the current for such a resistor has the form

$$V = C \cdot I^{\beta}$$

where $\beta = \tan \varphi$ is the slope of the approximately straight part of the voltage-current characteristic (Fig. 117) and C is the voltage at which $I = 1$ amp.

It is clear that the removal of the energy at high voltage is little hindered, but that the current through the surge arrester will decrease as soon as the surge has passed, which makes for rapid quenching. The resistor is usually included in the tube to exclude atmospheric effects on it.

Loadability

If the surge arrester is to continue to meet the demands made on it after a current has passed through it, the load to which it is subjected must not exceed a certain value. This load is expressed in watt-seconds. The sturdier type of Fig. 118 can stand 500 Wsec, and the type of Fig. 119 and 120 10 Wsec.

Typical application

Equipment such as kWh-meters which are attached to a high-current

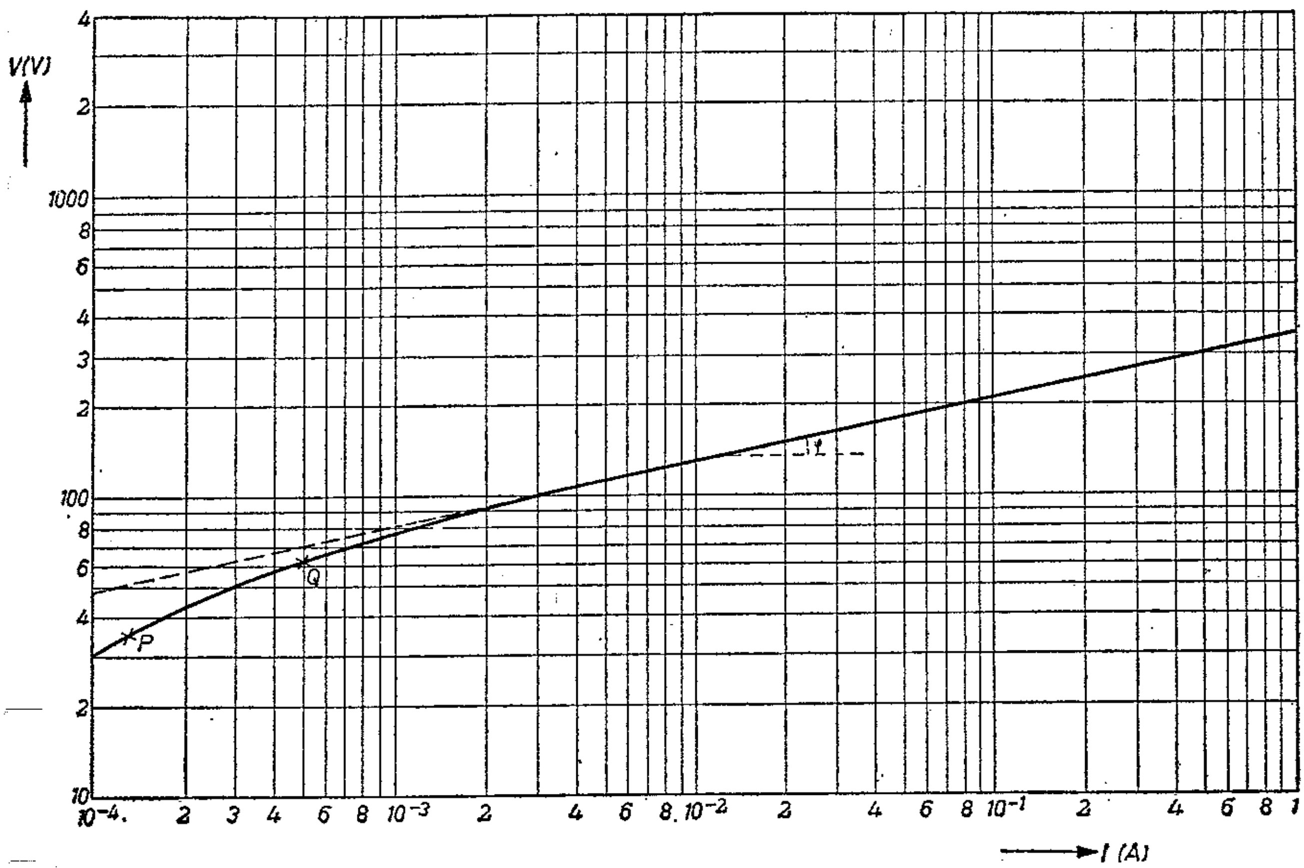


Fig. 117

Voltage-current characteristic of a VDR resistor plotted on a logarithmic scale. $C = 340$; $\beta = 0.21$.

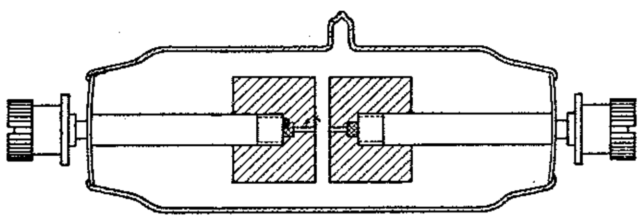


Fig. 118

Philips inert-gas surge arrester type 4390 in section. In the electrodes may be seen the cavities containing an alkali salt. A little of this compound evaporates at each discharge, and is deposited on the surface of the electrodes, among other places. This reduces the work function of the electrodes and thus the ignition voltage. The electrode leads pass through chrome-iron discs which are sealed into the glass envelopes. A large current surge can thus pass through the tube without danger of the glass breaking near the seal. Overall length 95 mm.

power transmission line for low voltages must be protected against breakdown as a result of overvoltages. If we assume that the line has a rms voltage of 220 V with respect to earth, the Philips tube type 4390 can be used for protecting it (see Fig. 118). The two electrodes are identical, as in most surge arresters, so it can be used with alternating current. The circuit is shown in Fig. 121.

The electrical data of this tube (and two similar ones) are given in the table below.

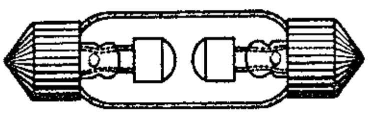


Fig. 119

Philips inert-gas surge arrester type 4371. The electrodes, made of a special alloy, are mounted on pinch seals. The tube with its two terminal caps can simply be pressed in place between two contact springs. Overall length 50 mm.

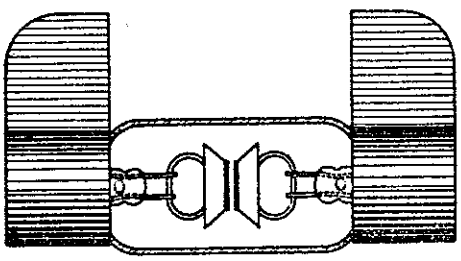


Fig. 120

Philips inert-gas surge arrester type 4372, with knife contacts. Length 62 mm.

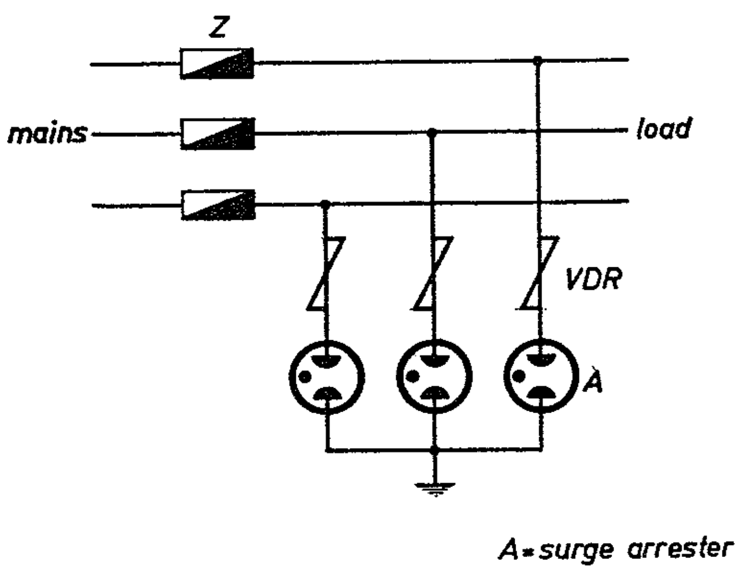


Fig. 121

Circuit with three surge arresters A and three VDR resistors for protecting a load connected to the 3-phase mains against overvoltages. Z = fuse.

TABLE XI

PHILIPS SURGE ARRESTER TYPE	4390 Fig. 118	4371 Fig. 119	4372 Fig. 120
static ignition voltage	700—910 V	150—200 V	280—350 V
min. quenching voltage	200 V	110 V	250 V
max. instantaneous peak current permissible for	25A/3 sec	5A/3 sec	2.5A/1 sec
fuse in series with surge arrester	25A	6A	6A
max. capacitive discharge (repeatedly permissible)	500 Wsec	10 Wsec	10 Wsec
max. mains voltage	175 V$_{\overline{\overline{---}}}$ 300 V_{rms}	70 V$_{\overline{\overline{---}}}$ 75 V_{rms}	200 V$_{\overline{\overline{---}}}$ 180 V_{rms}
overall length	92.5—98 mm	49—52 mm	60—65 mm
diameter	max. 26.5 mm	max. 14.5 mm	max. 19.5 mm

The ignition voltage given above was determined with 50 c/sec AC. The dynamic ignition voltage is considerably higher: measurements with a standard voltage surge gave values of 1500 to 3500 V. A suitable voltage-dependent resistor is included in series with each surge arrester, which ensures quick quenching when the normal operating conditions are regained. A normal fuse is also placed in each lead as an additional precaution.

V-c **Ionization tubes**

Introduction

Various methods are available for the measurement of gas pressures below about 10^{-3} torr *) with measuring instruments which give a continuous indication of the (possibly variable) pressure. Some of these methods involve the measurement of the pressure itself; others are based on properties of the gas which depend on the pressure. In this section we shall only consider those pressure gauges based on gas discharges:

1. the ionization gauge, for pressures from 10^{-3} to 10^{-12} torr;
2. the Penning gauge; the range of pressures may be 10^{-3} to 10^{-6} torr or 10^{-3} to 10^{-9} torr, depending on the type of gauge;
3. the Hobson-Redhead gauges, which can still be used at pressures of 10^{-12} or 10^{-13} torr.

*) 1 torr = 1 mm Hg

V-c-1 IONIZATION GAUGES *)

A heated filament emits electrons, which are accelerated in an electric field and used to ionize atoms of the gas whose pressure is to be measured. Measurement of the ion current allows the gas pressure to be determined. We are thus dealing with a non-self-sustaining discharge in the gas in question.

The pressure must be less thans about 10^{-3} torr, because above this pressure there is a risk that the discharge will become self-sustaining and destroy the gauge.

This gauge can be made as a triode or as a tetrode. The triode consists of a cathode filament, an anode grid for the acceleration of the emitted electrons, and an ion collector. The tetrode has, in addition to these three, a stabilizing grid in order to keep the electron current constant during the measurement.

An extra filament is sometimes also included as a spare, but this is not essential for the operation of the tube. In our further discussion of the ionization gauge we will restrict ourselves to the triode model.

At the low pressures for which this gauge is used (10^{-6} to 10^{-12} torr), the number of ionizations per electron is directly proportional to the pressure. Since the mean free path of the electrons at these pressures is large compared to the distance between the anode and the cathode, the probability of ionization by an electron moving from the cathode to the anode is small. If the path of the electrons can be increased in some way, the number of ionizations will increase in proportion, and the ion current at a given pressure will be greater, i.e. the sensitivity of the gauge will be greater. We will now describe how this is done.

In the triode ionization gauge shown in Fig. 122, the central filament f provides the primary electrons. These electrons are made capable of ionization by the anode a (accelerating electrode) which is arranged concentric with f. The distance between f and a is small compared with the mean free path of the electrons. Since a is made in the form of a grid, electrons can pass through it into the space between it and the third electrode, the ion collector Cl, which is made a few volts negative with respect to f. The electrons will then travel several times to and fro between f and Cl and will thus have more chance of ionizing an atom or a molecule. Experiments have shown that with most gases the ionization is maximum when the electron energy is about 100 eV (cf. I-d-3). The sensitivity of

*) Though these gauges do not contain a cold cathode we will mention them as a suitable introduction.

the instrument is thus large if a is made about 100 V positive with respect to f.

The pressure is proportional to the ratio I^+/I^-, where I^+ is the measured ion current at Cl. The electron current I^- from the cathode is set to a relatively high value, e.g. 10 mA, so that the small ion current which goes to f does not have any effect on the value of I^-. The ion current is dependent on the nature of the gas, since the ionization probability depends on the gas involved; this means that the pressure of an unknown gas or mixture of gases cannot be determined accurately in this way. Pressures of down to 10^{-8} torr can be determined with the gauge shown in Fig. 122. Special models can measure down to 10^{-12} torr.

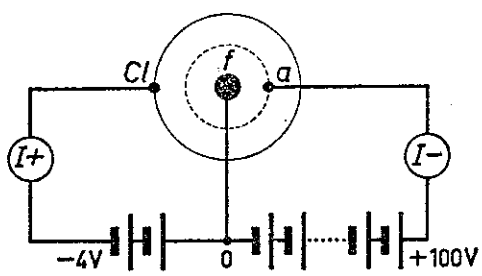


Fig. 122
Ionization manometer for measurement of pressures down to about 10^{-8} torr. A part of the electrons coming from the heater f pass through the meshes of the anode grid a and ionize the gas in the space between a and the ion collector Cl. The ratio of the ion current I^+ to the electron current I^- is a measure of the pressure.

One of the reasons for the above-mentioned lower limit for the pressure which can be measured is that soft X-rays are produced by the collision of the electrons with the accelerating electrode. This radiation frees photo-electrons from the ion collector, which add to the ion current to be measured and thus interfere with the result. Bayard and Alpert [59] designed another electrode arrangement which does not suffer so much from this trouble. They used a thin wire as the ion collector, with an anode cylinder round it and the hot cathode outside that. An arrangement of this type is shown in Photo 8. The chance of electron emission by the ion collector is much reduced, so that pressures down to 10^{-12} torr can be measured with this gauge.

Such an instrument is also sometimes used as a vacuum pump at low pressures [60]. If the potential of the wall and of certain electrodes is chosen properly, the ions are trapped. This effect can be a nuisance when the tube is used as a vacuum meter, since the pressure changes during the measurement.

If it is possible to increase the path of the electrons even further, the ionization will be amplified too. This possibility is realized in the Penning gauge, which we will now discuss.

V-c-2 PENNING GAUGE

The Penning gauge makes use of a self-sustaining discharge [23, 24]. If a DC voltage or a low-frequency AC voltage of about 1000 V is applied between the cold electrodes of a gas-filled tube, it has been found to be impossible to maintain a self-sustaining discharge if the gas pressure falls below 10^{-3} torr. However, if the shape and arrangement of the electrodes is properly chosen and a magnetic field is used, the discharge can be maintained down to pressures of 10^{-7} torr or even less.

There are two types of Penning gauge: a sensitive one and a less sensitive. Fig. 123 shows the arrangement of the electrodes and the magnet of the less sensitive type, for pressures between 10^{-3} and 10^{-5} torr. The cathode consists of the two plates P_1 and P_2, with the frame-shaped anode a in between. A magnetic field H is applied in the direction P_2—P_1. If this field were not there, electrons leaving P_2 or P_1 would go directly

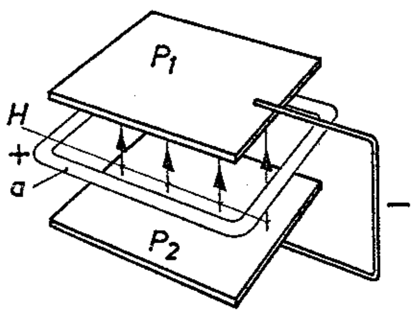


Fig. 123

Principle of the operation of a Penning gauge. A frame-shaped anode a is placed between two (cold) cathode plates P_1 and P_2
The electrons coming from P_1 and P_2 move along spiral paths because of the magnetic field H applied between P_1 and P_2, and pass to and fro several times before finally landing on a. The ionization probability is thus considerably increased, so that pressures down to 10^{-5} torr can be measured.

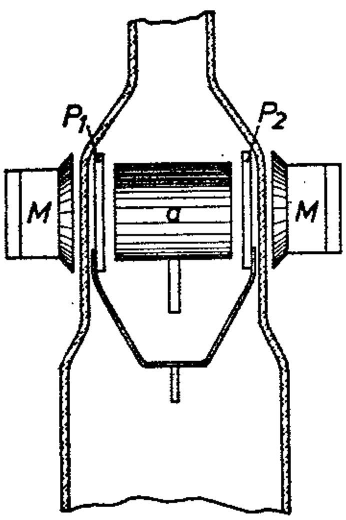


Fig. 124

Improved Penning gauge, with a cylindrical anode a placed between two cathode plates P_1 and P_2. The magnet M provides a magnetic field along the axis of a. The range of measurable pressures extends down to 10^{-9} torr.

to a. In the presence of a sufficiently strong magnetic field, however, electrons coming from P_1 move along narrow spiral paths in the direction of P_2. After passing through a, the electrons find themselves in an electric field of the opposite sign and are decelerated. Just in front of P_2 they reverse direction and return towards P_1 along spiral paths. This process may be repeated several times before the electrons finally reach a. Thanks to the considerable increase in the distance travelled by the electrons, the ionization probability increases so that even at very low pressures enough collisions with gas molecules occur to maintain a self-sustaining discharge.

The construction of the more sensitive type, for pressures down to 10^{-9} torr, is shown in Fig. 124. The cylindrical anode a is placed between the two disc-shaped cathodes, P_1 and P_2, while the field of the permanent magnet M is parallel with the axis of a. It has been found that zirconium is a suitable material for the cathode. The magnetic field has a strength of $3 \times 10^5/4\pi$ to $4 \times 10^5/4\pi$ A/m. The gauge can be made less sensitive, i.e. suitable for the measurement of higher pressures, by removing the magnetic field or by changing the polarity of the electrodes.

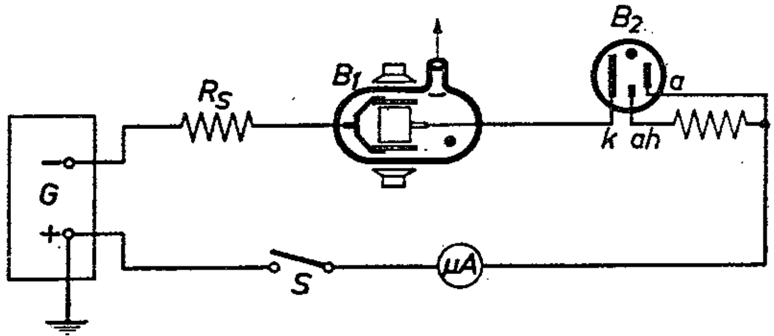


Fig. 125

Measuring circuit for a Penning gauge B_1. The magnitudes of the electron current and ion current can be read off from a μA meter or indicated by a tuning tube B_2 (cf. V-e-2). G is the DC voltage source, R_s a current-limiting resistance.

The measuring circuit shown in Fig. 125 consists of the Penning gauge B_1 in series with a microammeter and a limiting resistance R_s of 1 megohm. A tuning tube B_2 (see V-e-2) is often used to give a rough indication of the magnitude of the current. The supply voltage of 2000 V is supplied by the rectifier G. The variation of the current with the pressure for nitrogen, air and helium is shown in Fig. 126. In contrast with the well known McLeod gauge, the Penning gauge can also be used for condensible vapours.

This instrument is suitable not only for the continuous recording of pressures but also for the indication and detection of small leaks in vacuum equipment [24].

Like the ionization gauge, the Penning gauge can also be used as a vacuum pump at low pressures [24]. This must be borne in mind when it is used as a pressure gauge, as it will cause the pressure to change during the measurement.

Difficulties crop up if the Penning gauge is used to measure pressures below about 10^{-9} torr. In the first place, the discharge may fail to ignite at these low pressures, but the use of a Tesla coil usually solves this problem. Apart from this, the lowest measurable pressure is determined by the occurrance of field emission from the cathode plates at places where the field is high. The modification suggested by Hobson and Redhead brings about a great improvement in this respect.

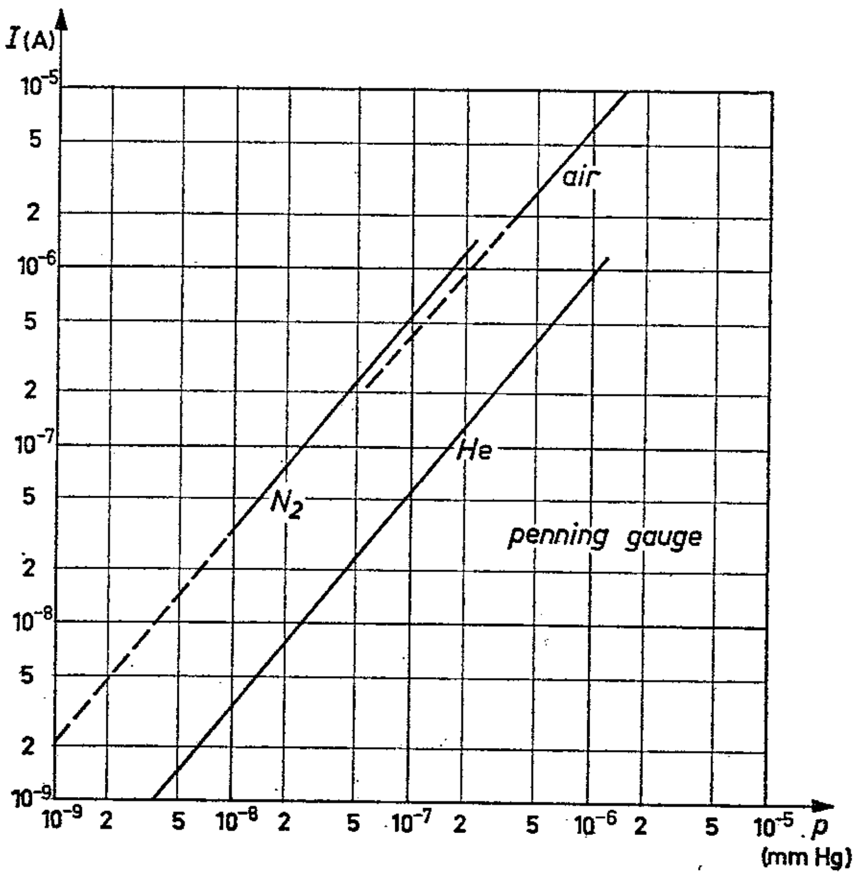


Fig. 126

Tube current as a function of pressure for nitrogen, helium and air, for the Penning gauge of Fig. 124.

V-c-3 HOBSON-REDHEAD GAUGES

In 1958 Hobson and Redhead suggested a number of designs, more or less based on the Penning gauge, in which the current due to field emission is kept separate from that due to ionization alone. Their "inverted magnetron gauge" (Fig. 127) has an anode wire placed in the direction of the magnetic lines of force, surrounded by the cylindrical box *Cl* which acts as the ion collector. The outer cylinder Cl_h is used as an auxiliary cathode, and shields the anode electrostatically from *Cl* by means of the tubes *d* connected to it. The ion current to *Cl* is measured separately. It is claimed that this pressure gauge can be used down to a pressure of 2×10^{-12} torr [61]. Their later design, the "magnetron gauge" (Fig. 128), is even more sensitive; it can be used down to 10^{-13} torr [62]. In this model, the magnetic field is parallel to the cylindrical anode *a*, which is placed between two collector plates *Cl* which are connected to each other. The edges of *a* are shielded by the two auxiliary cathodes Cl_h.

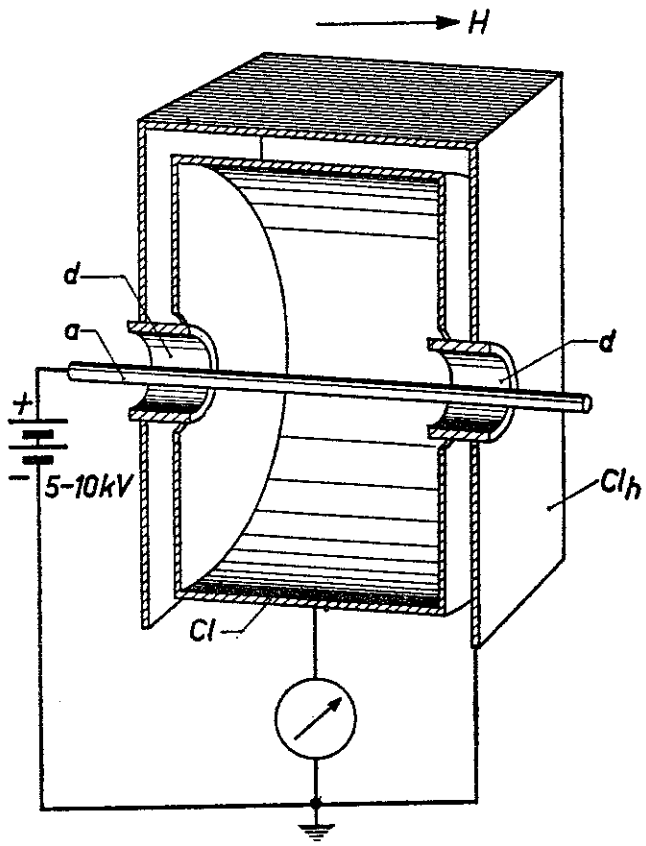


Fig. 127
Hobson-Redhead "inverted magnetron gauge". The outer mantle Cl_h screens the anode *a* from the collector *Cl*. The field-emission current is thus kept separate from the ion current. The lowest measurable pressure is about 2×10^{-12} torr [61].

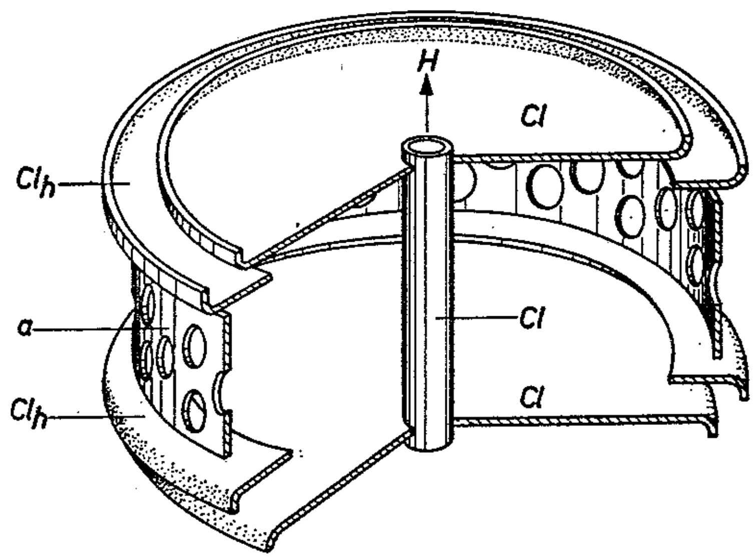


Fig. 128
Hobson-Redhead magnetron gauge. The flanges Cl_h screen the anode *a* from the ion collector *Cl*. Lowest measurable pressure about 10^{-13} torr [62].

V-d **Radiation counter tubes** [69, 84, 93]

V-d-1 INTRODUCTION

The phenomenon of radioactivity and the transmutation of the elements have been known for many years, but recently they have gained the attention of investigators outside the field of nuclear physics. The applications of radioactivity, nuclear fission and the interaction of radiation with matter have increased very considerably of recent years. Among these applications we may mention:

chemical investigations using tracers,
generation of energy by means of nuclear fission,
measurement of thickness with the aid of radioactive radiation.

In all these problems the detection, i.e. the observation, of the radioactive radiation plays an important part. Gas-filled detectors, in particular counter tubes, were the first devices to be used for this purpose.

The operation of a radiation detector is based on the principle that the kinetic energy of the incident particle or the quantum energy of the γ radiation is transformed into an electrical current pulse. This pulse is amplified if necessary and then measured or recorded with the aid of fairly simple equipment. The construction of the detector depends on the nature of the particles which must be detected: there are different types of detectors for α particles (doubly ionized helium atoms), β particles (electrons and positrons) and γ rays (electromagnetic radiation similar to X-rays).

V-d-2 RADIOACTIVITY

The phenomenon of radioactivity consists in the spontaneous disintegration of atomic nuclei with the emission of α particles, β particles and/or γ rays. Following on this disintegration, X-rays may also be emitted as a result of the rearrangement of the electronic shells. Nuclei may be divided into two sorts: radioactive, or unstable, and stable. Radioactive nuclei can be further divided into two groups: naturally occurring ones, which are to be found as such in the earth's crust, and artificial ones which are made in particle accelerators and reactors.

The nucleus of an atom is thought to consist of protons and neutrons. The chemical nature of an element appears to be determined by the number of protons only. A given chemical element may thus have several different kinds of nuclei, all with the same number of protons but with different numbers of neutrons. These different sorts of nuclei belonging to one element are called isotopes. Most elements have both stable and unstable isotopes. For example, hydrogen has two stable isotopes, H^1 and H^2, and one unstable one, H^3, these three isotopes contain 0, 1 and 2 neutrons per nucleus respectively. The unstable isotopes are known as radio-isotopes. Well known natural radio-isotopes are uranium and radium, and well known artificial ones e.g. sulphur (S^{35}), phosphorus (P^{32}) and carbon (C^{14}).

The α and β particles are both electrically charged particles, and as a result of their rapid motion they will ionize gases which they pass through, forming ion pairs consisting of an electron and a positive ion. Electromagnetic radiation such as X-rays or γ rays can not ionize gases in a direct way. But they can produce secondary electrons (or positrons) in matter, and each of these "secondary" charge carriers can give rise to a large number of ionizations in the gas because of the large energy it acquires from the radiaton.

α and β particles can be characterized by the following quantities:

electrical charge,
mass,
velocity and
kinetic energy.

The kinetic energy is expressed in keV or MeV (= 10^3 eV and 10^6 eV respectively). Electromagnetic energy is characterized by its wavelength or quantum energy; these two quantities are related by Planck's law

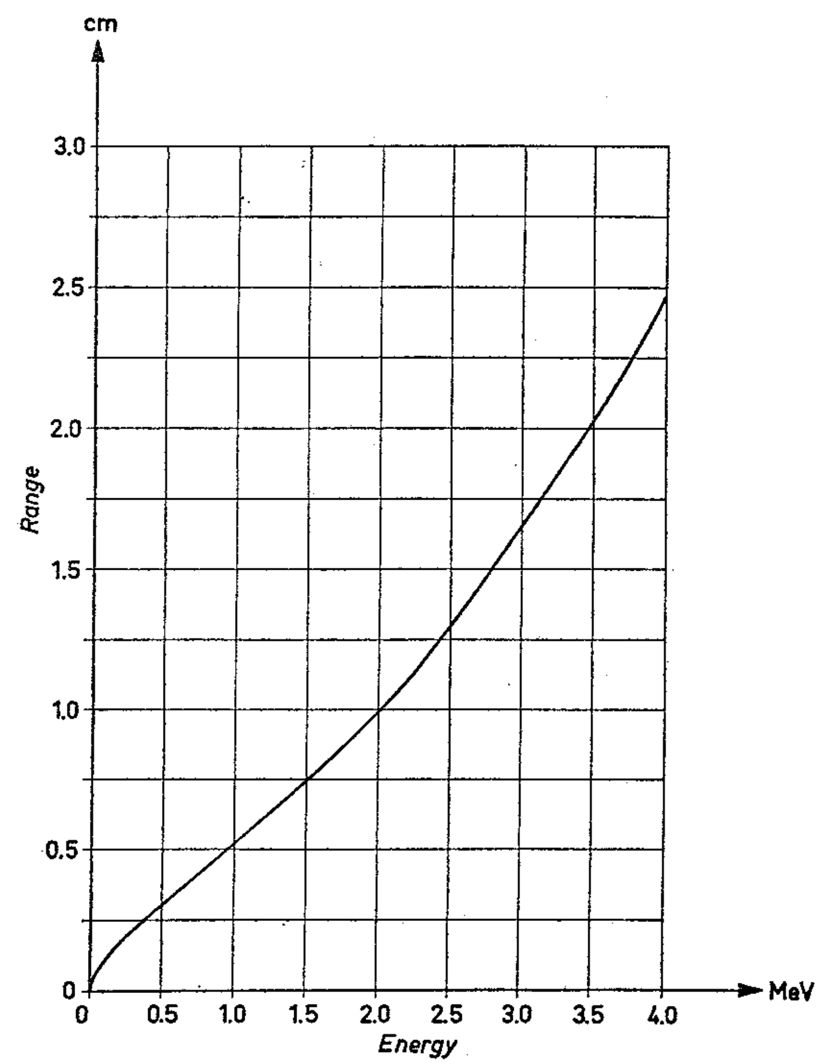


Fig. 129

Range-energy curve for alpha-particles in air (15 °C, 760 mm). Energy range 0 to 4.0 MeV [93].

($eV = h\nu$). The quantum energy is also expressed in keV or MeV. Other quantities which are characteristic for α and β particles and γ rays are their *penetrative power* and their *absorption coefficient,* and with α and β particles their *range,* i.e. the maximum distance they can penetrate into the material in question. The range is usually expressed in mg/cm^2, sometimes however in cm (Fig. 129).

V-d-3 DETECTION OF ELEMENTARY PARTICLES AND RADIATION WITH THE AID OF GAS-FILLED DETECTORS

The detection of radiation with the aid of these detectors is based on the fact that fast-moving charged particles ionize a gas in passing through it. This phenomenon is called *primary ionization,* in contrast to secondary ionization, which is discussed below. (The term primary ionization is used to represent not only the process of ionization, but also the magnitude and sign of the charge produced). The gas-filled space of the detector contains two electrodes. This may be seen in Photo 9, where the wire acts as the anode and the outer cylinder as cathode. If the voltage between these two electrodes is increased from zero, a series of different phenomena will be observed. In our discussion of these, we will assume that the position of the source of radiation with respect to the detector does not alter while the voltage is being increased, and that the radiation from the radioactive sample does not alter in the period in question. Fig. 130 shows the magnitude of the current pulses as a function of the voltage between the electrodes under these conditions. The lower curve refers to an experiment where the primary ionization was produced by electrons; the upper curve refers to α particles. It is clear from these curves that the primary ionization produced by α particles is considerably greater than that produced by electrons. If we plot the logarithm of the magnitude of the current pulses against the voltage, we see that the current first increases from zero to a certain value, and then remains constant over a certain range of voltages. If the voltage is increased further, the logarithm of the magnitude of the pulses increases linearly with the voltage. Finally the curve levels off again, and we see that at a certain voltage V_s the magnitude of the pulses produced by β particles is equal to that for α particles. This is called the start of the Geiger region.

The region in which the current through the tube is independent of the tube voltage is called the saturation region (*B*). All the charges landing on the electrodes come from the primary ionization caused by the incoming particles. There is no loss of charge due to recombination or diffusion, and neither is there a multiplication process which increases the number of charge carriers. To the left of the saturation region, we see a region in which charge is lost by recombination and diffusion (A). The higher the voltage, the less effect these two processes have. This region is of little importance for the use of the tube as detector.

Detectors which are designed for use in the saturation region are called ionization chambers.

The proportional region (C) lies to the right of the saturation region; here the current increases approximately exponentially with the tube voltage, so that the logarithm of the current is a linear function of the voltage. In this region we find a new phenomenon: gas amplification due to ionization by collision.

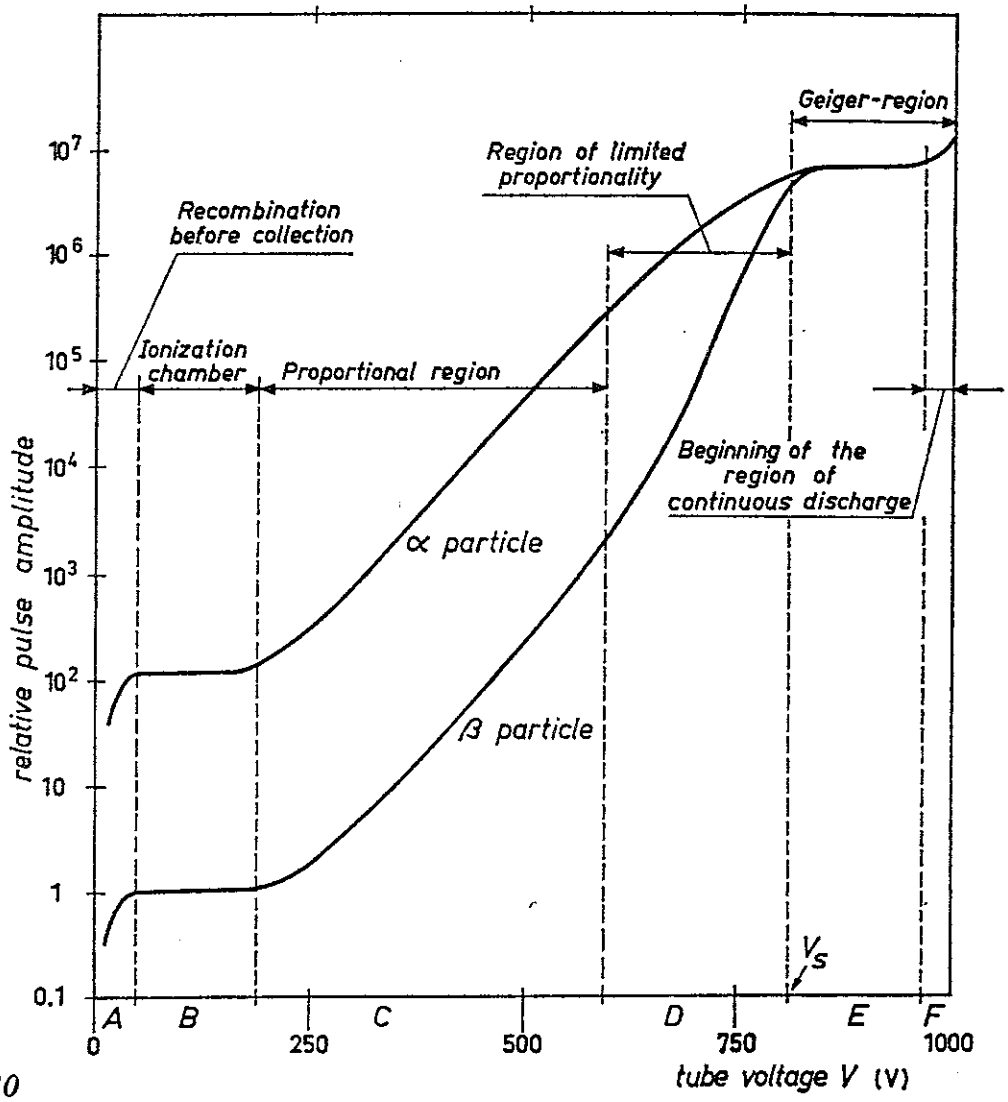


Fig. 130

Pulse amplitude as a function of tube voltage for ionization, proportional and Geiger regions of operation.

A = region with recombination and diffusion
B = saturation region
C = proportional region
D = region of limited proportionality
E = Geiger region
F = spurious-discharge region

The primary electrons move towards the (thin) anode, and where the electric field is strong enough they will give rise to ionization. The electrons produced in this way will cause further ionizations in their turn, so that the current will be considerably amplified (avalanche effect). The *gas-amplification factor* is defined as the ratio of the total charge which reaches the anode to the primary ionization.

If the composition of the gas and the shape of the electrodes are chosen properly, gas-amplification factors of up to 10^6 can be obtained before the system starts to be complicated by e.g. avalanche formation by photons (cf. V-d-6). The ionization is restricted to the immediate vicinity of the track of the incoming particles, and the current pulse is proportional to the primary ionization.

The Geiger region (E) is characterized by the fact that the size of the charge arriving at the anode is independent of the magnitude of the primary ionization. Thus, the current pulses due to α and β particles are the same size as each other, even though the primary ionization due to an α particle may be a factor 10^5 more than that due to a β particle. The lower limit of the Geiger region is sometimes called the Geiger threshold voltage (V_s). In the Geiger region, the magnitude of the current is independent of the primary ionization, but increases linearly with the voltage between the electrodes i.e. in proportion to the difference between the working voltage and the ignition voltage. The Geiger region usually extends over several hundred volts. It is bounded at high voltages by the spurious-discharge region (F) in which each particle to be counted may give rise to more than one current pulse. At slightly higher voltages, the tube goes over to a continuous discharge.

The proportional region and the Geiger region are separated by the region of *limited proportionality* (D). The charge produced per particle is here no longer proportional to the number of primary ionizations, but there is still some difference between the current pulses produced by α particles and those produced by β particles. The ratio of the charge pulses of α particles to those of β particles is lower than the ratio of the primary ionizations. This is due to space-charge effects: the first avalanche produces such a large positive space charge that the last avalanche reaches the wire at the moment when the electric field is already reduced by the space charge, so that the gas amplification is decreased.

V-d-4 THE IONIZATION CHAMBER

The ionization chamber operates in the saturation region, and it can be used either to count the integrated number of particles or to count the particles individually.

If the gas filling is chosen properly, an α particle can give rise to 10^5 ion pairs in the tube. If the ionization chamber is designed with a low capacitance, the voltage pulses due to the individual α particles may be large enough to stand out above the noise due to the amplifier. The range of a β particle in air is of the order of one metre. An electron will thus be able to lose only a small part of its kinetic energy by ionization within an ionization chamber of the normal size. The primary ionization caused by the electron will then in general not exceed 100 ion-electron pairs. This means that the individual voltage pulses caused by the β particles will not generally be detectable above the noise of the electronic amplifier. (The noise of a good amplifier is equivalent to 500 ion-electron pairs.) This means that electrons, and thus also γ quanta, cannot be counted individually with the aid of an ionization chamber; although if the intensity of the radiation is high enough it is of course possible to measure the mean current produced in the ionization chamber. In other words, the integrated intensity of α, β and γ radiation can be measured, but only α particles can be counted individually.

V-d-5 PROPORTIONAL COUNTER TUBES

The operating voltage of proportional counter tubes is so high that gas amplification due to ionization by collision is produced. A typical value for the amplification factor N is 10^4. The Philips tube type 18511 (Fig.

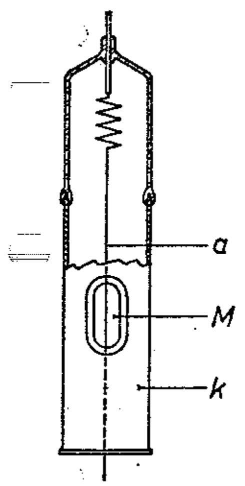


Fig. 131
Schematic view of proportional counting tube Philips type 18511 with mica side-window *M*.

131) is a typical example of such tubes. This tube is filled with a mixture of xenon and methane. The cathode cylinder has a diameter of about 20 mm, while the diameter of the anode is only 0.1 mm. Under these conditions, ionization by collision will only occur in the immediate neighbourhood of the anode, in a region about 0.5 mm in diameter, called the *active volume*. If now an X-ray quantum enters the tube through the mica window (see under non-self-quenching counter tubes, V-d-6, II), its energy

can be completely absorbed by the xenon. The primary ionization thus occurs in the part of the gas where no ionization by collision is possible (the *passive volume*). Only in this way can the voltage pulse on the anode be made independent of the place where the X-ray quantum is absorbed by the gas. The amplitude of the pulse is proportional to the energy of the quantum, because the number of primary ionizations is. The magnitude of the pulses is only a few millivolts, so a good linear amplifier is needed to measure them.

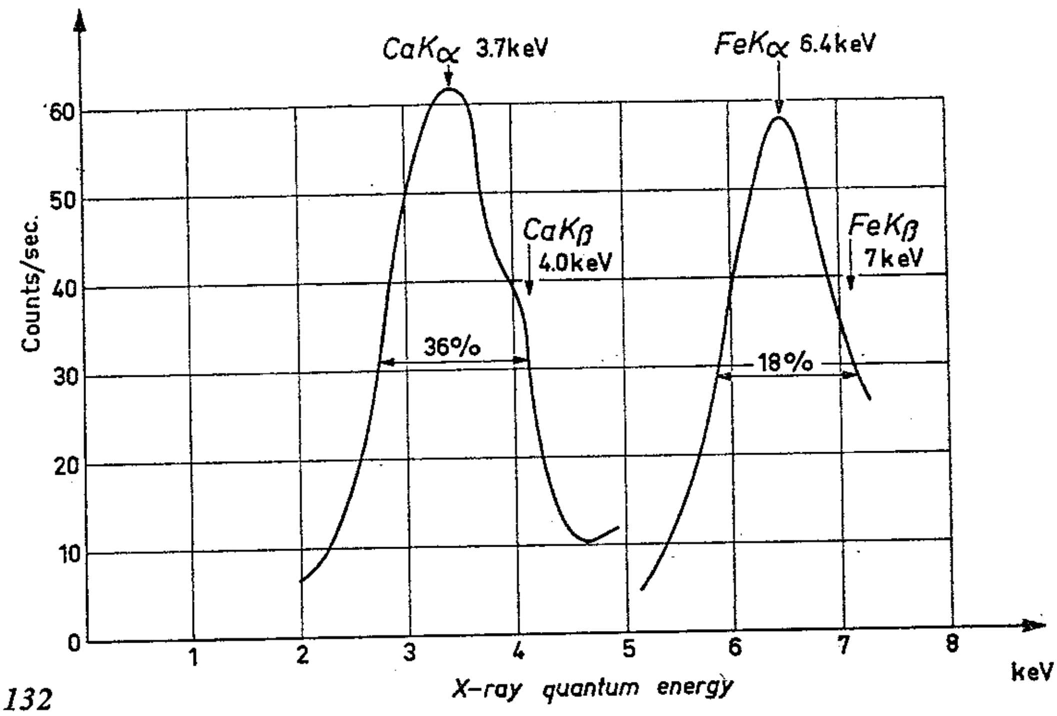


Fig. 132
Distribution of the amplitudes of the pulses of the proportional counter by irradiation with the *Ca* K_α and *Fe* K_α radiation.
(X- radiation with quantum energy of 3.7 and 6.4 keV respectively).

In Fig. 132 is shown the distribution of the amplitudes of the pulses at the output of the amplifier when the proportional counter is irradiated with mono-energetic X-rays (i.e. X-rays in which all the quanta have exactly the same energy). It will be seen that not all the voltage pulses have the same amplitude, but that fluctuations of 10—20 % occur. These fluctuations are mainly due to fluctuations in the primary ionizations. It may also be seen from this figure that the pulse amplitude corresponding to the peak of the distribution curve is proportional to the quantum energy of the radiation.

If in a given case an average of N ion-electron pairs are formed per X-ray quantum arriving in the tube, the standard deviation of the number of ion-electron pairs about this mean will be of the order of magnitude of $\sqrt{N}$, and the relative spread is thus $1/\sqrt{N}$. The relative spread will thus be less as the quantum energy of the X-rays increases. In practice the width of the distribution curve half-way up is taken as a measure of this spread (see Fig. 132). This quantity is called the resolution of the counter tube.

One interesting application of proportional counter tubes is the detection of neutrons. For this purpose, the tube must be filled with boron trifluoride gas. Slow neutrons will be trapped in the B^{10} nuclei and give rise to the reaction:

$$B^{10} + n \rightarrow He^4 + Li^7 + 2.2\ \text{MeV}$$

The energy produced is divided as kinetic energy between the He and the Li nuclei, which will move in diametrically opposite directions. Both particles will cause ionizations along their path, so the kinetic energy of the boron will again be transformed into primary ionizations. When the tracks of both particles fall completely within the tube, the primary ionization due to one neutron will produce about 70 000 charge carriers. This is enough to allow measurement without gas amplification, but even so gas

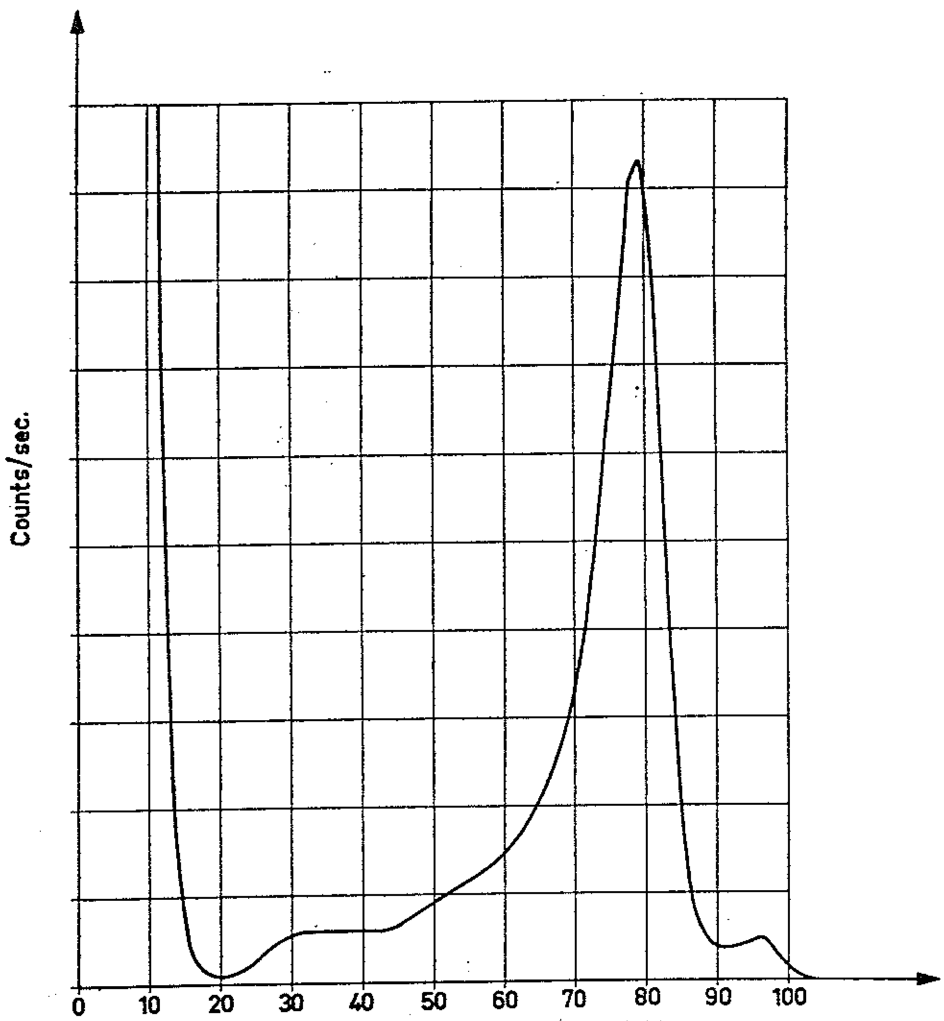


Fig. 133

Distribution of the amplitudes of the pulses of a borontrifluoride counting tube by irradiation with slow neutrons.

amplification will be used in a proportional counter tube because this simplifies the electronics. Fig. 133 shows the pulse-amplitude distribution curve for a BF_3 counter tube.

V-d-6 GEIGER COUNTERS

In 1908 Rutherford and Geiger published details of the first detector to work on this principle (Fig. 134). In 1928, Geiger and Müller described an improved model. The great difference between the detector designed by Rutherford and Geiger and that designed by Geiger and Müller is that the first was only able to detect α particles which passed close to the wire, while the latter could also detect electrons, even if they passed a considerable distance from the wire. In other words, the sensitive volume of the Geiger-Müller counter is nearly equal to that of the whole tube, while that of the Rutherford-Geiger counter only consists of the immediate neighbourhood of the anode filament. Moreover, the Rutherford-Geiger counter can only detect α particles, which naturally give rise to a considerable primary ionization, while the Geiger-Müller tube can also detect particles which produce very slight primary ionization (e.g. β particles).

These counter tubes can be divided into two groups:

I. Self-quenching tubes.

This group includes the well known argon-alcohol counter tubes, which have a filling of 90 mm argon and 10 mm ethyl alcohol. Other combinations of gases can be used for the filling, e.g. helium-isobutane.

II. Non-self-quenching counter tubes.

Many different gases and gas mixtures were formerly used for the filling of these tubes, e.g. hydrogen, argon-hydrogen and nitrogen. None of these

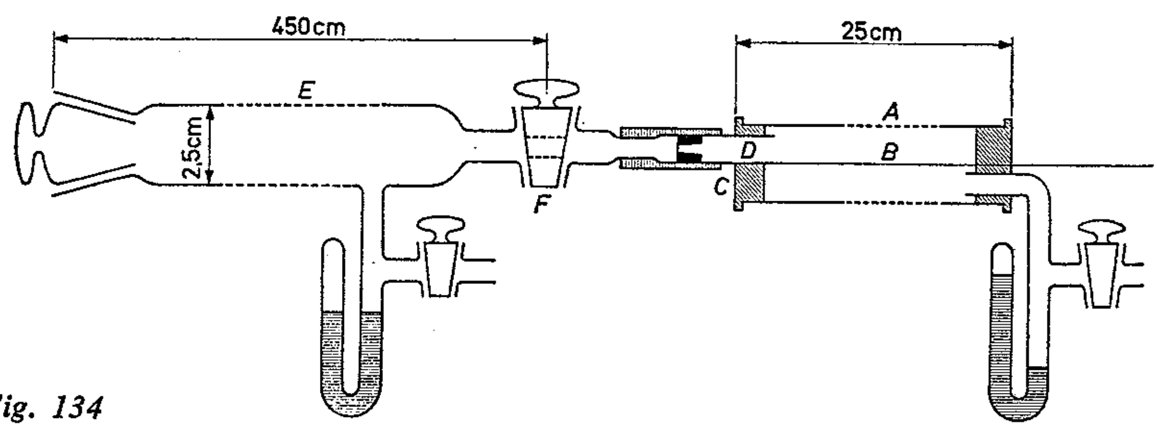


Fig. 134

Experimental design of an apparatus for magnifying the primary ionisation effect caused by the transfer of α-particles through a gas (according to Rutherford and Geiger, Phys. Z. 10/1909/1). Gas pressure 2 to 5 cm Hg.

A = ionisation room
B = wire 0.45 mm
C = rubber tube
D = glass tube
E = glass tube
F = tap with wide aperture

fillings are used any more: all such tubes now contain inert gases, with a small amount of halogen (at most a few tenths of a vol. percent).

V-d-6, I *Self-quenching counter tubes, containing a mixture of an inert gas and some organic vapour or gas.*

In self-quenching counter tubes, the discharge is always propagated along the anode filament. If for example an electron which enters a tube causes a primary ionization in the middle of it, the electrons which are produced move towards the anode, giving rise to an avalanche in the neighbourhood of this electrode. Also produced in this avalanche are UV photons, which will in their turn be able to produce ionizations at points some distance from their point of origin and thus give rise to new avalanches. This process repeats itself until the discharge has reached both ends of the anode filament. The velocity of propagation of the discharge is of the order of 10^5 m/sec., while the velocity of the positive ions is of the order of 10^2 m/sec. This means that the positive ions will have moved a negligible distance towards the cathode by the time that the discharge has reached the ends of the anode. There will thus be a high concentration of positive ions along the anode at this moment. These ions will give rise to a positive space charge which will weaken the original field of the anode and thus oppose the formation of further avalanches.

In the next phase of the discharge process, the positive ions will move to the wall of the tube (i.e. the cathode) in a period of e.g. 200 microseconds. The inert-gas ions wil undergo repeated collisions with molecules of the organic vapour on their way to the cathode, and since the ionization potential of the inert gas is greater than that of the organic vapour, all the inert-gas ions will have transferred their charge to organic molecules before they reach the wall. Only organic ions end up at the cathode, therefore, and these are not able to give rise to secondary emission. Secondary emission would however occur if inert-gas ions could reach the cathode, and the secondary electrons thus formed would be capable of starting new discharges. This is clearly undesirable, since then the discharge would not be quenched. The organic molecules thus play an essential role in the quenching process.

It follows from the above that the quenching of the discharge may be regarded as consisting of two separate phases:

a. the reduction of the electric field around the anode by the positive space charge,
b. the elimination of secondary emission from the cathode surface.

These tubes are called self-quenching because the discharge stops after a certain time, even though the voltage between the anode and the cathode does not alter appreciably.

A characteristic feature of such tubes is that the charge per pulse is independent of the external circuit. If we use the counter-tube circuit of Fig. 135, we find that the magnitude of the charge per pulse is not affected by variation of the series resistance R_s—R'_s or by an increase in the capacitance C_p in parallel with the counter tube.

The organic ions which reach the cathode are there neutralized, and dissociate to give H_2O, CO, CH_4 and unsaturated hydrocarbons. After a

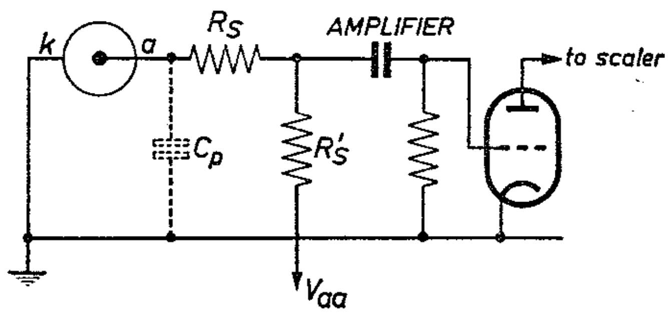


Fig. 135

Simplified circuit of a radiation counting tube and subsequent amplifier stage.
C_p = (parasitic) parallel capacitance,
R_S - R_S' = series resistance.

certain number of pulses, usually of the order of 10^8, so many of the molecules of the organic vapour have dissociated that the counter tube no longer works. There are of course still some undissociated organic molecules left, but not many.

V-d-6, II *Non-self-quenching halogen counter tubes* [50]

In the non-self-quenching counter tubes, as their name suggests, the discharge is not automatically quenched after a certain time; the anode voltage of these tubes must definitely decrease during the discharge, and remain low for a sufficiently long period. This can be ensured by means of the Neher-Harper circuit (Fig. 136). Another method which was used previously consisted in placing a large resistance (about 10^9 ohm) in series with the tube. As in the self-quenching tubes, the quenching of the discharge occurs in two phases. The formation of avalanches is stopped by the combined effect of the positive space charge and the reduced anode voltage. The charge per pulse in tubes of this kind is about a factor 100 greater than in self-quenching tubes, and so therefore is the space charge. The halogen in the gas filling (usually Cl_2 or Br_2) has the same function as the organic vapour in the self-quenching tubes. The inert-gas ions transfer their charge to the halogens, and the halogen ions are neutralized at the cathode and dissociate immediately. In contrast to the organic molecules, however, the halogen molecules dissociate reversibly; after a certain time the halogen atoms will combine to reform molecules, which means that the life of these tubes is much longer than that of the previous type (at least a factor 1000 better).

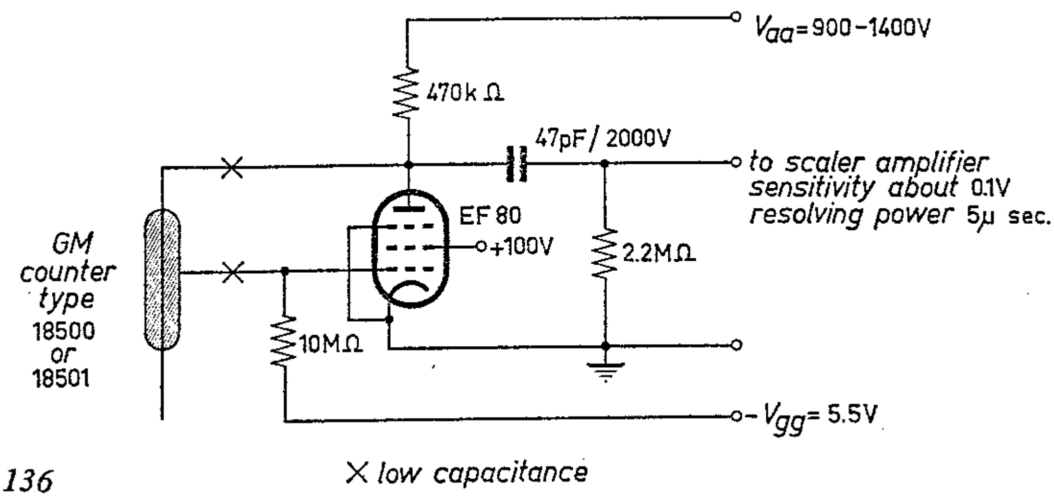


Fig. 136

Neher-Harper circuit to be used with non-self-quenching counting tubes.

The charge per pulse in the halogen counter tubes is dependent on the value of the capacitance C_p in parallel with the tube (Fig. 135): the larger this capacitance, the larger the charge. The charge per pulse also varies slightly with the value of the series resistance R_s, but as may be seen from Fig. 137 the influence of the latter is slight.

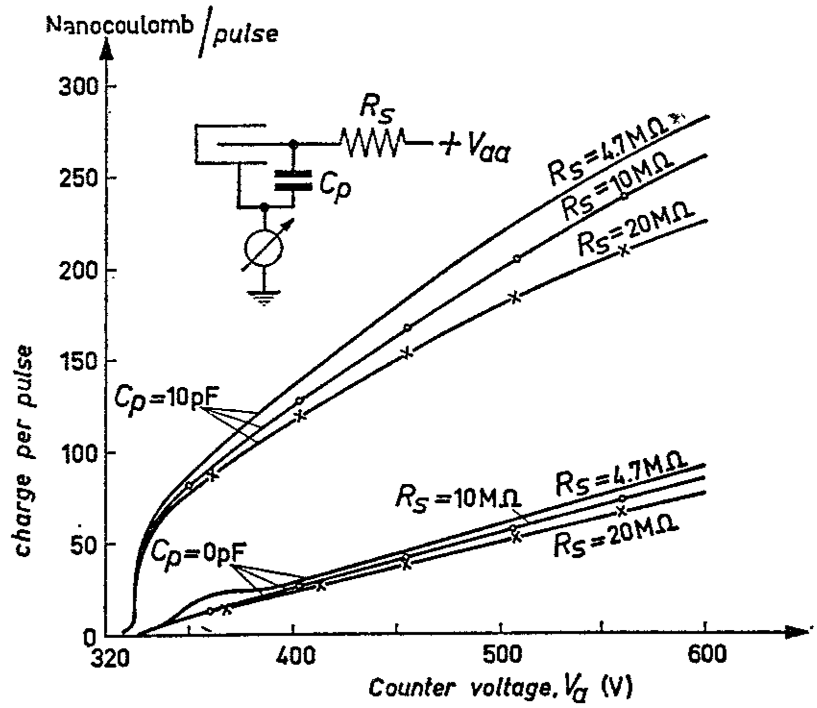


Fig. 137

Charge per pulse with a halogen counting tube as a function of the counter voltage V_a for various values of the parallel capacitance C_p and of the series resistance R_s.

The manufacturing technique for halogen counter tubes is much more complicated than for organic-vapour counter tubes. This is because the amount of halogen to be added to the gas is very small, of the order of 0.1 vol. %. A larger halogen concentration would lead to electrons attaching to the halogen molecules, and thus to a loss of primary electrons. The *sensitivity* (efficiency) of the tube is thus lowered, i.e. there is less chance that a particle entering the tube will cause a discharge. In a good counter tube, the sensitivity for electrons may amount to e.g. 98 %. If the partial pressure of halogen vapour rises to e.g. 1 mm Hg, the sensitivity can fall to 30 %. It is this necessity of restricting the halogen content of the gas to about 1/10 vol. % that complicates the manufacturing technique: halogens are chemically reactive, and special measures must be taken to prevent an appreciable part of the halogen from reacting with various parts of the tube. If the halogen content could be higher, this would naturally not present so much of a problem.

A typical construction for such a tube is shown in Photo 9, which represents the Philips counter tube type 18504. A thin metal wire which acts as the anode is placed along the axis of a thin-walled metal cylinder. This cylinder serves as the cathode and at the same time as the outer wall of the tube. This tube can be used for the detection of γ radiation. In order to make it suitable for the detection of electrons too, one end of the cathode cylinder is provided with a very thin mica window. The thickness of the metal wall or the mica window is usually specified in mg/cm^2. The mica window of the 18504 is 2-3 mg/cm^2, i.e. about 10 μ thick.

V-d-7 THE DEAD TIME AND THE RECOVERY TIME

It follows from what we have said above that a particle which enters the counter tube during the time that the electric field around the anode is weak will not be counted. The smallest time interval between two particles which still give two separate pulses in the counter tube is known as the *dead time*. We have seen that in the alcohol counter tubes after the discharge has reached the ends of the anode wire, which takes a fraction of a microsecond, the layer of positive ions moves towards the cathode. The field around the anode begins to recover as soon as this process begins. At a certain moment, the tube has recovered sufficiently to allow the next discharge to occur along the anode. However, pulses produced just after the end of the dead time will not be as large as normal ones, although the particles producing these pulses will at any rate be counted. The minimum time between the arrival of two particles each of which produces a pulse of the normal height is called the *recovery time*. For a self-quenching tube, the recovery time is precisely equal to the time the ions take to reach the cathode.

In the non-self-quenching halogen counter tubes, the situation is rather more complicated. This may be clearly seen from Fig. 138, which shows the anode voltage of the counter tube as a function of time. The dead time is indicated in this figure, and the time taken by the ions to reach the cathode is indicated by the break in the curve. It will be seen that the tube voltage has not yet returned to its original value by the time that all the positive ions have reached the cathode. Voltage pulses produced by particles which enter the tube just after this moment are thus not as large as normal. The recovery time for these tubes is larger than the transit time of the ions, in other words, it is partly determined by the value of the series resistance and the parallel capacitance, since these influence the

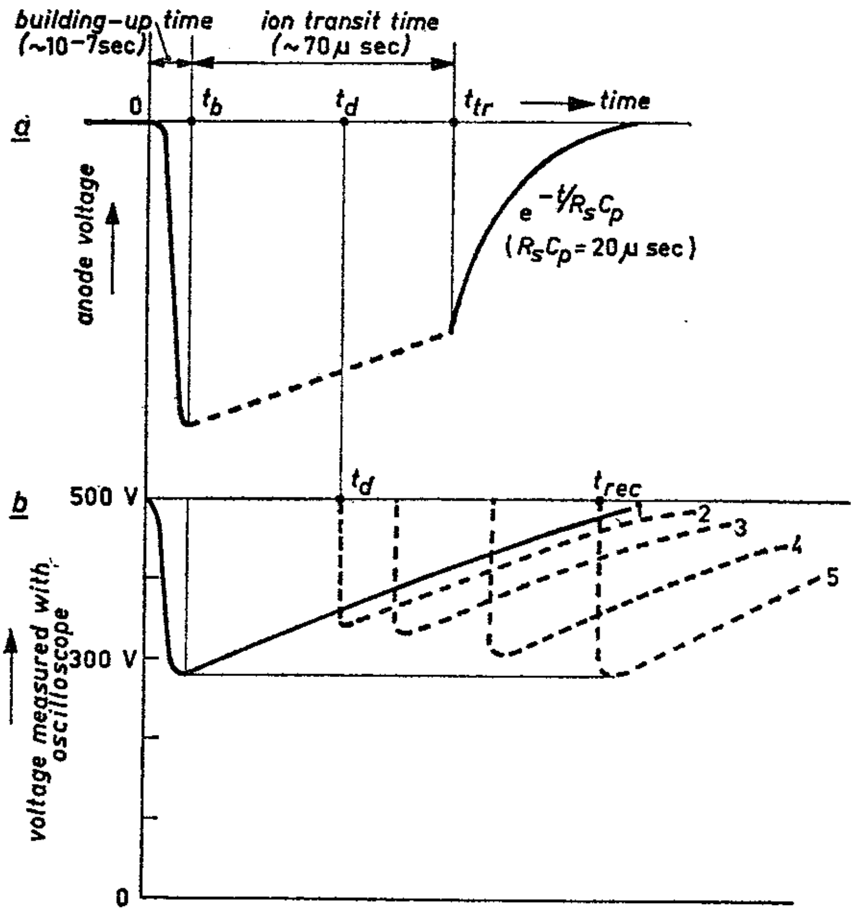


Fig. 138

a. Anode voltage of a non-self-quenching counter tube as a function of time.
b. Curves 1—5 represent pulses of different size.
Curve 1 is the pulse with normal height, curves 2, 3 and 4 are less high. At the time t_{rec} curve 5 again has obtained the normal height.
t_b = electron transit time (building-up time)
t_{tr} = ion transit time
t_d = dead time
t_{rec} = recovery time

time it takes for the tube voltage to regain is original value. It may be said in general that both the dead time and the recovery time of such counter tubes are determined by the transit time of the positive ions, and the value of the series resistance and the parallel capacitance. The relationship between these quantities is very complicated, since in this case the transit time itself will be a rather complicated function of the other two variables. A number of characteristics of the Philips counter tube 18506 (Fig. 139) show how the dead time depends on the tube voltage, the series resistance R_s and the parallel capacitance C_p. It may be clearly seen from these curves that the dead time increases with the values of the last two variables.

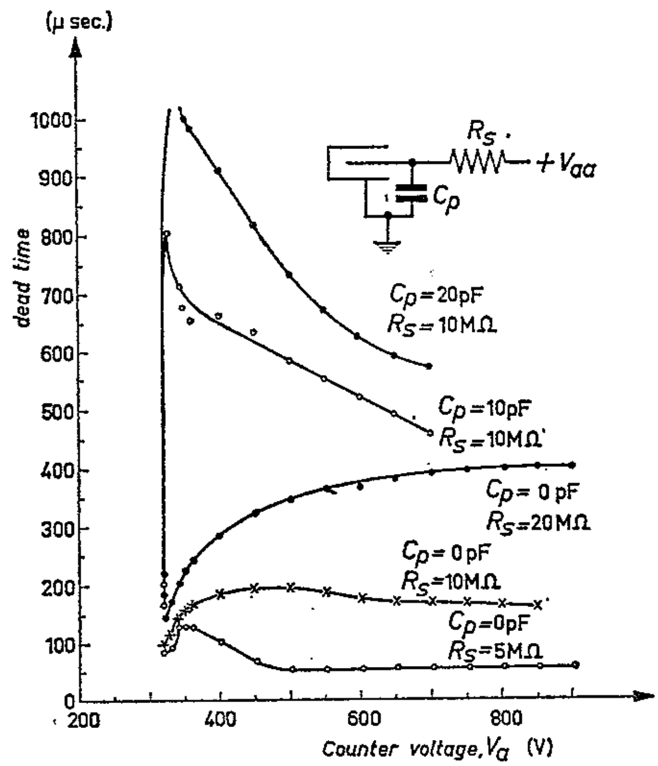


Fig. 139

Dead time as a function of the counter voltage V_a for various values of the series resistance R_s and the parallel capacitance C_p for a non-self-quenching halogen counter. (Philips counting tube type 18506). Anode diameter 8 mm, cathode diameter 28 mm.

V-d-8 THE COUNTING CHARACTERISTIC AND THE PLATEAU

One of the most important characteristics of a Geiger counter is the counting characteristic (Fig. 140). This curve shows the number of counts per second as a function of the tube voltage at constant irradiation. The counting characteristic consists essentially of three parts:

a. the initial region;
b. the plateau;
c. the spurious-discharge region.

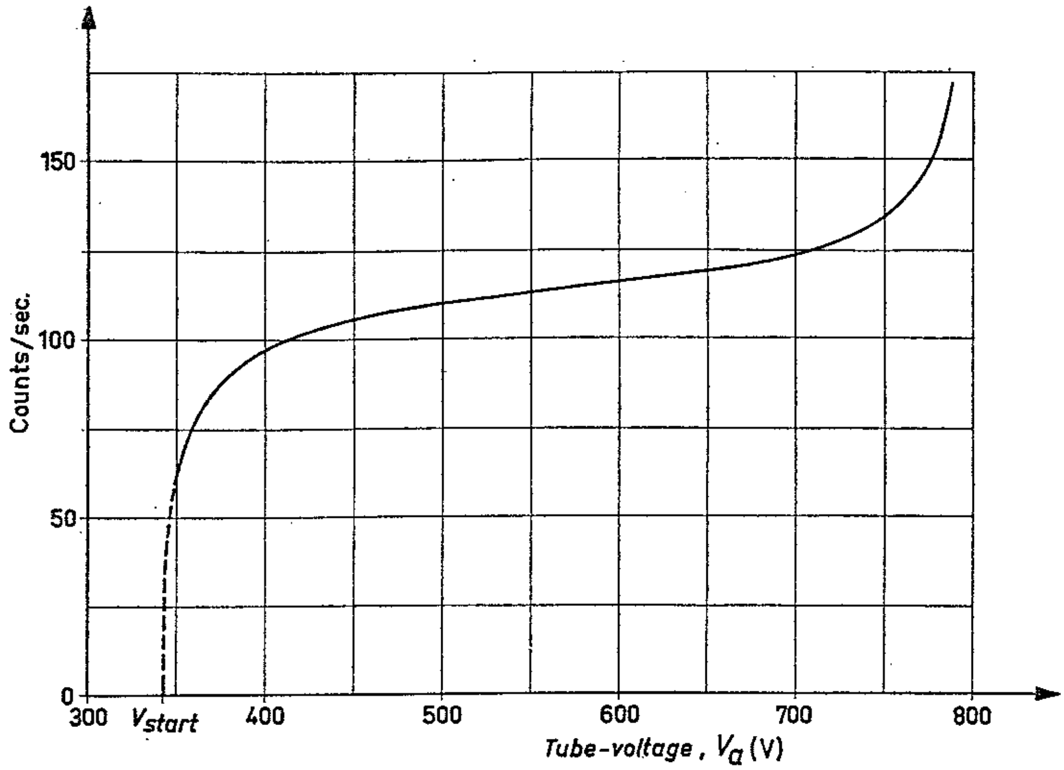


Fig. 140

Plateau curve of Philips counting tube type 18510.
This curve may be divided into three parts:
the initial region (curved part to the left),
the plateau (flat part) and
the spurious-discharge region (curved part to the right).

a. The initial region

Not all the incoming particles are counted at tube voltages in this region. It may be that the particles do give rise to a voltage pulse, but that this pulse is not large enough to be counted by the electronic counting equipment. It may be, on the other hand, that some of the incoming particles do not cause a Geiger discharge at all. One possible reason for this is that all the electrons of the primary discharge are captured by halogen atoms; another possibility is that the chain of avalanches is broken off for lack of secondary electrons.

b. The plateau

The plateau is the most important part of the counting characteristic (see Fig. 140). In this region, the number of particles registered increases only very slightly with an increase in the tube voltage. In an "ideal" counter tube, all incoming particles would give rise to one pulse — no more, no less — which could be counted by the counting equipment. In such a case, the plateau would be perfectly flat. In practice, however, it always has a slight slope; but in a good counter tube this slope amounts to only a few percent per hundred volts. In some special counter tubes, it is not possible to make the slope smaller than 10—15 % per 100 V. The value of the slope is determined by the construction of the tube, the geometry of the electrodes, the gas filling, the partial pressure of halogen vapour, etc.

Several reasons may be given for the existence of this slope. In the first place, it may be due to an increase in the active volume as the tube voltage is increased. The electric field at the ends of the anode is naturally weaker than in the middle, with the result that the ends of the anode only become active at higher voltages. This drawback can be considerably reduced by proper design of the tube, but it can never be eliminated completely [50].

A second reason for the increase in the number of particles counted is connected with the dead time. As we have seen (Fig. 139), the dead time varies very considerably with the tube voltage. As a result of this, up to 30 % of the incoming particles may not be counted at the beginning of the plateau, because they fall within the dead time of the preceding particle. At the end of the plateau, this counting loss may be reduced to 10 %. It is thus quite possible that the plateau has a slope of 30 % per 100 V all over the length at high counting rates, for this reason alone. This effect is naturally not found at low counting rates, the slope of the plateau is therefore usually specified at a definite counting rate; e.g. 100 counts/sec.

A third reason for the increase in the number of particles counted at higher tube voltages is the occurrance of double pulses. The above-mentioned quenching mechanism does not work so well at high tube voltages, and double or triple pulses occur. This is usually a statistical phenomenon: only a small fraction of the pulses are double, and an even smaller fraction are triple. The extent to which this effect plays a part is highly dependent on the values of the shunt capacitance and the series resistance.

As we have mentioned above, the slope of the plateau in a good counter tube is only 2—3 % per 100 V. This is of great importance for the designer of the electronic equipment, because it means that the supply voltage of the counter need not be stabilized very accurately. In fact, however, the slope in percent per 100 V is not so important to the designer as the quantity

$$\frac{\Delta N}{N} : \frac{\Delta V}{V}$$

It is very important that this should be low, which means that the tube voltage must also be low. The permissible variation in the supply voltage for a given accuracy can be simply calculated from the published data for the counter tube, making use of this expression.

c. The spurious-discharge region

As has been mentioned above, double and triple pulses can occur throughout the whole plateau, especially near the end. The sharp increase in the number of particles counted at the end of the plateau indicates that many pulses must be double or triple in this region. When the voltage is increased still further, the quenching mechanism fails altogether and the tube changes over to a continuous discharge which is no longer influenced by the presence of radioactive radiation.

In the self-quenching counter tubes filled with organic vapour, the re-ignition of the tube and thus also the occurrence of double and triple pulses is not affected by the series resistance and the shunt capacitance. The occurrence of spurious discharges in such tubes is therefore not influenced by the circuit. At counting rates below e.g. 100 counts/minute,

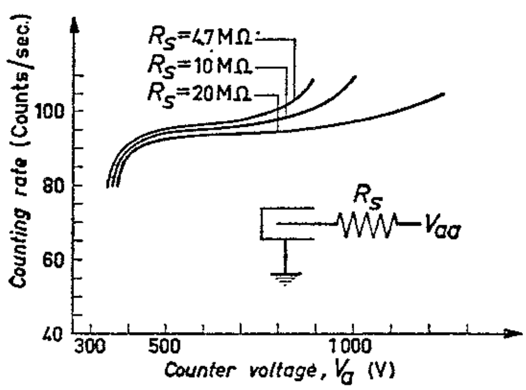


Fig. 141

Plateau characteristics for Philips tube 18506 for various values of the series resistance R_s.

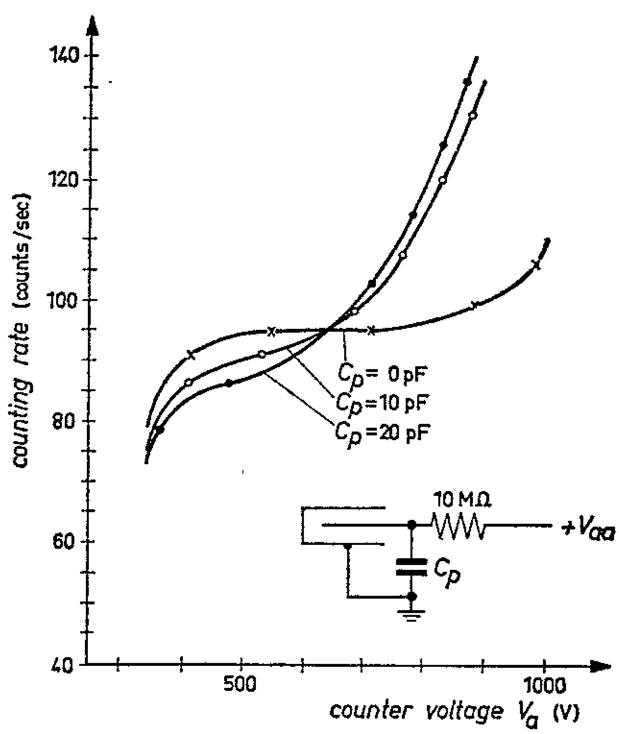


Fig. 142

Plateau characteristics for Philips tube 18506 for various values of the parallel capacitance C_p. The series resistance was 10 megohm in all cases.

the slope and length of the plateau are independent of the magnitude of the series resistance and the shunt capacitance.

In halogen counter tubes, which are non-self-quenching, the spontaneous re-ignition of the tube and the occurrence of spurious discharges *are* dependent on the two above-mentioned variables, and so therefore are the slope and length of the plateau. If the resistance is high (e.g. 10—30 Mohm), the plateau may be 600 V long (Fig. 141); but here we have the disavantage that the dead time is also very large (Fig. 139). In practice, the value of the resistance is always chosen so that the length of the plateau is about 200 V. If the length of the plateau is not so important and a very short dead time is desirable, the value of the resistance may be chosen lower than given in the published tube data.

An increase in the shunt capacitance has in general only unfavourable effects: the plateau becomes shorter and steeper, and the dead time increases (Fig. 142). Care must therefore always be taken that parasitic parallel capacitances are kept as low as possible.

V-d-9 THE BACKGROUND

Even if all radioactive substances are removed from the neighbourhood of the counter tube, a number of pulses will still appear. This is known as the background count, and is due to various different causes:

a. All materials, including those used to build laboratories, contain radioactive substances such as uranium, thorium, radium and also K^{40}. It is therefore necessary to screen the counter tube from its surroundings with a material which contains as little radioactivity as possible. Iron is a good choice; and lead is often used, because it allows a very compact and efficient screen to be made. Unfortunately, lead is by no means ideal for this purpose, because even when carefully refined it still contains radioactive lead isotopes. The half-life of the most important lead isotopes is 22 years, so lead which is a century or so old will be practically free of radioactivity. Mercury is practically as good as lead for screening purposes, but the use of mercury has a number of disadvantages in practice.

b. If the thickness of the screening is increased beyond a certain value, e.g. 10—20 cm of lead, it is found that the background does not decrease appreciably. This is because nearly all the pulses are now due to cosmic radiation, which is so powerfully penetrating that the lead offers practically no protection against it: 100 m of earth or water is needed to cut off this radiation. In principle, therefore, it should be possible to eliminate the cosmic rays by working at the bottom of a mine. A more elegant method will be discussed later in this chapter.

c. Finally, the radioactive impurities in the materials used in making the counter tube are also of importance. Radioactivity which is present in the tube itself will have even more effect than radioactivity in the screening material. In the first place, the tube material emits electrons, which are detected with an efficiency of nearly 100 %; and in the second place the solid angle over which the radiation is detected is practically 2π. It follows that the materials used for making the counter tubes must be chosen even more carefully than the screening materials.

V-d-10 CONSTRUCTION OF HALOGEN COUNTER TUBES

We shall now describe a number of different types of counter tubes, and some typical applications. The Philips counter tubes may be divided into:

end-window counter tubes,
cylindrical counter tubes,
hollow-anode counter tubes.

a. *End-window counter tubes*

The classical end-window counter tubes have a cylindrical cathode, with a thin window at one end and the anode lead at the other. The old counter tubes such as the 18505 (Fig. 143a) have a thin coaxial anode, and the mica window is insulating. The electric field at the point where the β radiation to be measured enters the tube is rather weak, while surface charges can build up on the insulating mica surface.

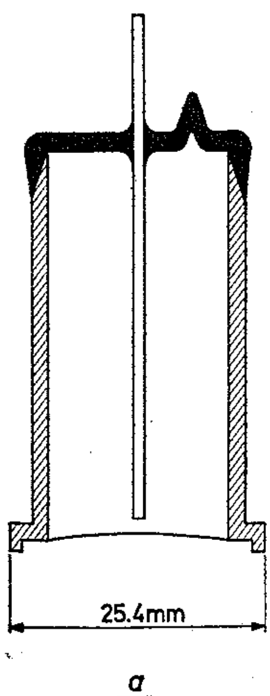


Fig. 143a
Schematic view of the electrode configuration of a conventional end-window beta-counter (Philips type 18505).

These handicaps are removed in the new types such as the 18515 and the 18516 (Fig. 143b). The anode is spherical with a diameter equal to about a third of that of the cathode, and the inside of the window has been made conducting. One advantage of this new construction is that

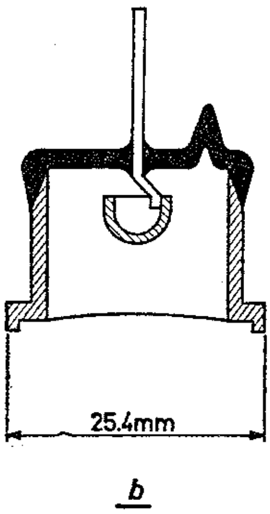


Fig. 143b

Schematic view of the electrode configuration for an end-window beta-counter with hemispherical anode and conducting window (Philips type 18515).

ionization by collision can occur near the cathode, so that the risk of electrons attaching on to electronegative gas molecules (bromine or chlorine) is eliminated. This means that the sensitivity is high. Incidental advantages of this new construction are a lower sensitivity for γ radiation, a low background and a shorter dead time.

b. Cylindrical counter tubes

The original Geiger counter tubes had this design, which is still used for the detection of β and γ rays. Philips tubes 18550 and 18552 can be used for the first purpose, and the 18503 and 18522 for γ radiation. Cylindrical counter tubes are normally used where a large active surface is needed.

c. Hollow-anode counter tubes

Philips was the first firm to put hollow-anode halogen counter tubes on

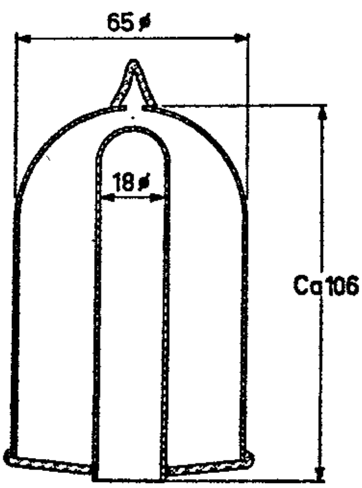


Fig. 144

Schematic view of Philips halogen counting tube with hollow anode type 18508 for γ-radiation in a 4π geometry.

the market. A typical example is the 18508, which can be used to measure the γ radiation over a solid angle of 4 π (Fig. 144). The radioactive sample is placed right at the bottom in the anode, so that all the radiation emitted by the sample is received by the counter tube. The effective solid angle is therefore very large, so samples of weak radioactivity can be counted. A second advantage is that the counting rate hardly depends on the position of the sample, as long as it is deep enough in the hollow anode. This is very useful if it is desired to compare radioactive samples of different shapes without having to correct for the difference in geometry.

Another interesting application of the hollow anode is found in the guard counter tubes 18517 and 18518. A combination of a cosmic ray guard counter tube and an end-window counter tube is shown in Fig. 145. The guard counter tube consists of two large concentric spherical electrodes, each with coaxial cylindrical parts. The end-window tube is placed inside the hollow anode of the guard counter tube. This ensures that all

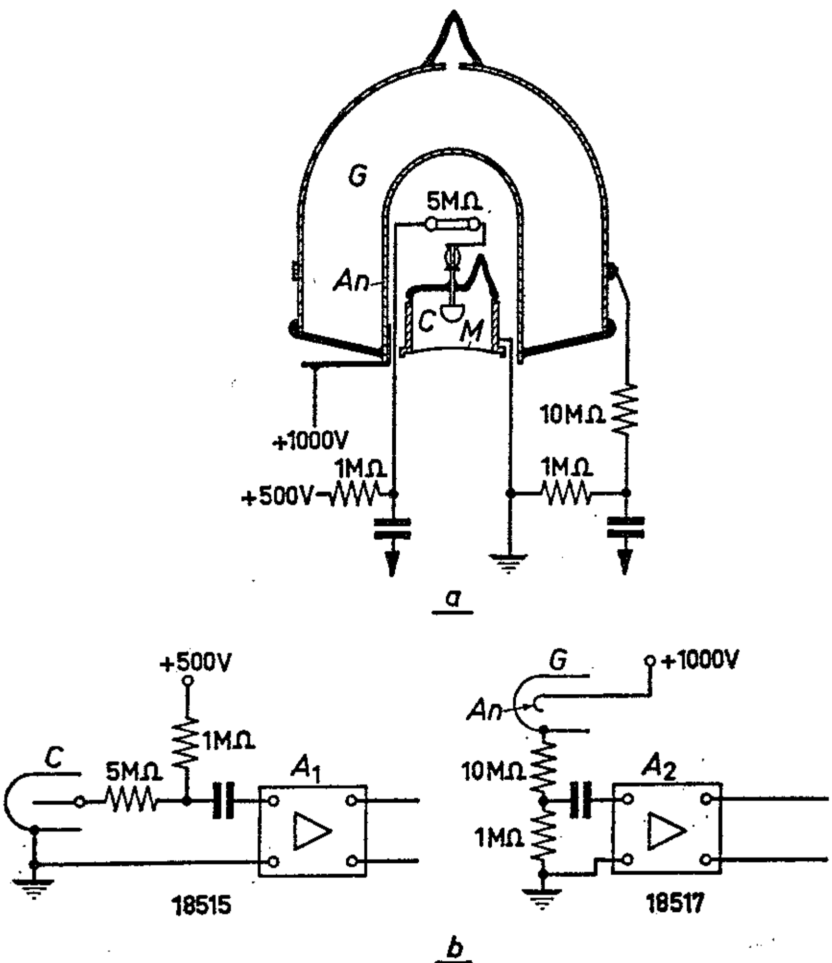


Fig. 145
a: Schematic view of the combination of the end-window beta-counter type 18515 (*C*) with mica window *M* and the cosmic ray guard counter type 18517 (*G*) with anode *An*.
b: circuits for the use of the combination given in *a*. A_1 and A_2 are amplifiers.

the mesons from the cosmic radiation which reach the end-window tube have passed through the guard counter tube first. (The penetrating power of mesons is so large that the stopping power of the counter-tube material is negligible). The electrical pulses from the two counter tubes are fed to an anti-coincidence circuit [77], which is adjusted so that the output pulse of the end-window tube is only counted when there is no simultaneous pulse from the outer counter tube. In this way all the mesons which strike the end-window tube (and which thus also excite the outer tube) are eliminated. The background of the 18516 end window counter can thus be reduced to less than 1 count/minute by use with the anti-coincidence arrangement, while use of the 18516 with the lead screening alone cannot reduce the background to less than about 7 counts/minute. This very low background is very important for counting very weak samples as in tracer work, and for radiation monitoring.

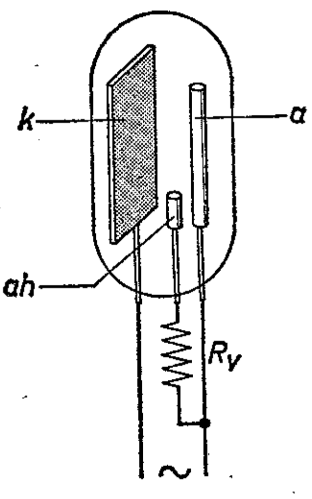


Fig. 146
Glow-discharge rectifier tube. When the cathode k is negative and the anode a positive, a preliminary discharge occurs between the auxiliary anode a_h and k, after which the main discharge between a and k ignites. If the polarity of the tube is reversed, no discharge can occur between k and a.

V-e **Some other non-controlled glow-discharge tubes**

V-e-1 THE GLOW-DISCHARGE RECTIFIER TUBE

We shall describe the operation of the glow-discharge rectifier tube with reference to the sketch of Fig. 146. There are two main electrodes, k and a, and an auxiliary electrode a_h. Suitable construction ensures that ignition can occur when k is negative with respect to a, and not *vice versa*; k thus acts as the cathode and a as the anode. In the half-period during which k is negative and a positive, ignition first occurs between a_h and k at a relatively low voltage; a small current flows in this auxiliary discharge, which is followed by ignition of the main discharge between k and a. If the voltage is reversed, the auxiliary discharge between k and a_h is not able to ignite the main discharge. The ignition voltage of the main discharge is made higher in the latter case (inverse phase) by the following means:

TABLE XII

DATA OF SOME RADIATION COUNTING TUBES

	proportional counter side-window 18511
use	x-ray
window: thickness (mg/cm²) eff. diam. (mm) material	2.0—2.5 7 × 18 mica
wall: thickness (mg/cm² or mm) eff. length (mm) outside diam. (mm) material	— 67 — Cr Fe
tube dimensions: max. diam. (mm) max. overall length (mm)	27.5 141
gas filling	Xe(org)
Geiger threshold (V)	>1900
operating voltage (V) do for pulse ampl. of 1 mV do for pulse ampl. of 100 mV	1500—1850 1525 ± 25 1730 ± 40
energy resolution Mn, K_α at 5.9 keV (%)	<22
background (Mn, $K\alpha$) (c/min)	about 15 6)
tube capacity (pF) weight (g) ambient temp. (°C)	2 85 –50 to+75

	end-window counting tubes	18505	18506	18515	18516
a	use	α, β, γ	β, γ	α, β	β
b	*window:* thickness (mg/cm²) eff. diam (mm) material	1.5—2 19.8 mica	2.5—3.5 27.8 mica	1.5—2 19.8 mica	10 27.8 CrFe
c	*wall:* thickness (mg/cm² or mm) eff. length (mm) outside diam. (mm) material	1.2 mm 37 22 CrFe	1.3 mm 37 30.5 CrFe	1.2 mm 13 22 CrFe	1.2 mm 18 30.5 CrFe
d	*tube dimensions:* max. diam. (mm) max. overall length (mm)	25.9 57	34 57	26 30	34 34
e	gas filling	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)
f	max. starting voltage (V) plateau (V) max. slope (%/100 V) max. dead time (μsec) max. background (c/min)	350 450—700 1) 2 1) 160 1) 15 2)	375 450—750 1) 2 1) 180 1) 25 2)	350 500—700 1) 3 1) 70 1) 5 3)	375 500—750 1) 3 1) 70 1) 9 3)
g	recomm. resist. (MΩ)	>2	>2	>2	>5
h	tube capacity (pF) weight (g) ambient temp. (°C)	2.5 40 –55 to+75	3.5 50 –50 to+75	1.5 15 –50 to+75	1.3 27 –50 to+75

(continued on next page)

TABLE XII (continued)

	cylindrical counting tubes 18550	 18552	 18503	 18522	hollow-anode counting tubes 18508	 18517	 18518
a	β>0.25MeV γ	β>0.3MeV γ	γ	cosmic ray γ	4 π γ liquid	in anti- coincidence with 18515	in anti- coincidence with 18516 or 18536
b							
c	36±4 mg/cm² 28 8 Cr Fe	50±10 mg/cm² 75 15.5 Cr Fe	250 mg/cm² 40 15 Cr Fe	0,5 mm 400 39 Cr Fe	1 mm 90 mm 18 mm (inside) Cr Fe	1 mm — 78 Cr Fe	1 mm — 78 Cr Fe
d	10 52	18 146	17 55	41 460	69 125	80 90	80 90
e	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)
f	380 500—650 7) 4 7) 50 7) 4 2)	400 450—800 5) 2 5) 70 5) 30 2)	325 425—650 1) 2 1) 100 1) 10 2)	600 700—1000 1) 3 1) 500 1) 110 4)	450 800—1100 4 1) — 200 2)	650 800—1200 8) 3 8) 1000 8) 75 3)	650 800—1200 8) 3 8) 1000 8) 75 3)
g	>2	>1	10	10	10	10	10
h	1.1 1.2 –50 to+75	4 8 –50 to+75	2 7 –55 to+75	15 200 –50 to+75	6.5 210 –50 to+75	5.5 175 –50 to+75	8 190 –50 to+75

Note 1) measured at 100c/s and R = 10 MΩ
Note 2) shielded with 5 cm Pb and 3 mm Al
Note 3) shielded with 10 cm Fe and 5 cm Hg (Fe outside)
Note 4) shielded with 5 cm Pb and 10 cm Fe (Fe outside)
Note 5) measured at 100c/s and R = 2 M Ω
Note 6) integrated background for pulses > 50 % of the pulse amplitude for Mn, K_α radiation; unshielded.
Note 7) measured at 100c/s and R = 5 MΩ
Note 8) measured at 50c/s and R = 10 MΩ

1. choosing a material for k with a lower work function than that for a;
2. suitable positioning of the electrodes;
3. the cathode fall still has to be formed when a is negative, while when k is negative the cathode fall is already present at k thanks to the auxiliary discharge.

Since the burning voltage will be at least 60 V, use of a glow-discharge rectifier is indicated at high operating voltages. This tube was once quite widely used, but has now largely been replaced by semiconductor diodes.

The glow-discharge diode still has advantages for certain applications, however; it gives a visible indication that current is flowing; and the inverse current is low, or even zero e.g. if the voltage supply on the primary of the rectifier transformer is cut off while charging batteries.

For these and other reasons, these tubes are sometimes still used, e.g. for charging the small batteries for hearing aids and for maintaining the voltage of buffer batteries.

V-e-2 TUNING TUBE

This glow-discharge tube owes its name to the use to which it was previously put as indicator for tuning a radio receiver on to a particular station. However, it was first used for oscillograph measurements with

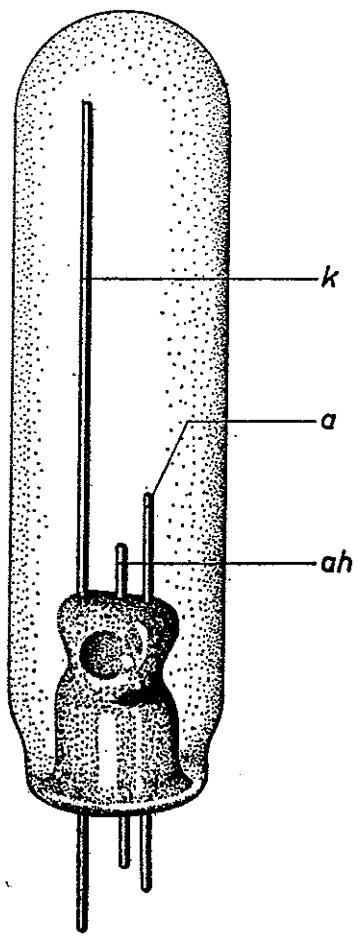


Fig. 147

Philips tuning tube type 4662. Ignition as for the tube of Fig. 146. The length of the part of k covered by the glow discharge is a measure of the glow-discharge current.

a rotating mirror. It contains a long rod-shaped cathode, a short rod-shaped anode, and an even shorter wire between the two which acts as an auxiliary anode (Fig. 147). The tube is filled with argon mixed with a little mercury. The ignition mechanism is similar to that of the glow-discharge rectifier tube (V-e-1). The tube is fed by a DC voltage, a permanent auxiliary discharge being maintained between k and the auxiliary anode a_h to prevent possible interruption of the main discharge if the current should suddenly decrease for some reason. As the current increases, to a maximum value of 1 mA, the length of the part of k covered by the glow also increases. With the construction described here, the length of the glow increases roughly logarithmically with the current; while if the anode is as long as the cathode and parallel to it, the length of the glow is roughly a linear function of the current. Among other things, this tube is still used to give a quantitative indication of the pressure in an evacuated space, in conjunction with a Penning gauge (see V-c-2). The circuit for this application has already been given in Fig. 125.

V-e-3 TUBES WITH EXTERNAL ELECTRODES

If a high-frequency voltage is applied to a neon-filled tube with two electrodes, a gas discharge will be initiated if the voltage is high enough. If the frequency is of the order of 1 Mc/sec, the ions will only move a very short distance to and fro each period, because of their large mass, and may be regarded as stationary. The only motion possible to them is a slow diffusion to the wall. The much more mobile electrons can cover much larger distances, and even at such high frequencies as 10^4 Mc/sec they can take up enough energy from the electric field for ionization, the displacement of the electrons at these frequencies is, however, also small compared to the dimensions of the tube.

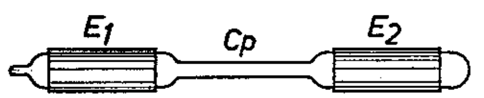


Fig. 148

Geissler tube with external electrodes E_1 and E_2 between which the discharge energy can be transferred at high frequencies. In the capillary middle part Cp of the tube, the discharge becomes a positive column, with a strong luminous effect.

Because the charge carriers move such short distances, there is no need to introduce the electrodes into the tube. At very high frequencies a discharge can even be obtained simply by placing a sealed tube filled with neon or neon-argon (pressure 1 mm) in the HF-radiation field. Such tubes are used in laboratory experiments to give a rough indication of the strength of the radiation field. For frequencies of the order of 1 Mc/sec, used e.g. in RF heating equipment, external electrodes in the form of cylindrical sheaths around the tube are used (see Fig. 148). The RF energy is transferred capacitively to the discharge. The tube is narrowed to a capillary in the middle, which increases the luminous intensity of the discharge, because under such conditions a positive column is produced (see I-g-2). Such tubes are known as Geissler tubes because they have the same shape as the original tubes of the same name; the original tubes had, however, internal electrodes.

Geissler tubes are used to indicate the presence of HF fields. It may be mentioned that at high frequencies (above 0.01—0.1 Mc/sec) the discharge is ignited if only the peak voltage is high enough (some kV), since the state of the plasma does not alter during the rest of the period. This also means that if the discharge is once ignited, e.g. with the aid of a Tesla coil, a peak voltage of a few hundred volts may be enough to maintain the discharge. This is not the case e.g. at 50 c/sec, where ignition occurs anew each period. It is, however, still possible to use Geissler tubes as indicators of high-voltage fields of 50 c/s.

V-f Glow-discharge relay tubes

V-f-1 INTRODUCTION

Just as in a thyratron the introduction of a third electrode between the anode and the cathode makes it possible to control the discharge, so can use be made of a switching electrode in glow-discharge tubes, to ignite the discharge at the desired instant. The ignition mechanism of the discharge is, however, different in the two different cases, as will be shown in the next section. Fig. 149 shows the Philips trigger tube type Z 50 T as an example. The switching electrode t, called the trigger (or starter) in this

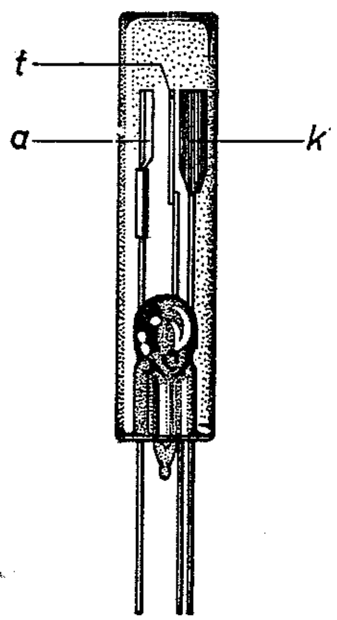


Fig. 149

Philips glow-discharge relay tube type Z 50 T. t = trigger. a = anode, k = cathode.

case, controls the moment of ignition of the discharge between the cathode and the anode. Here too, the trigger no longer has any control over the discharge as soon as the latter has been ignited. In order to be able to make use of the trigger again, the discharge must first be quenched by reducing the voltage between the cathode and the anode to less than the burning voltage. These trigger tubes, or cold-cathode relay tubes, have a lower tube current and a higher burning voltage than thyratrons. Among the advantages of trigger tubes we may mention the following: the cathode does not need to be heated, so the discharge can be ignited immediately after switching on (no warming-up time); the triggering power needed is low; since the tube current is low, so is the dissipation of energy in the tube, and the tube may safely be made small. Like the thyratron, the trigger tube is an electronic "on-off" switch, with only two stable states. It is used in time-switches, counting circuits, as a sensitive relay, etc. In such applications, the ignition and its build-up time and the quenching of the discharge play an important role. We shall now discuss these points, after which we shall describe the various types of tube.

V-f-2 IGNITION

The main discharge should be initiated by an auxiliarly discharge between the trigger and the cathode. The auxiliary discharge gives rise to a cathode fall with glow. A plasma is also produced, with more or less the trigger potential, from which the anode can extract charge carriers when the anode is positive with respect to the plasma. By means of these effects, the auxiliary discharge reduces the ignition voltage between cathode and anode. The amount by which the ignition voltage is reduced depends on the auxiliary-discharge current, or trigger current, as shown in Fig. 150. Thanks to this reduction of the ignition voltage, the anode voltage can be chosen so that ignition occurs when the trigger discharge is present, but not when it is absent. The trigger current in cold-cathode tubes need not be more than a few tens of microamps. Moreover, it is sufficient to let the trigger current flow for a short time; it is thus possible to feed the trigger discharge from a small capacitor, as we shall see below.

The main discharge cannot be formed until the trigger current is flowing. In this respect, the ignition mechanism differs from that of thyratrons, where in general ignition can occur as soon as the grid-cathode voltage reaches a suitable value, since the hot cathode emits electrons before the discharge is produced. To begin with, therefore, there will be no grid current at all in a thyratron, which is thus said to have a voltage characteristic or field characteristic.

The voltages at which glow discharges can be produced may be controlled within certain limits by suitable choice of the materials of the various electrodes and their geometry, and also of the composition and pressure of the gas filling. In connection with the demands made on the switching circuit (see e.g. Fig. 151), it is preferable to keep the ignition voltage of the auxiliary discharge low, which may be achieved by working near the minimum in the Paschen curve.

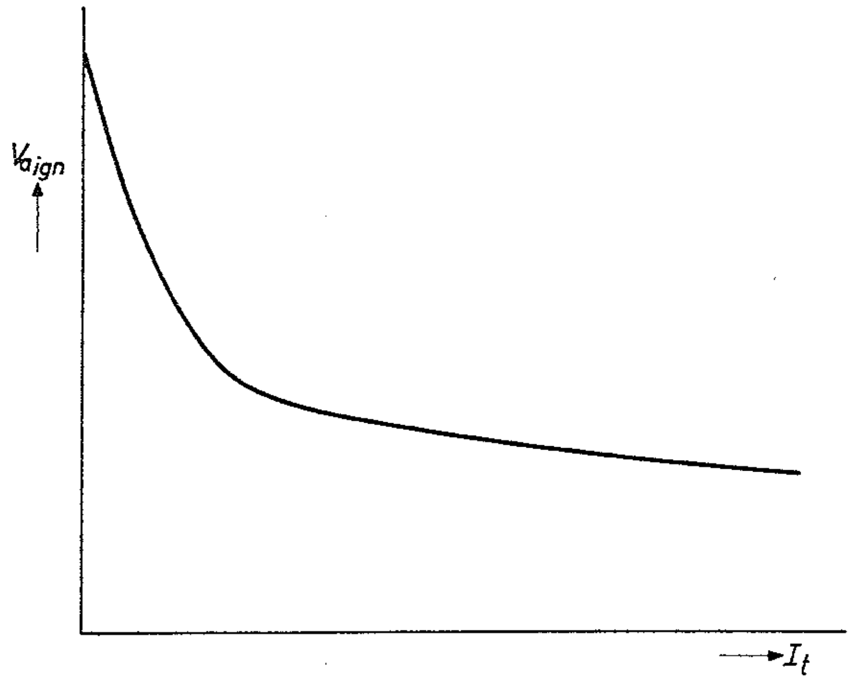


Fig. 150

Typical breakdown characteristic for the space between anode and cathode as a function of the trigger current I_t which is required for obtaining transition from trigger-cathode discharge to anode-cathode discharge.

If the trigger tube has an AC supply, care must be taken when the polarity of the voltage changes, that no discharge occurs between the negative anode and the positive cathode. Let us investigate in this connection how the ignition depends on the instantaneous anode and trigger voltages V_a and V_t, with reference to the ignition characteristic of the tube type 5823, shown in Fig. 152. This is a tube for 117 V AC, to be used as a rectifier for a mean current of 25 mA and with the trigger positive with respect to the cathode.

The area within the closed curve is divided into four quadrants. These represent the regions within which *no* ignition can occur between two given electrodes. The shaded area Ia to the right of quadrant I is the normal operating region for the tube as a rectifier. Here both the anode and the trigger voltages are positive with respect to the cathode, so that first the auxiliary discharge $k - t$ and then the main discharge $k - a$ is ignited. The ignition characteristic $V_a = f(V_t)$ corresponding to a given value of the resistance R_t in the trigger circuit will have more or less the form indicated by the broken line. Thus, as $+V_t$ is steadily increased to the right of the point S, the anode voltage needed for the ignition of the main discharge will gradually decrease, since the V_a required for ignition is determined by the value of the product of the trigger *current* $I_t \times R_t$ (cf. the curve of Fig. 150).

In the regions IIa, IIIa and IVa, outside the quadrants II, III and IV

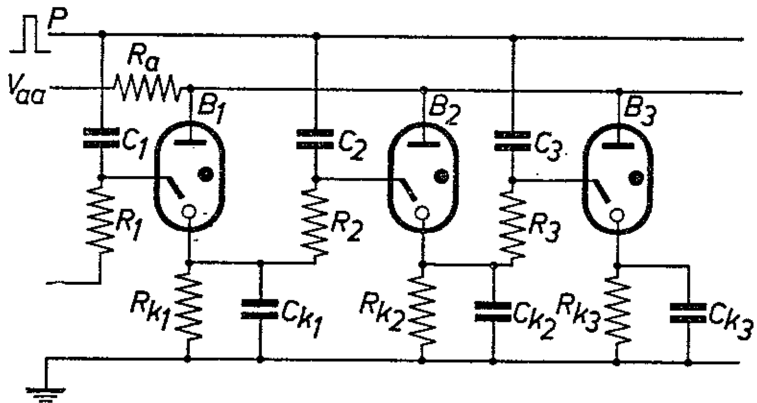


Fig. 151
Example of a counting circuit with three counting tubes (see text).

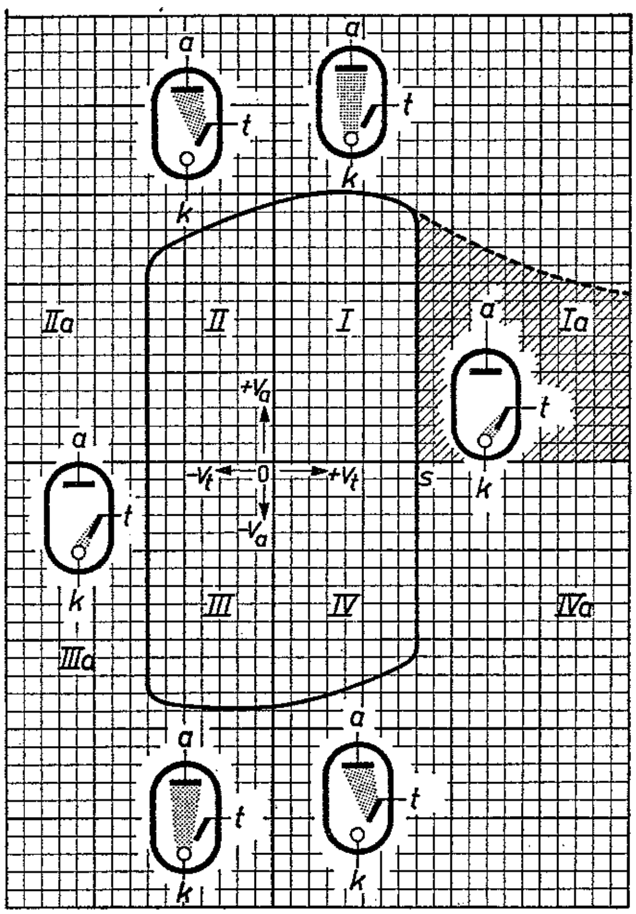
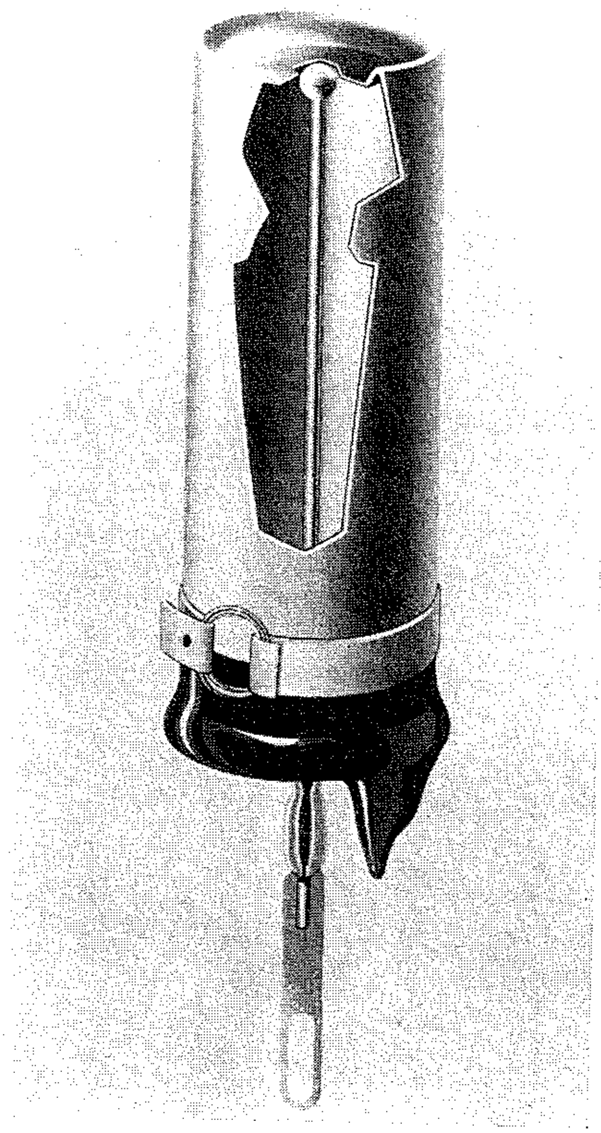


Fig. 152
Ignition characteristic of the trigger tube type 5823. The different sections of the loop refer to a discharge between the electrodes as indicated schematically.

Photo 9

Cut-away view of an (obsolete) radiation counting tube Philips type 18504 with mica end window. The metal strip around the tube serves as a cathode connection.



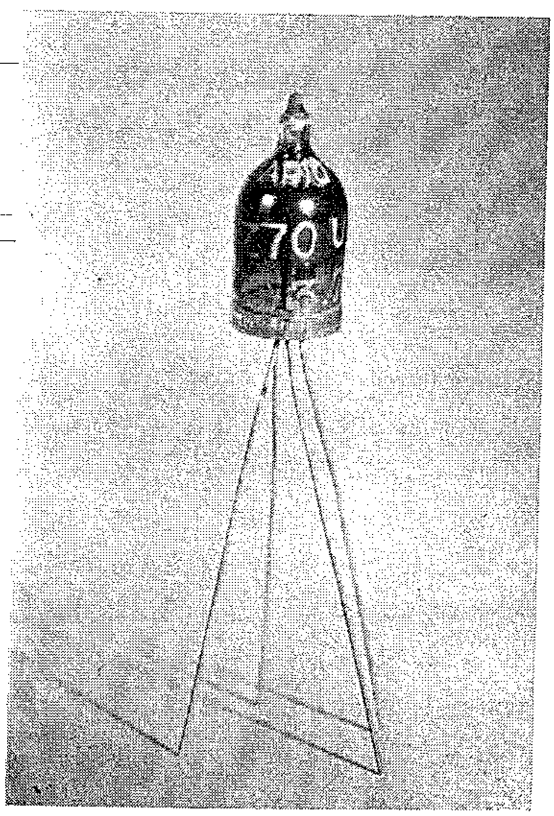


Photo 10

Photograph of a small trigger tube, Philips type Z 70 U, actual size.

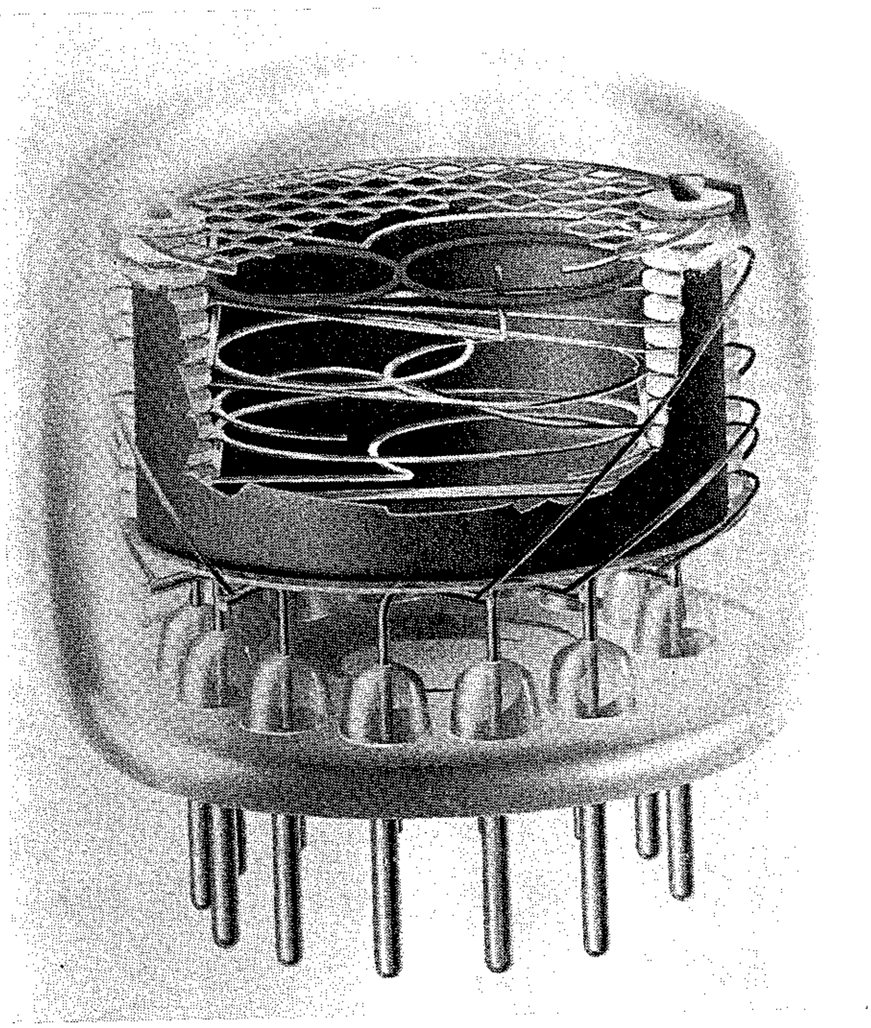


Photo 11

Cut-away photograph of the Philips indicator tube type Z 510 M.

respectively, undesired ignition can take place between the electrodes indicated in the figures. We should like to mention in particular the dangerous situation which can arise in region IVa, bottom right: when V_t is positive and V_a negative, an undesired ignition can occur between t and a. This situation, of which there is always some risk when an AC anode supply is used, can be made less critical, e.g. by ensuring that as long as the anode voltage is negative, V_t is scarcely positive (or even negative), so that the voltage between t and a is sufficiently low. This can

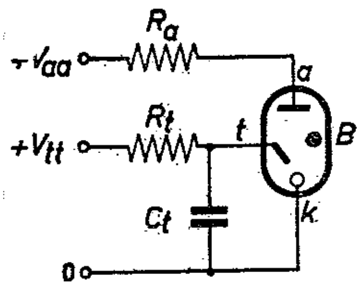


Fig. 153
Typical control circuit for a trigger tube with positive trigger voltage. The small capacitor C_t causes an extra trigger current pulse of short duration which makes the ignition of the main discharge less critical.

be achieved by suitable design of the control circuit for the trigger. The situation for normal ignition, i.e. during the positive phase of V_a, can be achieved with the aid of the circuit shown in Fig. 153, which is open to modification in various ways. $+ V_{aa}$ is chosen so that no discharge can occur between a and k unless the value of $+ V_{tt}$ is sufficiently high. The trigger current is limited in the first place by the series resistance R_t; but it is often advantageous to use a small capacitor C_t to give an extra current pulse of short duration, with a peak value considerably greater than that determined by R_t. The ignition voltage is thus made less critical, so that the slope of the broken line in Fig. 152 becomes much greater: the first part of this curve can indeed become almost vertical. A value of 100—[illegible]00 pF for C_t is sufficient for this purpose.

The cathode of the 5823 is coated with an alkaline-earth oxide in order to obtain a lower trigger ignition voltage and trigger burning voltage (70—90 V and about 60 V, respectively). While this tube has an auxiliary discharge with positive trigger, other tubes such as the Philips type Z 804 U work with a *negative ignition pulse*: when the voltage between the negative trigger and the cathode is high enough, the auxiliary discharge is produced between t and a, whereafter the main discharge between a and k can follow. The advantage of the negative trigger is that the plasma of the auxiliary discharge is then practically at cathode potential, so that the voltage needed between cathode and anode for the ignition of the main discharge is lower than with a positive trigger. Alternatively, instead of a lower anode voltage and a normal trigger current, we can choose to ignite the main discharge with a normal anode voltage and a lower trigger current. If the anode is fed with AC, the voltage between a and t during the negative phase of the anode (assuming that the trigger is permanently biased) is less than with positive trigger ignition (or trigger bias) as in tubes like the 5823. The risk of current flowing between anode and cathode in this interval is thus less, which is another advantage of these tubes.

Trigger tubes with special properties can be obtained by the addition of extra electrodes. For example, there are tubes with a fourth electrode which acts as an auxiliary cathode [63]. The "Cerberus", type GR 16, has an anode which is screened by an insulated metal cylinder (Fig. 154) so as to give a high inverse ignition voltage. This tube can be used on the 220-V AC mains and works with a positive starting pulse. The maximum

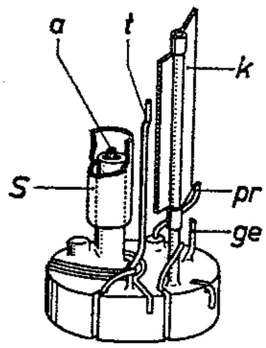


Fig. 154

Electrode arrangement of trigger tube GR16 for AC voltage. The anode a is screened by a metal cylinder S, resulting in a high inverse ignition voltage (a negative, k positive). t = *trigger*, pr = priming electrode, ge = getter.

cathode current is 20 mA. This tube also has a "priming" electrode pr. A continuous discharge is maintained between pr and the cathode, at a sufficient distance from the main discharge to ensure that the ignition voltages are not affected. This priming discharge ensures that there are always enough charge carriers in the gas, so that retardation of the ignition is prevented.

V-f-3 RETARDATION OF IGNITION

The ignition of the main discharge will be retarded by a certain time, which may be resolved into the *statistical retardation* (see I-e-1) and the *take-over time*. The statistical retardation, due to the fact that the formation of the first charge carriers in the gas is a random process, holds up the formation of the trigger discharge by a shorter or longer time. A very small quantity of radio-active material is sometimes placed in the tube in order to remove this delay, or a small proportion of a radio-active gas may be added to the normal filling. Another solution is irradiation with ultraviolet light. Where the tube envelope absorbs ultraviolet, or if the tube is used in the dark, or if the cathode it not coated with barium, a permanent auxiliary discharge of a few μA may be maintained between a "waker" electrode (or "primer" electrode) and the anode to provide the initial ionization.

If steps are taken to ensure this initial ionization, the trigger discharge will always ignite sufficiently rapidly (max. retardation about 100 μ sec.).

After the trigger discharge has once been produced, a second period of retardation follows, during which the main discharge is built up; this is called the *build-up time* or *take-over time*. If we allow the trigger current I_t to increase uniformly, then for each value of I_t a corresponding anode voltage can be found at which the main discharge is ignited. The build-up time of the main discharge is short, about 10 μ sec.

Under favourable circumstances, the total retardation time may be expected to be a few tens of microseconds.

V-f-4 QUENCHING (DE-IONIZATION, RECOVERY TIME) [25]

Just as with the thyratron, the switching electrode of a trigger tube cannot be used to quench a discharge once ignited between anode and cathode. Here too, the tube voltage must be lowered below the burning voltage V_{br}, for long enough to ensure that the discharge is not re-ignited when the tube voltage is increased again, before the trigger discharge is ignited. During this time, the de-ionization time, the ions and electrons must be given the chance to recombine.

As we have seen in IV-b-4, this time is not constant, but depends on the nature and pressure of the gas, the magnitude of the tube current just before quenching and the tube voltage during the de-ionization. It is also mentioned there that these factors depend on the values of the components used in the external circuit.

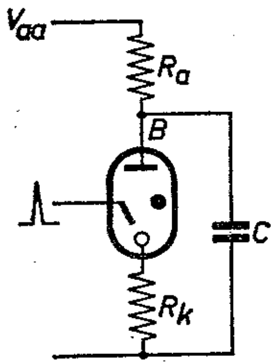
It is therefore more accurate and more practical to speak of the recovery time (see IV-b-4). This is the time, for a given circuit, after which the anode voltage can be applied again with the assurance that the main discharge will not re-ignite unless the trigger discharge is present.

The importance of the recovery time e.g. for the counting circuit of Fig. 151 is brought out during the discussion of the maximum possible counting frequency (see V-g-2). Here too, we see how in a series of tubes a given tube can be quenched with the aid of the following one.

Self-quenching

There is another method of quenching, which does not involve the co-operation of a second tube. In the circuit of Fig. 155, the tube is quenched after the passage of a current pulse. While the tube is cut off, the capacitor C is charged in series with R_a. If the tube then receives a trigger pulse, C is immediately discharged rapidly via the tube B and the cathode resistance R_k, after which the discharge breaks off because of the high value of R_a, which ensures that the continuous current through the tube is too low to maintain a discharge. C is then charged again. To each value of C corresponds a minimum value of R_a which ensures that B will be quenched reliably; $R_{a\ min}$ is of the order of 1—10 megohm.

A tube constructed like the Mullard type Z 801 U (cf. V-g-2) still quenches at relatively low values of R_a [63]. R_k, on the other hand, must not be too large so as to give a short RC time; the inductive properties of the tube, always present to a certain extent, and the self-inductance of the wiring aid the quenching.



Typical circuit for a self-quenching trigger tube.
Fig. 155

V-g **Counting tubes**

V-g-1 INTRODUCTION

The application of controlled cold-cathode tubes has not remained restricted to relay circuits, time switches and amplifiers for very low currents. They have proved very useful in the "electronification" of all sorts of industrial processes; but of recent years they have also proved their usefulness in electronic counting and calculating systems. They have established a place for themselves in this field, alongside vacuum counting tubes (the Philips E1T, the Ericsson trochotron with electrostatic and magnetic deflection of an electron beam), transistors and the like. The ever-increasing demands made on the counting speed have driven mechanical calculating machines, whose speed is limited because of the relatively high inertia of their moving parts, into the background [27, 28, 29]. When very high counting rates are not needed, glow-discharge trigger tubes come into consideration. As we have seen above, these tubes can give counting rates of up to a few thousand a second. Their "on-off" character (two stable states) makes them suitable for use in *digital* counting systems, i.e. systems in which numbers are represented by discrete stable states of the system.

Among the factors which must be taken into consideration when deciding whether a trigger tube can be used for a given application, we may mention the maximum counting rate, the power consumption (also of the trigger circuit), the supply voltage needed, how the final result is to be displayed, the life and volume of the counter.

V-g-2 TRIODES AND TETRODES (counting tubes with one cathode)

We have already seen in V-f-4 that not only the tube but also the external circuit has an effect on the counting rate. The power is of minor importance, and should preferably be kept small. Anode currents of tens of milliamperes need not be delivered provided that the result of the counting process is to be indicated by the discharge state of the tubes used. The simplest form of such indication is where the tube itself gives a visual indication of whether it is passing current or not. If a tube gives a discharge which is invisible or hardly visible, its state can be indicated by e.g. placing a neon glow-discharge tube in parallel with its series resistance. A typical example of a counting tube which itself gives an indication of its state is the sub-miniature Philips trigger tube type Z 70 U, whose electrode arrangement is shown in Fig. 156. With a current of 1—3 mA, the discharge is seen through the base of the tube as a clearly visible red glow.

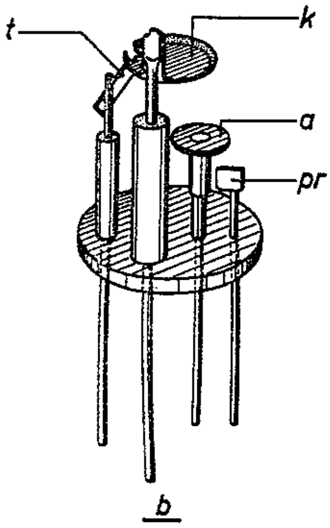


Fig. 156
Electrode arrangement of a small trigger tube, Philips type Z 70 U.
Trigger electrode *t* is placed quite near the cathode *k*. A continuous priming discharge is maintained between the negative primer *pr* and anode *a*.

The electrical properties of this tube are very constant, thanks to the molybdenum cathode which is treated by sputtering methods (cf. V-a-2).

The small dimensions (diameter 10 mm, length max. 25 mm, Photo 10) and the very low power make is possible to build a 1.2-W decade counter, including the necessary resistors and capacitors, on a printed wiring board measuring about 10 × 10 cm^2. The tube is simply soldered on to the wiring by its projecting lead wires.

The low power needed for the counting pulses applied to the trigger can be seen from the fact that a trigger current of as little as 20 μA (the transfer current) is enough to enable the anode to take over the trigger discharge. This tube also has an extra primer electrode which acts as an auxiliary cathode and passes a permanent current of about 1—10 μA. The task of this electrode is to maintain a slight preliminary ionization, to prevent retardation of the ignition. Ten of these tubes are needed for a decade counter. We shall mention some details of the external circuit during the discussion of the counting rate at the end of this section.

The tube type Z 70 W offers more possibilities. This is a modification of the Z 70 U, containing a second trigger electrode. The need for two triggers is felt for electronic addition and subtraction. One trigger is used for addition, and the other for subtraction. The counting circuit therefore contains two pulse lines, each of which supplies a series of corresponding triggers from a group of counting tubes.

The Mullard tube type Z 801 U is a tetrode whose fourth electrode is an auxiliary cathode. This tube was originally intended for use with positive trigger-voltage pulses [63].

The principle of a circuit using these tubes for counting high-frequency pulses, with a self-quenching discharge, is shown in Fig. 157. The trigger t

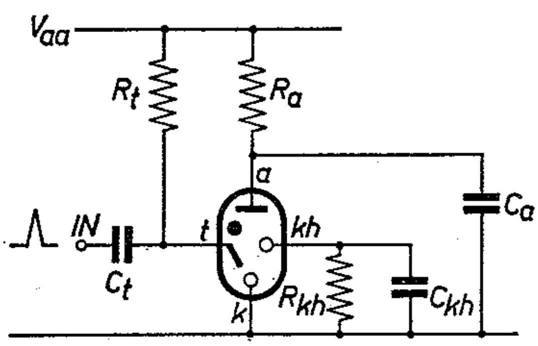


Fig. 157

Self-quenching circuit for measuring counting rates, using a cold-cathode tube with four electrodes and positive trigger pulses. The fourth electrode makes it possible to separate the functions of ignition and quenching, which can be useful for counting radiation in conjunction with Geiger-Müller tubes (counting rates up to 10 kc/s). Typical values of the circuit components are:
$R_t = 100\ \mathrm{M}\Omega$,
$Ct = 50$ pF, $R_a = 200\ \mathrm{k}\Omega$, $C_a = 0{,}01\ \mu\mathrm{F}$,
$R_{kh} = 1\ \mathrm{M}\Omega$ and $C_{kh} = 50$ pF.

is connected directly to the anode supply via the resistance R_t, so that the quiescent voltage on t is near the breakdown value for a discharge between t and k. The slightest positive pulse delivered via C_t, will thus ignite the trigger discharge. The fourth electrode is not in principle necessary for this purpose, but its addition does improve the recovery time (separation of the functions of ignition and quenching) and thus increases the possible counting rate. The main discharge, which follows the production of the auxiliary discharge, is first formed between a and the auxiliary cathode k_h, after which the potential of k_h rises owing to the presence of R_{kh} and C_{kh}. When it has risen sufficiently, the main cathode k takes over the discharge, C_a then discharges and the discharge is quenched. Since k_h does not immediately return to cathode potential, ignition of a discharge between k_h and a is not so easy; the recovery time is partly determined by the values of R_{kh} and C_{kh}.

This tube can however be used to better effect with negative pulses. This is desirable when the tube is used as an amplifier in conjunction with Geiger-Müller radiation counter tubes. Since the cathode of the latter tubes is normally at earth potential, negative pulses are produced in the series resistance. The ignition cycle of the Z 801 U when used for this purpose (see Fig. 158) is as follows. First a preliminary discharge is produced between k_h and t by the negative voltage pulse on k_h; the auxiliary discharge between t and k then takes over, and finally the main discharge a-k. Used in such a set-up, the tube has a very high sensitivity; an input charge of 3×10^{-11} C is enough to trigger the discharge, as against 5×10^{-10} C when positive pulses are used. This method permits counting rates of the order of 1000 c/s. Moreover, the pulse energy is found to be constant over a fairly wide range of anode supply voltages.

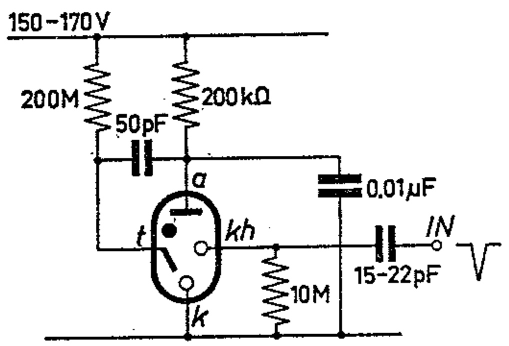


Fig. 158

Self-quenching circuit for a counting-rate meter for negative pulses and high count rates. This circuit, using the tetrode counting tube type Z 801 U, has a high input sensitivity.

Counting frequency

We shall now examine how counting actually takes place, with reference to Fig. 151, which shows a circuit with three counting tubes, B_1, B_2 and B_3. V_{aa} is the DC anode supply voltage, and periodic positive pulses are applied to the line P. If B_1 passes a current I, the voltage across the cathode resistance R_{k1} (of magnitude $R_{k1} \times I$) acts as trigger bias for B_2; the values of R_{k1} and the common anode resistance R_a are so chosen that this trigger bias is slightly less than the triggering voltage of B_2.

The next (positive) pulse applied to the pulse line P makes the trigger voltage high enough for a brief period for B_2 to be triggered. As a result of the passage of current by B_2, the voltage drop across R_a increases somewhat, as a result of which the voltage across B_1 falls below the burning voltage and the tube is quenched. The details of this process are as follows: the capacitor C_{k2} in parallel with R_{k2} acts as a short-circuit across the latter during the build-up of the current through B_2, because of its low impedance. The voltage across R_a during the ignition will thus remain practically equal to $V_{aa}-V_{br}$, where V_{br} is the burning voltage of the tube. The voltage across B_1 is therefore equal to $V_{aa}-IR_{k1}-(V_{aa}-V_{br}) = V_{br}-IR_{k1}$, i.e. less than V_{br}, during this period.

After B_1 is quenched, the initial situation has shifted along one place: B_2 is now burning and provides trigger bias for B_3, so that the next pulse on P will ignite B_3 and quench B_2, and so on.

The frequency with which the counting can proceed without disturbance depends mainly on the RC time constants in question. The charging time of C_{k2} is determined by $R_{k2} \cdot R_a \cdot C_{b2}/\ R_{k2}+R_a)$ during the ignition of B_2, and $R_{k1}\ C_{k1}$ determines the discharge time of C_{k1} during the quenching of B_1. Together, these two determine the time which must pass before the voltage across R_{k1} is again practically zero, so that the voltage across B_1 is once again greater than the burning voltage. If in the meantime the de-ionization process in B_1 has proceeded far enough, in other words if the tube has recovered sufficiently, it will not reignite.

The chance of complete recovery thus also depends on the frequency of the pulses on P, because a high frequency demands short RC times (R and/or C small), and the shorter the RC time the less chance the tubes have to recover. Trigger tubes in general cannot give counting rates of more than a few thousand per second.

Data of a number of trigger tubes are given in Table XIII.

While triode and tetrode trigger tubes can be used in many control circuits, special multi-cathode glow-discharge counting tubes have been developed for calculating purposes; we shall discuss these in the next section.

V-g-3 RING COUNTING TUBES (multi-cathode) [26]

We have seen above that a decade counting circuit can be made by combination of ten tubes, each with one anode and one cathode. In such a circuit, the tubes are connected by RC links, and on receipt of a control pulse the discharge is transferred from one tube to the next one, while the first is quenched.

Much work has been done in an attempt to combine such a set of counting tubes into one. These attempts have led to the development of glow-discharge tubes with one anode and many cathodes in the same discharge space. The cathodes with their auxiliary electrodes ("guides") are arranged in a ring round the anode, so that application of control pulses to the guides causes the discharge to jump from one cathode to the next one. In these *ring counting tubes,* the visible glow on a certain cathode (which may be given a special shape), indicates the number of pulses applied. If a decimal ring counting tube (i.e. one with ten cathodes) is combined with a second one, it is possible to count up to 99; with three tubes one can count to 999, etc.

TABLE XIII

OPERATI[illegible] DATA OF SOME TRIGGER TU[illegible]

TUBE TYPE	5823/ Z900T	Z50T	Z70U	Z801U	Z804U	GR16
Anode supply (DC or AC)	DC or AC	DC	DC	DC	DC or AC	DC or AC
Max. anode voltage, or $V_{a\,rms} \times \sqrt{2}$ (V)	200	175	310	170	400	360
Burning voltage between anode and cathode (V)	nom. 62 max. 85 (I_a=25mA)	nom. 61 max. 67 (I_a=2-6mA)	nom. 118 max. 121 (I_a= 3mA)	nom. 105 (I_a=2mA)	min. 108 max. 115 (I_a=15mA)	nom. 110 max. 115 (I_a=20mA)
Typical ignition voltage between trigger and cathode *) (V)	80	71	145	—	–125	130
Minimum ignition voltage between trigger and cathode *) (V)	73	66	139	—	–119	120
Maximum ignition voltage between trigger and cathode *) (V)	105	90	151	—	–131	140
Burning voltage between trigger and cathode (V)	61 (I_a=25mA)	—	—	—	—	—
Necessary trigger current (I) (μA)	nom. 50 max. 400 (V_a=140V)	nom. 50 max. 100 (V_a=130V)	nom. 20 (V_a=250V)	—	—	nom. 5
Necessary trigger current (II) (μA)	max. 160 (V_a=175V)	—	—	—	—	—
Typical/maximum primer current (μA)	—	—	3/5	0.4/0.6	—	—
Minimum voltage between primer and anode (V)	—	—	210	—	—	—
Maximum mean cathode current (mA)	25 (t_{av}= 15 sec. max.)	6	3 (t_{av}= 1 sec. max.)	2.5 (t_{av}= 15 sec. max.)	40	20
Maximum peak cathode current (mA)	100	24	12	10	—	40
Maximum mean auxiliary-cathode current (mA)	—	—	—	1.0	—	—
Maximum peak auxiliary-cathode current (mA)	—	—	—	4.0	—	—
Ionization time *) (μsec)	20	50	—	—	—	—
De-ionization time (μsec)	500	200	—	—	—	—

*) When the tube is illuminated.

Various manufacturers have succeeded in making useful ring counting tubes. Some of these have two guides per cathode, and need a double pulse to make the discharge jump from one cathode to the other. Other tubes work with a single square-wave pulse of short duration, or with sinusoidal pulses and three guides per cathode. A number of types can count in both directions [30].

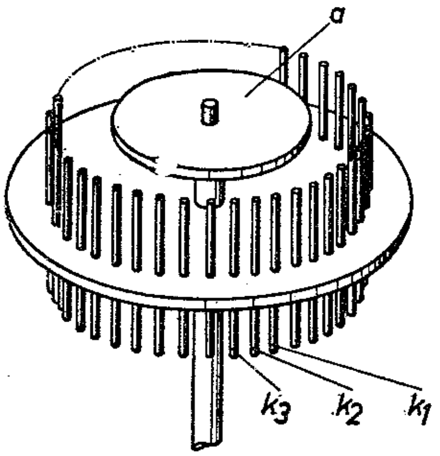


Fig. 159

The 10×3 electrode rods of the decimal ring counting tube type GS10C. If k_1 is a main cathode, k_2 and k_3 are "guide cathodes". a is the anode.

We shall now describe one two-pulse tube with its ancillary circuit, to give a clearer idea of how these ring counting tubes work.

The tube we shall choose for this purpose is the dekatron counting tube type GS 10 C (made by Ericsson), whose electrode configuration is sketched in Fig. 159. Fig. 160 shows how the electrodes are connected within the tube. Three times ten cathode rods are arranged round the

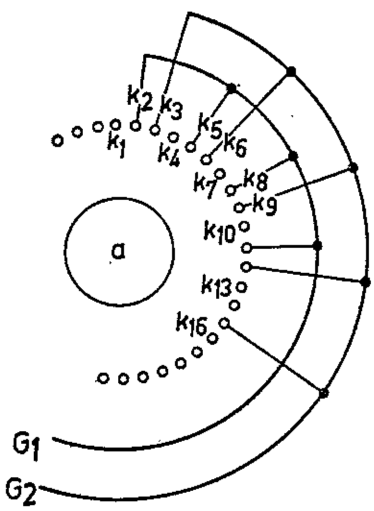


Fig. 160

Sketch of the internal connections between the various electrode rods of the ring counting tube type GS 10 C. The main cathodes k_1, k_4, k_7 ... are not connected. The other electrodes are connected in two guide groups, G_1 and G_2.

disc-shaped anode. All thirty lie on one circle, but they can have one of three different functions. We distinguish the main cathodes and the take-over cathodes or guides.

The main cathodes k_1, k_4 etc. are not connected within the tube, but the two sets of guides, k_2, k^5.... and k^3, k^6.... are. The letter S (for "selector") in the type number of this tube means that all the main cathodes have leads which pass through the envelope, so that they can be selectively connected to the external circuit. For the rest, there is one anode lead and one lead for each of the sets of guides: 13 pins in all.

Fig. 161 shows the GS 10 C in a counting circuit. A double negative control pulse can transfer the discharge from one main cathode to the

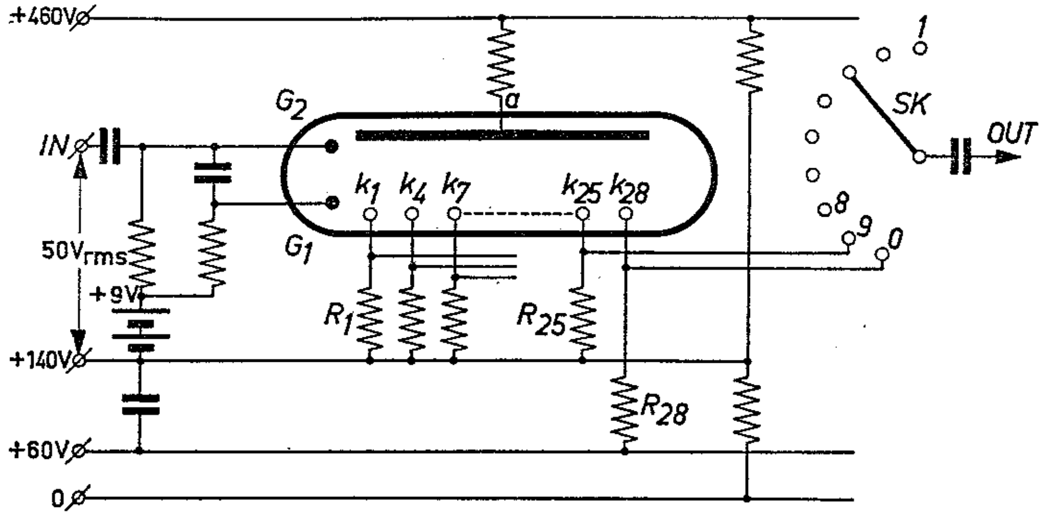


Fig. 161

Example of a counting circuit for a ring counting tube type GS 10 C. The guides G_1 and G_2 receive pulses from an AC voltage source of 50 V_{rms}. The guide circuit shown in the figure makes double pulses from these, with a phase difference between the voltages on G_1 and G_2. As soon as one of the main cathodes k_1, k_4, k_7 etc. ignites, a voltage jump is produced on the corresponding cathode resistance. The position of the switch *SK* determines which voltage jump will be delivered at the output.

next, as follows. The two sets of guides have a constant bias, slightly positive with respect to the main cathodes. This ensures that the discharge will always tend to remain on one of the main cathodes. Let us suppose that in a quiescent state k_1 is covered by the glow discharge. If now the neighbouring guide electrode k_2 is made sufficiently more negative than k_1 (peak pulse voltage greater than positive bias), the glow discharge will jump from k_1 to k_2, and k_1 will be quenched. If then the set of guides containing k_3 is made more negative than k_2, k_3 will begin to glow and k_2 will be quenched. When the second negative pulse has passed, the neighbouring main cathode k_4 is more negative than k_3, so the discharge will jump to k_4 and remain there until the next pair of pulses comes along.

The discharge will have no tendency to jump back from k_3 to k_1, because the voltage difference needed for this has been found to be five times as much as that for the jump from k_3 to k_4. One double control pulse thus causes the originally stable glow discharge on the main cathode

k_1 to jump to a stable position on main cathode k_4. A second pulse pair takes the discharge to the next main cathode, and so on. By reversing the order of the pulse pair, the tube can be made to count in the opposite direction (subtract). The selector switch *SK* can be connected to any one of the resistances R_1–R_{28} in series with the main cathodes; as soon as the corresponding cathode has taken over the discharge, a voltage pulse can be delivered via *SK* to a following decimal counter tube.

The maximum counting rate is 4000 c/s. Further data are given in Table XIV.

TABLE XIV

OPERATING DATA OF THE DEKATRON GS 10 C

Maximum counting rate, sinusoidal or square-wave pulse	4000 c/s
maximum anode current	550 μA
minimum anode current	250 μA
minimum anode-cathode voltage	400 V
maximum voltage difference between guides and cathodes	140 V
nominal anode current	325 μA ± 20 %
burning voltage ($I_a = 325\mu A$)	192 V
cathode series resistance	0—270 kΩ
amplitude of output pulses	0—45 V

V-h **Indicator tubes**

When use is made of the tubes mentioned in the previous section, the number which is the result of a given counting operation must be "read off" (one might even say "translated") from the position of the lit-up tube in a decade, or from the position of the glowing cathode rod in a ring counting tube — assuming that the discharge is visible. It is however possible to display the result directly in numbers with the aid of an *indicator tube,* which does not take part in the counting operation. The glow discharge has also proved useful in realizing such tubes.

A cathode made in the shape of a number will give the required visual indication as long as the cathode current is so high that the whole surface is covered by the glow discharge. This principle is made use of in the Philips indicator tube type Z 510 M.

The numbers from 0 to 9 made out of thin wire are placed one right behind the other in a glass envelope filled with a gas mixture consisting mainly of neon. All ten electrodes are connected to pins in the base of the tube. Each electrode can be chosen as the cathode, while the other nine act together as the anode (Photo 11).

The wire figures are so thin that even the rear one can be clearly seen through the other nine when it is covered by the glow discharge. The choice of which electrode is to light up is made by the selector switch S (Fig. 162). Several variations of this type of indicator tube are available.

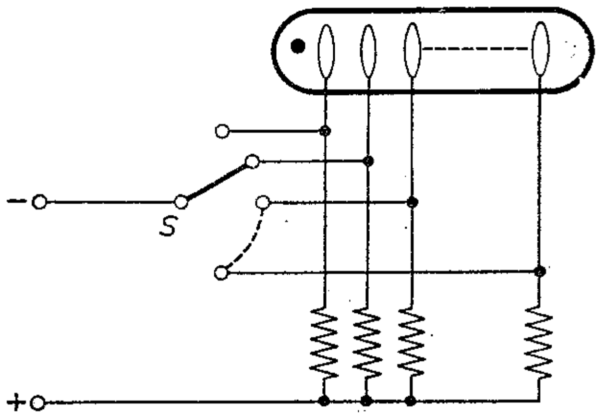


Fig. 162
Circuit for indicator tube type Z510M. The position of the switch S determines which cathode will light up.

The tube current naturally depends on the size of the figures, but is always a matter of milliamperes. It is thus possible to include these tubes in the electronic counting circuit.

Is must be remembered however that in this case the current and the voltage (some tens of volts) for the indicator tube must be supplied by the electronic circuit. It is therefore not possible to place such tubes directly behind e.g. a transistorized circuit. We shall now describe a construction for an indicator tube which makes this possible.

Decimal ring indicator tube

Transistorized counting circuits can be constructed with a resolution as high as that of circuits using radio tubes. The indication of the results must occur separately, as transistors cannot do this themselves. If it is wished to use a glow-discharge indicator tube for this purpose, the difficulty arises that the output signal produced by a transistor is too small to ignite normal indicator tubes. Moreover, the relatively large glow-discharge current needed to make the figures visible can cause errors in the counting. The tube we shall now describe presents an answer to these problems [58].

The photograph of the electrode system shown in Photo 12 shows an annular cathode plate made of molybdenum, divided into twenty sectors. Ten of these (the narrow ones) are covered with an insulating layer; the other ten can each act as the cathode k. They can be marked with the numbers 0 to 9, e.g. with the aid of a number plate placed round the cathode ring inside the envelope. A circular nickel-wire anode a is placed above the cathodes. A trigger t is arranged between a and each of the cathodes. The gas filling consists of about 15 cm neon, mixed with 0.1 % argon. The argon is added for the following reason. It may be seen from the Paschen curve (see Fig. 12) for this gas mixture that the ignition voltage varies very little with $p \times d$ in a wide range near the minimum of the curve. In other words, at a given pressure the distance between the electrodes has very little effect on the ignition voltage. This makes it possible to simplify the construction of the indicator tube.

We shall explain the operation of the tube with reference to the simplified circuit diagram of Fig. 163. The tube is fed with rectified AC voltage (e.g. 50 c/s). Before ignition, the triggers and the anode all have the same voltage with respect to the cathodes. When there is no control signal, ignition can always occur between one or other of the triggers and the corresponding cathode, or between the anode and one of the cathodes. If however a triggering control voltage V_t is applied to one of the trigger

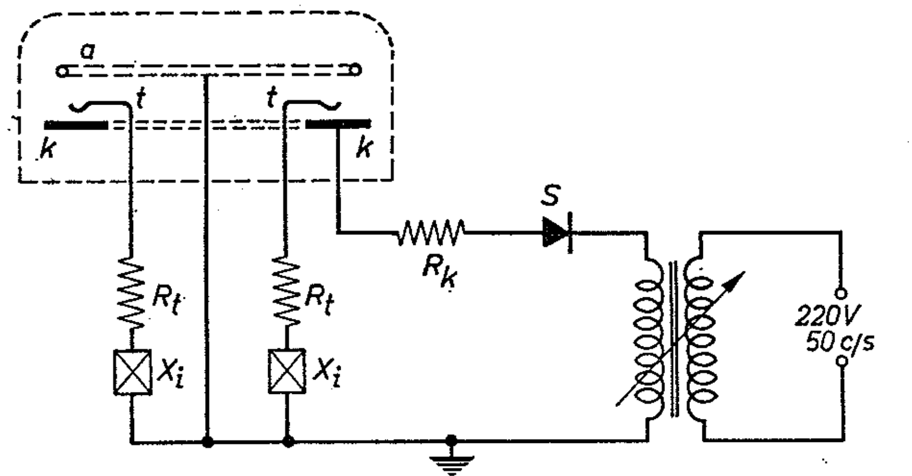


Fig. 163

Circuit for the indicator tube of Photo 12, a anode (earthed), k cathodes, t triggers, X_i voltage source which delivers the control signal. The current of the main discharge is limited by the resistances R_k, that of the auxiliary discharge by R_k together with one of the resistances R_t. The tube is fed with AC rectified bij S [58].

circuits, the trigger in question will ignite first. V_t has a value of a few volts, and is delivered by the voltage source X_i, i.e. one of the positions in the transistorized counting circuit. The value of the supply voltage is not critical, since it is the same for all triggers. What matters is which trigger first reaches the trigger ignition voltage as a result of the extra voltage V_t. After the auxiliary discharge of about 50 μA has been formed between a given t and k, the main discharge a-k will also ignite. The main discharge with a current of several mA is thus fed from the mains. The discharge is periodically quenched because of the sinusoidal voltage used, but will always be reignited on the same cathode as long as V_t remains applied to the corresponding trigger. As the counting proceeds further, V_t will move to another trigger, and the discharge will then be ignited on the cathode belonging to that trigger. The rate at which V_t moves, i.e. the counting rate of the transistorized counter, does not matter here; it may even be so great that the indicator tube cannot follow it. This tube only needs to display the final result of the counting, when the counter has stopped.

This indicator tube will not disturb the counting circuit, as the trigger current is low.

A tube has been built on this principle which can be controlled by a signal of not more than 5V with 50 μA, while the glow discharge gives a clear indication of the number in question.

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.

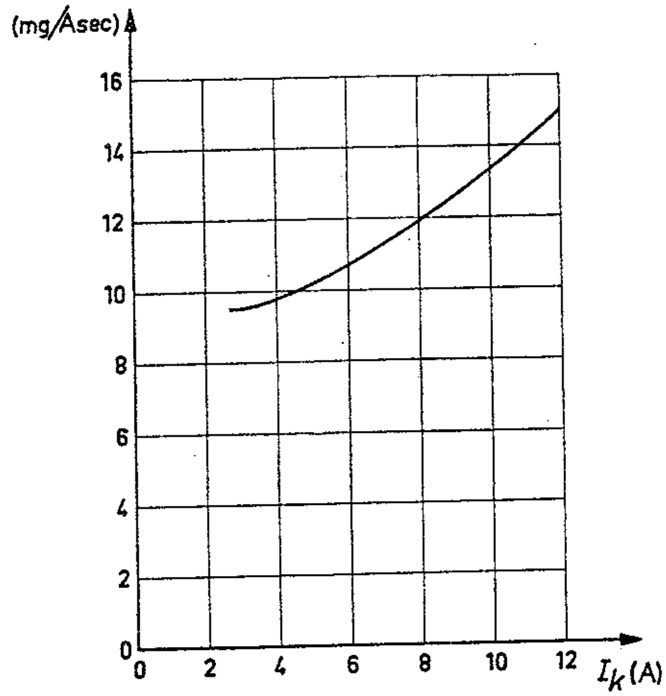


Fig. 164
Specific evaporation of mercury at a cathode spot as a function of the current.

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

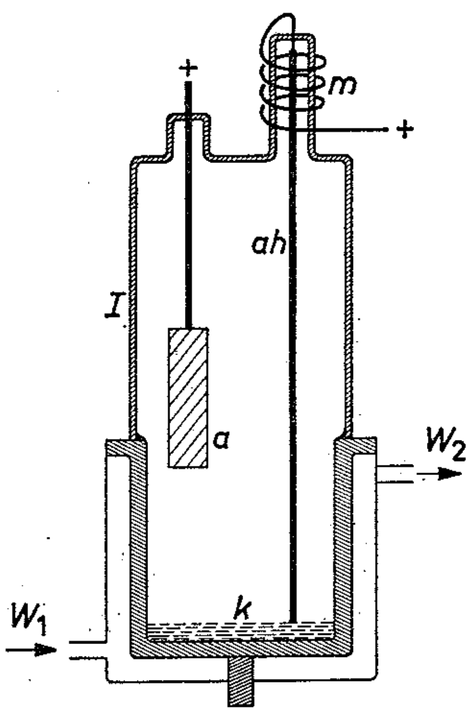


Fig. 165

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.

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).

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

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

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

VI-c The ignitron for resistance welding [43]

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

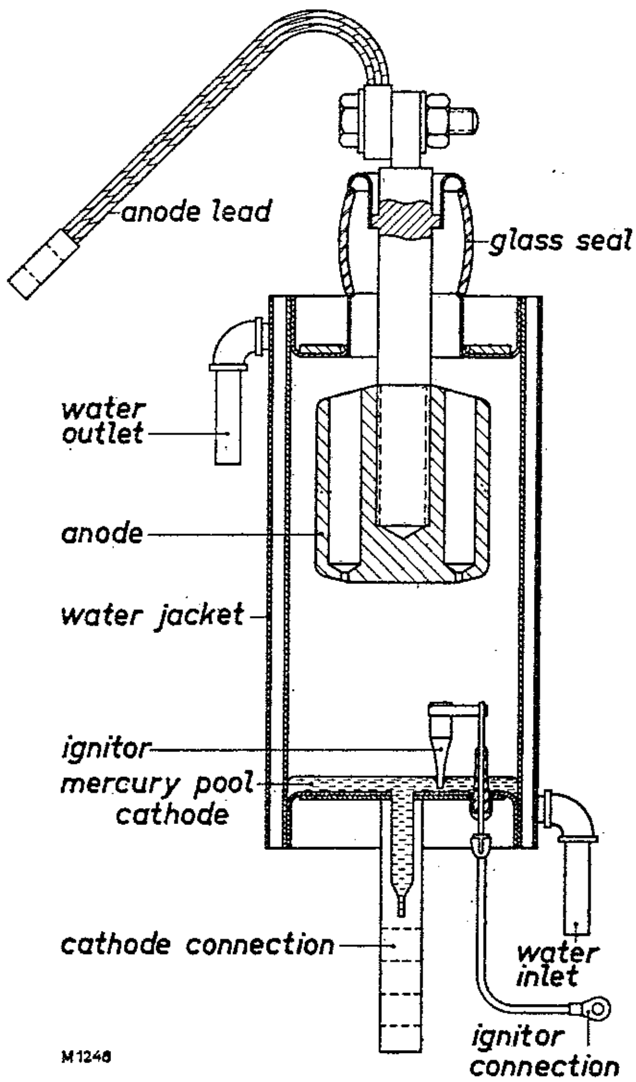


Fig. 166
Construction of a steel ignitron for welding purposes (simplified sketch).

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).

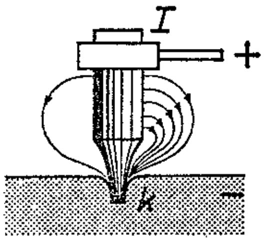


Fig. 167
Ignition rod *I* (positive) of semiconducting material. The specially shaped point dips into the (negative) mercury pool *k*, which forms a downwardly curved meniscus along the line of contact. The lines of force are closer together near the bottom of the slit.

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.

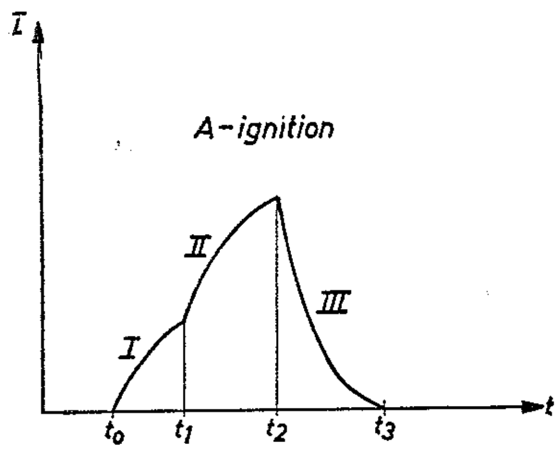


Fig. 168

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

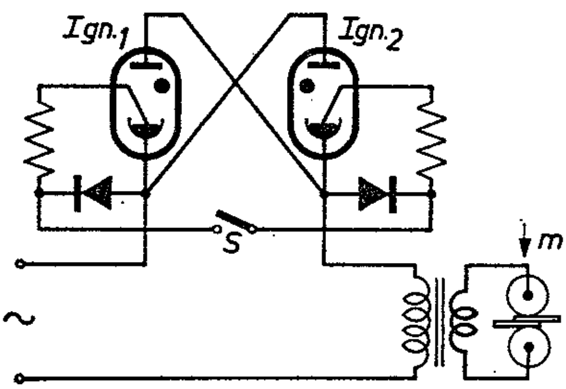


Fig. 169

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.

heater of the thyratron, no extra source of power is needed for ignition.

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

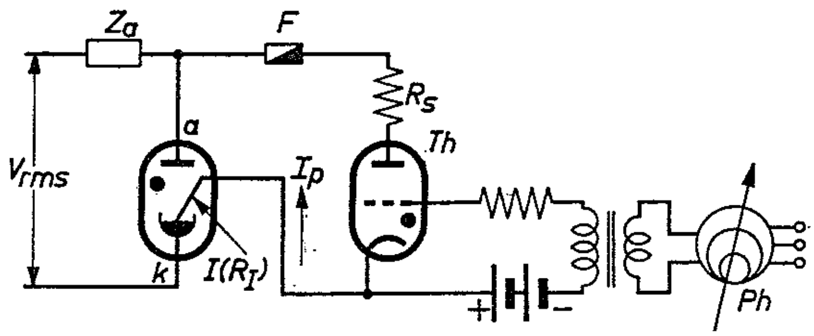


Fig. 170

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.

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 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].

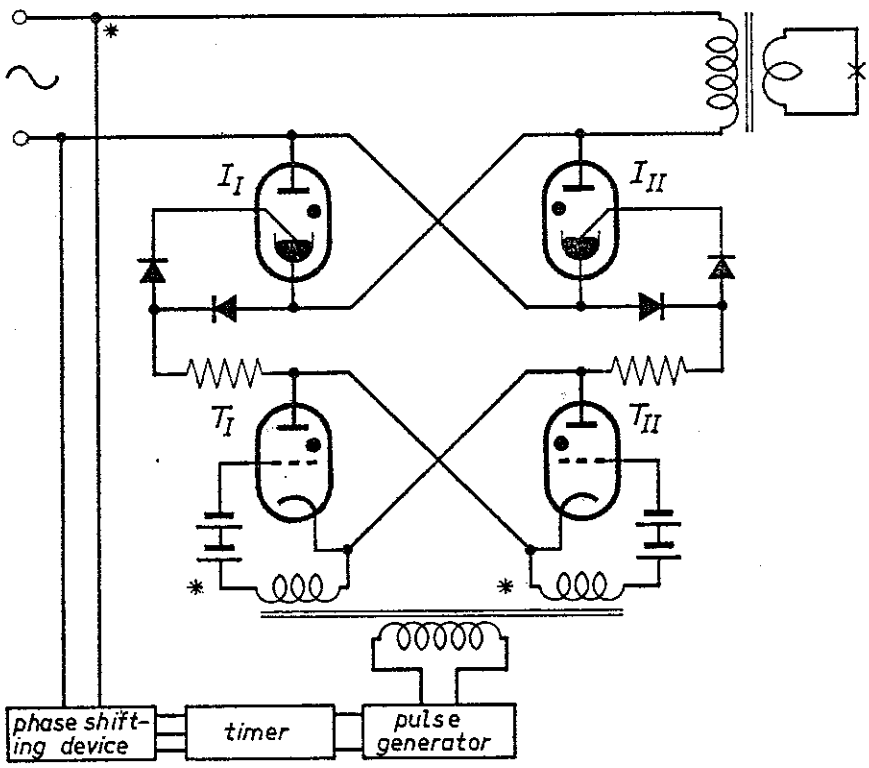


Fig. 171

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

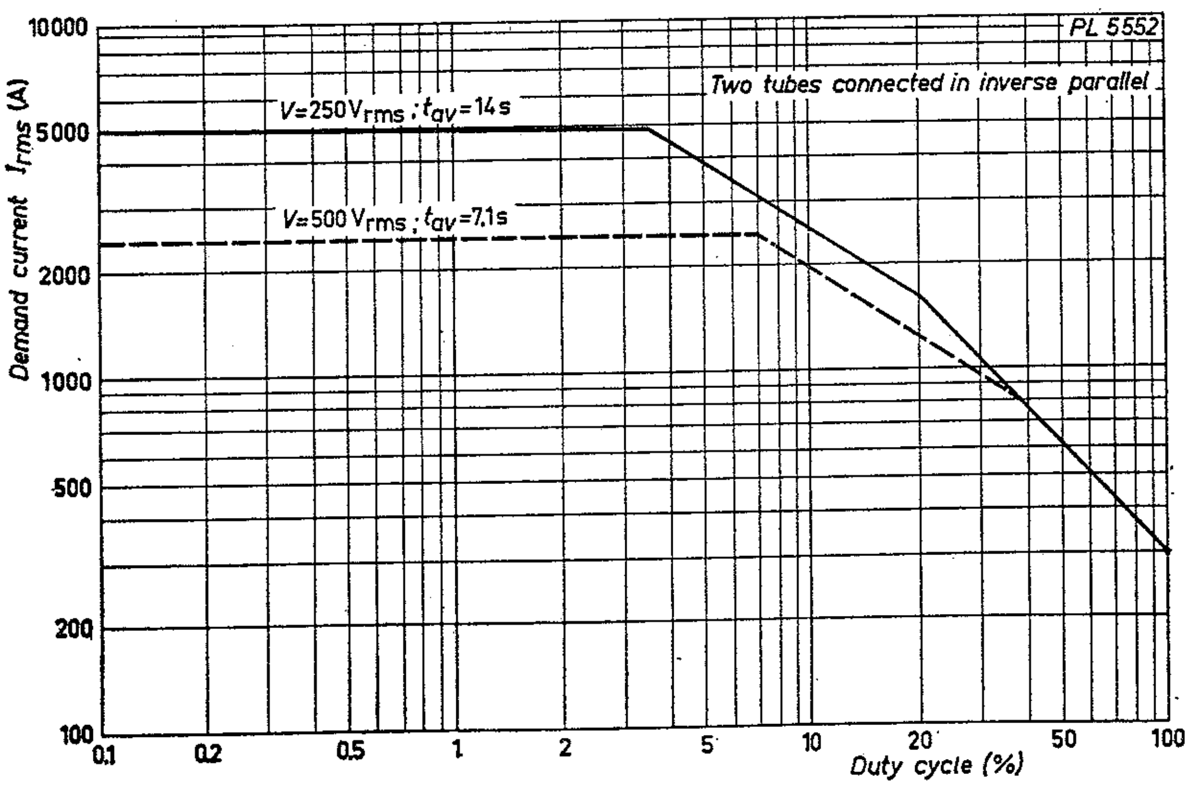


Fig. 172

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

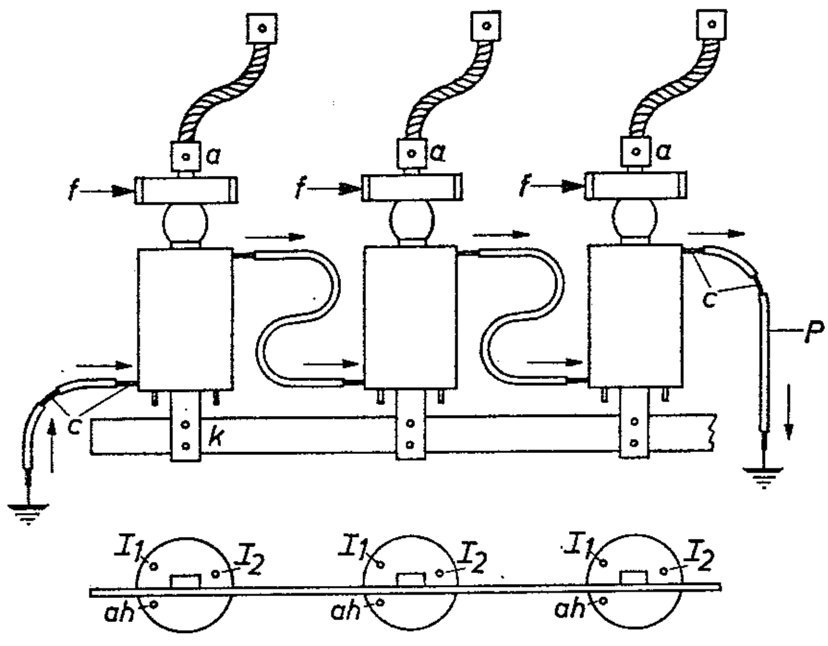


Fig. 173

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.

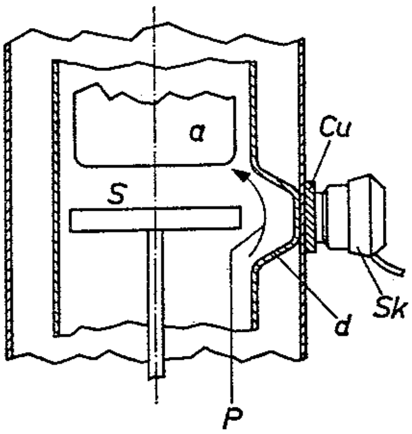


Fig. 174

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

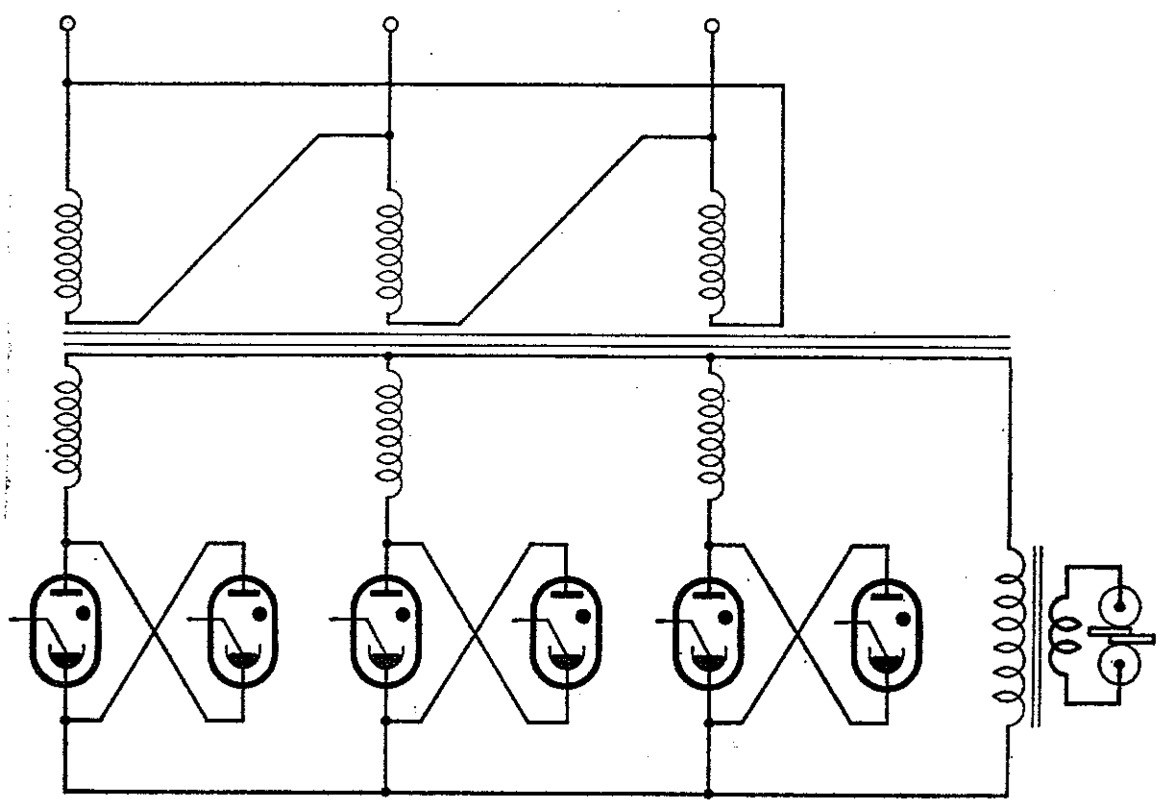


Fig. 175

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

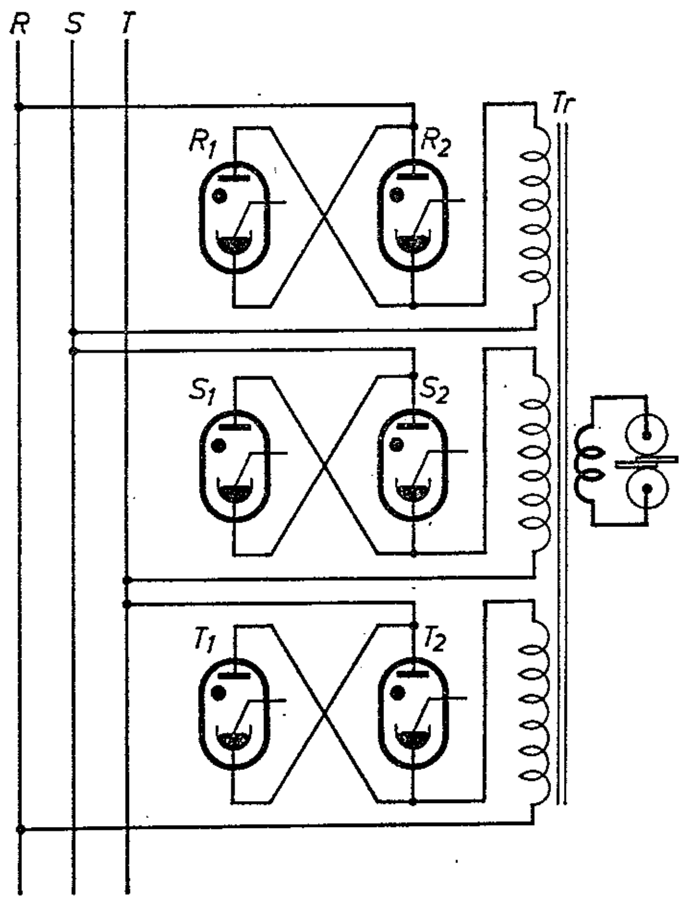


Fig. 176

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,

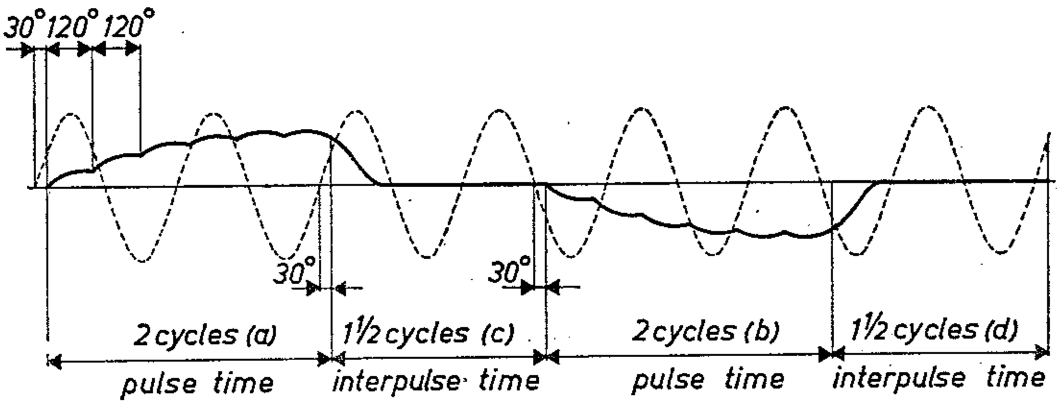


Fig. 177

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.

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.

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

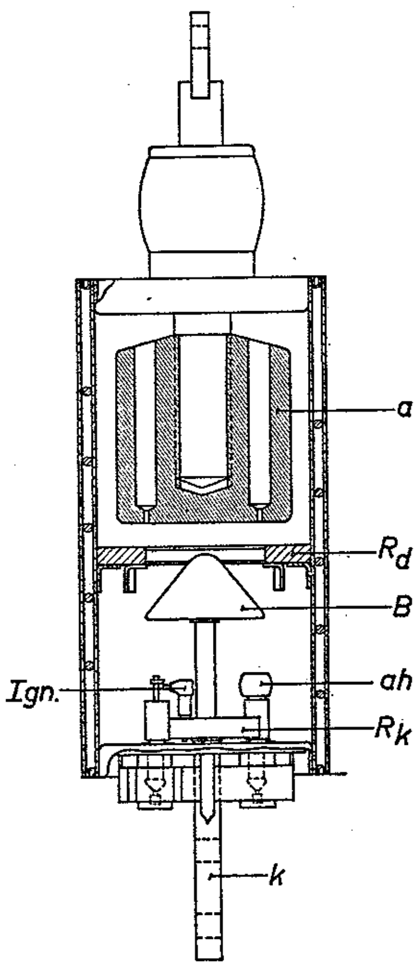


Fig. 178

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

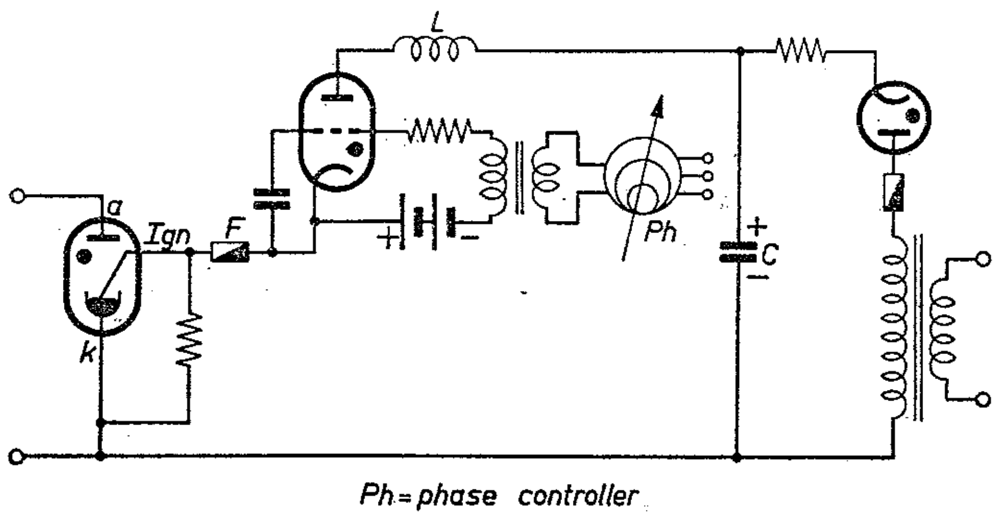


Fig. 179a

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.

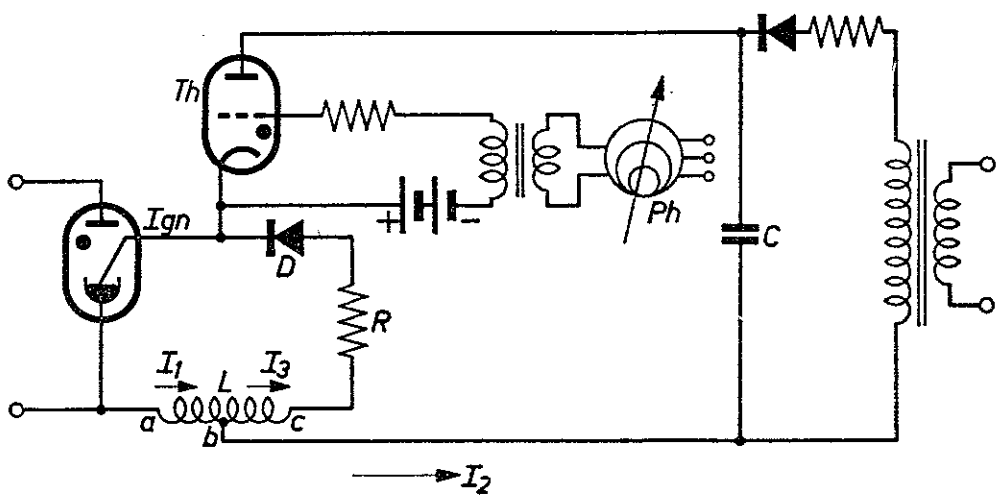


Fig. 179b

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, $C = 5$ μF, 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

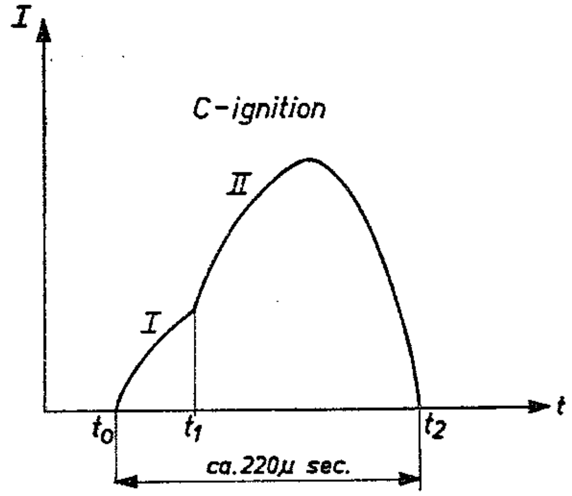


Fig. 180
Current through the ignition rod as a function of time for C ignition. During period *I* there is not yet any cathode spot; this is formed at time t_1. The variation of the current during period *II* is mainly determined by L and C (see Fig. 179a).

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 $V_{av} = 200$ V, we find that the mean ignition power at mains frequency $f = 50$ c/s is:

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

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

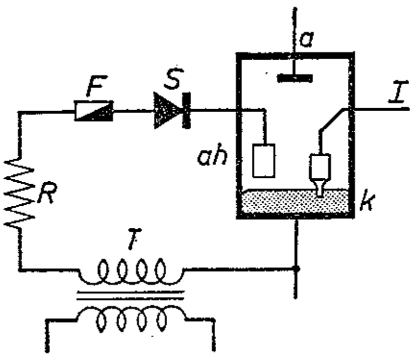


Fig. 181

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

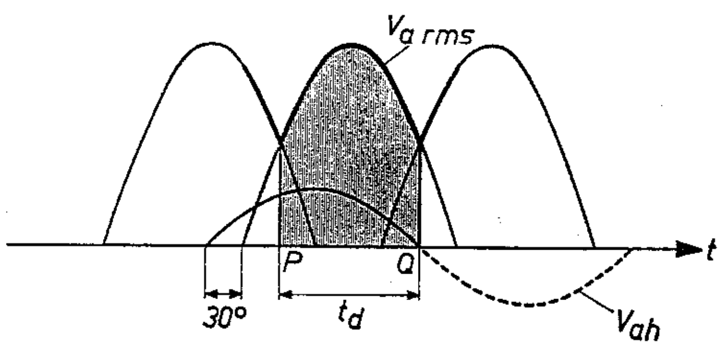


Fig. 182

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.

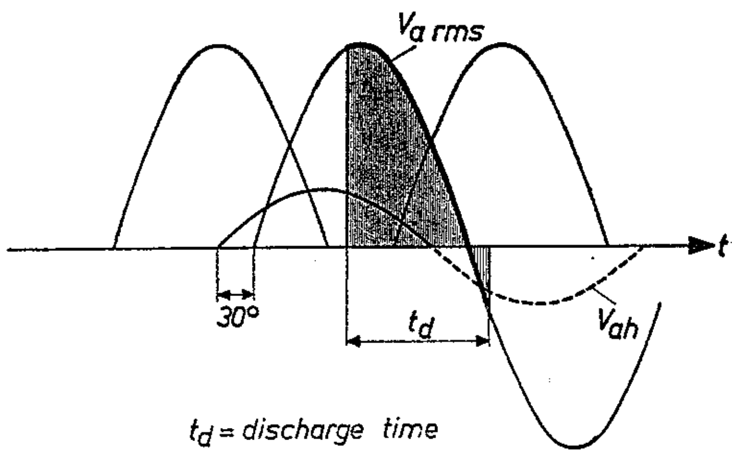


Fig. 183

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 $V_{ah\mathrm{I}}$ must

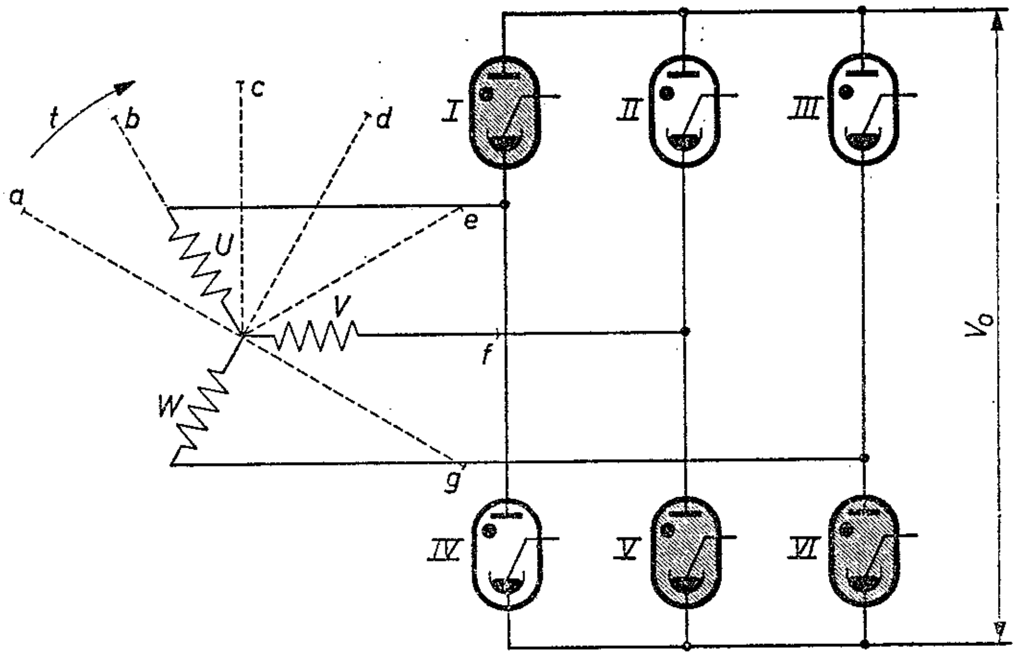


Fig. 184a

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°.

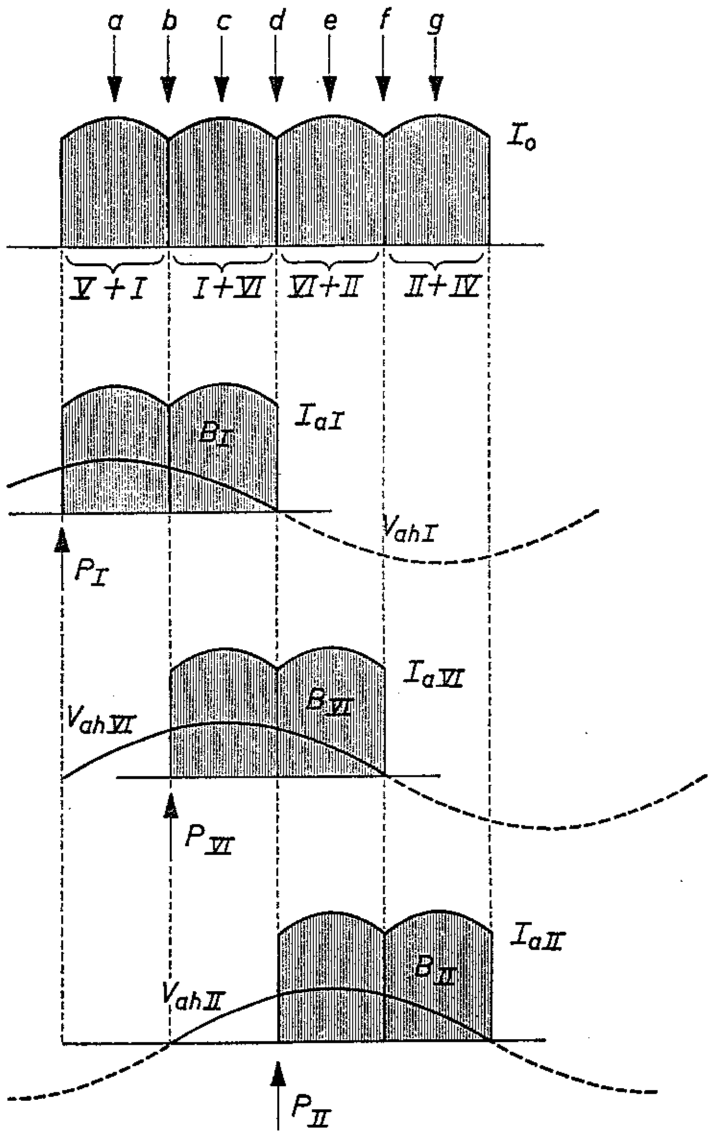


Fig. 184b

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_{ahI} 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_o is the total DC current with 6-phase ripple given off by the assembly, I_{aI} 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

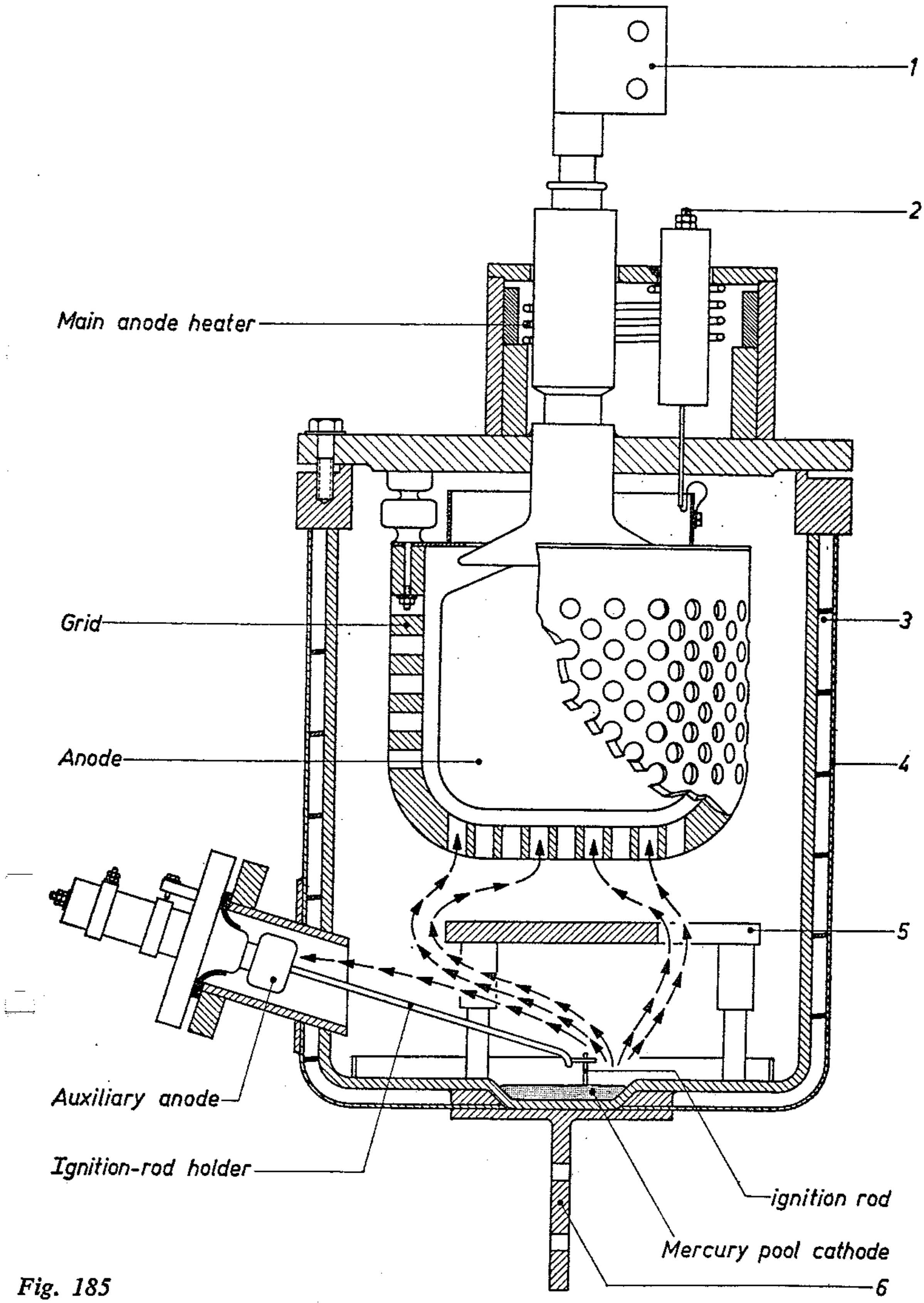


Fig. 185

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
2. grid terminal
3. cooling-water space
4. cooling jacket
5. splash baffle
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

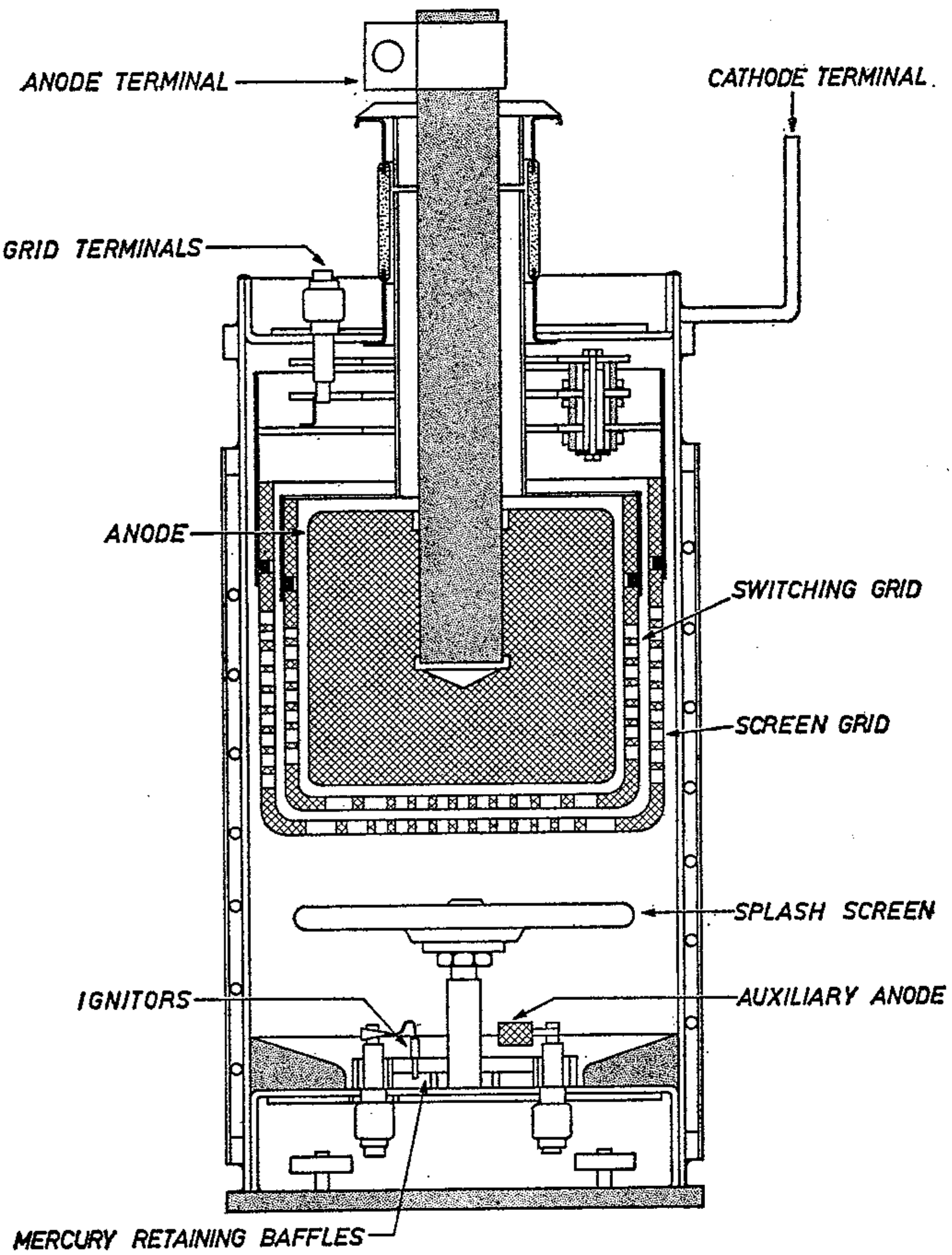


Fig. 186

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

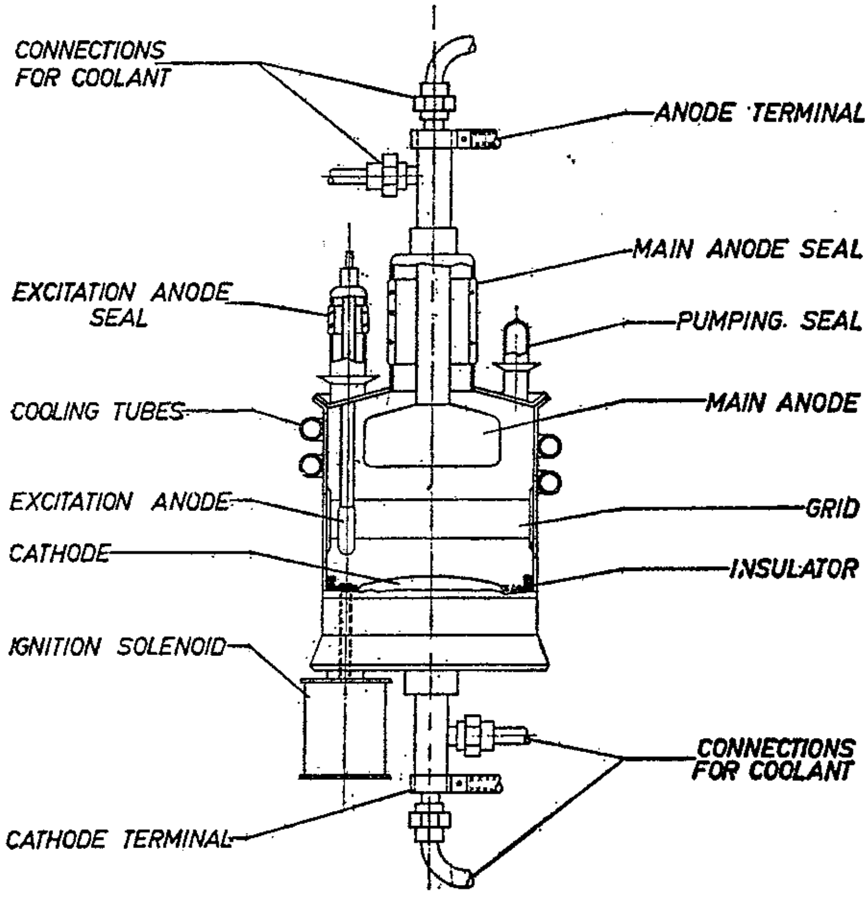


Fig. 187

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].

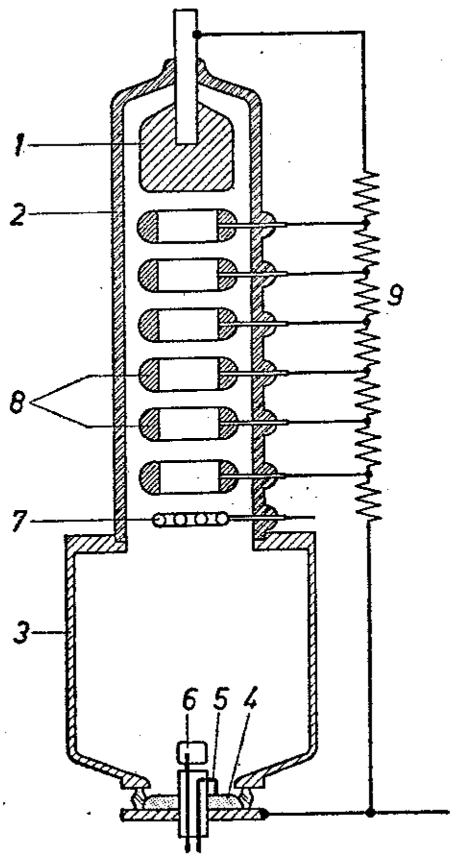


Fig. 188

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

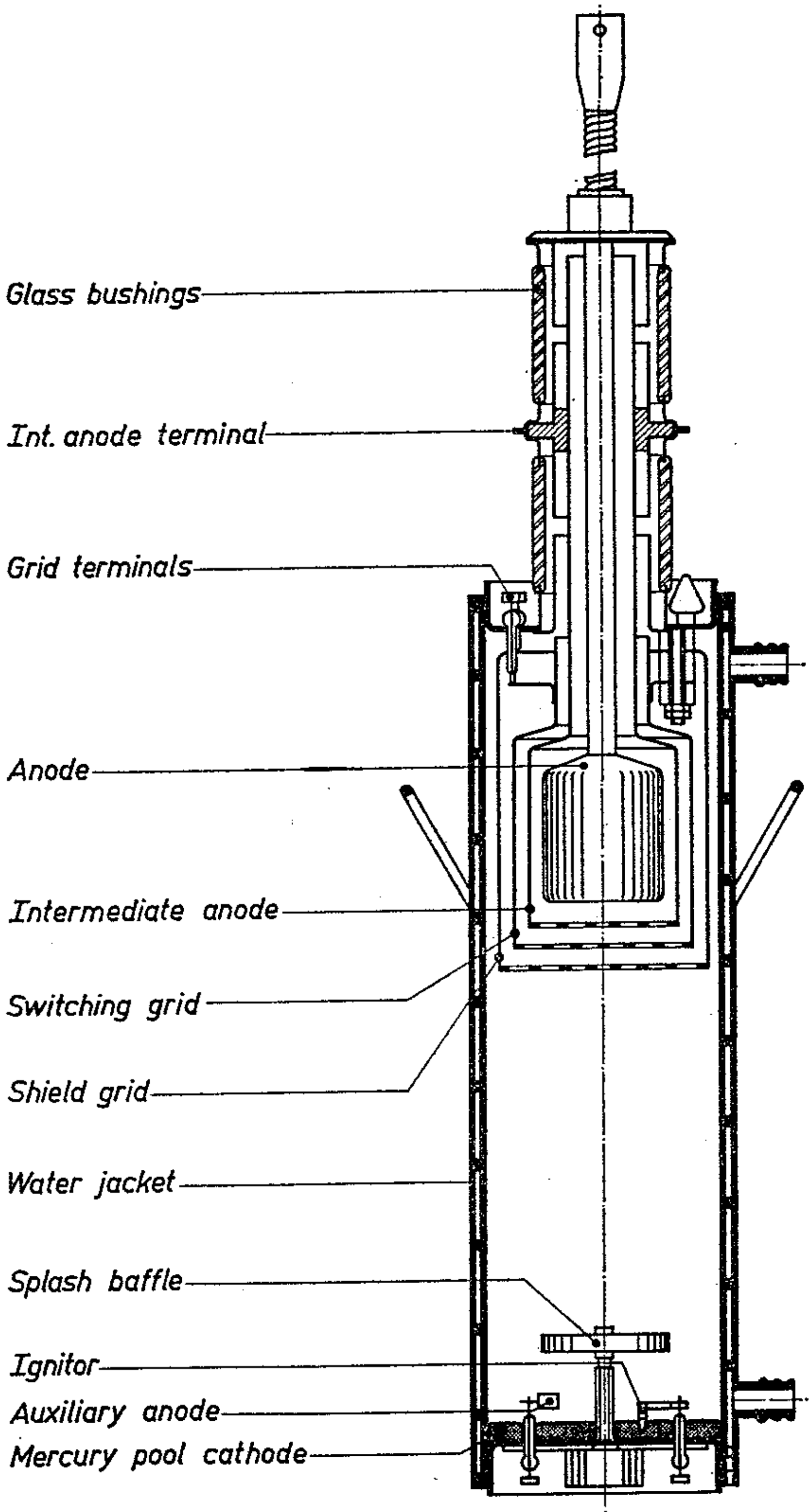


Fig. 189

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 (for 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}	=	$\lessdot$ 32 V (main discharge) 12—15 kV (ignition rod)	
f	=	300 c/sec max	
t_{Hg}	=	10—40 °C	

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

Ignition

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

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

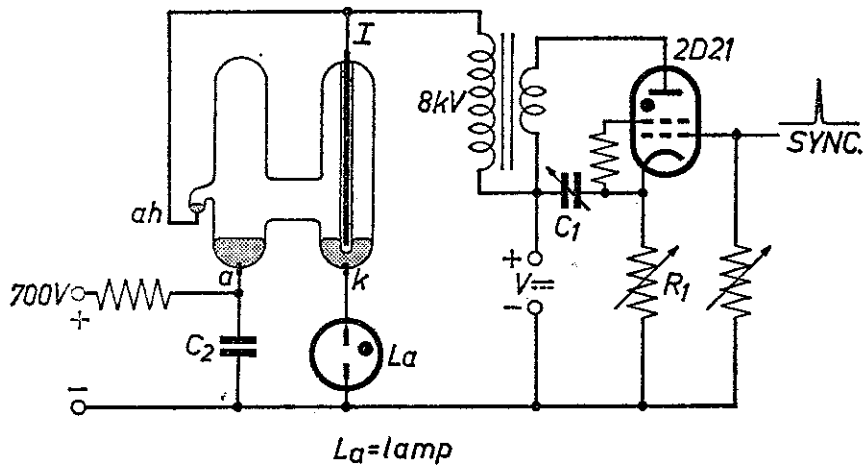


Fig. 190

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

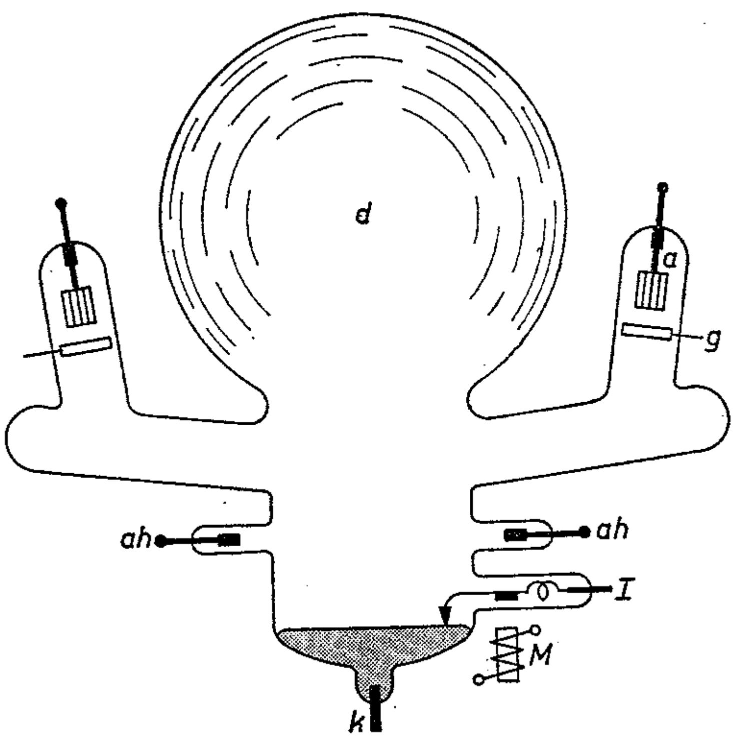


Fig. 191

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-

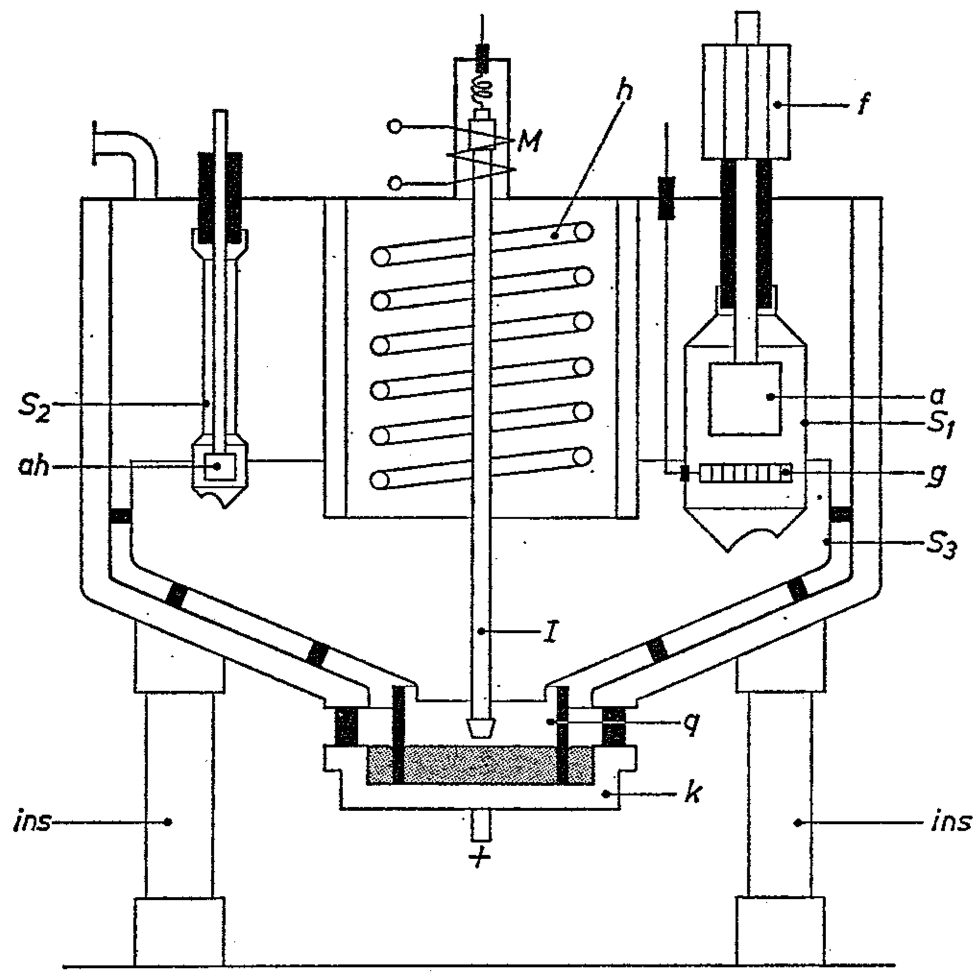


Fig. 192

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

CHAPTER VII

PHOTOCELLS WITH GAS AMPLIFICATION

VII-a **Introduction**

Means exist for transforming nearly all forms of energy into electricity. For example, a dynamo or a piezo-electric crystal may serve for the transformation of mechanical energy; a thermocouple changes heat into electricity, and various types of microphones can be used to produce electricity from sound energy. Light is transformed into electricity by the photosensitive layer of a photocell, which emits electrons when it is illuminated; under the influence of an electric field, these electrons give rise to the photoelectric current.

Many investigations in the field of photoelectricity were made by men like W. Smith, W. G. Adams and A.E. Day around 1875. The sensitivity of the semiconductor selenium to light was noticed and studied. It was found possible to transform light variations into variations in the current flowing through a circuit incorporating a selenium cell, since the resistance of this photocell depended on the amount of light falling on it. This phenomenon is called an *internal photoelectric effect,* since the changes take place inside the substance which is illuminated.

The *external photoelectric effect,* i.e. the emission of electrons by certain substances when they are illuminated, which was discovered in 1887 by H. Hertz and W. Hallwachs, has however proved to be of much more importance. For the sake of completeness we will briefly mention here a third type of photocell, the photovoltaic cell, which produces a slight e.m.f. when illuminated.

The number of photons available to stimulate the emission of electrons in the external photoelectric effect is usually relatively small; and as we will see later, even if there were much more light, the current would be limited by the size and emissive power of the photosensitive layer. The emission current produced is thus very small, of the order of a few microamperes. It has however proved possible to use this photoelectric current for various applications, by amplifying it in one way or another.

PHOTOEMISSION

Einstein's law has already been given in Chapter I: a photosensitive substance can only absorb radiation (light) in quanta; the absorption of these current cannot increase any more. This region is represented by the horizontal portion of the I_a/V_a characteristic shown in Fig. 196. In this region, the cell current is not sensitive to fluctuations in the anode voltage.

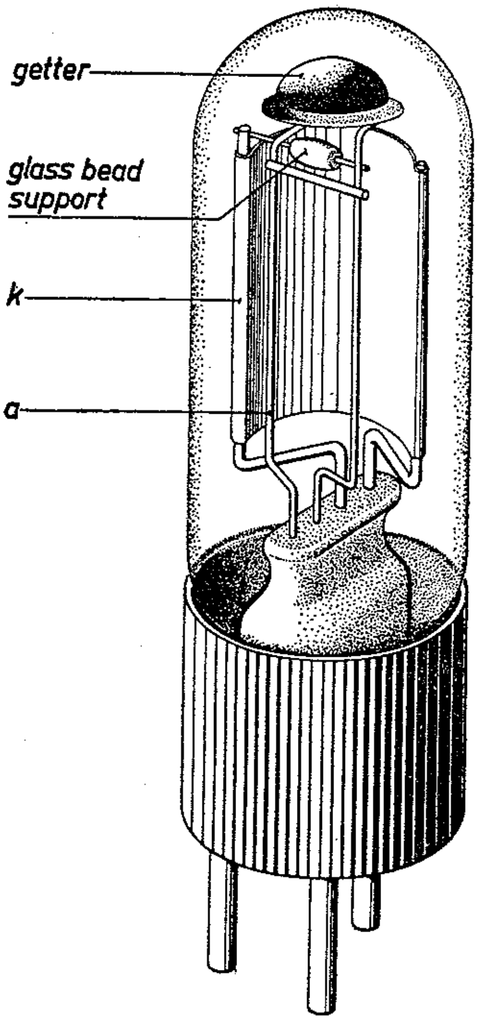


Fig. 193

Photoelectric cell having a semicylindrical metal cathode support and a frame-shaped anode.

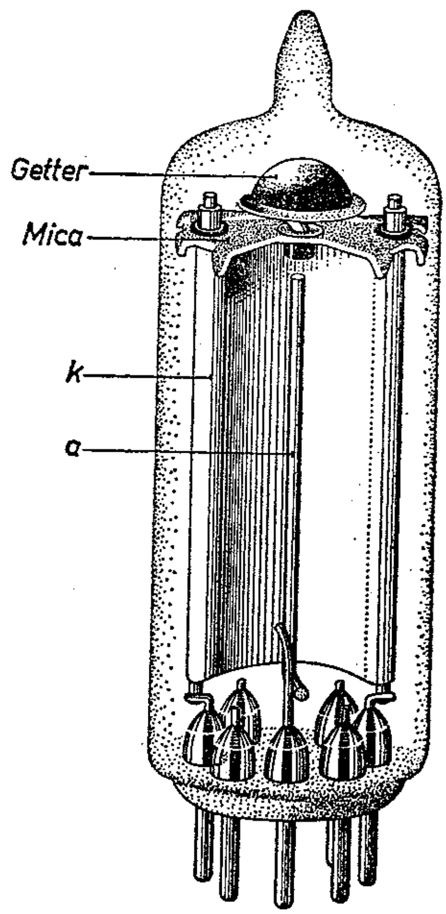
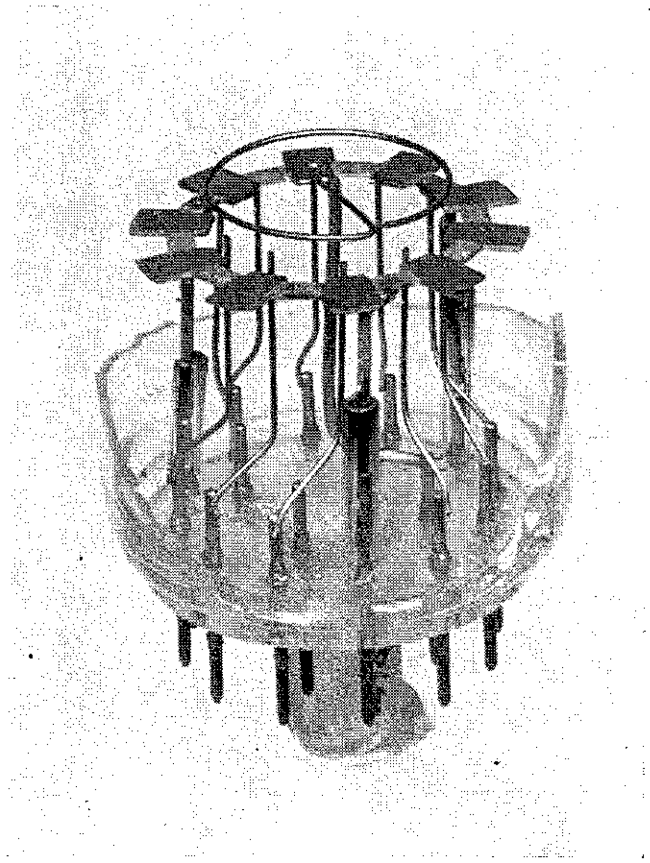


Fig. 194

Photoelectric cell; the cathode k is prepared on a metal plate. The anode a has the shape of a rod. A getter is evaporated on the top of the tube; it is screened from the cathode by a mica disc.

Photo 12

Assembled electrode system of an indicator tube for a decimal counting circuit using transistors [58].



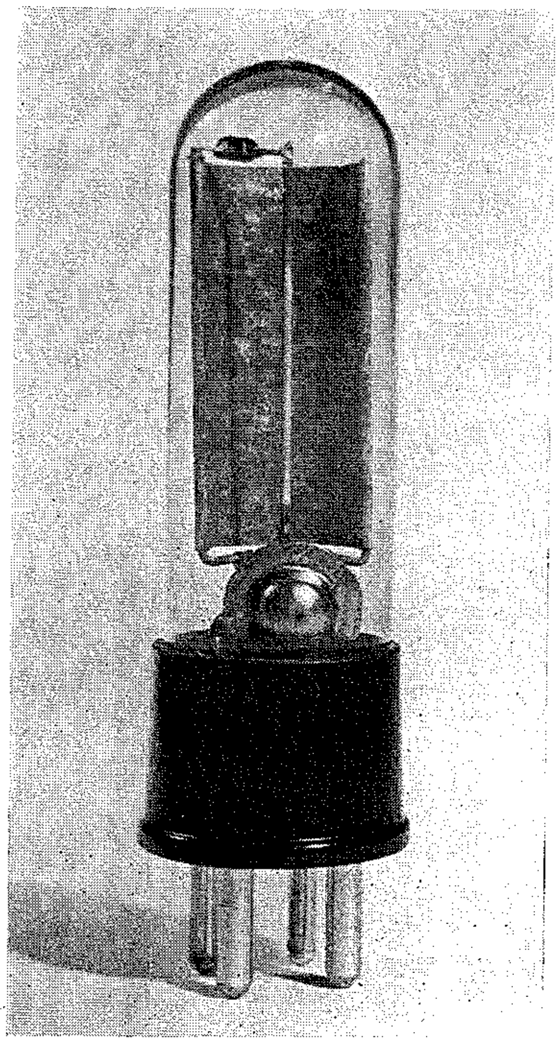


Photo 13

Philips gas-filled photocell 3554.

quanta gives rise to the emission of electrons. For each such substance there exists a minimum value of the frequency of the light, ν_0 below which electron emission is no longer possible; this is known as the red frequency limit [48]. The minimum energy which an electron must possess in order to be able to escape from the solid phase is known as the work function $e\varphi$; it follows that

$$h\nu_0 = e\varphi \tag{1}$$

In other words, it is not the *intensity* of the light but its *frequency* which determines whether electron emission will occur; but the value of the emission current is proportional to the luminous flux. The sensitivity of the cell is expressed in amperes per lumen (see Types of Photocathodes, page 260).

APPLICATIONS

The amplified signal obtained from the photocell can be used to activate a relay, or for sound transmission. The most usual applications are in talking films, brightness control of lights and the automation of all sorts of industrial processes.

THE CONSTRUCTION OF THE PHOTOCELL

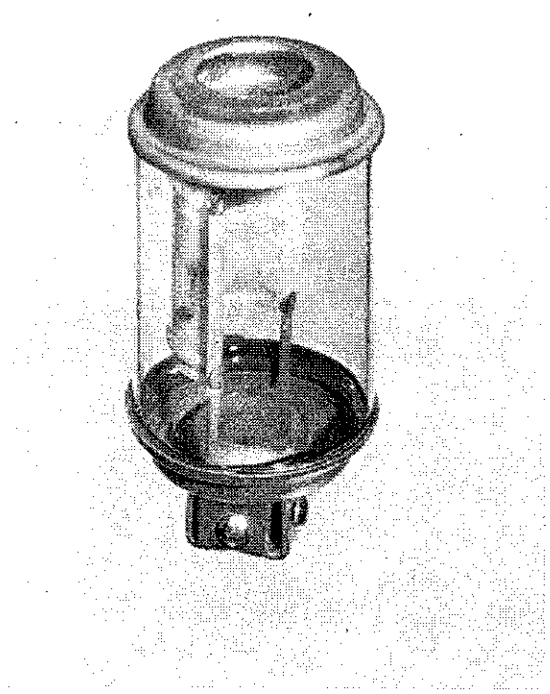
The photocathode has already been described in II-c-4. The construction of the gas-filled photocell does not differ from that of the vacuum photocell. We will now give a few examples of the types of constructions used.

The outside of a photocell is not very impressive: there are a number of styles, which are used for all the models. (Fig. 193, 194, 195). A photo-
cell. We will now give a few examples of the types of constructions used.
one end to support the electrodes. An insulating cap with lead pins can then be cemented on to the edge of the seal; or the base can be made of sintered glass (see II-f-2) with the leads melted into it. The photocathode is sometimes deposited on the inside of the glass envelope. In one much used style, the cathode has the form of half a cylindrical plate, with the anode in the form of a rod near the axis of the cylinder. The anode is also sometimes a wire frame; it is usually designed so as to interrupt the incident light as little as possible. In the types shown in Fig. 193 and 194, the light enters from the side; Fig. 195 shows a type in which the light enters from above.

SATURATION OF THE VACUUM PHOTOCELL

If the voltage across a vacuum photocell is increased at a constant luminous intensity, the emission current increases rapidly at first, but then more and more slowly until after a certain value of the voltage the *saturation* region is reached: all the electrons emitted by the cathode reach the anode, so the

Photo 14
RCA gas-filled photocell 921.



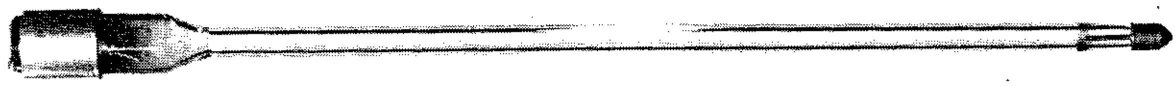


Photo 15
Philips neon-filled noise diode K 50 A.

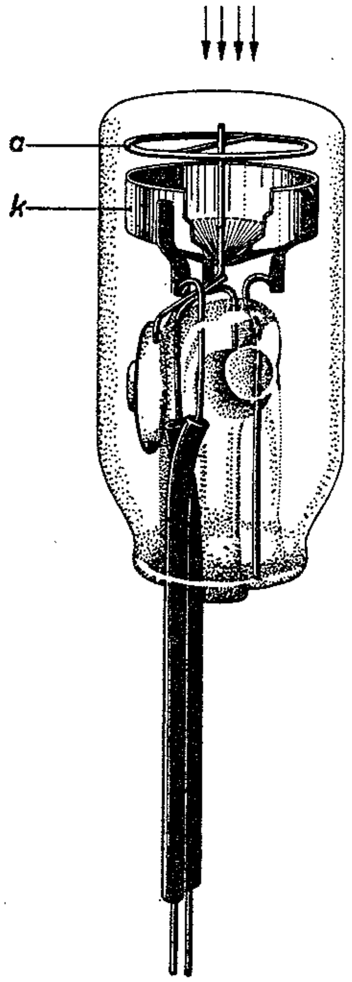


Fig. 195

Philips photoelectric cell 58 CG having a cup-shaped metal cathode-support k and an anular anode a. The light enters from above.

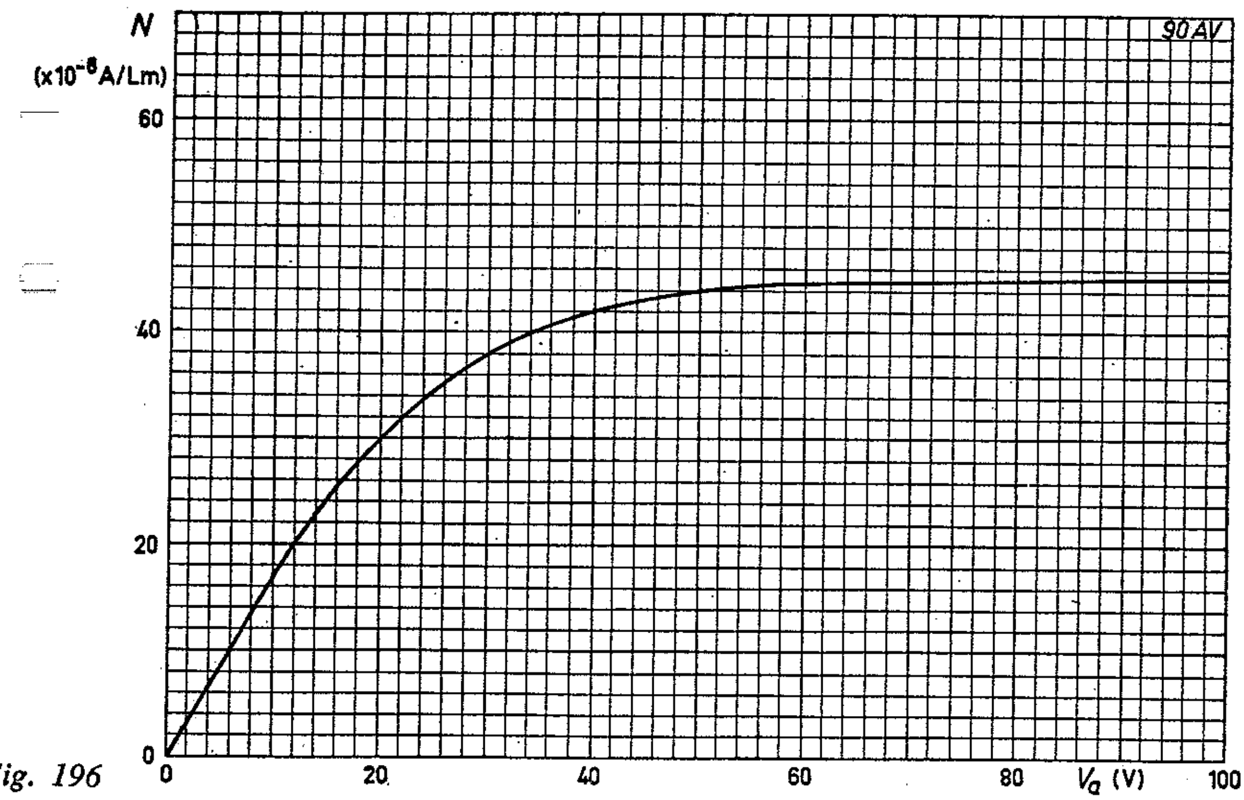


Fig. 196

Current-voltage characteristic for a vacuum photoelectric cell measured at constant illumination.

TYPES OF PHOTOCATHODES

We will only consider here the two most important types of photocathodes: the caesium-caesium oxide type and the caesium-antimony type. From now on, we will call the caesium-caesium oxide type simply the "*C*" type; this is prepared by depositing a layer of caesium on a layer of silver oxide. The silver oxide converts part of the caesium to caesium oxide, and remains behind as silver particles finely dispersed among the caesium oxide, thus increasing the conductivity of the oxide. A minute layer of pure caesium remains on the surface.

We will call the caesium-antimony photocathode the "*A*" cathode from now on: this is made by depositing caesium on a thin layer of antimony.

These two types differ mainly in the way their sensitivity varies with the wavelength of the incident light. Fig. 197 shwos the spectral sensitivity curves of both types. Curve I, for the *C*-cathode, has a maximum in the region of red to infrared; while curve II, for the *A*-cathode, has its maximum in the ultraviolet to violet.

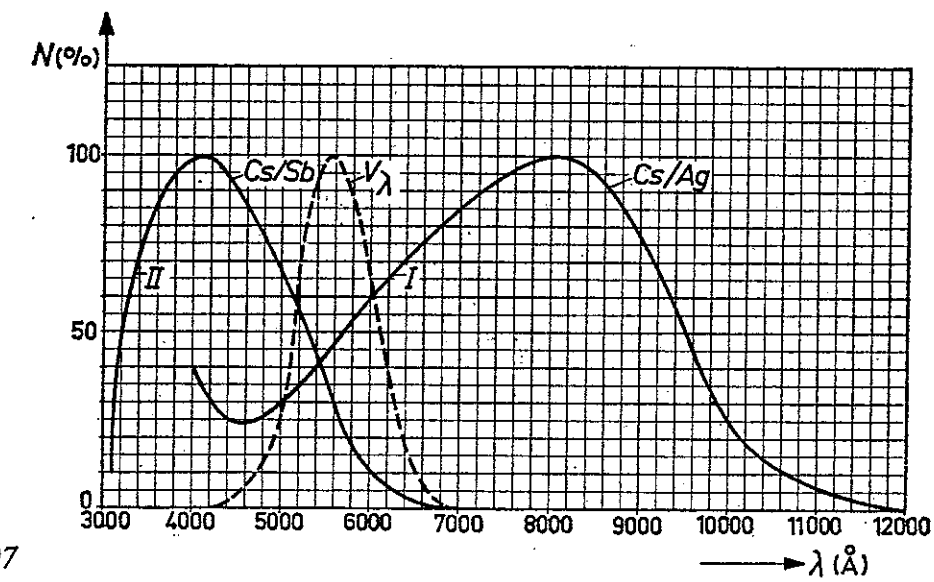


Fig. 197

Spectral sensitivity curves.
I. for *C*-cathode consisting of caesium on silver oxide,
II. for *A*-cathode consisting of caesium on antimony,
V_λ for the human eye.

Since the luminous flux of the light falling on the cell is determined with the aid of V_λ*), the photocell with a *C*-cathode will give a relatively large current with a light source such as an incandescent lamp which emits a large amount of red and infrared and a relatively small current with daylight which contains only a small amount of red. The reverse is true with a cell having an *A*-cathode.

*) The spectral sensitivity curve V_λ for the human eye lies between curves I and II.

If the temperature of the filament of the electric lamp is increased, the relative amount of blue and violet light it emits is increased: published data on the sensitivity of the photocell therefore always include the filament temperature of the lamp used for the measurements.

Thus, the sensitivity of a given *C*-cathode in a vacuum photocell for an electric lamp with a filament temperature of 2700 °K was 20×10^{-6} A/Lm, but only 4×10^{-6} A/Lm for daylight; while the sensitivity of an A-cathode for daylight is about 80×10^{-6} A/Lm, and for an electric lamp with a filament temperature of 2700 °K only 45×10^{-6} A/Lm.

THE ENVELOPE

The envelope of a photocell is practically always made of glass. This transmits visible light and other radiation with wavelengths of above 3500 Å satisfactorily; if radiation with smaller wavelengths has to reach the cathode, the envelope must be made of glass which is transparant to UV, or of quartz glass.

It is sometimes desired to measure radiation with wavelengths lying in a narrow range. A light filter in the form of e.g. a piece of glass of suitable composition is then placed between the light source and the photocell.

DARK CURRENT AND LIMITING TEMPERATURE

A photocathode still emits a small number of electrons even if it is not illuminated. This is attributed to the low value of the work function of the cathode, so that thermal emission is possible even at room temperature. The photocell current due to this effect is known as the *dark current*; it is however very small (of the order of magnitude of 0.01 μA in vacuum cells). It increases rapidly with an increase in the temperature. The maximum permissible ambient temperature is therefore usually 75 °C, or at most 100 °C. Another reason for limiting the temperature is to prevent deterioration of the sensitivity as a result of changes in the cathode surface.

VII-b **The photocell with gas amplification**

It often happens that the electron current excited by the light in a vacuum photocell is so small that it must be amplified considerably. Now the noise present in any circuit as a result of such things as the thermal motion of the electrons in the resistors, etc., is also amplified along with the useful signal, and it may even happen that the useful signal is completely masked in the noise so that there is no point in using the photocell.

If we could amplify the signal inside the cell, we could obtain a better signal-to-noise ratio. In other words, the output signal of the photocell would then be made big enough not to be masked by the noise. This can be done in one of two ways:

a. by use of an electron multiplier;
b. by filling the photocell with gas.

In method a., the photo-current impinges on a series of electrodes which have a high secondary-emission factor, so that the anode current is much greater than the current from the cathode. The amplification obtained in this way can be 10^6 or more, but the construction of the tube is very complicated. Such a photocell is called a photo-multiplier, a detailed description of this falls outside the scope of this book. The interested reader is referred to references [48] and [49].

GAS AMPLIFICATION

In simple cases, where the amplification need not be very great, a gas filling may be used. The tube is then of simple construction, like the vacuum cell. This second method is based on an increase in the electron production as a result of ionization of the inert gas in the cell. An inert gas filling is used because it does not react with the photosensitive layer. In practice, argon is generally used because it has a low ionization potential compared to other inert gases, and not too high an atomic weight. The amplification thus obtained depends on:

1. the number of electrons n produced in each avalanche by one primary electron (the α effect);
2. the number of secondary electrons γ $(n-1)$ emitted by the cathode owing to bombardment by the $(n-1)$ ions produced by one primary electron (the γ effect).

The effectiveness of the α effect depends on the mean free path of the electrons in the gas i.e. on the density of the gas, the size of the molecules and the anode voltage. At low pressures there are not many collisions, and at high pressures the electrons lose too much energy by

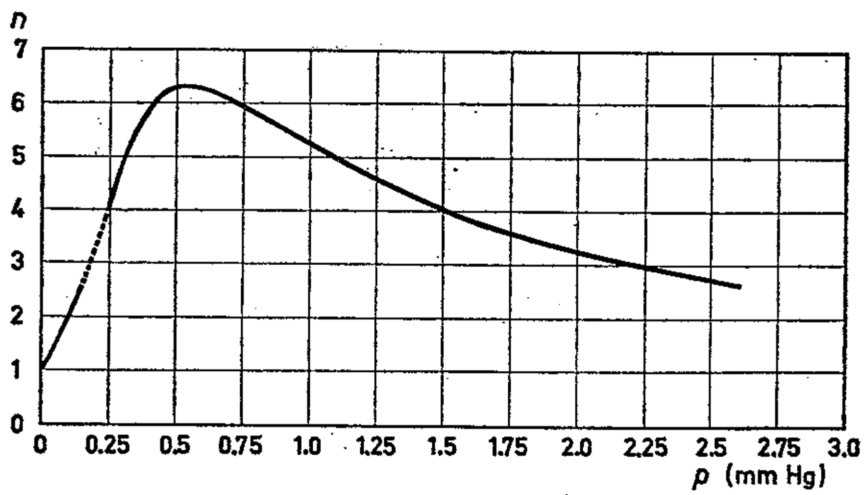


Fig. 198

Number of electrons n formed in each avalanche in an argon-filled cell as a function of pressure p at a constant anode voltage [51].

elastic collisions so that they cannot gain the velocity which they need in order to cause ionization. Fig. 198 shows the number of electrons formed in each avalanche as a function of the pressure at a constant anode voltage. According to this figure, the optimum pressure is about 0.55 mm Hg; but in fact low pressures (about 0.1 mm Hg) are used to keep the inertia of the cell low (cf. VII-d).

Calculation shows (see I-g-1 and ref. [48], page 125) that as long as breakdown does not occur the total number N of electrons formed by one photoelectron is

$$N = \frac{n}{1-\gamma\,(n-1)} \tag{2}$$

This number is called the gas amplification.
The value of γ is about 1/3.

The above-mentioned phenomena can be traced in the current-voltage characteristic of the photocell at constant illumination of the photocathode (fig. 199): as long as the voltage V_a is less than the ionization potential of argon (15.7 V), the curve is more or less the same as that for a vacuum photocell (concave to the horizontal axis). The saturation region is reached at about 15 V. If V_a is made more than the ionization potential, new electrons and ions are formed in the gas, and the value of N becomes greater than 1. The curve thus becomes convex to the horizontal axis. The value of N at a given value of V_a can be determined from Fig. 199: it is simply

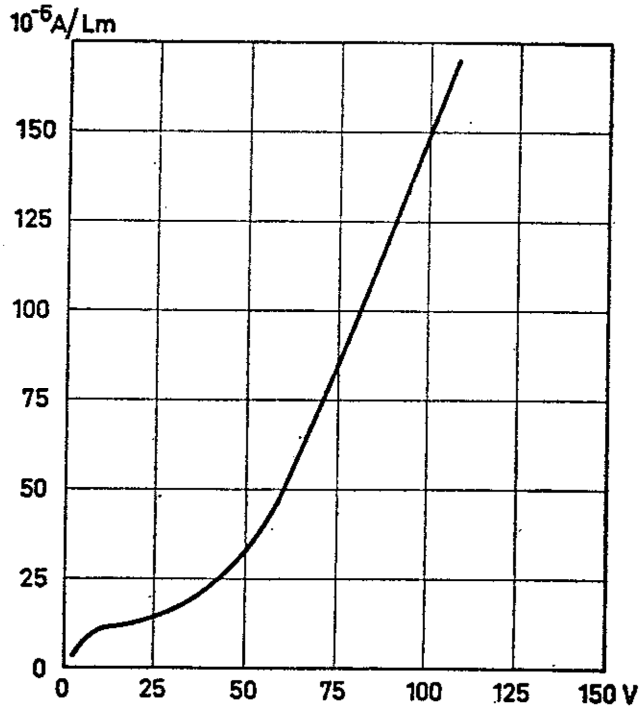


Fig. 199
Current-voltage characteristic of a gas-filled photoelectric cell at constant illumination.

equal to the ratio of the current at V_a to that at $V_a = 15$ V. Since the current through the gas cell varies so strongly with the anode voltage, it is necessary to keep the latter very nearly constant if the cell is to be used for measurements.

A vacuum cell illuminated by daylight (cf. page 259) may have a sensitivity of 80×10^{-6} A/Lm, while a gas cell can give a sensitivity of about 600×10^{-6} A/Lm under favourable circumstances.

BREAKDOWN

For values of V_a under about 100 V, the discharge produced in the gas-filled photocell is not self-sustaining; the current depends on the illumination, and becomes zero if there is no illumination. If however the voltage is increased much above 100 V, we get breakdown and the discharge changes to a self-sustaining glow discharge. The voltage at which this occurs depends on the nature of the gas, the density of the gas, the geometry of the tube and to a certain extent on the intensity of illumination. A breakdown voltage of about 150 V has been measured for several types of photocell in the dark.

A self-sustaining glow discharge arises when the value of n becomes so large that the value of $\gamma\,(n{-}1)$ becomes equal to 1 (see I-g-1). Under these conditions the current is independent of the illumination and is only limited by the resistance in series with the cell. The cell thus no longer reacts to the light falling on it.

The photocathode is damaged by the glow discharge, which must therefore be avoided.

THE VALUE OF N

N will of course be increased if the anode voltage is raised but care must be taken not to approach too close to the breakdown voltage. For example at $V_a = 120\,\text{V}, N$ is found to be 7.5 in Fig. 199 and it may assumed that N will always lie between 5 and 10 in practice. But the higher the value of N, the greater the "random" variation in the current at constant illumination. This superimposes an extra amount of noise on the signal; this effect is discussed further in VII-e.

If moreover the light is modulated, the amplification will be found to decrease as the modulation frequency increases. This effect is discussed in VII-d.

VII-c **Permissible cathode load**

The permissible current density from the photocathode of a gas-filled cell is the same as for a vacuum cell, varying from 1 to 5×10^{-2} A/m² according to circumstances. If this value is exceeded, the sensitivity of the of the photo-electric current produced by a light signal with a constant depth of modulation decreases as the modulation frequency increases. In other words, the optimum pressure (0.55 mm Hg) gives a large amplification but a quick drop in the frequency characteristic of the cell; while a lower pressure gives a lower value of N but a more nearly level characteristic.

Calculations [51] show that the number of ion transit times which must elapse for the photoelectric current to fall off to a negligible amount is a function of γ $(n-1)$ (see VII-b). Taking reasonable values for the variables involved, it can be shown that the inertia of the cell will cause an appreciable distortion of the output signal at modulation frequencies above 15 kc/s. The results of measurements made in this connection are shown in Fig. 200. This figure shows the value of the amplification,

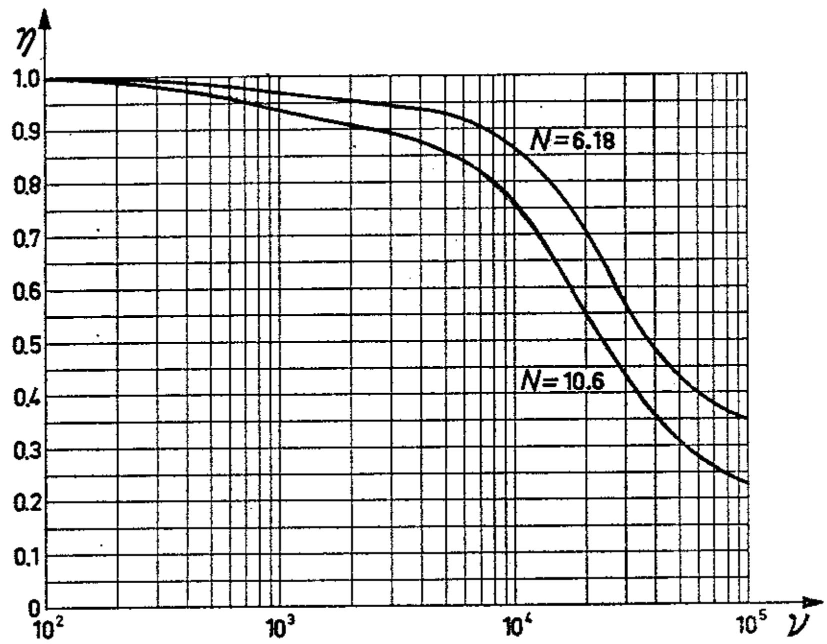


Fig. 200

Fraction η of the amplification N for low frequencies that is obtained for higher frequencies ν. Measured curves for the values $N = 6.18$ and $N = 10.6$ [51].

expressed as a fraction η of its value at low frequencies, as a function of the frequency for two different values of N. At very high frequencies the value of η for $N = 6.18$ approches 0.35, i.e. the fraction of the amplification due to the inertialess electrons without the intervention of the γ effect is 0.35 of the total amplification at low frequencies. In other words, the cell current at very high frequencies tends to n times the direct photocurrent, where $n = 0.35 \times 6.18 = 2.2$.

The η–ν characteristic of a photocell as measured deviates to a certain extent from that calculated on the above-mentioned considerations, especially in the frequency range from 1 to 5 kc/s. This has been explained as being due to the presence of particles which are even slower than ions, i.e. metastable atoms (see Campbell [53]. These excited atoms, having no charge, move quite independently of the field. Some of these will diffuse towards the cathode, following the "drunk man's walk" typical of thermal motion, and thus taking considerably longer than the ions to get there. On colliding with the cathode, they will free electrons from its surface which will also contribute to the photoelectric current, but with an appreciable delay. This explanation has been verified [54].

THE MODULATION-FREQUENCY CHARACTERISTICS IN PRACTICE

We must now enquire how important this attenuation of the high frequencies is in practice. One important application of photocells is the sound pick-up in talking films, where modulation frequencies of up to about 10 kc/s must be dealth with. In order that all frequencies below this value should be adequately reproduced, the characteristic must not fall by more than 2 dB in this range, i.e. the value of η at 10 kc/s must be at least 0.75.

It will be seen from Fig. 200 that this condition is just satisfied with the maximum attainable gas amplification $N = 10$. If necessary, this decrease of 25 % in η can be compensated by a suitable choice of the frequency characteristic of the amplifier.

In the field of television, however, the frequencies to be dealt with extend right up to several Mc/s: a gasfilled photocell for television purposes has therefore nothing but disadvantages compared to a vacuum photocell or a photomultiplier.

VII-e **Noise in gas amplification**

We will consider only one application of gas-filled photocells in this section: the reproduction of sound for talking films. If the reproduction is to be good, the background noise accompanying the recording must be kept as low as possible. In other words, the signal/noise ratio must be kept high. Both the signal and the noise voltage are taken from the resistance R in series with the photecell. Apart from the noise produced in R itself by thermal motions which we have already discussed, there is also the noise produced in the photocell (see ref. [49], pages 431—432).

The noise from the cell appears to depend mainly on two things:

1. the shot effect at the cathode;
2. the magnitude of the gas amplification factor N.

The shot effect depends on the fact that the primary electrons do not leave the cathode in a constant stream, even if the illumination is constant, but randomly. This effect is however slight at normal luminous intensities. The mean square of the current fluctuation $\bar{I}$ is proportional to the band width $\Delta\nu$ considered and to the mean photoelectric current $\bar{I}_f$:

$$\bar{I}^2 = F^2 \, . \, 2e \, \bar{I}_f \, \Delta \, \nu. \tag{3}$$

where e is the charge of the electron and F the noise factor, which expresses the fact that the shot effect is partly annulled by the space charge.

In a gas-filled cell the primary photocurrent through the cell is amplified by the factor N; as we have seen, this means that the noise energy due to the shot effect is approximately proportional to N^2, since by the amplification in the gas both $\bar{I}_f$ and e in quation (3) are multiplied by N. But the signal energy also increases as N^2, so the ratio

$$\frac{\textit{thermal noise energy in the load resistance} + \textit{shot-effect energy}}{\textit{signal energy}}$$

will decrease approximately as $1/N^2$, provided that the first term in the numerator is large compared to the second one, which is usually the case.

INFLUENCE OF THE VOLTAGE

The factor F^2 in equation (3) depends on the anode voltage. The value of F^2 is less than 1 in a vacuum cell at low anode voltages, and increases to 1 as the voltage is increased to the point where the current becomes saturating. The shot-effect energy due to the primary electrons is here proportional to the primary photoelectric current $\bar{I}_f$.

In a gas-filled cell the number of electrons is increased and the current amounts to $N \, \bar{I}_f$, however, the proportionality factor for the shot-effect energy is increased by a factor N^2 $(1 + Q^2)$, where Q is an extra scatter factor caused by the spread of the individual values of N, which is negligible for $N=5$ to 6 or less, but which must be taken into account for $N = 10$, i.e. at high anode voltages. It is therefore advisable to keep V_a as low as possible not only to prevent breakdown but also to keep the noise level low.

VII-f **Some examples**

Photocells were originally fairly big things. This does not matter much for many industrial applications, but as the sound reproduction methods in talking films developed the demand for small photocells became steadily greater. A small photocell can be placed in the sound head together with the first amplifier tube, which is advantageous for several reasons.

Photo 13 shows a Philips photocell 3554, specially suitable for industrial uses because of the relatively large cathode area. Table XX includes the

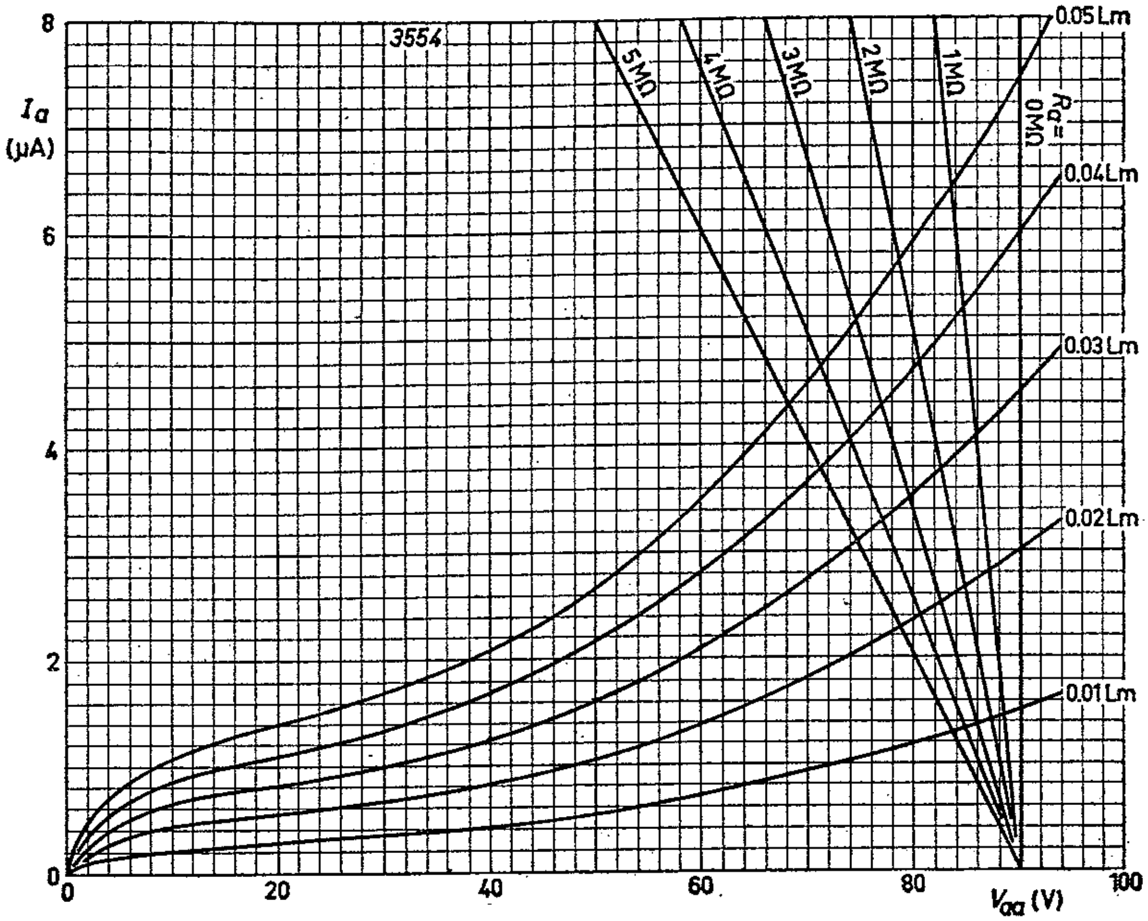


Fig. 201

Current-voltage characteristics for Philips photocell 3554.
Illumination varied in steps:
0.01 Lm; 0.02 Lm; 0.03 Lm; 0.04 Lm and 0.05 Lm.
Resistance lines $V_a = V_{aa} - I_a R$ shown for $R = 1 \cdots 5$ M Ω and $V_{aa} = 90$ V.

operating data of this photocell. The photo-sensitive layer is deposited on a semi-cylindrical metal cathode, and the rod which forms the anode is placed at the axis of the cathode cylinder. Some I_a/V_a characteristics of this cell are shown in Fig. 201.

The recent model of the RCA type 921 (see Photo 14) is smaller than the above-mentioned photocell. Two metal end plates are sealed on to the cylindrical glass envelope. One of these bears a small plate which serves as the anode and does not obstruct any of the incoming light. The semi-cylindrical cathode is fastened to the other end plate. The sealed-off end of the glass tube which was sealed on to this plate and through which the cell was evacuated, is protected against damage by a metal cap. This cap and a cavity in the anode cover serve as the terminals.

The smallest photocell sold at present is the Philips 58 CG (Fig. 195). The annular anode is mounted above the cup-shaped cathode. The simplest model of this photocell has two lead wires coming out of the glass envelope, by means of which the cell can be soldered directly into the amplifier.

The amount of light falling on to the cell through the slit in the film is usually so small that there is no danger that the sensitivity will be prematurely reduced, as long as the operating instructions are complied with; but the light source should be switched off as soon as the film is removed.

The usual circuit is shown in Fig. 202. The resistor R_1 shown in this figure serves at the same time to limit the anode current and to couple the circuit with the next amplifier stage.

This resistance determines the magnitude of the output signal, and also

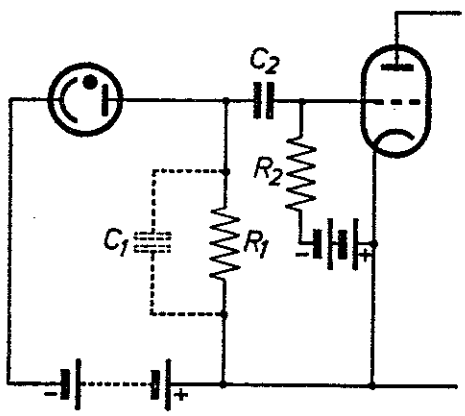


Fig. 202

Usual photocell circuit
R_1 = load resistance
C_1 = parasitic anode capacitance
R_2 = grid resistance
C_2 = coupling capacity

its quality in connection with the interelectrode capacitance of the cell and the unavoidable parasitic shunt capacitance due to the leads of the following amplifier tube. A photocell with a low interelectrode capacitance is therefore to be recommended, but above all the leads to the first amplifier tube should have a low capacitance. This is one of the reasons why the photocell is almost always built into the sound head together with this tube.

TABLE XX

DATA OF SOME GAS-FILLED PHOTOCELLS

	PHILIPS type 3554	R.C.A. type 921	PHILIPS type 58 CG
photosensitive layer	caesium on oxidized silver	caesium on oxidized silver	caesium on oxidized silver
region of maximum sensitivity	red and infrared	red and infrared	red and infrared
projected cathode surface	5.2 cm^2	2.8 cm^2	1.1 cm^2
sensitivity at $V_a = \ldots$V	150×10^{-6}A/Lm *) 90 V	at 0 c/s 135×10^{-6}A/Lm at 5000 c/s 119×10^{-6}A/Lm at 10000 c/s 108×10^{-6}A/Lm **) 90 V	108×10^{-6}A/Lm *) 85 V
dark current at $V_a = \ldots$V	90 V a) $<0.1\ \mu$A ($t_{amb}=50°$ C) b) $<2.5\ \mu$A ($t_{amb}=100°$ C)	— 0.01 μA (25° C)	85 V a) $<0.1\ \mu$A ($t_{amb}=50°$ C) b) $<2.5\ \mu$A ($t_{amb}=100°$ C)
series resistance	1 M Ω	2.5 M Ω (I>2 μA) 0.1 M Ω (I<2 μA)	1 M Ω
gas amplification factor	$\leqslant 7$	10	$\leqslant 7$
C_{ak}	3.4 pF	1 pF	3.0 pF
max cell voltage	90 V	90 V	90 V
max cathode current density	20×10^{-3}A/m^2	45×10^{-3}A/m^2	15×10^{-3}A/m^2
max ambient temp.	100° C	100° C	100° C
total length excluding pins	max. 88 mm	max. 44 mm	max. 33 mm
max diameter	30 mm	22.5 mm	16 mm

*) Measured with an incandescent lamp of colour temperature 2700 °K.
**) Measured with an incandescent lamp of colour temperature 2870 °K.

CHAPTER VIII

SPECIAL TUBES

VIII-a Noise tubes

The sensitivity of a receiver for radio signals is limited by its internal noise. To measure the noise quantitatively, one must have a noise standard, i.e. a set-up which provides an accurately known amount of noise and with which other noise sources can be compared. A saturated vacuum diode may be used for this purpose, as the fluctuation of the tube current is theoretically known [94]. However, such a diode can only be used up to a frequency of about 1000 Mc/sec. For measurements at higher frequencies, i.e. in the UHF region, the column discharge in a gas-filled "noise tube" can be used as a noise standard.

As has already been mentioned (I-f), the elastic collisions undergone by the electrons in a gas discharge give these electrons velocities whose distribution corresponds with that for free electrons in a gas which has been heated to a very high temperature. These electrons emit electromagnetic radiation which is similar to that emitted by a thermal radiator of the same temperature, and which is picked up by a receiver as HF noise [76, 89, 90].

The noise temperature is expressed in decibels above 290 °K, that is about room temperature. (The concept decibel (dB) will be discussed below.) For neon, the noise temperature is about 40 times room temperature, so the noise power of such a thermal noise source is about 10 log 40 = 16 times greater than that of a resistance at room temperature. (The noise power is proportional to the noise temperature expressed in dB.)

As we have already seen in I-g-2, various phenomena in the column discharges are dependent on the nature of the gas, the pressure p_o and the radius r of the column. The electron temperature T_e in the column, and thus the noise, is also dependent on these factors — and on the current: at high currents, the gas is ionized stepwise, via the excited state, as well as directly, and this affects the electron temperature [88].

The column discharge in the long neck of a noise tube is the real source of the noise. The variation of T_e as a function of $p_o \,.\, r$ for this discharge in neon has been measured by Druyvesteyn and de Groot [73, 74], and is shown in Fig. 203. The electron temperature can thus be read off from this graph for a given pressure and a given column diameter.

It is no simple matter to calibrate the noise temperature of the tube, but this may be done by e.g. measuring the probe characteristic of the discharge. A thermally heated wedge-shaped ceramic resistor is often used as a noise standard for absolute measurements of the noise temperature [95].

Under certain circumstances, however, the influence of the current on the electron temperature is slight over a wide range (see Fig. 204 [88]. The gas pressure must be at least several mm, and the conductance of the column discharge must not be too small. The tube current is usually of the order of 100 mA. Such a tube can be used in a wide frequency range; only transit-time effects limit the frequency. The matching of the noise tube with the other equipment is only difficult if the pressure is high.

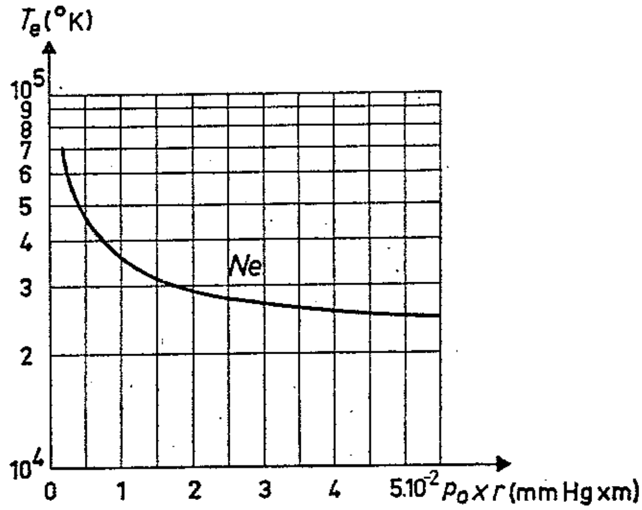


Fig. 203

Theoretical relation between electron temperature T_e and product of gas pressure p_0 for neon and radius r of discharge tube [74].

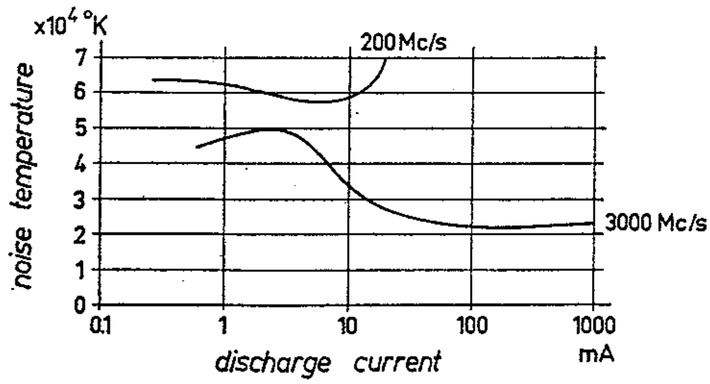


Fig. 204

Example of measurements of effective noise temperature of discharge for $P_0 = 2.80$ mm Hg [88].

Originally, it was found by Mumford that a fluorescent lamp is suitable for noise measurements [75]. Such lamps are still used, but as the filling contains mercury the pressure in these tubes depends on the ambient temperature. A calibration curve is therefore needed to give the relationship between the ambient temperature and the noise temperature. Later, special tubes have been developed by e.g. Bendix, Bell, the Kay Electric Co. and Philips (Photo 15).

ARRANGEMENT OF THE TUBE

When a noise tube is used in a waveguide, the plasma in the tube must be matched with the waveguide, i.e. all the available noise power must be able to disappear in the waveguide. The tube must be made long and thin, to obtain a positive column discharge of the required temperature. It is possible to arrange such a tube in several ways with respect to the waveguide. One way is to stick the tube through the waveguide at a certain angle (Fig. 205). Another method is to place the tube inside a helix, so that coaxial measuring equipment can be used, especially at low frequencies [91]. We shall now consider the first method in somewhat more detail.

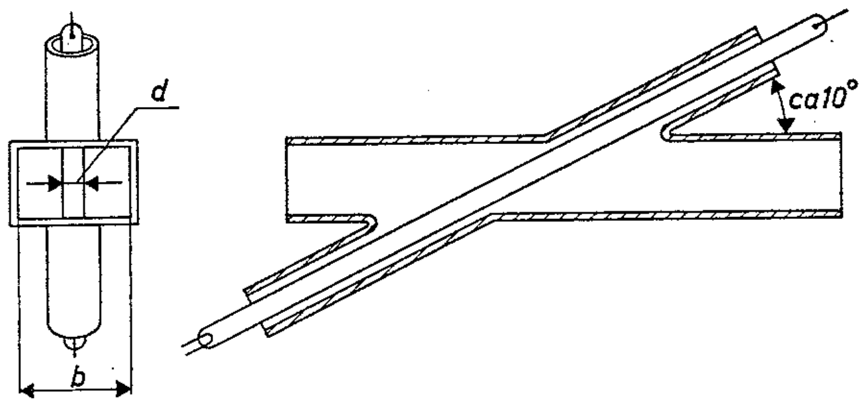


Fig. 205

Example of a noise-tube set-up. The tube passes at an angle through a waveguide. The precise value of the angle depends on the type of tube used. The ratio of the two diameters *d* and *b* is important in this connection.

The angle between the axis of the tube and that of the waveguide is important for proper matching of the terminal impedance with the characteristic impedance of the waveguide. This matching is never perfect. The *voltage standing-wave ratio* is a measure of the deviation from complete matching. When matching is not perfect, the travelling wave in the waveguide is accompanied by reflections, which gives rise to standing waves and to places where the field strength is maximum and minimum (F_{max} and F_{min}). The ratio F_{min}/F_{max} is called the voltage standing-wave ratio, and tends to unity as perfect matching is approached.

The tube should further be placed with the anode at the receiver end, since this makes for the best matching. Finally, attention must be paid to the relation between the diameter of the tube and that of the waveguide.

Example

Let us take as an example the Philips noise tube type K50A (Photo 15), whose operating data are given in table XXI. This is a neon-filled diode which can be used in waveguide systems for the 3-cm waveband. The noise power is practically independent of the ambient temperature and the operating temperature. Within certain limits, it also depends very little on the tube current (see Fig. 206). Because of the long narrow neck in which the discharge occurs, the ignition voltage is several thousand volts. The supply voltage of 500 V is thus insufficient to ignite the tube, and the ignition circuit of Fig. 207 is used.

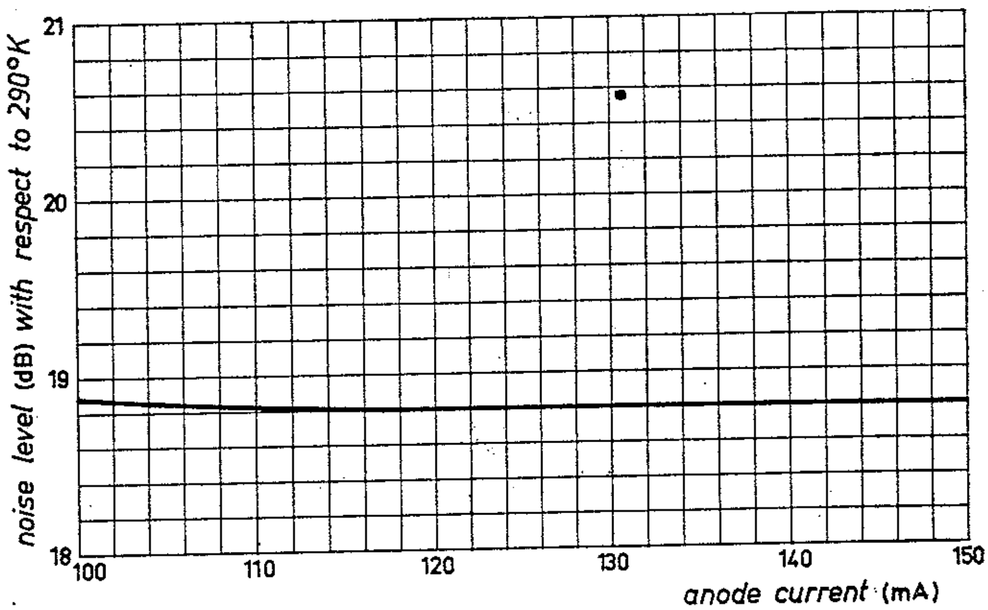


Fig. 206
Noise level of the Philips diode K50A as a function of the tube current.

The available noise power of the discharge may be assumed to be $kT\Delta f$, where Δf is the bandwidth of the equipment used and k is Boltzmann's constant. The noise voltage is given by Nyquist's equation

$$\overline{VV^*} = 4\,k\,.\,T_e\,.\,R_e\,.\,\Delta f$$

where R_e is the ohmic terminal resistance at the input side of the waveguide, which is equal to the impedance of the noise source. (Fig. 208.) This resistance (which is usually wedge-shaped) is only used when the tube is not burning.

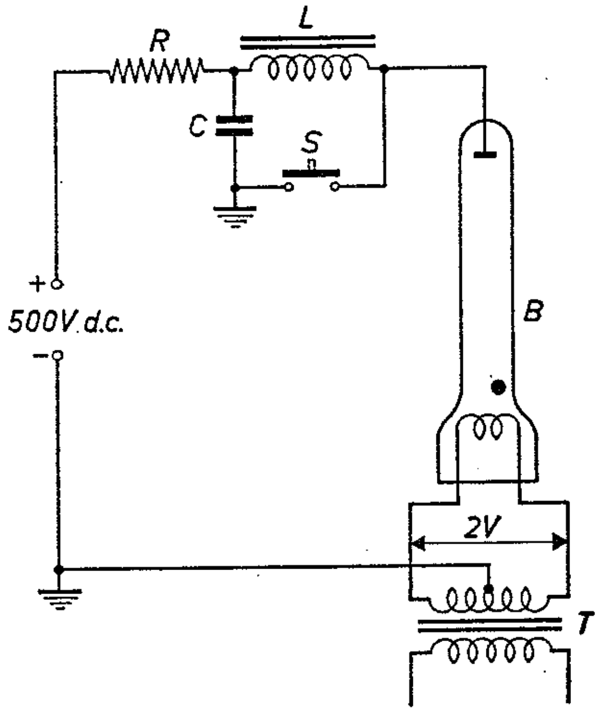


Fig. 207

Ignition circuit for the Philips diode K50A. The discharge of C if S is closed causes a high voltage on L.
$C = 0.01\ \mu F$, $L = 8$ henry, $R = 2700$ ohms.

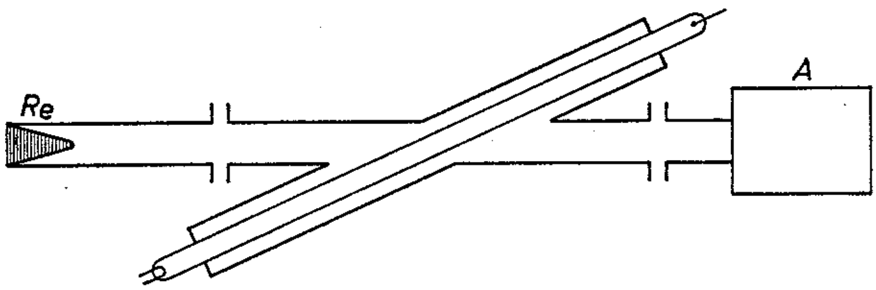


Fig. 208

Waveguide with noise tube preceded by the wedge-shaped terminal resistance R_e and followed by the amplifier A.

The noise figure N of the receiver is given by

$$N = \frac{T_e/T_o - 1}{P_e/P_o - 1}$$

This is determined by measuring the noise power delivered by the receiver for two temperatures T_e and T_o of the resistance of the noise generator. When the tube is ignited (T_e), we can write for the power delivered:

$$P_e = G \, . \, k \, . \, T_e \, . \, \Delta f + P_i$$

and when the tube is quenched:

$$P_o = G \, . \, k \, . \, T_o \, . \, \Delta f + P_i$$

where the internal noise of the receiver is denoted by P_i and G is the amplification factor.

It is only necessary to measure P_e and P_o to determine N for the set-up, since T_e and T_o are known. T_o is usually taken as 290 °K, since this is more or less room temperature.

According to the operating data, the noise level of the K50A is 18.8 dB. This follows from $T_o = 290$ °K and $T_e = 22\,330$ °K, since
$10\,{}^{10}\log\,(T_e/T_o - 1) = 18.8$.

The noise factor of a good receiver for e.g. 3000 Mc/s is less than 4 dB.

THE DECIBEL

The *decibel* is frequently used in pure and applied physics as a means of comparing two quantities. In amplification technique, for example, the amplification factor is expressed in these units to give the relationship between the input and output power of an amplifier or attenuator, or between its input and output voltages.

In this chapter, the decibel is used to express the noise figure of a radio receiver. In order to avoid the large numbers involved in such measurements, it is convenient to compare the logarithms of the quantities in question. Another good reason for doing this is that sense impressions and physiological effects, which are sometimes involved in such measurements, follow logarithmic laws.

The "bel" was originally used as a unit of amplification: the number of bels is by definition the logarithm to base ten of the ratio of the two powers P_1 and P_2:

$$\text{number of bels} = {}^{10}\log P_2/P_1.$$

The bel is however rather too big for a practical unit, and therefore the tenth part of a bel, the *decibel,* is now used as a unit:

$$\text{number of decibels} = 10\,{}^{10}\log P_2/P_1.$$

The decibel is sometimes also used to express the ratio of two voltages or currents. Since voltages (or currents) occur squared in the formulae for electrical power, it follows that

$$\text{number of decibels} = 20\,{}^{10}\log V_2/V_1 \text{ (or } 20\,{}^{10}\log I_2/I_1).$$

A power amplification of 2000 thus corresponds to 33 dB, and a voltage amplification of 100 to 40 dB.

The decibel is thus not a unit of absolute power (or some other quantity) but of relative power. In other words, the power in question must always be compared with a certain reference value. In some fields, a standard reference level has been chosen, e.g. a power of 1 mW in telephony and microwave receivers. Values expressed in decibels thus only mean something if the reference value is also given. It may be seen from the literature that different workers often choose different reference levels.

Another similar unit, used especially in German technical literature, is the *neper*. The number of nepers is equal to the natural logarithm of the ratio of two amplitudes, currents or voltages. It thus follows that 1 neper = 8.68 dB.

TABLE XXI

OPERATING DATA FOR THE PHILIPS NOISE TUBES TYPES K 50 A AND K 51 A

	K 50 A	K 51 A
	for 3 cm waveband	for 10 cm waveband
Heater voltage V_f (volt)	2	2
Heater current I_f (amp.)	2	3,5
Heating time t_w min. (sec)	15	15
Ignition voltage V_{ign} (volt)	6000	6000
Anode voltage V_a (volt)	approx. 165	approx. 140
Anode current I_a (mA)	125	200
Min. Anode current $I_{a\,min}$ (mA)	50	100
Max. anode current $I_{a\,max}$ (mA)	150	300
Ambient temperature t_{amb} min. (°C)	—55	—55
max. (°C)	+75	+75
Noise level in test amount with respect to 290 °K (dB)	18,8	19,1

VIII-b **The plasmatron** [86]

CONSTRUCTION AND OPERATION

We have seen that the thyratron is a switching tube for large currents. It is not however possible to obtain continuous and reversible control with a thyratron, as it is with a vacuum tube. This is however possible with a plasmatron, which moreover does not have the inconveniently high impedance of the vacuum tube.

This gas-discharge tube, which is filled e.g. with about 1 mm of helium, contains a plasma with a high concentration of electrons and an equal concentration of positive ions, which is used as a conductor. This plasma is found between an anode and a hot cathode which acts as the main cathode; it is however *formed* between a second hot cathode (the auxiliary cathode) and the two above-mentioned electrodes, both of which acts as an anode with respect to the auxiliary cathode.

The two functions of the electrons in such a tube, to form a very conductive plasma by ionization of the gas and to carry the largest part of the active tube current, are thus carried out by electrons from two separate thermally emitting cathodes in the plasmatron, while in the thyratron all the electrons come from a single cathode.

Fig. 209 shows a sketch of the tube in its simplest form. These is an ionization or generator compartment and a conducting or operating compartment. The auxiliary cathode k_h is placed in the former, with a sort of cylindrical screen g_c (the "garrote") around it. This screen is usually connected to the cathode, and has one (or more) small apertures in it. No ionization is possible within the garrote, but the relatively few electrons which emerge from it in the direction of the main cathode k are able to produce sufficient ionization to form a very dense plasma when a sufficiently high voltage V_1 is applied between k_h and k.

The field is concentrated on the garrote.

The plasma thus formed has a high conductivity, of the order of 1 ohm-cm, and makes it possible for a relatively large current to flow in the operating compartment, that is between the main cathode k and the anode a. Under these conditions, the voltage V_2 between these electrodes can be low, and is always less than the ionization voltage of the gas (cf. [67] p. 148).

The variation of the main current I with the anode voltage V_a for various values of the auxiliary current I_h is sketched in Fig. 210.

It will be seen that it is possible to vary the main current continuously over a considerable range by means of a relatively small variation in I_h, which causes a variation in the density and conductivity of the plasma. This can be achieved e.g. by varying the internal resistance of a vacuum triode which is placed as a modulator in the auxiliary-current circuit (Fig. 209). The current can be regulated continuously and reversibly in this case because the voltage between the anode and the main cathode is less than the ionization voltage of the gas. If the anode is fed with AC, the back current of positive ions while the anode is negative is very small, only a few mA.

Another way of controlling the current is to place a grid in the operating compartment. The construction of the tube then becomes as shown in Fig. 211; it is then no longer necessary to use a vacuum triode as a control element. Changing the density of the ion layer round the more or less negative grid causes a variation in the effective cross- section of the plasma region, and thus alters the conductivity of the plasma [87].

The curves of Fig. 212 give an impression of the current-voltage characteristic for various values of the grid voltage V_g, at constant auxiliary current.

The modulation frequency characteristic is better if the modulation is performed with the aid of a grid than if a vacuum triode in the auxiliary circuit is used. In the latter case, the density of the whole volume of plasma is controlled, while in the first case only that part of it near the grid is affected. Even with grid modulation, however, the frequency

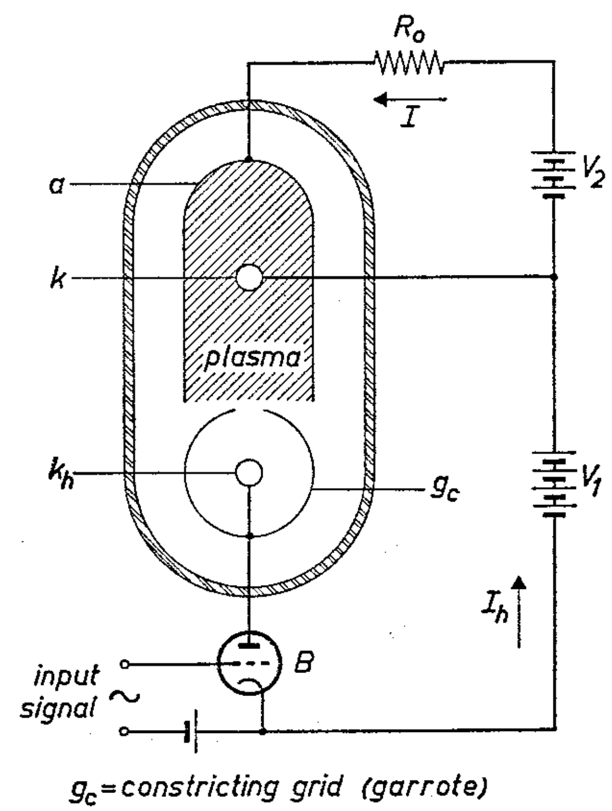


Fig. 209

Circuit arrangement for diode operation of a plasmatron. Generator compartment between k_h and k, operating compartment between k and a. B = modulator tube. R_o = load.

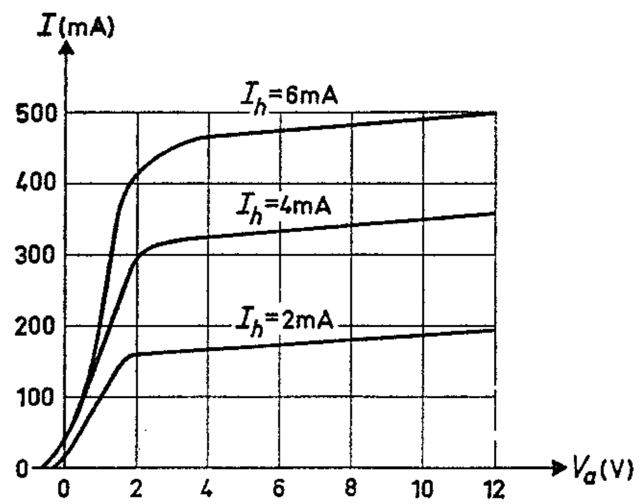


Fig. 210

Main current I of a plasmatron used as a diode, as a function of the anode voltage V_a for various values of the auxiliary current I_h.

characteristic begins to flatten off above 10 kc/s (Fig. 213). This is because of the much slower motion of the ions compared to that of the electrons during the de-ionization (cf. VII-d).

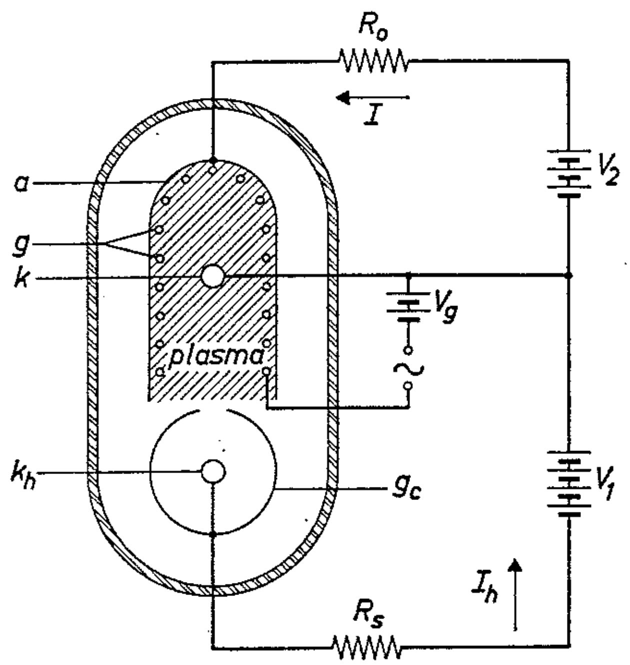


Fig. 211
The triode plasmatron. The grid g replaces the vacuum triode B of Fig. 209 as regulating element. R_s = current-limiting resistor. R_O = load.

Application

The high amplification and relatively high power which can be obtained with these tubes (power amplifications of 17 dB and more have been mentioned) makes them very suitable as output tubes in AF amplifiers; the AF transformer would then no longer be necessary. Plasmatrons should be suitable in car radios and for controlling motors. Very little is known however about these and other applications: potential users are not yet very interested because the life of the tubes is still unsatisfactory.

Plasmatrons are put on the market by Bendix, among others.

VIII-c **Neutron generators**

Introduction

A neutron source is necessary for certain experiments in the fields of fundamental physics, biology, chemistry and the medical sciences [96, 105]. Neutrons are uncharged particles with a mass approximately equal to that of the proton (the positively charged nucleus of a hydrogen atom). They can be produced by nuclear reactions, e.g. by bombarding the nuclei of certain elements with helium nuclei (α particles), which are emitted by certain naturally radioactive elements, e.g. radium. As a result of this bombardment, the element emits radiation with a great penetrative power, which can be detected e.g. with the aid of the radiation counter tubes described in Chapter V. At the same time, neutrons are released from the nucleus. These neutrons can be used e.g. to make many other elements radio-active in their turn.

Now the yield of nuclear reactions carried out with the aid of radium is not high. For example, the amount of radium needed to produce 1.7×10^6 neutrons per second from the element beryllium under optimal conditions of mixing is about 100 mg. Considering the scarcity of radium, this is an expensive way of producing neutrons, especially as for most purposes a neutron yield of at least 10^7—10^8 per second is desirable.

A much better way of producing neutrons has been known since about 1932 (Cockcroft and Walton), based on giving gas ions a high energy artificially with the aid of particle accelerators. The most suitable gas to use for this purpose is deuterium (symbol D) i.e. hydrogen whose nucleus consists of a proton and a neutron instead of just a proton, otherwise known as heavy hydrogen. The advantage of this hydrogen isotope is that its nucleus (i.e. its ion) can easily penetrate into the nucleus of the element to be bombarded, because of its low electric charge and mass. In this method, deuterium ions or deuterons (symbol d) are first made in a gas discharge, and are then given a high velocity in a strong electric field. The deuterons accelerated in this way are capable of releasing neutrons from a disc of a suitabel material placed in their path.

Although such "accelerator neutron sources" are much more complicated and unwieldy than neutron sources using naturally radioactive substances, they are much more effective and also have other advantages. For example,

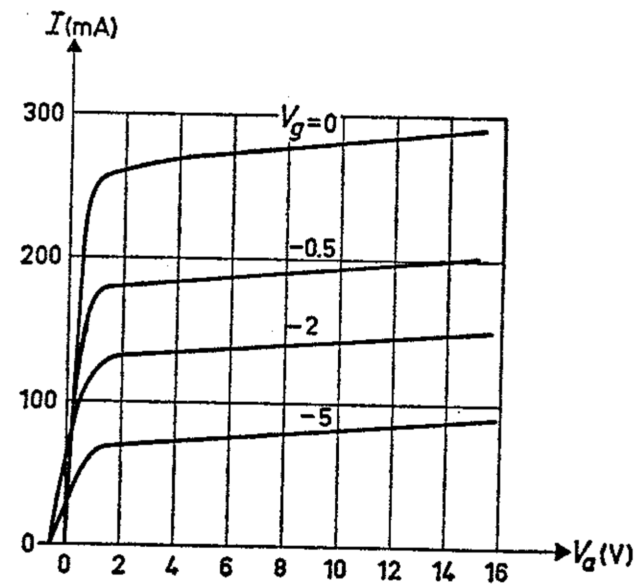


Fig. 212

Current-voltage characteristics of a triode plasmatron for various values of the grid voltage V_g and a constant auxiliary current $I_h = 10$ mA.

the number of neutrons produced can easily be made much larger, and they have a higher energy. Mono-energetic neutrons can be produced in this way, and the production can be controlled. We may mention as an example that 6.3×10^{15} deuterons per second, which corresponds to a current of 1 mA, accelerated by a voltage of 1 MV, can lead to the production of 7×10^{9} neutrons per second if they bombard a target of "heavy ice" (solid D_2O). This is much more than could be produced by the α particles from 100 mg of radium.

We shall now go into somewhat greater details about how the deuterons are produced, and how they are used to produce neutrons.

VIII-c-1 THE CONSTRUCTION OF A NEUTRON GENERATOR

A neutron generator always contains the following three components:

an ion source,
an ion-accelerating system and
a "target".

Ion sources

The ions needed in a neutron generator are formed in a gas discharge [103, 104]. The gas pressure must in general lie in the region from 10^{-1} to 10^{-2} mm Hg; on the one hand the mean free path of the electrons as regards collisions with gas molecules must be less than the dimensions of the discharge space, to make ionization possible; while on the other hand the pressure must be kept as low as possible so that the necessary extraction voltage of several kilovolts can be applied between the electrodes without giving rise to undesirable secondary discharge phenomena and so that the gas consumption can be kept low (see below).

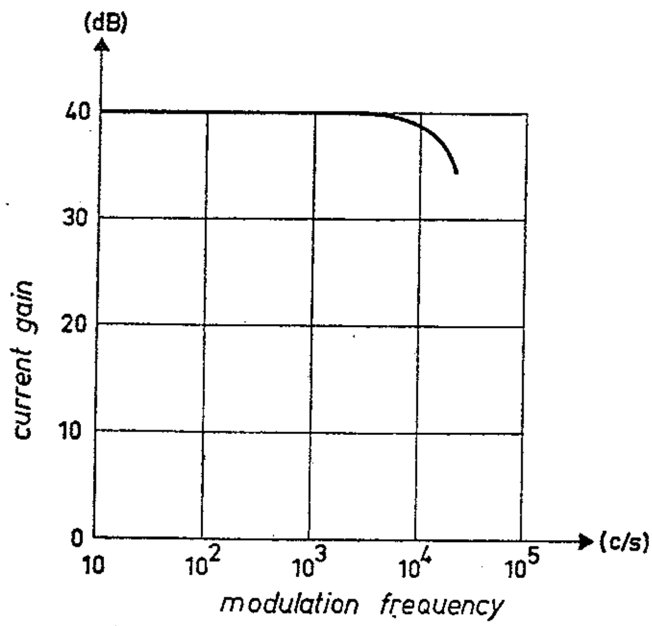


Fig. 213

Modulation characteristic of a triode plasmatron at an anode voltage of 6 volts.

If a hydrogen isotope is used as the gas, both atomic ions and molecular ions can be formed. It is generally desirable to have atomic ions, because they produce more neutrons (cf. Fig. 219). However, molecular ions are naturally formed first in the discharge; atomic ions can only be formed after some atomic hydrogen has been produced by collision of the molecules with electrons:

$$H_2 + e \rightarrow H + H + e.$$

A good ion source is expected to deliver a high ion current without using much gas. Gas is used up not only by clean-up (see II-b-2) but also in an other way, as we shall see presently.

Some of the fast ions, produced in the discharge, pass through a narrow channel into a second space, where they are given a much higher velocity. Various suggestions are made in the literature about the form which this channel should have in order to ensure that a large part of the ions will be able to get through it, and that the ion beam emerging from it should be sharply focused [103].

The energy of the ions emerging from the channel should be as homogeneous as possible.

Of the various types of ion sources which exist, we will only mention the Penning ion source and the ion source with HF discharge. The Penning source will be treated below, in the discussion of an easily transportable sealed-off neutron generator, so here we shall only describe some details of the second, more modern type.

Ion source with HF discharge

In this ion source, the electrons get the energy they need for ionization from a HF alternating field, which can e.g. be applied between two electrodes placed outside the discharge space [104]. An even simpler and in some respects better solution is to place the discharge space in a coil through which a HF alternating current flows. The discharge vessel can then be made of an insulator with a low recombination coefficient for atomic ions, e.g. Pyrex glass. A high percentage of atomic ions, in some cases amounting to 90 %, can then be produced. The plasma is kept at a positive potential by means of a suitable electrode.

An extraction probe is used to get the ions out of the plasma. The maximum ion current is obtained with a certain probe voltage. Various improvements have been made to the probe and the channel in the course of time, to increase the ion current and to decrease the gas consumption. This gas consumption is mainly caused by the pressure difference necessary between the discharge space and the neighbouring acceleration space. It is now posible to obtain a continuous ion current of 10 mA, and a gas consumption of 40 cm^3 (at normal temperature and pressure) per hour. The inhomogeneity of the ions coming from the channel is estimated at some hundreds of electron-volts, which is acceptable for most experiments in nuclear physics.

The accelerating space

The ions coming from the channel must be accelerated in one or more stages through a voltage of hundreds or thousands of kilovolts, so that they will hit the target with enough energy to release fast neutrons from it. The ion accelerator is usually built up of several stages, to avoid field emission.

The voltage between the electrodes of a single stage is usually not more than 200 kV.

The electrode system of the accelerator has rotational symmetry, and thus also acts as an electric lens. If the electrodes are given a suitable shape, the ions are focussed into a narrow beam.

Because of the high voltage between the electrodes, the gas pressure in the accelerating space must be much less than in the discharge space where the ions are produced: in the accelerating space, the mean free path of the ions for collisions with gas molecules must be long, to prevent breakdown occurring as a result of the ignition of an independent discharge.

In order to meet these requirements, the distance between the electrodes must be about 1 or 2 cm.

Fig. 214 shows as an example an accelerating space in five stages for 1 MeV, with the preceding HF ion source [108].

The target

The DD and DT reactions are usually used for the production of neutrons. In order to bring about these reactions, deuterons (deuterium ions) which have been accelerated through a high voltage are allowed to fall on a target which must contain as much deuterium or tritium (T) as possible. Titanium and zirconium are very suitable materials for the target, because they can absorb large amounts of hydrogen and its isotopes. These metals are evaporated in an extremely thin layer on to a support, e.g. a silver disc, and are then saturated with the hydrogen isotope [101].

Titanium is to be preferred to zirconium because it can stand higher temperatures (200 °C) and gives a higher neutron yield. Under favourable conditions, an ion beam of 1 μA and 200 kV falling on a titanium-tritium target can produce about 10^8 neutrons/sec.

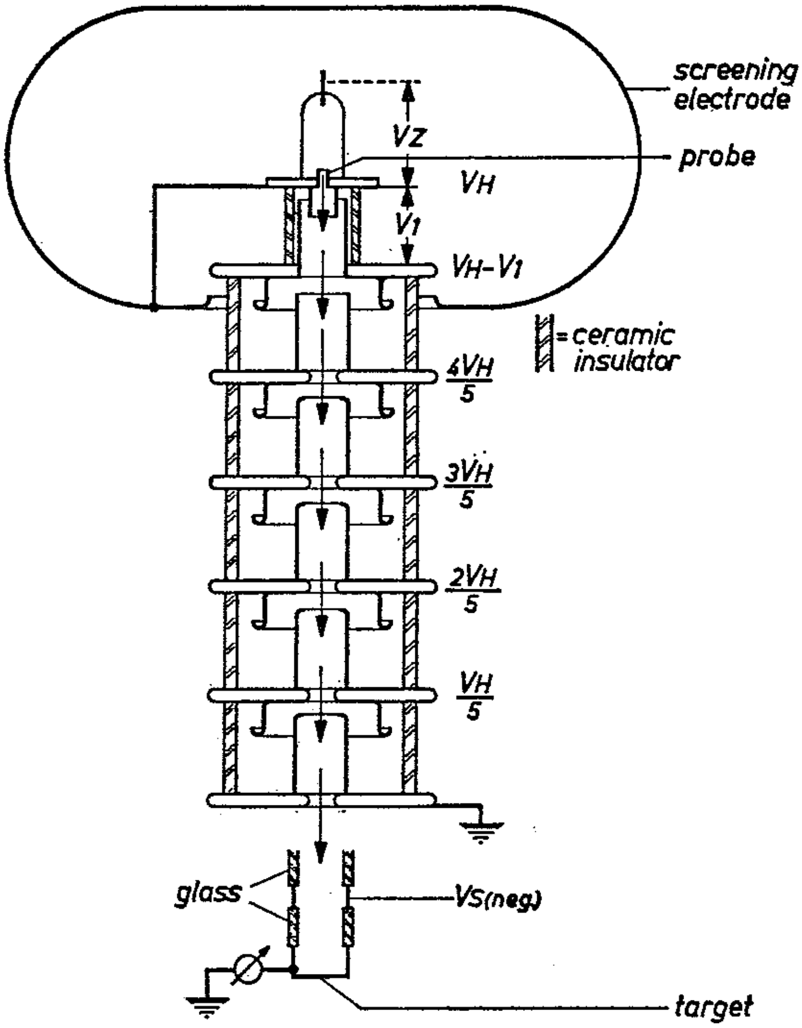


Fig. 214

Sketch of a Thonemann *HF* ion source with five-stage accelerating system for 1 MeV [108].
V_z = "Suction voltage" with respect to the probe.
V_1 = voltage across the first accelerator lens.
V_H = high tension of the cascade generator.
The probe is connected to the screen electrode, and thus has the voltage V_H. The ions leave the tube with a voltage $V_H + V_Z$. An electrode with a negative voltage V_S of a few hundred volts is situated above the target to reduce the emission of secondary electrons.

VIII-c-2 A SEALED-OFF TUBE AS NEUTRON GENERATOR

The increasing importance of neutron physics in science and industry has brought about a demand for suitable neutron sources. Those containing radioactive substances, e.g. Ra-Be and Po-Be generators, are simple in construction and easy to use, but they produce a complex neutron spectrum which often has a strong gamma background. Moreover, the intensity of the neutrons is limited and cannot be controlled.

The other types of neutron generators described above are rather elaborate, mainly because, as we have seen, a pressure difference must be maintained between the ion-source compartment and the accelerating space. The gas removed by pumping from the accelerating space must be continually made up for near the ion source. A controllable gas supply and a vacuum pump are therefore indispensible as auxiliary equipment, and this makes the whole installation rather difficult to move about.

Various attempts have been made to make this equipment more compact and if possible mobile. One important step in this direction would be getting rid of the vacuum pump, so that the generator could take the form of a sealed-off tube. As long ago as 1937, Penning showed in principle how this could be done [98]. The life of the Penning neutron generator was limited, as a result of gas clean-up in the electric discharge, and the neutron yield was not very large (about 10^5 per second), so the tube was never put to any practical use.

Of recent years, Reifenschweiler has carried out fundamental investigations in this field, which have led to the production of a tube which Philips has now put on the market and which we shall now proceed to describe.

Fundamental demands made on the construction

The gas pressure in all parts of a sealed-off neutron tube must naturally be the same. The arrangement of the electrodes in the ion source and the ion accelerator, and the voltages applied to them, must therefore be specially adapted to work at this pressure. The gas consumption in a sealed-off tube must be small or must be compensated for, so that the pressure remains within certain limits during the life of the tube.

The life is among other things determined by the durability of the target, which cannot be replaced when it is worn out in a tube of this sort.

We shall notice how these demands are met in the description of the various parts of the tube, given below.

The ion source

A good ion source for a sealed-off neutron tube should fulfil the following demands:

1. low gas pressure,
2. high ion current,
3. low gas clean-up,
4. large proportion of atomic ions,
5. low power,
6. reliability in continuous use,
7. long life,
8. simple and robust construction,
9. simple maintenance.

An improvement of the Penning ion source and of the accelerating system, combined with a gas reservoir (replenisher) which moreover allows the pressure to be adjusted, has led to a tube which satisfies nearly all these conditions [97]. The only condition which is not fulfilled is the fourth: only 5 % of the ions are atomic ions. In view of the fact that all the other conditions *are* fulfilled, however, this disadvantage has proved to be acceptable.

A small permanent magnet (Fig. 215a) is included in the tube. The magnetic field is parallel to and concentric with the axis of the tube. This field makes it possible to maintain a glow discharge at the low gas pressure in the tube (about 10^{-4}—10^{-2} mm Hg) with an electrode voltage of a few kilovolts. The gas pressure used is usually about 10^{-3} mm Hg. The anode consists of a hollow cylinder which is placed between the two sections of the cathode. The ignition voltage is about 1 kV.

One of the cathodes has the form of a soft-iron cup which encloses most of the discharge space. The bottom of this cup contains a hole or channel through which a large proportion of the ions can pass into the accelerating space.

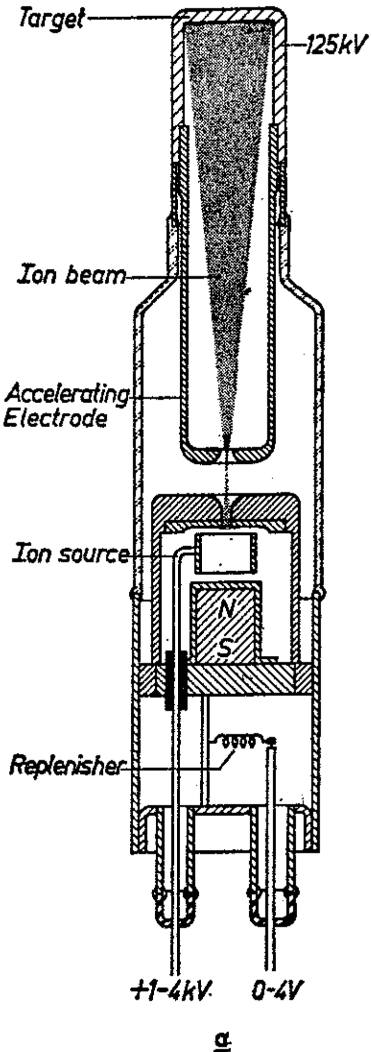
The magnetic lines of force pass through the soft-iron wall. This prevents a part of the magnetic field from continuing into the neighbouring accelerating space, where it might give rise to breakdown. Fig. 216 shows how the magnetic field strength decreases along the channel through the cathode, and that the accelerating space is completely free from magnetic lines of force.

The gas pressure can be controlled within wide limits by varying the current through a replenisher coil. This coil consists of a zirconium wire saturated with deuterium and tritium, wound round a tungsten support (cf. IV-b-5); it is placed behind the ion space. This wire gives off gas or absorbs it according to the voltage applied to it, in a way which has been described earlier; see Fig. 217 [97].

The gas pressure can be simply stabilized by allowing the ion-source current to control the replenisher voltage.

The accelerating space

After leaving the channel and having been accelerated, the ions enter the field-free space of the long accelerating electrode in the form of a narrow, slightly divergent beam of angle about 0.1 radian (Fig. 215a). The shape of the beam and the distance from the opening in the accelerating electrode to the target can be chosen so that the whole surface of the target is bombarded by ions. This is why the chrome-iron accelerating electrode is



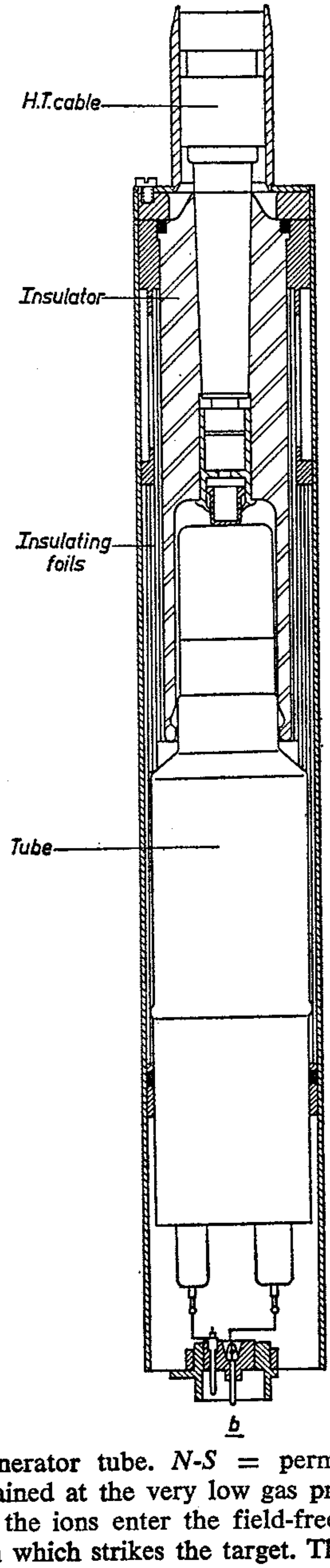


Fig. 215a

Cross-section of a sealed-off neutron-generator tube. *N-S* = permanent magnet which enables the ionization to be maintained at the very low gas pressure used in the tube. After having been accelerated, the ions enter the field-free space of the accelerating electrode as a divergent beam which strikes the target. The gas pressure can be controlled by means of the heater current of the replenisher.

Fig. 215b

hollow, while the shortest distance from it to the channel is only about 1 cm. Accelerating voltages of up to 200 kV are permissible in the gap with this construction, which also ensures that electrons produced from the target cannot get to the accelerating gap. The whole tube is enclosed in a metal sheath (Fig. 215b). Layers of plastic foil with oil are used as insulation between the tube and the metal sheath.

The target

Tritium targets which can be used in conventional neutron generators are on the market [101]. They consist of a silver disc about 0.2 mm thick, with a thin film of titanium or zirconium about 1 μ thick evaporated on to it. This film is then saturated with tritium.

The target should emit as many neutrons as possible when bombarded by the accelerated ions. The neutron yield is mainly determined by the accelerating voltage and the ion current. Since the temperature of the target may not exceed a certain limit (200 °C for Ti-T targets), care must be taken that the ions bombard the whole surface of the target; this also makes the loadability maximum. The special construction of the accelerating system takes care of this, as we have seen.

If only part of the target is bombarded, the temperature increases too much there, and the neutron yield drops.

Titanium targets have been found to be more temperature-resistant than zirconium ones. At a temperature of 200 °C, tritium is still not lost from a titanium target. Moreover, titanium produces relatively more neutrons than zirconium, because it captures the deuterons better.

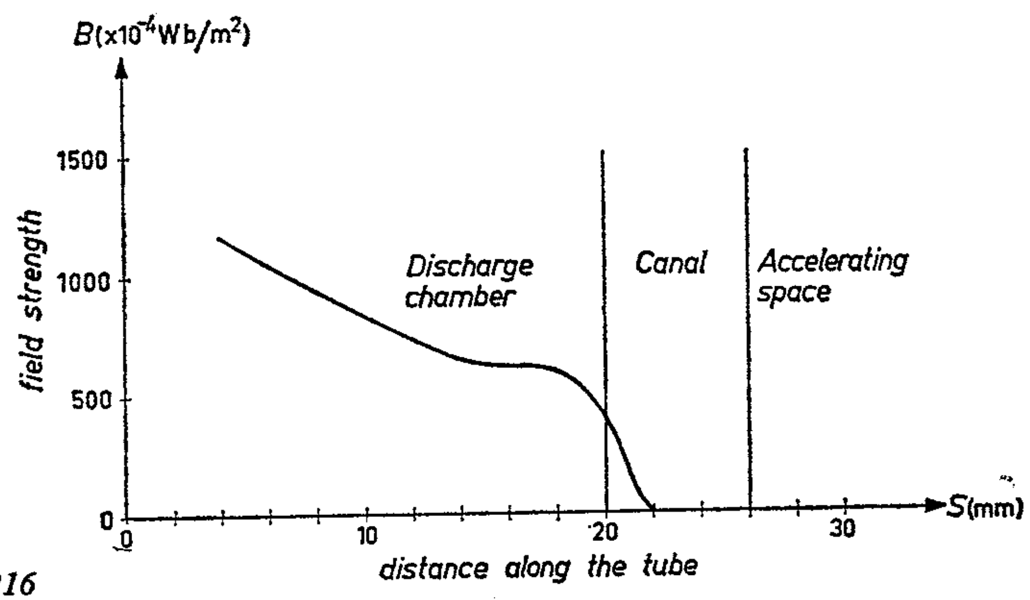


Fig. 216

Configuration of the magnetic field caused by the permanent magnet of Fig. 215a. The field is attenuated in the channel, and the accelerating space is completely field-free, as a result of which breakdown in the gas there is prevented.

If it was possible to make titanium targets which were able to make up their own loss of tritium, this would be a great step in the direction of a long life for the tube. Such a self-replenishing target for the DD reaction, the "drive-in target", has been thoroughly investigated by e.g. Fiebiger [102].

If a metal disc with a sufficiently low diffusion coefficient for hydrogen is bombarded with deuterons for long enough, it can be made into a deuterium target: the deuterons penetrate into the metal and spread by diffusion. If the deuteron bombardment continues, neutrons are produced by the DD reaction:

$$_1H^2 + {_1H^2} \rightarrow {_2He^3} + {_0n^1} + 3.265 \text{ MeV}.$$

If the bombardment is continued even further, the neutron production increases until a state of saturation is reached, when as many deuterons leave the target as reach it. Fiebiger found that gold gives the highest neutron yield under these circumstances, four times as much as titanium.

Following on from this, the conclusion was reached that if the tube was filled with half deuterium and half tritium, a simple self-replenishing target for the DT reaction

$$_1H^2 + {_1H^3} \rightarrow {_2He^4} + {_0n^1} + 17.6 \text{ MeV}$$

should be realizable, with a considerably higher yield than with the DD

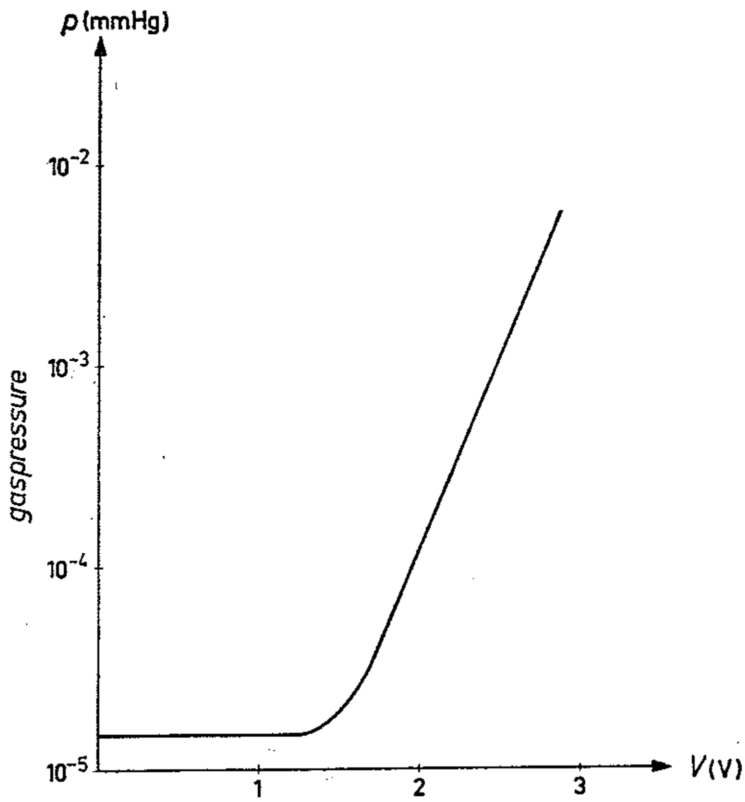


Fig. 217

Variation of the gas pressure as a function of the replenisher voltage in the tube of Fig. 215a.

reaction [97]. Once such a target was saturated, it should be able to keep working for the whole life of the tube; and the neutron production need not fall, as long as the replenisher compensates for the gas clean-up in the ion source.

It can be calculated that with the usual accelerating voltage the neutron yield of such a target will only be a third of that with a target of the same metal saturated with tritium and bombarded with deuterons. The advantages of long life and constant production more than compensate for this, however.

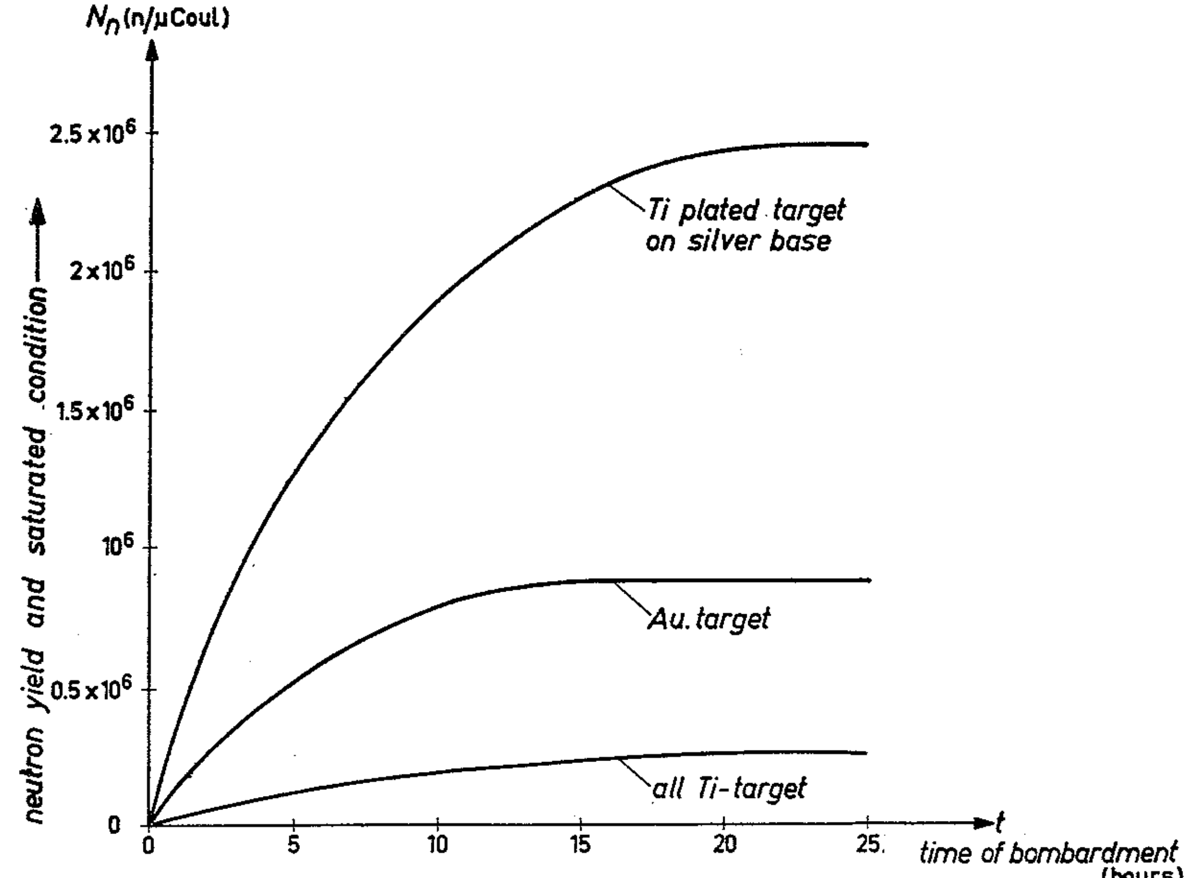


Fig. 218
Neutron yield N_n in neutrons per microcoulomb of some drive-in targets as a function of the time of bombardement.

The neutron yield of a gold disc in the saturated state was 8×10^7 n/sec with an ion current of 100 μA and an accelaration voltage of 125 kV.

A much better method is to use a thin film of material with a high diffusion coefficient for hydrogen and which can at the same time absorb hydrogen strongly, on a support with a low diffusion coefficient for hydrogen so that the hydrogen atoms cannot diffuse away. Titanium and zirconium are suitable for the top film. Since they have a lower atomic stopping power than gold, titanium-coated drive-in targets should give a higher neutron yield than gold ones with the same atomic ratio. A silver disc with a film of titanium about 1 μ thick on top was found to give a good yield. Fig. 218 shows the neutron yield of a titanium-coated silver target, a gold one and an all-titanium one, under the same conditions, as a function of the bombardment time.

Apart from the advantage of a higher neutron yield, self-replenishing titanium-coated targets can stand high temperatures better than plain gold ones: they can stand 200 °C, while the neutron yield of a gold target already falls of considerably at 150° C. Pumping the tube out at the normal temperature of 400—450 °C does a drive-in target no harm, because the bombardment needed to saturate it is not carried out until after the tube is sealed off.

The neutrons emitted by this target in all directions can pass through the walls almost without hindrance, and have an energy of about 14 MeV under the above-mentioned conditions.

The self-replenishing target goes on producing neutrons as long as there is gas in the tube, so that the life of the tube now depends largely on the replenisher.

Results

The neutron yield is determined from measurements on activated copper with the aid of Geiger-Müller counters. The experimental and calculated values for various accelerating voltages are shown in Fig. 219.

Curve 1 shows the calculated yield of a titanium/tritium target with an atomic ratio of 1 : 1, for bombardment with deuterons.

Curve 2 shows the calculated yield if the beam consists of molecular ions instead of atomic ions. At an accelerating voltage of 100 kV, the yield is about a third of that obtained with atomic ions (deuterons).

Curve 3 shows the calculated yield of a DT mixture in a titanium-coated self-replenishing target bombarded with molecular ions. Here again, the yield is about a third of that obtained with an "all-tritium" target bombarded with pure deuterium (molecular ions).

Curve 4 shows the measured yield of a conventional tritium target in a tube filled with pure deuterium.

Curve 5 shows the measured yield of a self-replenishing titanium-covered target in a tube filled with a DT mixture. It will be noted that the actual yield of such a target is nearer to the calculated value than for commercial targets. Targets of this sort give 2.4 — 3 $\times$ 10^8 neutrons per second at an accelerating voltage of 125 kV and an ion current of 100 μA, under which conditions the operation of the tube is very stable.

The generator described is capable of pulse operation if the ion-source voltage is applied pulse-wise. Pulses with a minimum duration of 5 microseconds can be produced in this way. With a duty cycle of 1 %, a maximum neutron yield of 3×10^{10} n/sec can be achieved during the pulse [106].

Applications

The sealed-off neutron generator described above enables the research worker to make radioactive isotopes of nearly all the elements of the periodic table, for use e.g. in biology and the medical sciences. Because of the short half life of many of these substances, it is a great advantage if they can be made on the spot. The mobility of the generator is useful here.

It can also be used in all sorts of fundamental work in nuclear physics, where a yield of 10^8 n/sec is sufficient. It is also useful for chemical analyses (activation analysis, geological investigations). It is especially useful for "oil-well logging" [99, 100], where it is used as follows: it is

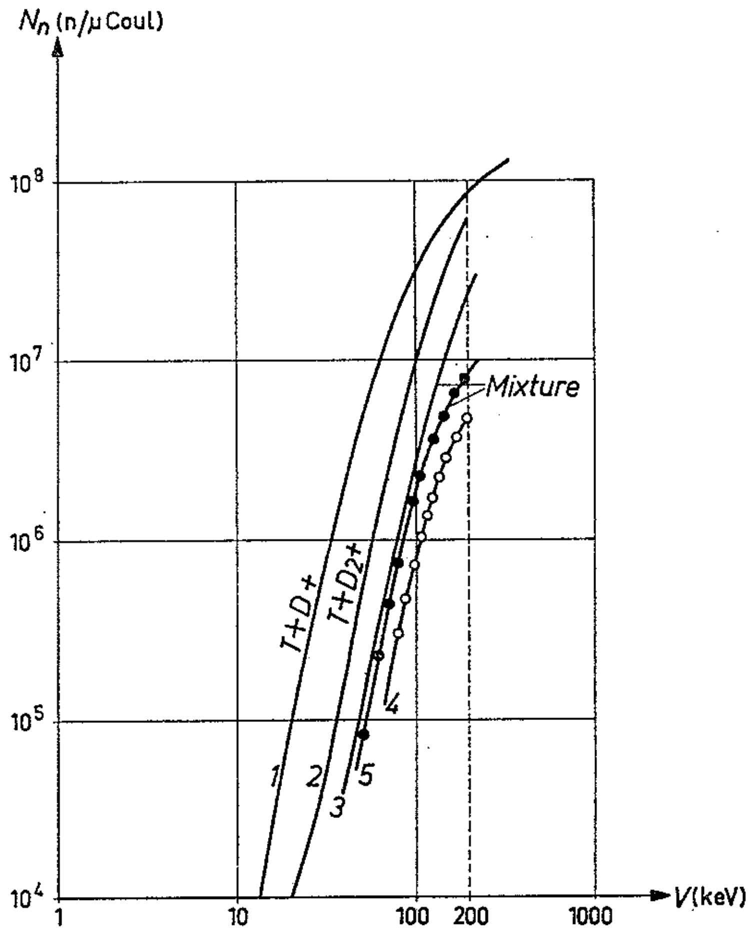


Fig. 219

Neutron yield N_n in neutrons per microcoulomb as a function of accelerating voltage V for some titanium targets. For further explication see text.

lowered down the borehole together with a radiation detector. Analysis of the scattered neutrons or of the gamma-radiation excited can show whether oil or natural gas is present.

We may also mention the important field of reactor physics, especially when it is used in pulse operation for the investigation of screening materials for neutrons. Finally, it is of great use in training neutron physicists.

The above list certainly does not exhaust all the possibilities, and many more uses will doubtless be found as these tubes are developed further.

PHYSICAL CONSTANTS

e = charge of an electron (1.6×10^{-19} coulombs)

h = Planck's constant (6.625×10^{-34} watt.second^2)

k = Boltzmann's constant (1.38×10^{-23} joule/°K)

SYMBOLS

a = anode
a_h = auxiliary anode

C_{ag} = anode-grid capacitance
C_{gk} = grid-cathode capacitance
C_{kh} = auxiliary cathode capacitor
C_p = parallel capacitance
C_t = triggering capacitor

E(*or* F) = electric field strength

f = frequency or filament (heater)
F(*or* E) = electric field strength
F_c = commutation factor
F_r = arc back factor

g = grid
ge = getter

i_{ahp} = peak current of auxiliary anode
i_{am} = crest value of sinusoidal alternating current
i_{ap} = instantaneous peak value of an alternating current
i_{ignp} = peak value of ignition current
i_{surge} = surge current
$i_{surge\ p}$ = peak value of a surge current
I_{ahav} = average current of auxiliary anode
I_{av} = average current
$I_{av\ max}$ = maximum average current
I_e = emission current
I_f = heater current or photo-electric current
I_g = grid current
I_{gem} = grid emission current
I_{gl} = glow current

I_h = auxiliary current
I_o = *DC* output current
I_{pr} = current through primary transformer winding
I_{rms} = *rms*-value of *AC* current
I_s = electron current density
I_{sat} = saturation current
I_t = trigger current

j = current density

k = cathode
k_h = auxiliary cathode

m = mass (electron)
M = mass (atom)

p = pressure of a gas
p_o = gas pressure reduced to O °C
p_r = priming electrode (primer)

q = multiplication factor (secondary electrons)

R_a = series resistance of the anode
$R_{a\ min}$ = minimum value of R_a
R_g = series resistance of the grid
R_I = resistance of ignition rod
R_k = series resistance of the cathode
R_{kh} = series resistance of the auxiliary cathode
R_o = ohmic load resistance
R_{prim} = resistance of primary transformer winding
R_s = series resistance
R_{sec} = resistance of secondary transformer winding
R_{sh} = shunt resistance
R_t = total ohmic resistance in the circuit or series resistance of the trigger
R_v = ballast resistance

$\left.\begin{array}{l} S \\ S_c \end{array}\right]$ = screen

t = time or temperature or triggering electrode (trigger)
t_{amb} = ambient temperature
t_{av} = averaging or integration time

$t_{de\ ion}$ = de-ionization or recovery time
t_f = preheating time of filament
t_{Hg} = temperature of mercury condensate
i_{ion} = ionization time
torr = mm *Hg*
t_s = duration of surge current
t_w = warming up time

T = one period of an alternating voltage (current) or absolute temperature (in degrees Kelvin, 273 + °*C*)
T_e = electron temperature in °*K*
T_o = room temperature in °*K*
T_w = true temperature in °*K*

v = velocity
$v_{ahp\ forw}$ = forward peak auxiliary anode voltage
$v_{ahp\ inv}$ = inversed peak auxiliary anode voltage
v_{am} = crest value of sinusoidal alternating anode voltage
$v_{ap\ forw}$ = forward peak anode voltage
$v_{ap\ inv}$ = inversed peak anode voltage
v_{gp} = peak value of grid voltage
v_m = most probable velocity of a gas

V_a = voltage at the anode or excitation voltage of atoms
V_a' = excitation voltage of metastable atoms
V_{aa} = *DC* anode supply voltage
V_{agl} = anode glow voltage
V_{arc} = arc voltage
V_{arms} = sinusoidal alternating anode voltage
V_b = battery voltage, counter voltage
V_{br} = burning voltage
V_d = breakdown voltage
V_f = filament voltage, heater voltage
$V_{f\ rms}$ = sinusoidal alternating filament voltage
V_g = voltage at the grid
V_{gcrit} = critical grid voltage
V_{gg} = *DC* grid supply voltage
V_{go} = quiescent value of grid voltage (zero excitation)
$V_{g\ rms}$ = sinusoidal alternating grid voltage
V_i(or V_{ion}) = ionization voltage
V_{ign} = ignition voltage
V_{ion}(or V_i) = ionization voltage

V_k	= cathode fall
V_L	= choke voltage
V_o	= *DC* output voltage
$V_{p\,forw}$	= forward peak voltage
$V_{p\,inv}$	= inversed peak voltage
V_{pr}	= voltage on primary transformer winding
V_{rms}	= *rms*-value of *AC* voltage
V_s	= (Geiger) threshold voltage
V_{sec}	= voltage on secondary transformer winding
V_t	= trigger voltage
V_{tt}	= *DC* trigger supply voltage
V_z	= ohmic and inductive voltage drop
$V_{=}$	= *DC* voltage
W_{arc}	= energy losses in the arc
W_f	= filament (heater) losses
W_g	= power of grid circuit
W_{ign}	= power of ignitor circuit
W_m	= mean kinetic energy of gas particles
W_o	= *DC* output power
X_L	= inductive resistance of the choke
Z_a	= anode impedance
α	= Townsend's ionization coefficient ($= \eta \times F$) or ignition angle
γ	= ionization coefficient (gamma effect)
ε	= base of the natural logarithms (≈ 2.718)
η	= ionization coefficient (per volt)
λ_e	= mean free path of the electrons
μ	= control ratio of a thyratron
ν	= frequency (light or radiation)
φ	= work function

AN ABSTRACT OF: THE TRON FAMILY

A dictionary of many well-known and not so well-known tubes and other electronic devices having a common suffix 'tron'.
Compiled by W. C. White, General Electric Company,
Electronic Industries, Jan. 1946, p. 80-83 and p. 130-136,
completed with some other 'tron'-tubes.

Gas-filled tubes

*) Excitron	A type of mercury pool tube containing a holding anode and a special form of starting electrode. *Excitron Mercury Arc Rectifiers*, O. K. Marti. Transactions AIEE, 1940; V. **59**, p. 927.
Gusetron	Sometimes called Gausitron. A mercury-arc pool tube. An insulated probe type electrode dips into the mercury pool to provide cyclic ignition. *A new form of Ignitor of Mercury Pool Tubes*, K. J. Germeshausen. Phys. Rev. Jan. 15, 1939, p. 228.
*) Ignitron	A pool tube with a single main anode in which an ignitor is used to initiate an arc spot on the cathode before each conducting period. *New Method of starting an arc*, J. Slepian, and L. R. Ludwig. Electrical Engineering, Sept. 1933; V. **52**, p. 605.
Kathetron (Cathetron)	A gas-content thermionic cathode triode having the grid external to the envelope. *The Kathetron – A control Tube with External Grid*, Palmer H. Craig. Electronics, March 1933; V. **6**, p. 70.
Neotron	A gas-filled tube designed particularly as a pulse generator. *Gas-filled Tubes as pulse generators*, F. J. G. van den Bosch. Electronic Engineering, April 1945, p. 474.
Permatron	A gas or vapor-content thermionic cathode diode. Cyclic anode current flow is initiated by a magnetic field change. *The Permatron and its application in Industry*, W. P. Overbeck. Electronics, April 1939; V. **12**, p. 25.
*) Phanotron	A hot cathode, gas or vapor content diode in which no means are provided for controlling the current flow. It is essentially a rectifying device. *Gas-filled Thermionic Tubes*, A. W. Hull, Transactions A.I.E.E., July 1928; V. **47**, p. 753.

Plomatron	A name suggested for the grid-controlled, mercury-arc rectifier. London Electrician. December 18, 1942, p. 669.
Pulsatron	A double-cathode, gas-filled triode. *Gas-filled Tubes as Pulse Generators*, F. J. G. VAN DEN BOSCH, Electronic Engineering, April 1945, p. 474.
*) Sendytron	Japanese designation for a mercury-pool tube in which the arc is initiated by a high-voltage probe electrode. Electro-Technical Journal of Japan, August 1938; V. **2** No. 8, p. 180. See also Wireless Engineer; Nov. 1938, p. 641, No. 4609.
Strobotron	A cold-cathode discharge tube with control electrode designed to pass heavy currents for very short periods of time. Used for high-speed photography. *A cold-cathode arc discharge Tube*, K. J. GERMESHAUSEN and H. E. EDGERTON. Electrical Engineering, July 1936, p. 790.
Takktron	A gas-filled, cold-cathode diode designed for the rectification of low-currents at high voltage. *A Portable Instrument for Measuring Insulation Resistance at High Voltage*, F. W. ATKINSON and R. B. TAYLOR. Electrical Engineering, April 1945; V. **64**, p. 164. *Industrial Testing with High Voltage*, Electronic Industries, Nov. 1945, p. 106.
*) Thyratron	A hot-cathode, gas-content tube in which one or more control electrodes initiate, but do not limit, the anode-current except under certain operating conditions. *Hot Cathode Thyratrons*, A. W. HULL. Gen. Electric. Rev. April 1929; V. **32**, p. 213.
Trignitron	A trade name for a mercury-pool type of tube used in a welding control device sold by the Electronic Power Co., Inc., Electronics, July 1944, p. 58.
Alphatron	A particular form of ionisation tube used for measuring the degree of vacuum.
Capacitron	One form of pool cathode tube.
Cathetron	(See Kathetron).
*) Dekatron	A cold cathode gas-discharge counter tube.
*) Plasmatron	A thermionic gas-filled tube in which continuous control is exercised over the anode current.
Tacitron	A form of low-noise thyratron having a grid of special design so that the tube current can be interrupted by grid action.

*) = discussed in this book.

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