GAS TUBES

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Edited by
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PREFACE

When a gas or vapor is admitted into a tube, the characteristics of the tube are markedly changed from the high-vacuum state. These radical differences have been used successfully by the electronics designer to permit the development of many fundamental gas-tube types for literally hundreds of industrial applications.

For example, one member of the gas tube family, control-electrode rectifiers known as thyratrons, electronically serve almost every industry. Because they are available in a wide range of ratings, thyratrons may be used in circuits ranging from the control of large power amounts at lower voltages (in welding and motor control) to the sorting, grading and counting of merchandise. The thyratron may serve as a rectifier (ac to dc), as an inverter (dc to ac), as an electronic switcher or contactor to open and close circuits rapidly, or as control tubes. Since this is only one type of gaseous tube, the importance of understanding the basic theory pertaining to gas tubes is evident.

This book has been organized to help the student understand the more important ideas basic to this area of electronics. Thus, specific attention has been given to the meaning of ionization, the movement of ionic particles, principles of gas conduction, non-self-maintaining discharge, self-maintaining glow discharge, arc discharge, space-charge effects in gaseous rectifiers, mercury-vapor rectifiers, the principles of gas tube voltage regulators, circuit action, the design of a voltage regulator circuit and aspects of electronic voltage regulation. An entire chapter is devoted to thyratrons, outlining the essentials from the fundamental action of a thyratron in

a d-c circuit to various types of the thyratron circuits. Other types of gas-filled tubes, from phototubes to the large ignitron are also presented. In all the materials are such as to give the electronic technician, engineer, experimenter, amateur and/or student additional background which will serve as a most useful tool.

Grateful acknowledgement is made to the staff of the New York Institute of Technology for its assistance in the preparation of the manuscript for this book.

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CONTENTS

Chapter 1

IONIZATION IN GASES

1. The Meaning of Ionization

Atoms and molecules, the normal building blocks of matter, are electrically balanced systems in which the total positive charge is equal to the total negative charge, leaving a net charge of zero. In the fundamental picture of the atom, the positive charge is borne by the nucleus in which reside protons and neutrons while the total excess negative content resides in the orbiting electrons.

Molecules in the atmosphere are constantly subjected to bombardment and collision. These involve both high- and low-speed particles such as alpha particles emitted from radioactive materials in the earth's crust, and secondary cosmic ray particles from the upper atmosphere. The nucleus of the oxygen or nitrogen atom of the air of which these molecules are composed is seldom disturbed by chance collisions with moving particles because it makes a relatively small target. On the other hand, the orbiting electrons are very likely to become involved in direct collisions which lead to their dislocation from the atom to which they belong.

When a neutral atom gains or loses one or more electrons it becomes an *ion*. The *loss* of electrons results in a net positive charge on the dismembered particle which is then termed a *positive ion*. Much less frequently, an atom may *gain* one or more electrons to form a negative ion. The term *ion* is thus much less definitive than other common particle names — electron, proton, etc. — because it does not state the polarity of the charge, the mass of the particle, or the magnitude of charge it carries. Because of the predominance

1

of positive ions in electrical phenomena, the term ion as used in this book will refer to *positive* ions whether or not they are qualified by the adjective "positive;" reference will be made to negative ions by consistently prefixing the adjective "negative."

Chance encounters between positive and negative ions in the atmosphere result in gradual recombinations to form neutral atoms. But there are always several hundred charged particles per cubic centimeter of ordinary air.

2. Movement of Ionic Particles

Since an ion is a charged particle, a force is exerted upon it when it is placed in an electrostatic field or a magnetic field. The commonest method whereby an electrostatic field may be made to

CATHODE   ANODE
(NEGATIVE ELECTRODE)   (POSITIVE ELECTRODE)
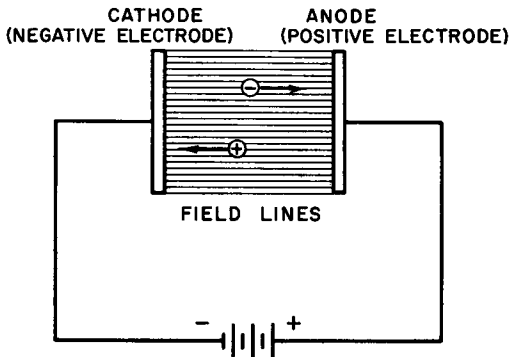
FIELD LINES

Fig. 1. Field lines and potential gradient between two parallel charged electrodes.

act upon an ion is that in which two electrodes connected to a source of electrical potential are made to establish a *potential gradient, G* (Fig. 1). Positive ions in such a gradient are accelerated toward the *cathode* or negative electrode while negative ions move in the direction of the *anode*.

The force exerted on an ion in such a field depends upon the charge on the particle e (coulombs) and the potential gradient E_1 (volts per cm). Expressed in dynes, the force equation is:

$$F = Ge \times 10^7 \qquad (1)$$

The kinetic energy acquired by a charged particle as it traverses the voltage gradient is determined by the magnitude of the charge e

in coulombs and the difference of potential V in volts between the two electrodes. In this case, the energy is given in coulomb-volts or *joules*. That is,

$$W = Ve \qquad (2)$$

in which W is energy in joules, V is potential difference in volts, and e is charge in coulombs.

The kinetic energy of any moving particle may be expressed in terms of its mass m (gms) and velocity v (cm/sec) thus:

$$W = \tfrac{1}{2} mv^2 \qquad (3)$$

in which W is in ergs, m in gms, and v is velocity in cm/sec.

Since a joule $= 10^7$ ergs, Equation 3 expressed in joules is

$$W \text{ (joules)} = \tfrac{1}{2} mv^2 \times 10^{-7} \qquad (4)$$

From Equations 2 and 4, we derive:

$$Ve = \tfrac{1}{2} mv^2 \times 10^{-7} \qquad (5)$$

Solving for v, the velocity of the particle:

$$v \text{ (cm/sec)} = 4.47 \sqrt{\frac{Ve}{m}} \times 10^3 \qquad (6)$$

Problem 1. Find the velocity acquired by an electron in falling through a difference of potential of 10 volts. The approximate charge and mass of an electron are roughly 1.6×10^{-19} coulombs and 9.1×10^{-28} gms, respectively.

Solution. Substituting in Equation 6:

$$v \text{ (cm/sec)} = 4.47 \sqrt{\frac{10 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-28}}} \times 10^3$$

$$= 4.47 \sqrt{10 \times 1.76 \times 10^8} \times 10^3$$

$$= 4.47 \times 4.20 \times 10^7$$

$$= 18.8 \times 10^7 \text{ cm/sec}$$

Since 1 km $= 10^5$ cm $= 0.621$ mile

$$v = 1880 \frac{km}{sec} = 1170 \frac{mile}{sec}$$

Problem 2. Find the velocity acquired by a mercury ion in falling through the same difference of potential, if the ion bears a positive charge equal numerically to one electron (singly ionized). The mass of a mercury ion of this kind is roughly 4×10^5 times as great as that of an electron.

Solution: Since velocity varies inversely as the square root of the mass, then the velocity of the mercury ion will be roughly $.0016 \times$ the velocity of the electron, or approximately *1.9 miles per second*.

Often it is of greater importance to know the momentum of a moving ion rather than its velocity. (For all particles in motion at a speed substantially less than that of light, the classical mechanical concept of conservation of momentum may be applied.) This means that the thoroughly practical objective of mathematically determining the force necessary to deflect a moving ion from its path is easily realizable. This problem arises in television, X-ray work, mass-spectrograph analysis, and many other research problems.

Momentum is defined as the product of mass and velocity. That is:

$$\text{Momentum} = mv \qquad (7)$$

in which m is mass in gms, v is velocity in cm/sec, and momentum is expressed in gm-cm/sec.

As momentum is directly proportional to mass, the mercury ion of Problem 2 has a much greater momentum than the electron even though its velocity is considerably less. This follows from the consideration that a particle in an accelerating field acquires a velocity that is inversely proportional to the *square root* of the mass while the momentum is proportional to the *mass itself*. Hence, the product mv in a given field must be greater for particles of greater mass.

This principle is fundamental in the operation of the mass-spectrograph and the television picture tube. In the former case, mixed particles are separated by a magnetic field which deflects less massive particles to a greater degree than the more massive ones. In a picture tube, negative ions that might damage the phosphor of the screen are prevented from reaching it by deflecting the electrons toward the screen through the action of a magnetic field while the heavy negative ions are unaffected and continue on a path which carries them away from the screen.

3. Principles of Gas Conduction

A pair of electrodes immersed in a gas give rise to conduction phenomena very different from those obtained under similar circumstances with charged electrodes in a vacuum. If a voltage is applied to gas-immersed electrodes separated by a small distance (*e.g.,* distances of 1 or 2 cm), a current begins to flow immediately. Thermionic emission plays no part here since neither of the elec-

trodes is heated enough to produce this effect. This small initial current is due to the ionization of the gas by external influences such as cosmic rays and light photons. Normally, the ions thus formed reach a definite concentration and then begin to recombine to form neutral atoms. The rate of recombination forms an equilibrium state with the rate of formation so that the average number of ions free to act as charge carriers remains fairly constant for a given set of conditions. The process of recombination is a random one; it occurs most readily when ions and electrons chance to drift near each other at low speeds.

As the voltage gradient between the electrodes is increased, the ions move more and more swiftly toward the oppositely charged electrode (Equation 6) and the opportunities for recombination diminish. This leads to an increasing gas current until the point is reached where all the ions produced by external particles and radiation are carried to the oppositely charged electrode, all of them thus contributing to the gas current. Further increases in the potential gradient from this point does not result in a further growth of gas current. The magnitude of the current under these conditions, however, is too small to be of practical value.* Should the external ionizing source be removed by shielding or other methods, the conduction current ceases immediately. In Fig. 2, the range from 0 to A shows the variation of gas current with voltage up to saturation; from A to B, saturation current flows.

4. Non-Self-Maintaining Discharge

As the electrode potential is further increased beyond E_1, the current again begins to rise. Restricting our thinking to the electrons that are liberated from the atoms acted upon by the external ionizing agents, we can analyze the action which then takes place qualitatively. If the voltage between electrodes is high enough, a liberated electron may gather sufficient kinetic energy as it falls through the established potential to free a second electron from the first atom it collides with. Now two electrons are available for further ionization by collision. Since the process is cumulative, it is evident that the possibilities are good for very large currents to flow in the gas. Al-

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*The maximum current obtained in this way is called the saturation current and is expressed in amperes per square meter of cross-sectional tube area. It is in the order of $10-22$ amp/m2.

though the current may rise to 20 times its original value (Point C in Fig. 2), it is still dependent upon the original supply of electrons from the original ionizing source. If this source is removed, the current again falls to zero in an extremely short time. For this reason, such a discharge is known as a non-self-maintaining type.

One of the best examples of an application of a non-self-maintaining discharge is the gas-filled photocell. The process is started by light photons which fall upon a surface having photoemissive characteristics, *i.e.*, a material which emits electrons when struck by light. This surface serves as the cathode of the tube and is made
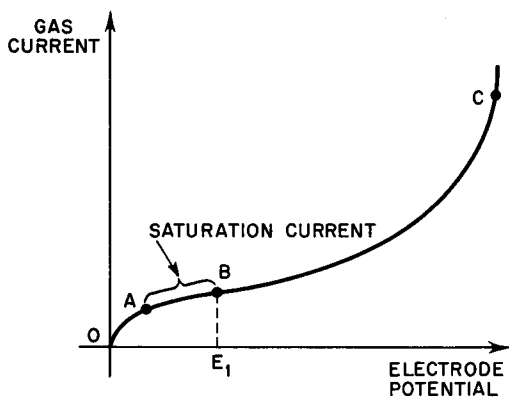
Fig. 2. Variation of gas current with voltage.

negative with respect to another electrode in the same envelope. As the photoelectrons are drawn toward the anode they develop sufficient kinetic energy to ionize gas molecules in their path. The electrons liberated by ionization contribute to the total gas current by serving as charge carriers so that the intensity of the current rises to a figure from 10 to 20 times as great as it would be in a vacuum. As the brightness of the light is increased, the *increment in current is far greater than it would be, had the whole process taken place in a non-ionizing atmosphere or in a vacuum.* Herein lies the unique value of the gas photocell: the presence of gas gives rise to intensified current changes which then result in *gas amplification.* Thus, gas phototubes are more sensitive to light variations than their vacuum prototypes.

The large number of electrons liberated from ionized atoms by the single original electron from the cathode is known as an "*electron avalanche.*" If *a* symbolizes the number of *new* electrons

(or ions) formed by one electron traveling a distance of 1 meter through a gas, and d denotes the actual distance between the cathode and the anode of any type of gas-discharge tube, then the number of electrons comprising an electron avalanche started by a single primary electron is shown thus:

$$\text{Number of electrons in avalanche} = \varepsilon^{ad} \qquad (8)$$

where E is the base of the Naperian system of logarithms. The term a in this equation is often called the *first Townsend coefficient,* after the investigator who first proposed a tenable theory explaining "glow discharges." Equation 8 may be amplified by using the expression to show the number of electrons that reach the anode compared to the original number that left the cathode. Thus:

$$n_a = n_c \, \varepsilon^{ad} \qquad (9)$$

in which n_a is the number of electrons reaching the anode, n_c is the number of electrons leaving the cathode, and ε^{ad} is the avalanche number. If both sides of Equation 9 are multiplied by the electronic charge, the resulting expression is that of the currents in the gas:

$$I_a = I_o \, \varepsilon^{ad} \qquad (10)$$

in which I_a is the current at the anode and I_o is the current at the cathode. Since I_o in the type of tube we have been discussing is produced entirely by external excitation (light in the phototube), when I_o drops to zero as the excitation is removed, I_a also becomes zero. This explains the non-self-maintaining nature of the discharge.

5. Self-Maintaining Glow Discharge

Should the voltage between the electrodes in the gas discharge tube now be further increased, the current-rise curve becomes steeper and steeper until the gas in the tube *breaks down* and starts to glow. The glow is usually accompanied by a heavy current, limited principally by the external series resistance. If this resistance is small or not present at all, the current may be destructively great. Removal of the original ionizing source will have no effect in this case. The discharge continues in a *self-sustained* state, although outside agencies may have played a part in its initiation.

To explain the occurrence of gas breakdown we must search further for some other mechanism of electron production in the

system. We find this in the emission of secondary electrons from the cathode due to positive ion bombardment of this electrode. Calling the secondary emission current I_s, the electron current due to external excitation I_e, and the total electron current at the cathode I_o, then:

$$I_o = I_s + I_e \qquad (11)$$

The total electron current at the cathode is I_o. This means that the ionic current reaching the cathode must be the difference between the anode current I_a and the electron current at the cathode I_o. That is:

$$\text{Ion current} = I_a - I_o \qquad (12)$$

On the basis of statistical averages, a single ion in a gas tube will dislodge n number of electrons from the cathode. Using this symbol, Equation 12 may be re-written:

$$I_s = n \ (I_a - I_o) \qquad (13)$$

where I_s is the secondary emission current. By combining Equations 11, 10 and 13, the following expression for I_a is obtained:

$$I_a = \frac{I_e \ \varepsilon^{ad}}{1 + n - n\varepsilon^{ad}} \qquad (14)$$

From a mathematical point of view, the anode current I_a tends to increase without limit when the denominator of the fraction in Equation 14 approaches zero. This can occur when:

$$n\varepsilon^{ad} = 1 + n \qquad (15)$$

Since an infinite current is impossible, the equations imply that there will be a very great increase of current as $n\varepsilon^{ad}$ approaches $1 + n$. Thus, the transition from the non-self-maintained discharge to the self-maintained discharge occurs as the left-hand term of Equation 15 approaches $1 + n$.

Referring once again to the phototube as an example, ratings assigned to these photosensitive units by their manufacturers always include a maximum cathode-to-anode potential figure. The reason for this is now obvious. Since these units are intended to operate in the non-self-maintained discharge state, exceeding the rated potential brings the tube closer and closer to the condition in which $n\varepsilon^{ad}$ approaches $1 + n$. When the self-maintained discharge finally oc-

curs, the ionic bombardment of the cathode is sufficiently intense in most cases to irreparably damage the photosensitive surface, thus ruining the tube.

The criterion for establishing the self-maintained charge condition may be easily analyzed on a qualitative basis. Although ions are not ordinarily as effective as electrons in producing secondary emission, given enough ions and enough kinetic energy for each, a condition can be attained in which the following occurs:

1 electron liberated from the cathode by external ionization sources

produces

1 electron avalanche which then

produces

a sufficient number of ions so that at least one of them can be counted upon to

produce

one new secondary electron at the cathode.

The new secondary electron now takes the place of the original electron liberated by external sources, making the external source unnecessary to sustain the discharge. This condition occurs only when:

$$n \ (\varepsilon^{ad} - 1) = 1 \qquad\qquad (16)$$

Equation 16 is actually the equivalent of Equation 15. This makes the latter the criterion for determining the initiation of a glow discharge.

6. Arc Discharge

When the voltage applied to a circuit of which a gas tube forms a part is still further increased, there is a gradual onset of an effect called the "abnormal glow." In this condition, the current density at the cathode increases and the voltage drop across the tube rises as well. This last is the reverse of the voltage conditions which prevail during normal glow discharge, as discussed in Section 5. Although the voltage increase may be large under certain conditions, it is not at all proportional to the current; the relationship between voltage and current in the abnormal glow condition is determined by the gas pressure, the nature of the cathode material, etc.

As the current density is still further increased, there is a sudden transition to a condition known as "arc discharge." The voltage drop

decreases severely while the current begins to concentrate on one small spot on the cathode. Once this state is reached, the magnitude of the current becomes a function of the external resistance and is not influenced by the tube to any significant degree. Furthermore, the volt-ampere characteristic of an arc displays a *negative resistance*; that is, the graph of voltage-*vs*-current, in which the current is the independent variable, has a negative slope. This, of course, is contrary to the behavior of normal circuit components in which voltage drop increases with increasing current.

The high temperatures of the gases and the electrodes that follow the onset of an arc discharge suggest that some other mechanism beside positive ion bombardment of the cathode is responsible for the additional supply of electrons that constitute the greatly increased current. For this reason, arcs are usually classified in terms of the mechanism which releases the extra electrons.

A thermionic arc is one in which the cathode is heated to high temperatures by the arc discharge itself or by some external power source. The energy present, in the form of thermally excited molecules, causes the emission of electrons in large numbers. Carbon arc lamps and certain types of tungsten "sun lamps" are examples of a self-maintained discharge of the first thermionic type; mercury-vapor rectifiers and gas-filled thyratrons are typical cases where thermionic emission is obtained by heating the cathode via an externally activated filament.

A Low-Boiling-Point Cathode Arc is a discharge in which a heavy emission of electrons occurs from a low-boiling-point liquid in a very strong electric field. Large industrial mercury-pool rectifiers belong in this class.

7. A Summary of the Characteristics of Gaseous Discharge

The current through the gas of a gaseous conductor can be increased by increasing the applied emf or by reducing the external resistance. Figure 3 shows the change sequence which takes place in the characteristics of a gaseous tube as a result of current increase. (Note that Fig. 3 is a continuation of the curve shown in Fig. 2.) The logarithmic ordinate (Y) axis indicates the extremely wide range of currents encountered. Since the voltage-drops specified by the coordinates on the abscissa (X) axis are functions of the type of gas used, its pressure, the material of the cathode, and the distance

between the electrodes, these are intened only to convey the general nature of the variations. The portion of the volt-ampere characteristic included between points A and C has already been discussed in Sections 3 and 4. At point C, electron avalanches cause the criterion for self-maintained discharge to be attained and a normal glow discharge occurs from D to E. Further current-increase
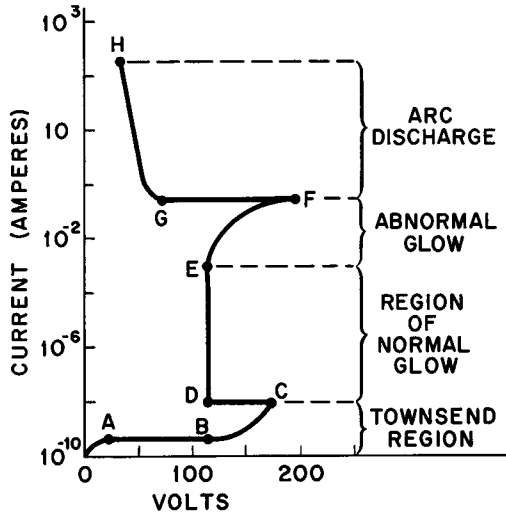
Fig. 3. Volt-ampere characteristics of a gas discharge starting with the non-self-maintaining Townsend discharge through the arc discharge.

produces the abnormal-glow region in which the voltage across the tube increases with rising current. At F, the transition to arc conditions takes place with a sudden large decrease in the voltage-drop to point G. From G to H, the characteristic assumes the negative-resistance nature mentioned previously.

8.   The Plasma

Plasma is a region within a discharge in which the number of positive ions is substantially the same as the number of electrons, yielding a zero net charge. When a free electron whose energy content has come from the applied electric field collides with a gas molecule, ionization may occur. If it does not, the collision is an *elastic* one in which the electron does not impart much of its kinetic energy to the molecule since the latter possesses a much greater mass. After a number of elastic collisions, the electron may eventually ion-

ize a gas molecule; in this case, the original electron and the freed electron share the energy in approximately equal parts.

Because of their smaller mass, the electrons tend to move out of of the plasma to a greater extent than the positive ions. Many of them move to the glass walls of the tube imparting to it a negative charge of a few volts. This negative voltage will attract positive ions while it repels other electrons forming a *sheath* with a positive charge. Sheaths may be either positive or negative depending upon the initial charge of the body around which they form. Positive sheaths form around negative bodies and, conversely, negative sheaths form in the vicinity of positively charged objects.

The two terms — plasma and sheath — frequently appear in gas-tube literature. Although they have many quantitative aspects, the simple definitions given above are adequate at this time.

Review Questions

1. Define the following terms: ion; electron; proton; potential gradient; force equation, expressed in dynes.
2. What is the velocity acquired by an electron in falling through a potential of 1200 volts?
3. What velocity would a mercury ion acquire in falling through the same difference of potential as Problem 2?
4. Differentiate between velocity and momentum as it relates to the passage of particles, such as electrons or mercury ions, in an accelerating field.
5. An electron which has acquired a velocity by falling through a 10-volt difference-of-potential is injected into an area in which the retarding potential gradient is 50 volts per cm. Calculate the distance the electron will move into this area before its direction is reversed.
6. Explain a "non-self-maintaining discharge" and give an application showing its use.
7. Explain a "self-maintaining glow discharge."
8. List qualitative criteria which permit analysis of the self-maintained charge condition.
9. What is the reason that ratings assigned to phototubes always include a maximum cathode-to-anode potential figure?
10. What is meant by the terms "plasma" and "sheath" as they relate to gas tubes?

Chapter 2

GASEOUS RECTIFIERS

9. High-vacuum Rectifiers

To study gaseous rectifiers we must first examine the principles and faults of high-vacuum rectifiers. Then we can make an intelligent evaluation of each type.

High-vacuum rectifiers make use of thermionic emission either from a directly heated cathode (filament) or from a cathode that is indirectly heated by an enclosed heater around which the cathode, in the form of a thin cylindrical sleeve, fits snugly. (See Fig. 4A and B.)

When the cathode temperature rises high enough electrons are emitted from its surface in large quantities. If there is no other electrode in the evacuated envelope, the distribution of electrons within the tube is dependent on the initial velocity and direction of the emitted electrons. The distribution of electrons within the tube is such that most will be concentrated near the cathode; some will reach the envelope wall. The negative charges deposited on the wall — as well as the electrons which swarm around the cathode— exercise a repelling force on newly emitted electrons from the cathode. These, therefore, tend to return to the cathode causing no other measurable effects.

Now, suppose that a second conducting element is placed within the same enclosure and a source of potential connected between the emitting cathode and the new electrode. The polarity of the applied voltage should be such as to make the new electrode positive with respect to the cathode; hence the new electrode becomes an anode.

In these circumstances, electrons begin to move toward the anode in large numbers. From the electrostatic-charge point of view,

we might say that the movement is explained by the attraction of unlike charges — electrons are negative and the anode is positive. This approach certainly has merit; but it breaks down in many practical situations. It is far better to visualize the conditions in a high-vacuum tube as those which arise from the establishment of an *electric field* between the anode and cathode (Fig. 5).

A nearly uniform electric field exists between two parallel flat electrodes across which a potential has been applied. Such a field
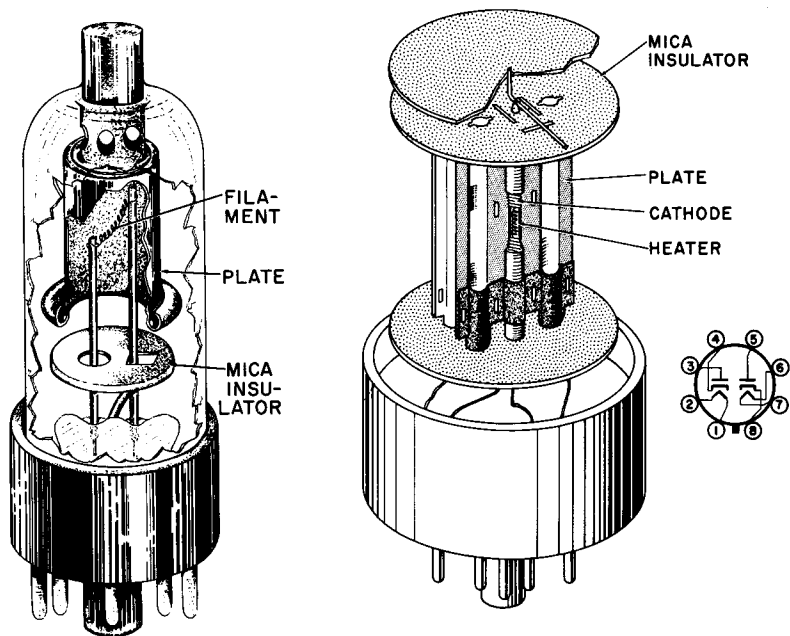
Fig. 4.   Half-wave vacuum rectifiers: (A) directly heated; (B) indirectly heated.   RCA

consists of electric lines of force which are considered to leave a positive point (i.e., a positive charge) on a positive surface at right angles. Each electric line of force must terminate at a positive charge at one end and an equal negative charge at the other.* Such an electric field establishes a voltage gradient "down" which an electron can fall (Fig. 1). Although is is convenient to consider electronic motion in vacuum or gas tubes as merely a matter of electrostatic

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*For a more extensive treatment of electric fields, refer to ELECTROSTATICS, edit. by A. Schure, John F. Rider, Publisher.

attraction, the use of the field concept yields much more fruitful results.

If the d-c source in Fig. 5 is replaced by an a-c generator, rectification occurs because thermionically emitted electrons can move toward the anode only when the field polarity is such as to permit

Fig. 5. A fundamental diode circuit.
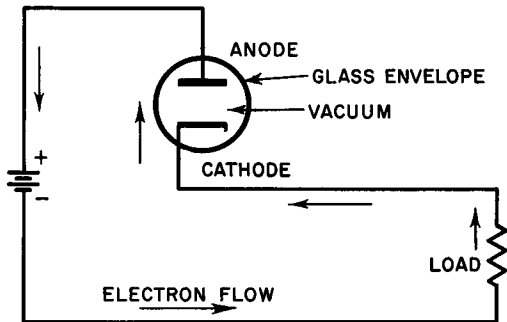
them to "fall" in that direction. Current flows in the load circuit, therefore, only during each half-cycle of the a-c input where the anode is made positive with respect to the cathode (Fig. 6).

10. Space-Charge Effects

For the moment let us adopt a fundamental point of view concerning the events that occur within a diode, in this case a two-element, thermionic high-vacuum tube. We are interested in two separate and distinct phenomena:

1. The velocity with each electron, or a statistical average electron, reaches the anode, and
2. The number of electrons that arrive at the anode each second which, in effect, is the same thing as the number of electrons that pass a given point in the load in each second.

If a potential gradient is established between the cathode and anode, *its steepness will affect only the velocity of the electrons arriving at the anode.* For temperature-limited operation, this may be illustrated by an analogy: Suppose a man standing at the top of a hill starts a series of balls rolling down the incline. If he places one ball per second at the starting point, *then one ball per second will reach the bottom of the hill, regardless of its slope.* Obviously, the

number of balls that arrive at the bottom of the incline *depends only upon the rate at which the man supplies them*. Similarly, the number of electrons that reach the anode per second is *theoretically* a function of the cathode-emission rate, not of the cathode-anode voltage gradient. Since cathode-emission rate may be shown to de-
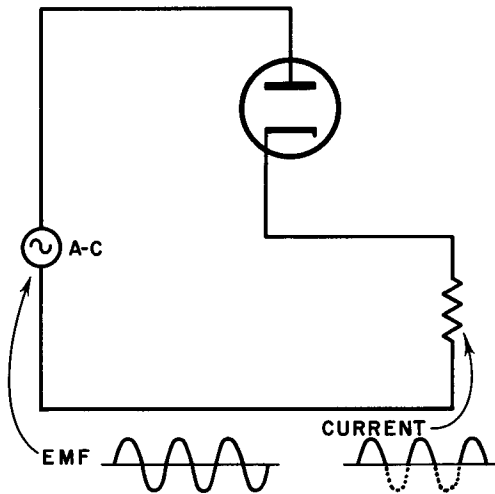

Fig. 6. Rectification by a high-vacuum diode.

pend upon cathode temperature and the number of electrons per second that arrive at the anode may be considered the *anode or plate current*, then the following fundamental conclusions may be drawn:

1. If no other effects exist, anode current is a function of cathode temperature and

2. Anode current is independent of cathode-anode voltage.

Since experiment does not fully bear out these conclusions we know that *another factor does exist*. This is *space charge*.

At high plate voltages (*i.e.*, steep-potential gradient between the cathode and plate), the plate current is largely independent of the difference of potential between the two elements (Fig. 7). When the operating temperature t_k of the cathode is comparatively low, the plate voltage loses its ability to affect the plate current at a rather low voltage (point A). In the particular case shown, even a relatively low anode voltage is capable of drawing the electrons away from the cathodes as fast as they are emitted. As the cathode

temperature rises and increasing numbers of electrons are emitted from its surface, the plate voltage must also be raised if the anode is to continue to attract all the available electrons (*e.g.*, point B in Fig. 7). Why should the three linear segments of the curve merge into one line long before reaching zero anode voltage? When the voltage is low enough — below point A — the same current flows regardless of the cathode temperature, the current magnitude being determined only by the plate voltage. On the other hand, when the plate voltage is increased to a high enough value (point B), it no longer has any appreciable effect on the plate current which, in this case, is a function only of the cathode temperature. Why should this be?

The explanation lies in the effect contributed by the electrons in mid-flight between the cathode and plate. Before the appearance of these particles in the intervening space, the electric field produced
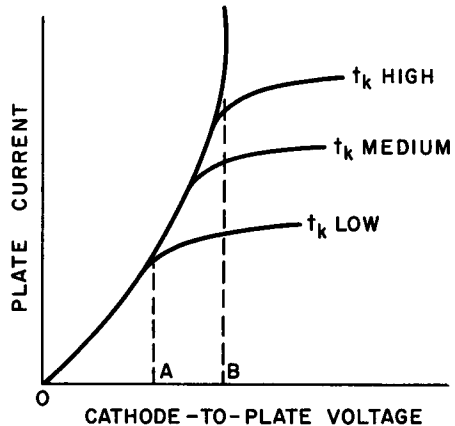
Fig. 7. Curves showing the variation of diode plate current with variations of plate voltage and cathode temperature for a thoriated tungsten filament.

by the plate voltage consisted of lines of force which terminated at positive charges on the anode and negative charges on the cathode. Now the lines can terminate on the moving electrons themselves (Fig. 8). The formerly uniform linear electric field is now considerably modified. The moving cloud of electrons now form a negative "body" which terminates the lines of force; the cloud is termed the *space charge*. From the implications of the figure, it can be seen that the electric field around the cathode is now very close to zero so that many of the emitted electrons fall back into the cathode. Thus, that part of the plate current emitted from the cahode which

reaches the plate (plate current) is reduced by the space charge. The space charge acts as a second negative electrode or virtual cathode in the tube near the cathode. Each time one electron arrives at the plate, the negative terminus of the particular line of force which took it there disappears so that the line now becomes available again to find a new terminus. This permits another electron
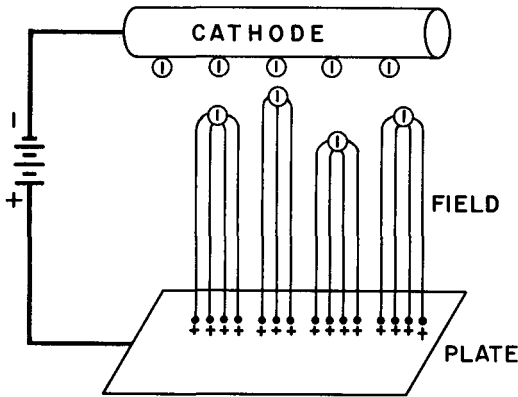

Fig. 8. Electrons in motion modify the field between the cathode and plate.

to enter the space-charge area from the cathode, thereby establishing an equilibrium condition whose characteristic depends upon the magnitude of the applied plate voltage. This accounts satisfactorily for the common portion of the curve in Fig. 7 in which cathode temperature (t_k) has no apparent effect and in which plate voltage has complete control of the plate current. It is often said that the cathode does not directly supply the plate with electrons; that is, the cathode supplies electrons to the space-charge region, which in turn provides electrons for absorption by the plate circuit. Although this may be a play on words, it correctly brings the concept of the electric field into the space-charge picture.

11. Two Kinds of Saturation

The ideas discussed in the preceding paragraph can be summarized and differentiated in the following manner:

Temperature Saturation. If all of the electrons being emitted by the cathode of a diode at a given temperature are drawn to the plate, then no further increase of potential gradient can make any difference in the plate current. This is called *temperature saturation.*

Space-charge saturation. If the cathode is emitting more elec-
trons than can be accounted for in the form of plate current, an
increase of plate voltage will produce a rise in plate current. There-
fore, the limiting factor at the lower plate voltage is the space
charge, and the tube is said to be operating at *space-charge satura-
tion* at the voltage predicated for the initial condition.

12. Voltage Drop Across High-Vacuum Rectifiers

Consider the circuit shown in Fig. 9. If there were no such
phenomenon as space charge, very little work would have to be
expended to accelerate the electrons from the cathode to the plate
due to the tiny mass of the electrons. This almost infinitesimal

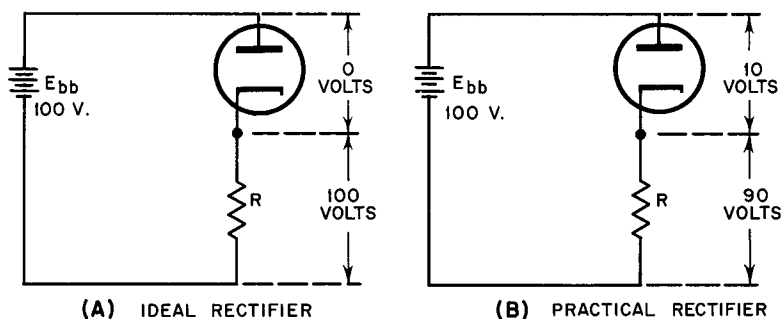(A) IDEAL RECTIFIER   (B) PRACTICAL RECTIFIER

Fig. 9. An ideal rectifier (A) passes current in one direction without the need for
cathode-to-anode voltage; a practical rectifier (B) always shows a voltage drop
across its terminals.

quantity of work could be accomplished by a similarly infinitesimal
potential difference between the two tube elements. Thus, in an
ideal rectifier, the actual voltage drop across the tube would be so
small as to be negligible in comparison to an applied voltage of 100
volts, for example. In this case, the entire voltage drop of the source
E_{bb} would appear across the load resistor R and none at all across
the tube.

In the presence of a space charge, however, a substantially
greater amount of voltage would be required to accomplish electron
transit because of the repelling effect of the space-charge cloud as
explained in the previous section. Furthermore, as the plate current
increases, the number of electrons in the cloud increases, and the

voltage requirement rises accordingly. In a diode circuit (Fig. 9B) it is clear that the voltage across the diode terminals multiplied by the current passing through the tube *measures the power loss within the tube itself;* this loss manifests itself in the form of heat energy lost to the circuit.

This is one of the chief disadvantages of high-vacuum rectifiers; it is a disadvantage which has limited their use to relatively low-current circuits such as one finds in radio and television receivers. High-vacuum rectifiers are not suitable for industrial applications in which hundreds of amperes of rectified current are needed for the operation of heavy machinery.

13.   Introducing Gas into the Tube

Consider a heated cathode and an anode in a glass envelope from which most of the air has been removed. A small amount of gas at low pressure is admitted. Also assume that the distance between the cathode and plate is great enough so that the mean free path of each emitted electron is quite long. (The mean free path is generally taken to mean the average distance an electron travels between collisions.) As the length of an individual electron's path increases, the probability of collision increases for conditions corresponding to a particular *mean* free path. Thus, as the length of an individual path increases, the chance for ionization to occur becomes greater. Assuming that the mean electron path and the applied voltage are both great enough, a large number of gas molecules will become ionized. Although the reasoning which follows applies equally to all types of ionization, for the sake of clarity it is better to assume that all the gas molecules that are struck by high speed electrons are *singly ionized*; that is, that one electron is liberated from each gas molecule after each collision. This leaves one singly charged positive ion adjacent to one freed electron at the instant of impact. The presence of additional electrons in the interelectrode space is not at all advantageous because these merely add to the space charge already there. The existence of ions in this space, however, presents a different aspect: these could help to neutralize the space charge and in so doing could reduce the power losses discussed in the previous section.

At the moment when the electron separates from the ion, both particles find themselves in a field of the same intensity. Also, both

particles possess the same magnitude of electric charge (of opposite sign) and are therefore subject to the same accelerating force. Problem 2 (Section 2) showed that the velocity acquired by a mercury ion in a given electric field is roughly .0016 times the velocity that an electron would gain in the same field. If the gas is mercury, then, the positive ions would *move slowly*, comparatively speaking, toward the cathode while the electrons from the same ionization event *race* at high speed in the direction of the anode. Thus, long after the newly born electrons have reached the anode, the positive ions are still drifting through the interelectrode space. Now, consider that there are billions of such ions present in the vicinity of the space charge at any given time: thus it becomes evident that their joint effect can properly neutralize the space to a degree where the electrical state of the interelectrode space may be considered a *plasma* (Section 8).

This radically alters the characteristics of the tube as compared with that of a high-vacuum type. The differences are summarized in Section 14.

14. The Effect of Gas in a Thermionic Tube

In a vacuum diode, there is a substantially uniform distribution of electric field between the anode and the space charge region, with a virtually zero field at the cathode. With the introduction of a gas such as mercury-vapor, however, the potential distribution changes completely: the field at the cathode is quite high while that in the plasma is nearly zero. Any voltage drop which does occur in the gas tube takes place near the cathode rather than in the plasma.

Since space charge effects have been nullified, the tube drop is much smaller than that of the vacuum type. More important even than the absolute magnitude of the drop is the fact that the *potential across the tube remains essentially constant over a wide range of plate currents*. In a mercury-vapor tube this drop is from 10 to 15 volts. This means that rectifier power supplies utilizing mercury-vapor tubes can be expected to provide appreciably better *voltage regulation* under varying load conditions, a very important consideration in practice. There is a straightforward explanation for this constancy: increased current results in a larger number of ions. Thus, as the space charge tends to build up with increased electron emission from the cathode, it continues to be cancelled by the greater number

of positive ions formed by more frequent collisions. As one might expect, gas rectifiers exhibit a negative resistance characteristic in which the internal tube resistance is roughly proportional to the inverse of the current through the tube. Under these conditions, the anode-to-cathode voltage-drop does not change (within limits).

The maximum current obtainable in a gas-filled rectifier is the saturation thermionic emission current from the cathode plus an appreciable increment due to the high-intensity electric field at this electrode. If more current is passed through the tube than the cathode can safely deliver, the voltage drop begins to rise. When it exceeds 22 volts (or thereabouts), the cathode begins to undergo extremely heavy ionic bombardment and may begin to disintegrate. (This effect is called cathode *sputtering* and the voltage at which it begins to occur is known as the *disintegration* voltage.)

Heater and plate voltages may be applied simultaneously to a high-vacuum rectifier without deleterious effects. If this procedure is followed with a gas rectifier, the cathode may be permanently damaged. This effect is explained thus: For the first few seconds after both voltages are applied, the temperature of the cathode is much too low to supply electrons by thermionic emission. On the other hand, the anode potential produces a relatively uniform field which is just as strong at the cathode as anywhere else in the enclosure. This condition encourages a self-maintained discharge with is accompanying intense bombardment of the cathode by positive ions of large mass. Since mercury-vapor rectifiers use *oxide-coated cathodes* — these are usually nickel sleeves coated with barium and strontium oxides in the proper proportion to yield a plentiful supply of electrons at low temperature — such cathode sputtering will cause the oxide to flake off causing permanent injury to the cathode structure.

15. Mercury-vapor Rectifier Ratings

Current Ratings. All types of gas-rectifier tubes are rated in terms of *average* current. This is the maximum continuous current which the tube can handle without overheating, the average to be taken over a given period of time as recommended by the manufacturer. For example, a small mercury-vapor rectifier such as the FG-190 is rated at an average current of 1.25 amperes continuously. A second important current rating is the permissible *peak current*

which is defined as the maximum current that should be permitted through the tube in each conducting cycle; for the FG-190, the peak current rating is 5.0 amperes. Some tube types are also rated for maximum *surge current* which is the peak current for a very definitely specified period of time. Thus, the surge current rating of an FG-190 is 20 amperes *for 0.1 second.* It is important to remember that operation at or near the surge current rating — for even a short time — may seriously reduce tube life.

Voltage Ratings. During the portion of the a-c input cycle when the rectifier is not conducting, the anode is negative with respect to the cathode and operates like a non-thermionic type of discharge tube. *Maximum inverse peak voltage* is the highest voltage the tube will stand in an inverse direction without the possibility of flashback. The maximum peak inverse voltage rating of an 866-A mercury-vapor rectifier — a very popular type for low power applications — is approximately 10,000 volts. The complete set of ratings for this tube follows:

RATINGS — MERCURY-VAPOR RECTIFIER 866-A

Average current .... 0.25 ampere
Peak current .... 1.0 ampere (per cycle)
Surge current .... 9.0 ampere for 0.1 second
Maximum Inverse Peak Voltage ...... 10,000 volts (approx.)

Aside from those factors we would expect to influence the maximum inverse peak voltage rating of a gas tube (type of gas, gas pressure, tube geometry, etc.) , three other important influences must be taken into account. (1) The frequency of the applied voltage. At high frequencies, the likelihood of flash-back is increased since the gas may not have time to de-ionize completely before the next half-cycle arrives, (2) The current flowing in the tube. Heavier currents encourage earlier flashback since such currents produce large numbers of ions, some of which may still be present when the inverse portion of the cycle is applied, (3) Condensed mercury temperature. There is always a small pool of liquid mercury in a mercury-vapor rectifier; this pool is the source of the vapor itself. As the liquid heats, the gas pressure is increased and the maximum inverse peak voltage the tube can stand diminishes. In the case of the 866A, for instance, the maximum inverse peak voltage rating is 10,000 volts or better when the temperature of the condensed mercury is below 50° C. Should the temperature of the condensed mer-

cury rise to 80° C due to a change in ambient conditions, the maximum inverse peak voltage drops to approximately 5500 volts.

16. Filters for Mercury-vapor Rectifiers

The output voltage of a rectifier is pulsating d-c having a large a-c component. Filter networks consisting of capacitors and iron-core inductors (chokes) are most frequently used to minimize this
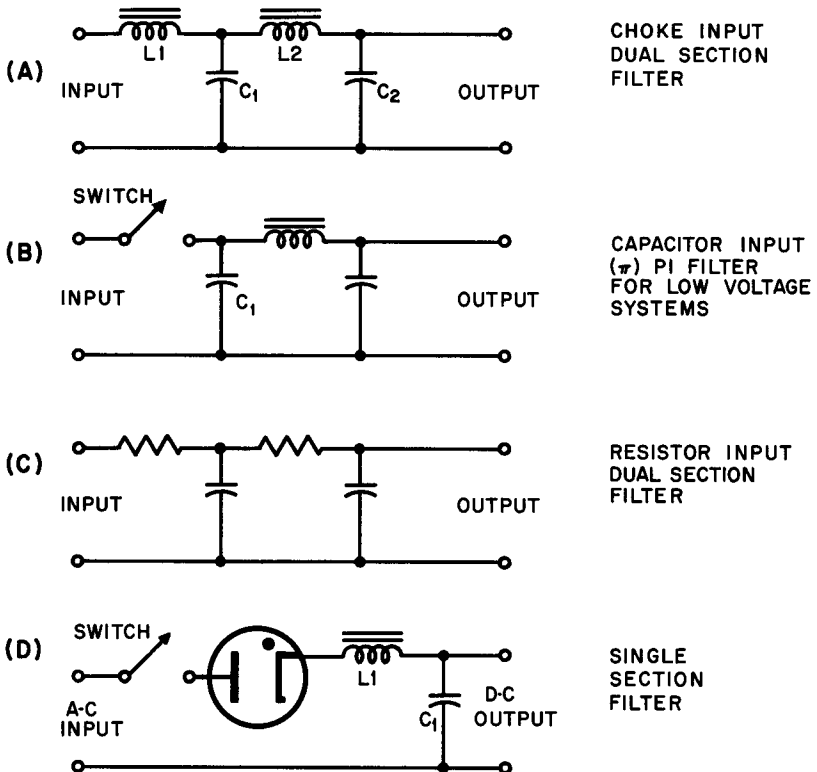

Fig. 10. Types of filter networks.

component, although resistors are sometimes used in conjunction with or to replace the chokes. Several representative filter systems are shown in Fig. 10.

The network of Fig. 10A is known as a *series-inductance input* or choke input arrangement and is the type generally recommended

for use with gas rectifiers. C_1 is in an uncharged condition before power is applied (Fig. 10D). At the instant that the switch is closed, a charging current flows into C_1 through the rectifier. Series-inductance L_1 limits the magnitude of this surge current to a safe value for the particular rectifier in use by virtue of the L-C time constant of these components.

In a straightforward capacitance-input filter such as that of Fig. 10B, the only resistance between the rectifier and C_1 aside from the connecting wires is that of the rectifier tube. Consequently, upon closure of the switch, the surge current may well exceed the safe rating of the tube by several hundred percent. The filter network shown in Fig. 10C illustrates the arrangement in which resistors replace chokes. Although this system may be designed for use with gas rectifiers, it has other disadvantages: the resistors must be rated at sufficient power dissipation for the load, and the voltage drop across the resistive filter components may become excessive even with reasonable loads, thereby nullifying the principal advantage of the mercury-vapor tube — low voltage drop.

Review Questions

1. Explain the process of rectification in high-vacuum rectifiers.
2. What is space charge? How does it affect anode current? What other factors affect anode current?
3. List and explain two types of saturation.
4. Explain the power loss within a high-vacuum rectifier and show why this constitutes a major disadvantage of this type of tube.
5. Explain the ionization process that takes place when gas is introduced into the tube.
6. What is the effect of gas in a thermionic tube tube with respect to the size of the voltage drop across the tube? Why is this so?
7. What are "cathode sputtering" and "disintegration voltage"?
8. Heater and plate voltages applied simultaneously to a gas rectifier tube may permanently damage the cathode. Why?
9. Typical mercury-vapor rectifier ratings might include: average current; peak current; surge current; maximum inverse peak voltage. What is meant by each?
10. Draw a typical filter used with mercury-vapor rectifiers.

Chapter 3

GAS TUBE VOLTAGE REGULATORS

17. Principles of Gas Tube Voltage Regulators

Referring back to Fig. 3, we see that a gaseous discharge in the normal-glow region possesses *constant-voltage characteristics*. The voltage drop across the conducting gas in the region from point D to point E does not vary materially even though the current changes over a wide range of values. Thus, as long as a cold cathode tube is working under the conditions which provide a normal glow, it will be found that the voltage across it will increase very little with a rise of current. Advantage may be taken of this characteristic by incorporating the gas two-element tube in a circuit which has the ability to hold the output d-c voltage constant under conditions of changing line voltage and changing load.

A fundamental regulator circuit using a cold-cathode diode is shown in Fig. 11. The 0C3 (VR-105/30) has been chosen as the regulator tube. The characteristics of this tube as given by the manufacturer are listed in the table below.

(1) D-c anode supply voltage (minimum) .... 133 volts
(2) Continuous d-c operating current .... 40 ma (max)
(3) Ambient temperature range .... −55° to +90° C
(4) D-c starting voltage .... 115 volts (approx.)
(5) D-c voltage drop across terminals (normal) .... 118 volts
(6) Regulation tolerance 5-40 ma) ....
        average change in anode-cathode voltage 2 v (+ or −)
        maximum change 4 v

To learn about the operation of the VR tube, examine these characteristics closely:

(1) The 0C3 (Fig. 12) will not break down into a self-maintained normal glow discharge until the voltage applied between its terminals is as least 115 volts (A to K). This 115 volts is an average value — some tubes may break down at a lower value. This applied

Fig. 11. A fundamental voltage-regulator circuit using a single gas tube.

E_i
(D-C INPUT FROM RECTIFIER)

+   R   0C3

A

K

REGULATED E_O
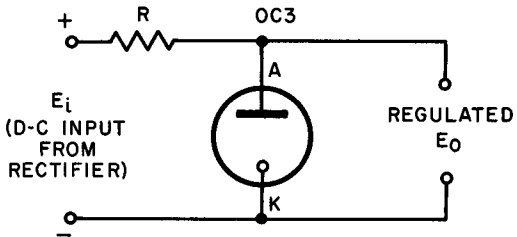
potential is generally known as the *starting voltage*. It is a function of the element spacing, element dimensions, gas material and gas pressure. Starting voltage is also a function of the ambient light level. The required breakdown must be larger when the tube is operated in darkness than in light. These tubes have, as an anode, a thin central post which lies along the axis of an encircling cylinder about $7/8$ inch in diameter. The outer cylinder serves as the cathode. The circuit arrangement must be such that the initial voltage across both the resistor R and the VR tube is at least 133 volts to start the action. This voltage is necessary to insure breakdown throughout life. The average value required for new tubes is 115 volts.

(2) The cathode and anode dimensions of this particular voltage regulator permit a current of approximately 40 ma to flow without excessive heating; hence, the tube can dissipate approximately 4-2 watts maximum. In normal use, a maximum current of 30 ma is usually recommended.

(3) The wide ambient temperature range shown implies that good voltage regulation does not depend to any great extent upon external temperature conditions.

(4) The d-c starting voltage is the potential required between the anode and cathode to start the normal-glow discharge.

(5) Once the normal-glow discharge begins, the potential across the tube terminals drops to approximately 105 volts; this voltage

is maintained throughout the normal-glow region over a wide range
of currents (from 5 ma to 40 ma) .

18.   Circuit Action

Variation of Line Voltage. Assume that the line voltage which
feeds the rectifier-filter system tends to rise in value. As it does so,
the d-c input voltage (E_1, Fig. 11) increases causing an increased
current in the series circuit consisting of R and the VR tube. In-
creased ionization in the gas tube results in a lower internal resist-
ance which, in turn, maintains the voltage across the tube at very

MICA
INSULATOR

CATHODE

PLATE

JUMPER
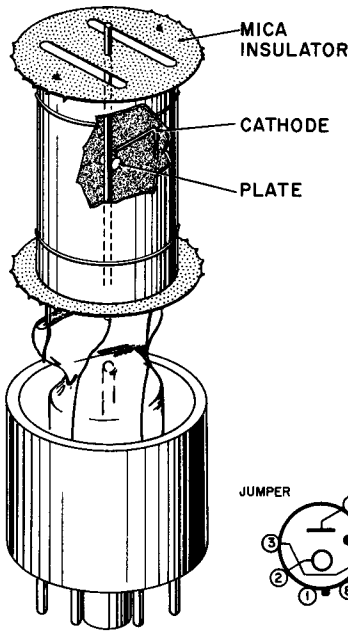
Fig. 12.   Essential elements of a VR tube
(0C3). RCA

close to the original value. The increased line voltage is absorbed
in the form of a greater voltage drop across R (due to the increased
series current) . A fall of line potential has the opposite effect, re-
sulting in a smaller drop across R, but the same voltage across the
VR tube. The amount of change the line voltage may undergo is
limited by the 5-40 ma rating of the tube; if the voltage is permitted
to rise too high, the tube will overheat and eventually destroy it-

self. Too low an applied voltage will cause the glow to extinguish so that the VR tube will then "look" like a virtually open circuit to the power supply and load. Under these conditions, there is no voltage regulation at all since the same situation may be simulated by removing the VR tube altogether. It is likewise possible that too low an applied voltage may also cause the current to drop below 5 ma without extinguishing the glow entirely. This causes erratic fluctuations in the output voltage.

Variation of Load. Consider a load whose resistance is such as to permit a current of 20 ma to flow through the VR tube. If the load resistance should now diminish, a greater current will flow through R causing a larger voltage drop to appear across it. Without the VR tube in the circuit, this would result in a proportionately smaller voltage across the load resistance, i.e. poor regulation. In this case, however, the increased voltage drop across the resistor leaves less voltage for the VR tube, thereby reducing the tube current. The resulting decrease in ionization increases the tube's resistance so that the same voltage drop appears across it (105 volts in this case). Thus, the load is still connected across 105 volts and the regulation is improved.

19. Design of a Voltage Regulator Circuit

Full appreciation of the action of a VR tube is best obtained by working through an illustrative example in the design of a VR circuit like that shown in Fig. 13.

Suppose that the figures given are these:

(E_i) Power supply variation: 250 v to 300 v
(I_L) Load current variation: 10 ma to 30 ma
VR Tube: E_o = 150 volts regulated
        I_{vr} = 30 ma max, 5 ma min.
        E_{min} = 165 volts (starting voltage)

The problem is to determine the optimum value for the series resistor R.

Step 1. Determine the resistance R when the input voltage E_1 is largest and the load current is smallest (I_L). It is at this time that the VR tube would take the maximum allowable current. The current through R is the sum of I_{vr} and I_L, or 30 ma plus 10 ma = 40 ma. At the same time, the input voltage E_1 is 300 volts while

the voltage drop across the VR tube must be 150 volts. Thus, the voltage drop across R = 300 − 150 = 150 volts.

From these values, R = 150/.04 = 3,750 ohms

Step 2. Check to make certain that the VR tube current is not less than 5 ma when E_i is minimum (250 volts) and load current is maximum (20 ma). With E_i equal to 250 volts, the voltage drop across R = 250 − 150 = 100 volts. Then the current through both the VR tube and the load is 100/3750 = .027 amperes. With the load current given as 20 ma, the current left for the tube is .027 − .020 = .007 = 7 ma. This exceeds the minimum rating of 5 ma and is therefore acceptable.

Step 3. Check to determine whether or not starting voltage is obtained under the most adverse conditions: supply voltage E_i at a minimum (250 volts) and load current at a maximum (20 ma).
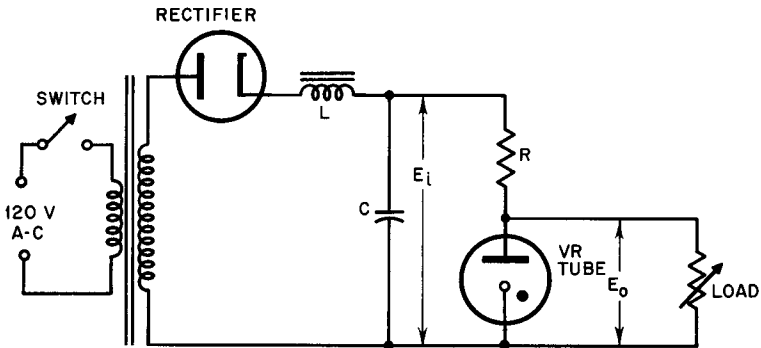
Fig. 13.   VR tube design circuit.

With the supply voltage equal to 250 volts, the voltage across the resistor (with the VR tube in the nonconducting state) is E_r = .02 × 3,750 = 75 volts. This leaves 250 − 75 = 175 volts as the potential applied across the VR tube for starting purposes. Since this is in excess of the rated starting voltage of 165 volts, no trouble should be experienced when the circuit is first turned on.

Commercially available VR tubes may be used singly to provide output voltages of 75, 90, 105, and 150 volts. (0A3, 0B3, 0C3, and 0D3 respectively). When regulated voltages in excess of these values are needed, two or three of the commercially available types may be connected in series in any combination, since all of the ones listed

above have the same current ratings. Other commonly used tubes are the 7-pin miniature types 0A2 and 0B2. These have nominal output voltages of 150 volts and 105 volts respectively. Figure 14 illustrates a complete practical power supply using full wave rectification which provides three regulated voltages: 330 volts, 180 volts; and 75 volts. Such a power supply might be found in a high-quality public address system (audio amplifier) in which the 330-volt tap
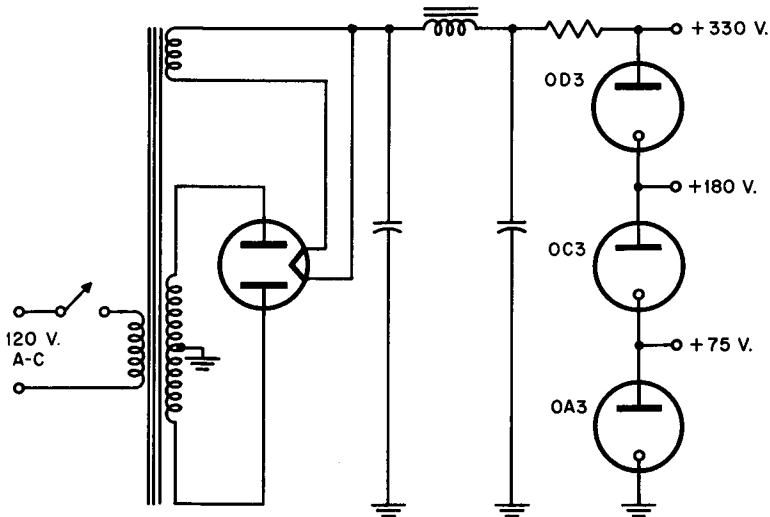

Fig. 14. Practical power supply providing three regulated voltages.

is used to supply plate voltage for the audio power output tubes, the 180-volt tap for screen voltage for the same tubes and plate voltage for the voltage amplifiers which precede the output stage, and the 75 volts for screen potential for the high-gain preamplifier stage or stages.

20. Electronic Voltage Regulation

The design of many types of electronic equipment calls for power supplies in which the voltage output must be very precisely regulated. An additional requirement often encountered is that of variable voltage control as well.

Figure 15 shows a circuit in which the d-c amplifier properties of a triode vacuum tube (used in conjunction with a gas regulator tube as a source of reference voltage) are used to govern the grid voltage of a control tube. The triode (V2) is adjusted to operate as a class-A amplifier while a second triode V1 acts as a variable resistance. V1 is inserted in the circuit in series with the d-c output connection from the power supply proper. The class-A amplifier
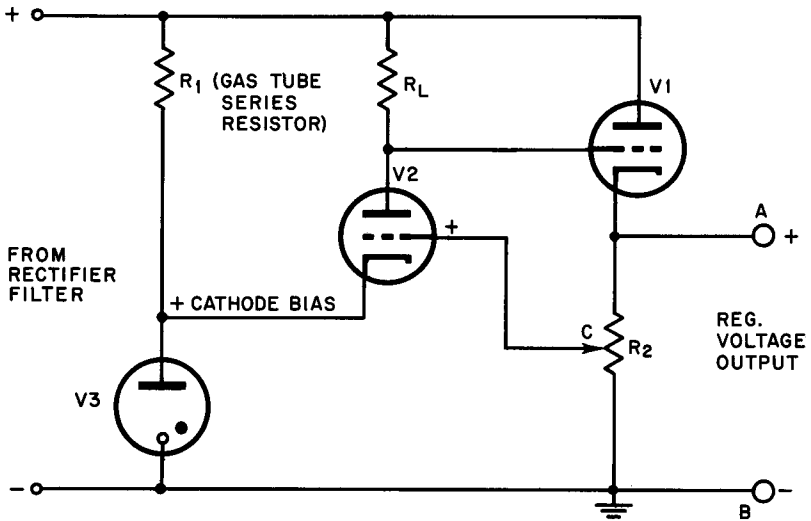

Fig. 15.   An electronic voltage regulator circuit.

is connected in such a manner that an adjustable fraction of the output is applied to its grid so that any voltage variations present in the d-c output cause the amplifier to change the grid voltage of the series control tube V1. The operation of the system is best understood by following a sequence of voltage variation, feedback, and correction.

Assume that d-c voltage output between terminals A and B changes in an upward direction as a result of line variation, load variation, or even residual ripple that has not been removed by the filter network. Point C must then become more *positive* with respect to ground. The plate current of V2 must increase due to the positive bias. The increased voltage drop across R_L reduces the plate voltage of V2 and hence the *positive* grid voltage of V1 with respect to ground. Since the grid of V1 is now less positive than it was before,

its internal resistance increases thereby producing a smaller voltage output across A and B. Note that the phasing is such that the original tendency to change has been counteracted by the voltage-drop variation across V1.

No mention has yet been made of a very essential part of the arrangement: the voltage regulator tube V3. If V2 is to operate in
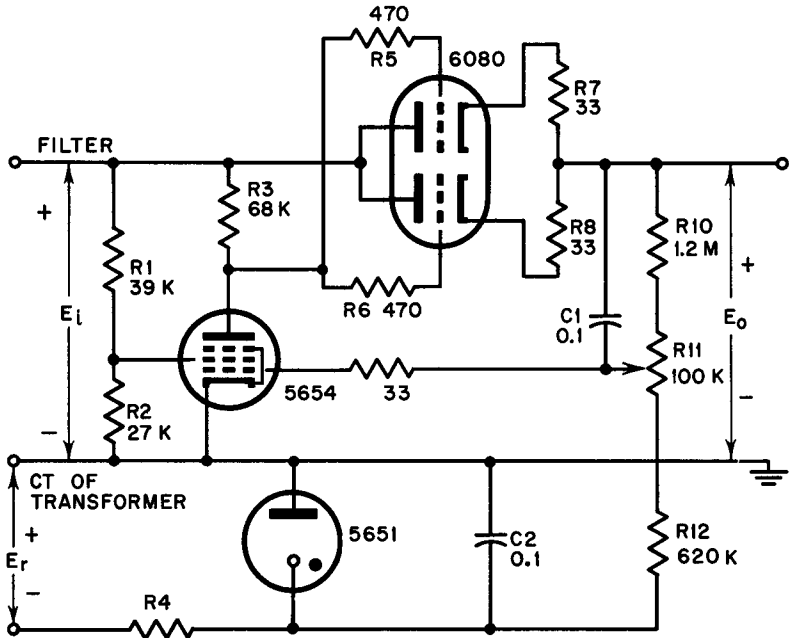
$E_o = 150$ V
$E_i = 200$ V MIN.
$E_r = 150$ V MIN.

NOTE:
SELECT R4 TO AVAILABLE E_r SO AS TO DRAW 2.5 MA THROUGH 5651
SELECT ALL RESISTORS FOR TEMPERATURE STABILITY.

Fig. 16.   A practical voltage-regulated power supply.

class-A with a large positive voltage on its grid (from point C), the cathode of the tube must be positive to an even greater extent so that the grid is negative with respect to the cathode. Furthermore, the cathode potential must be held to a constant value — at least within a few percent — if V2 plate-current changes induced by variations in output voltage are not to change the cathode potential as well. If this were to occur, V2 would shift its operating point with

each small change and be far less effective as a control element. For this reason, the voltage drop across V3 is called the *reference potential*; it is the only potential in the circuit that does not change with line or load variations.

The setting of potentiometer R2 determines the net output d-c voltage of the system. As its wiper is moved farther downward (toward common ground), the grid of V2 becomes increasingly negative with respect to its "constant" cathode voltage and its plate current diminishes, causing the voltage at the grid of V1 to increase in a positive direction. The consequent reduction in the plate resistance of V1 permits a greater voltage to appear across A and B. Similarly, when the wiper is moved toward higher positive voltages, the voltage drop across R_L increases making the grid of V1 more negative. This results in increased series resistance and the output voltage goes down.

A voltage regulating system such as the one just described is also effective in reducing output ripple to about the same extent as it reduces variations in line voltage. Variations in input voltage to the regulator from the rectifier filter are handled in the same manner as a change of line voltage. The values of the components R_1, R_L, R_2, etc. are shown on the basis of the requirements of the particular tubes and voltages used. In practice, a pentode is generally employed as V2 to take advantage of its large transconductance; this necessitates additional small parts for adjusting the screen and plate voltages to the proper relative values. Figure 16 illustrates a practical voltage-regulated power supply using modern vacuum tubes.

Review Questions

1. What is the starting voltage for the 0C3 tube?
2. The maximum allowable voltage range of a 0C3 regulator tube should not be more than _____ volts.
3. What is the maximum current range of the 0C3 voltage regulator tube?
4. Check a tube manual to determine typical allowable current ranges for a number of octal voltage regulator tubes; for miniature tubes; for the 5651.
5. What is the maximum recommended current through a VR 0D3 tube?
6. A power supply delivers 350-400 volts. A load connected to this supply needs 150 volts at 30 ma. A series dropping resistor and a VR 150 are used to supply this circuit. Find:
     a) a value usable as a series resistor allowing a maximum of 30 ma through the VR tube;
     b) the minimum current through the VR tube.

7. A load needs 225 volts regulated. What tubes would you use and how could you connect them?
8. How does V1 act in the circuit of Fig. 15?
9. What is the purpose of the VR tube (V3) in Fig. 15?
10. How can we observe if a VR tube is operative?

Chapter 4

THYRATRONS

21. Construction of a Triode Thyratron

When a control grid is inserted in a thermionic gas diode, the properties of the resulting triode are completely different from those of a vacuum triode. Gas tubes containing a heated cathode, one or two *grids,* and a plate are known as *thyratrons;* many small modern thyratrons are equipped with a *shield grid* inserted for the purpose of reducing control grid current. These will be discussed later. The construction of a typical triode thyratron is shown in Fig. 17A.

The grid is usually a hollow cylinder that envelopes both the anode and the cathode with a baffle containing small holes placed between the two elements. The baffle almost completely shields the anode from the cathode so that a small grid voltage may completely neutralize the large potential, thus preventing the initiation of the arc at voltages where it would normally begin.

22. Fundamental Action of a Thyratron in a D-c Circuit

How a thyratron differs from a vacuum triode is easily demonstrated by considering Fig. 17. If T were a vacuum triode, moving the wiper from the minus side toward the plus side of the bias supply would cause a relatively smooth increase in plate current as indicated by the reading of the milliammeter in the plate current. Likewise, the opposite movement of the wiper would have the opposite effect — a smooth plate current decrement.

Fig. 17. 884 triode thyratron: (A) cutaway view (RCA); (B) circuit to illustrate thyratron action; (C) plate current-grid voltage curve of a vacuum triode; (D) plate current-grid voltage curve of a thyratron.

When the vacuum tube is replaced by a thyratron, the following sequence is obtained:

(a) With the wiper fully minus, the plate milliammeter reads zero.

(b) As it is advanced toward the positive side of the battery, the plate current does not rise until the grid voltage has reached a certain critical value.

(c) When the critical value of grid voltage is attained, the plate current suddenly *rises upward* to its maximum value under the conditions imposed by the voltage of the B supply and the value of R_2.

(d) Further movement of the wiper of R_1 has absolutely no effect upon the plate current as read by the milliammeter.

(e) As the setting of R_1 is changed back toward the minus side, the plate current continues to flow at its maximum value even though the wiper is moved to the full negative position. The voltage on the grid no longer influences the reading of the milliammeter.

It is important to note at this time that a *thyratron must never be operated without a plate load*. Although this is permissible in a vacuum tube circuit — one, for instance, in which the static characteristics of the tube are being measured — the absence of a plate load is almost certain to damage the thyratron irreparably if it is
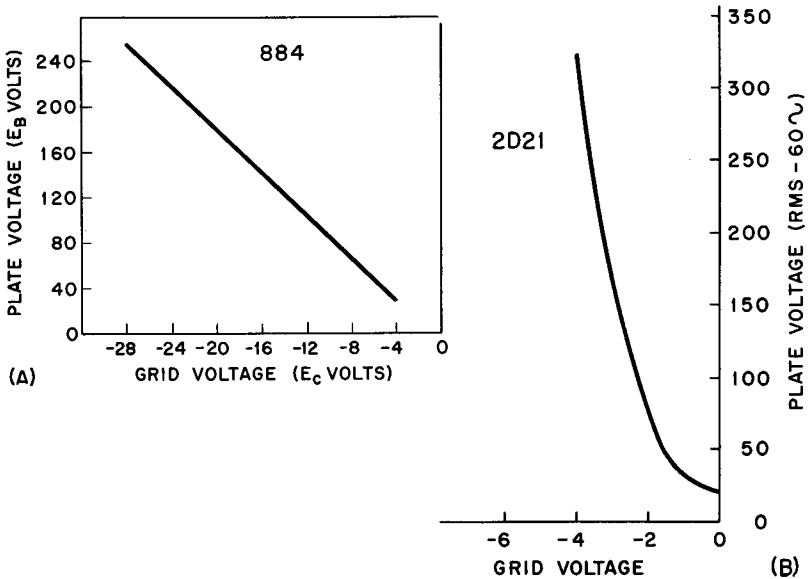
Fig. 18.   (A) Critical grid curve for RCA 884 thyratron triode (argon-filled); (B) Critical grid voltage *vs* anode voltage curve for average 2D21 with 2-megohm grid resistor.

allowed to undergo the sequence described above. At the instant when the discharge in the thyratron is initiated (point A in Fig. 17D), the resistance of the tube drops to a very low figure. Without a series limiting resistor, plate current is excessive and the resulting heavy ionization will cause damaging cathode sputtering.

Once the arc has been started, the grid completely loses control over plate current. After arc initiation, the grid is immersed in a plasma and is separated from it by a positive ion sheath so that varying the grid potential merely serves to change the thickness of the sheath rather than the field gradient. The simplest way to extinguish the arc at this point is to remove the anode potential or reduce it to a figure below the value needed to maintain the arc. When a thyratron suddenly begins to conduct it is said to *fire*. The term

extinguish refers to the transition from the fired state to the state in which complete deionization occurs.

23. The Critical Grid Curve

The bias voltage at which a given thyratron fires differs for different anode potentials. From a qualitative point of view,* it is apparent that a higher plate voltage tends to make the tube fire even though the grid may be appreciably negative. As the anode potential is lowered, firing may be prevented by smaller and smaller negative grid voltages. The value of the series limiting resistor (R_2 in Fig. 17B) has no effect on the firing potential since, before the arc begins, there is no current flowing in the resistor and hence no voltage drop. Thus, the anode potential before firing is equal to the source voltage.

Complete firing characteristics of any thyratron may be established in the form of a curve called the *critical grid curve* (Fig. 18A). This particular tube is argon-filled and contains a constant number of gas molecules; its critical characteristic curve is very close to a straight line over its rated range. For example, to determine the anode firing potential required for a grid voltage of −20 volts, merely find the intersection between the −20 ordinate line and the curve and read the required plate voltage as 142 volts. The graph is used in a similar manner to ascertain the grid potential needed to prevent the thyratron from firing at a given anode voltage.

Often, more curvature is encountered than is reflected in the graph of Fig. 18A. The curves of the 2D21 (Fig. 18B) show a more typical picture. The critical grid voltage curve is a function of the series grid resistor.

Mercury-vapor thyratrons which are quite prevalent in high-current industrial applications display a family of critical grid characteristics since the condensed mercury temperature now enters as a third parameter. A typical set of curves for a mercury vapor thyratron are given in Fig. 19. The curves clearly indicate that lower condensed mercury temperatures require less negative grid voltage to prevent firing. As the mercury temperature rises, the gas pressure increases; this sets up a situation in which the tube finds it easier to fire with given grid voltages, hence larger and larger grid voltages are necessary to prevent initiation of the arc.

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*Some thyratrons require a positive grid voltage to fire.

24.   Quantity Grid Control of Thyratron Trigger

The excellent conductivity of an ignited thyratron immediately suggests the use of this tube as a switch in a d-c circuit. In proper operation, the grid current is very small, a condition that requires very little switching power. In this manner, a very light switch may
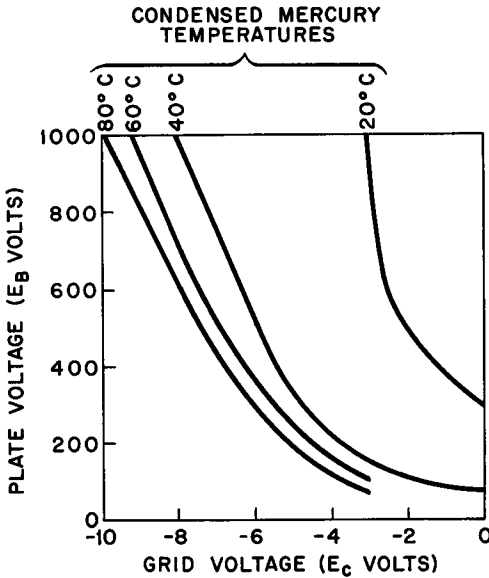

Fig. 19. Control character-
istics (critical grid curves)
mercury-vapor thyratron FG-
27A.

be used to apply or remove power from devices of much greater power dissipation without switch arcing or pitting. To distinguish this action from others which follow, the term *quantity* grid control is usually employed to describe this form of switching or trigger action.

To start, let us consider the circuit of Fig. 20 in which a small switch is used to apply power to a heavier load. With switch SW closed, the grid of the thyratron is made substantially more negative than its critical potential at the particular anode voltage being applied. When SW is opened, the grid immediately returns to ground potential (same potential as the cathode) so that the negative bias is zero. The thyratron fires, thus powering the load; it should be noted, however, that closing SW at this time will *not* turn off the

power to the load for reasons given in Section 22. Removal of power can be accomplished in this fundamental arrangement only by removing the anode potential. (We will show later how another small switch may be connected for power shut-off as well as power application. The anode voltage switch in this circuit would have to be sufficiently large to handle the shut-off arc.)

Observe that the thyratron in the circuit of Fig. 20 is acting as a latching relay. Even momentary depression of a spring return switch at SW results in continued power to the load. It possesses certain important intrinsic advantages over an electromagnetic relay: a thyratron does not have moving contacts which might corrode and pit; ordinary relays require a relatively long impulse applied
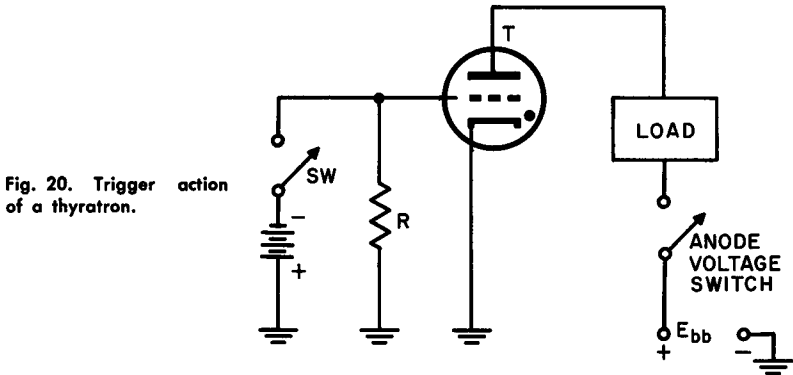
Fig. 20. Trigger action of a thyratron.

to their coils for reliable operation — not much less than 1/100 second even for good relays. The thyratron, on the other hand, has an ionization time of a few microseconds at the most so that a momentary closure over even this tiny interval will suffice to trigger the circuit.

Of the various gases that have found application in thyratrons, three types are now in favor for the reasons given below:

Mercury-vapor: Low internal voltage drop, capable of carrying heavy currents. Disadvantage: sensitive to temperature and therefore more difficult to control.

Argon: Higher internal drop than mercury but not sensitive to ambient temperature. Argon tubes are used in light-load circuits where repeatability is important.

Hydrogen: Very fast de-ionization time, hence excellent in applications where extremely short pulses are available for triggering.

25.   Thyratron Cut-off with Capacitor

It was stated in Section 24 that the extinguishing of a fired thyratron operating on d-c may be accomplished by means other than the use of a large heavy-current switch. Of the many ways to do this, the use of a *commutating capacitor* as shown in Fig. 21 is perhaps the simplest and easiest to apply. Both switches are springloaded, SW1 being normally closed and SW2 normally open. To trigger the thyratron on, SW1 is momentarily opened. This grounds the grid through R1 permitting the tube to fire since, with the grid
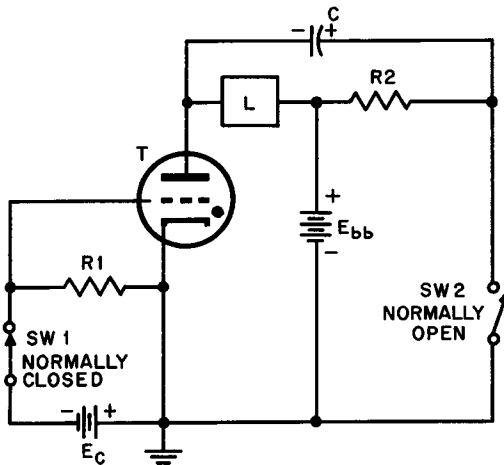
Fig. 21. Thyratron cut-off circuit using a commutating capacitor.

at ground potential it is more positive than its critical value. Plate current flows through the load and energizes it, but at the same time the commutating capacitor C charges with the polarity shown in Fig. 21. The reason for this charge is easy to see: while T is conducting it behaves as though it were a very low resistance so that the left plate of C takes on a potential very close to that of the negative side of E_{bb}. The right hand plate of C is connected to the positive side of E_{bb} through R2 and, since no steady current flows through R2, there is no voltage drop in this resistor; hence the right plate assumes the same potential as the plus side of the source E_{bb}. Therefore the total voltage across C is E_{bb} minus the voltage drop in the tube — about 15 volts. When SW2 is closed, the voltage on C is instantaneously applied to the anode and cathode of T; since this voltage is the inverse of the normal supply voltage, it subtracts from the

latter causing the anode-to-cathode voltage to drop to about 15 volts. This is well below the voltage required to maintain the arc; hence the thyratron extinguishes in some tubes. When SW2 is released, T does not fire again because SW1 is normally closed and E_c is connected to the grid and cathode in the correct polarity to keep the grid below its critical voltage.

In some circumstances the plate would have to be driven below 15 volts to extinguish the tube, since normal tube-drop may well be less than this. This circuit usually makes the anode negative with respect to the cathode to insure recovery of grid control. The plate-to-cathode voltage which exists at the instant SW2 is pressed, depends on the value of the capacitor C and on the load L.

26. A Thyratron in an A-c Circuit

Theater lighting, electroplating, and welding are a few examples of industrial processes in which a controlled amount of rectifier current is necessary. Such control may be accomplished by a variable power transformer or a rheostat in the d-c output of the rectifier; but neither of these methods is particularly satisfactory. Variable transformers are expensive and output rheostats are highly inefficient. The development of large thyratrons at relatively low cost has made current control inexpensive and efficient. Before attempting to develop a-c control circuits, it is essential to understand the anode and grid potential relationships in a-c circuits.

Although the critical grid curve for, say, an 884 thyratron is sufficient to predict the tube's behavior in any type of circuit, a more lucid analysis of a-c action is made possible by transferring the coordinates of the curve of Fig. 18A to a plot of sinusoidal nature. Consider a circuit such as that of Fig. 22 in which a d-c source is available to change the negative bias on the thyratron grid and in which the anode potential is sinusoidal a-c.

Since the curve of Fig. 18A gives the minimum grid potential needed for conduction to occur for each value of plate voltage, the grid potential which just permits conduction at each point in the cycle of sinusoidal plate voltage may be found point by point from Fig. 18A for an 884 thyratron. In Fig. 22B, the solid sine-wave segment above the horizontal axis represents the anode potential which might make the thyratron fire if the grid voltage is below critical value; the dashed segment is negative anode potential which cannot

Fig. 22.   An a-c thyratron circuit.
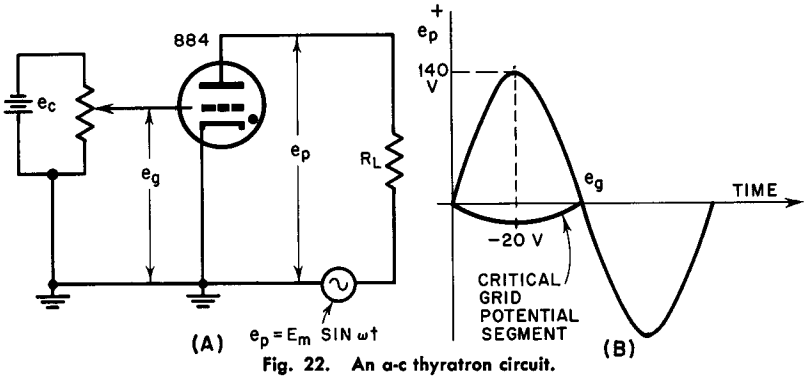
fire the thyratron under any conditions and so needs no considera-
tion at all. The solid curve beneath the time axis shows how the
critical grid voltage must change with anode potential to just prevent
the tube from firing throughout the positive half of the anode po-
tential cycle. For example, suppose that e_p reaches 140 volts maxi-
mum. Then, for peak anode voltage, e_g would have to be —20 volts
to just prevent ignition of the thyratron. Evidently, each specific
anode potential must have associated with it some value of negative
grid potential to establish this condition. The critical grid potential
segment in Fig. 22B is a plot of these points throughout the positive
half of the anode potential cycle.

Referring to Fig. 23, we can analyze the magnitude and wave-
form of the current that flows through the load (i_p) as a first step
in the comprehension of thyratron behavior in a-c circuits. Let us
assume that a certain fixed negative bias potential e_g is applied to
the grid. This bias line intersects the critical grid voltage segment
at point X in Fig. 23. This means that conduction will begin
when the applied potential reaches the value e_t — that is, the point
directly above the intersection X. Thus during the period 0 to A
the tube is extinguished. At A the thyratron fires and its current
i_p (ignoring the microsecond or less required for ionization) in-
stantly rises to point B. During the remainder of the conduction
period, i_p follows Ohm's Law according to the equation:

$$i_p = \frac{E_m \sin \omega t - E_o}{R_L} \tag{17}$$

where E_o is the voltage drop across the conducting thyratron (from

10 to 15 volts) , E_m is the peak value of the sinusoidal applied voltage, and R_L is the resistance of the load. This accounts for the shape of i_p.

At the instant when e_p reaches a value equal to the tube drop E_o, i_p must equal zero. Calling the angle at which ignition occurs Θ_f, and the angle at which extinction takes place Θ_e, we can state the following relationships:

$$e_p = E_m \sin \omega t \tag{18}$$

In this case, e_p is the applied voltage. Before firing, however, the anode potential of the tube is the same as the applied voltage in the absence of plate current. Hence,

$$e_p = e_{bb} \text{ before firing.} \tag{19}$$

The voltage at which firing begins, e_f, is:

$$e_f = E_m \sin \Theta_f \tag{20}$$

Solving Equation 20 for the firing angle Θ_f we have:

$$\Theta_f = \text{arc} \sin e_f/E_m \tag{21}$$

The thyratron extinguishes when the applied a-c anode voltage drops
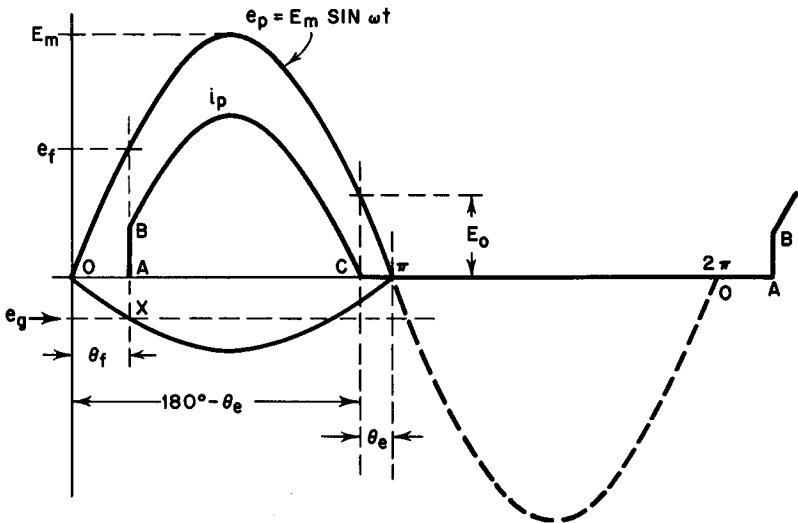
Fig. 23. Relations between plate voltage, plate current, and grid voltage in a typical thyratron.

below E_o. Hence the extinction angle is related to the voltages in this way:

$$E_o = E_m \sin (180° - \Theta_e) \qquad (22)$$

Solving for Θ_e

$$\Theta_e = 180° - \text{arc } \sin E_o/E_m \qquad (23)$$

Also, the total angle of conduction may be expressed as:

$$\Theta_c = \Theta_e - \Theta_f \qquad (24)$$

These equations have intrinsic value in that they relate firing and extinction voltages to the corresponding angles of the positive half of the applied voltage cycle. A further advantage of collating these equations is that it is now possible to obtain a statement for the *average load current* supplied by a thyratron during the entire a-c cycle. The derivation of the final equation requires a knowledge of integral calculus and will not be undertaken here.* It may be stated, however, in this manner:

$$I_{av} = E_m/2\pi R_L (1 + \cos \Theta_f) \qquad (25)$$

This simplified form of the final equation is obtained by assuming

------

*Derivation of I_{av}

$$I_{av} = \frac{1}{2\pi} \int_0^{2\pi} i_p \, d(wt) \; - \text{ general form.}$$

for firing interval from Θ_f to Θ_e, we integrate over these limits, also substituting for i_p as in Equation 17.

$$I_{av} = \frac{1}{2\pi} \int_{\Theta_f}^{\Theta_e} \frac{E_m \sin wt - E_o}{R_L} \, d(wt)$$

Evaluating the integral yields:

$$I_{av} = \frac{E_m}{2\pi R_L} \left[\cos \Theta_f + \sqrt{1 - \left(\frac{E_o}{E_m}\right)^2} - \frac{E_o}{E_m} (\Theta_e - \Theta_f) \right]$$

If E_o is substantially smaller than E_m — the usual case — then this equation may be simplified to:

$$I_{av} = \frac{E_m}{2\pi R_L} (1 + \cos \Theta_f)$$

(since with this assumption, the second term reduces to unity and the third term drops out entirely) .

that E_o is small compared to E_m. In most applications, this is perfectly true since E_o is in the vicinity of 15 volts while E_m for industrial thyratrons often runs over 800 volts.

Equation 25 shows that the average d-c value of the load current may be smoothly controlled by changing the grid bias, since bias variations cause the firing angle to shift along the time axis. Control of output current in thyratrons by means of bias magnitude changes is sometimes referred to as *quantity grid* control; more often, the process described here is called *gradual control*. The limits of variation of the firing angle, with d-c grid control, are from zero to 90°, with maximum d-c current flowing at $\Theta_t = 0°$.

27. Phase Shift Control of a Thyratron

A serious deficiency of simple bias or quantity control of thyratrons as described in Section 26 is that the firing angle can be varied only over the limited range from 0° to 90°. A thyratron under quantity control in a *d-c* circuit acts as a self-latching relay because once the discharge has been initiated the grid loses control and the tube continues to conduct as long as the anode voltage remains above the arc-maintaining potential (about 15 volts). As we have seen, however, the current passing through the thyratron and its load in an a-c circuit is made variable by varying the grid voltage; also, the grid regains control of the tube on every alternate half-cycle of the applied anode voltage when the latter dips below the horizontal axis.

It is apparent on examination that quantity grid control can never provide complete control of the anode current from the full-off to the full-on condition because of the 0° to 90° limitation. To clarify this point consider the two extreme conditions: (1) If the firing angle Θ_t is made 0°, the tube will conduct for almost a full half-cycle. This is the full-on condition. (2) If the firing angle is advanced to very close to 90°, the thyratron will ignite at the peak of the a-c anode potential *but will remain ignited for the rest of the quarter cycle.* This is *not* the full-off state. Thus, if the plate load were an incandescent lamp, then running the bias increasingly negative would gradually dim the lamp; but long before it reached an "almost out" condition it would extinguish completely. In an industrial application such as house-light control in theaters, this situation would be intolerable.

Complete control over thyratron load current may be realized by applying phase-shift grid control to vary the firing angle from 0° to 180°. To obtain phase control, an a-c voltage of the same frequency as the anode supply voltage is fed to the grid of the tube. The phasing of the grid voltage is made variable by suitable cir-
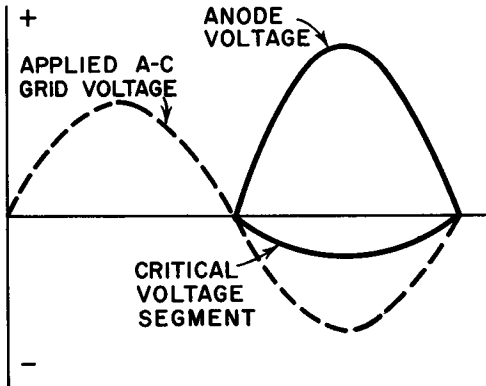

Fig. 24. An alternating voltage of large magnitude applied to the grid 180° out of phase with the anode voltage.

cuitry to be described shortly. To start, let us apply an alternating grid voltage which is 180° out of phase with the anode voltage and is considerably more negative at its peak than necessary to keep the thyratron cut-off during the entire half-cycle.

Figure 24 shows quite clearly that the thyratron cannot fire at any time under these circumstances because the applied grid voltage is always more negative than the critical grid potential. During the next half-cycle the grid will, of course, go positive but at the same time the anode potential will be negative so that constant extinction is obtained throughout the full 360°. The relative phasing of grid and anode voltages in Fig. 24 may be referred to either as a 180° lead or a 180° lag.

If the phase of the grid voltage is now shifted to a new position such as that shown in Fig. 25, it would be logical to say that the grid voltage is now retarded with respect to the anode voltage by some angle less than 180°. Now, the applied grid voltage intersects the critical voltage segment at point X and a line drawn parallel to the vertical axis intersects the anode voltage curve at point F (line AB). Hence, the thyratron fires now at point F and remains conducting for virtually all the rest of the half-cycle. Evidently,

advancing the phase of the grid voltage further and further along the anode voltage half-cycle will permit the tube to fire earlier in each case. When the grid voltage arrives at the in-phase condition with the anode voltage, the thyratron will fire just as the anode voltage rises above ionization potential at the beginning of the cycle and will continue to conduct throughout the half-cycle. This is the full-on condition. Thus, phase-shift control permits a full range of plate current with smooth variations from the full-off to the full-on state. All that remains is to design a circuit that will provide a phase shift from 180° out of phase to the zero phase condition for the grid voltage with respect to the anode potential.

28. Phase-Shifting Circuits

Phase-shifting of one voltage with reference to another is easily accomplished by circuits that combine resistive-inductive or resistive-capacitive components in phase -shifting networks. One of the simplest arrangements to set up and adjust is the R-C network shown
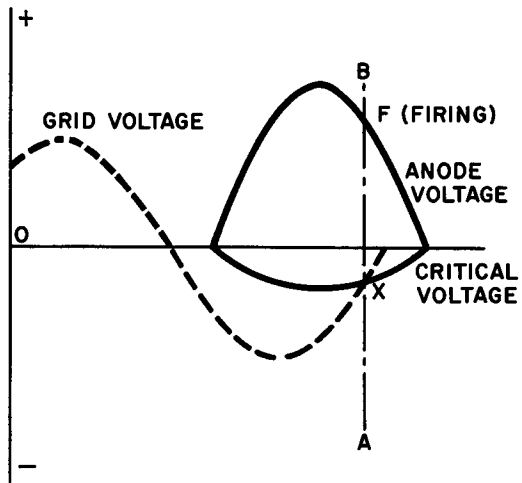
Fig. 25. The alternating grid voltage is now lagging the anode potential by some angle less than 180°.

in Fig. 26. A low-voltage center-tapped transformer supplies the a-c bias voltage for the thyratron with a variable resistor R and a capacitor C connected across the whole secondary winding. Grid voltage is taken from the junction between R and C and is referred to G, the point to which the cathode is connected.

Taking point Y as the zero-reference, the current which flows through the R-C combination due to the applied voltage YX must lead E_{yx} by an angle Φ which depends upon the ratio of capacitive reactance X_c to resistance R. The vector diagram in Fig. 26 shows that I is leading E_{xy} by the angle Φ. The voltage drop in the resistance must be in phase with this current so that vector JX is drawn
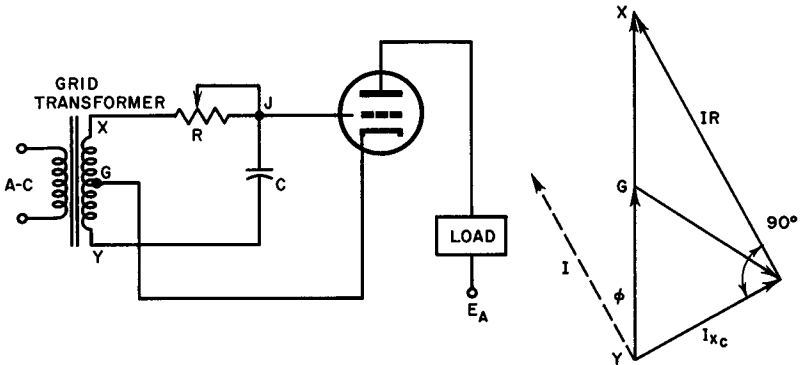

Fig. 26. An R-C phase-shifting network.

parallel to I; on the other hand, the voltage drop in the capacitor must lag behind the current by 90°, thus vector JY is shown at right angles to I and IR. Since vectors JY and JX must total to vector YX, these voltages form a closed triangle in which vector JG represents the magnitude and phase of the varying potential applied between the grid and cathode of the thyratron. Vector JG thus lags behind vector GX — the condition necessary to realize a varying grid potential whose phase may be shifted for purposes of grid control.

Examine the vector diagram in Fig. 26: If R is made zero, vector JX becomes zero, and the grid voltage JG falls into phase with the applied anode voltage. This permits the thyratron to fire at the beginning of each cycle, thus permitting the maximum average anode current to flow. As the resistance is increased, vector JX grows, causing the angle between the grid voltage and anode voltage to increase. As the grid voltage is retarded to an increasing extent, the tube fires later and later in the cycle bringing about a greater diminution of anode current. Phase-shift grid control thereby makes extremely smooth variation of average anode current possible by means of a relatively low-wattage control element, R.

29. Thyratron Grid Resistor and Preconduction Current

In the discussion concerning the fundamental behavior of a thyratron, it was pointed out that the tube fired when the grid potential was reduced below a certain critical point. After ignition, the anode current of a thyratron cannot be interrupted by making the grid negative once again since the latter electrode loses control once ionization has begun.

To understand (1) the physical conditions existing after a thyratron is fired and (2) why the tube is endangered unless certain precautions are taken, examine the voltage conditions in the tube structure.

Although a potential of several hundred volts may exist between anode and cathode before ignition occurs, once the gas has ionized the voltage drops to a smaller figure such as 15 volts. The grid of of the tube at this time is then immersed in a field having a potential gradient whose magnitude is determined by the voltage between anode and cathode, i.e. about 15 volts. The grid will therefore tend to assume some potential in the vicinity of 15 volts and any attempt to change this voltage — as, for example, varying the d-c bias — will result in large grid currents. To avoid damaging the element, a resistor is always connected in series with the grid potential. If its value is between 15,000 and 100,000 ohms, such a resistor will allow the grid to establish its own potential with a very small grid current. Since some voltage can occur across this resistor due to preconduction current, the size of this resistor will influence the critical grid voltage curve.

Another factor is important in thyratron application: pre-conduction grid current. The value of a thyratron as a self-latching relay for example, lies in the tiny grid power requirements for control of the tube before conduction begins. The control surface is very much larger than the equivalent element in a vacuum tube; furthermore, the thyratron grid is immersed in the plasma during conduction and inevitably collects an appreciable quantity of cathode material. Measurement shows that a normal thyratron in good condition exhibits a much larger grid current before conduction than the equivalent vacuum tube. This means, of course, that the source of control voltage for the grid must be capable of supplying power rather than merely voltage. This disadvantage is almost completely overcome in shield-grid thyratron design.

30. Shield-grid Thyratrons

Figure 27 shows an internal view of a typical shield-grid thyra-tron. In this tube, structural precautions have been taken to isolate the control grid from the electron-ion stream that flows between the anode and cathode. The shield grid is a cylindrical structure which completely surrounds the cathode and control grid and is provided
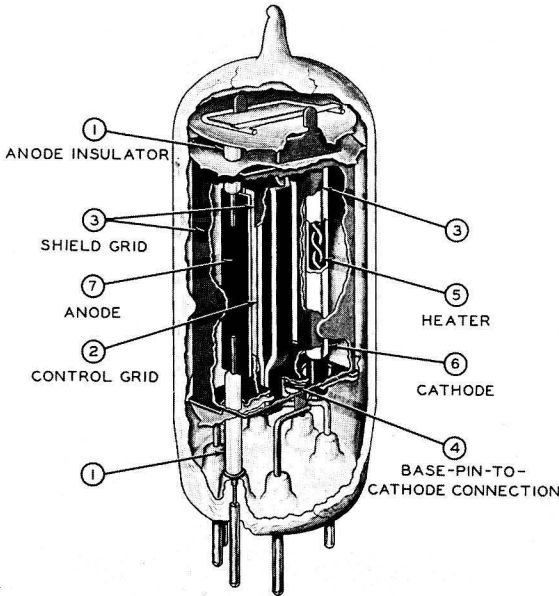

ANODE INSULATOR

SHIELD GRID

ANODE

CONTROL GRID

HEATER

CATHODE

BASE-PIN-TO-
CATHODE CONNECTION

Fig. 27. Internal fabri-cation of a typical shield-grid thyratron (2D21), RCA

with two baffle plates which confine the arc stream to a path which is well inside the metallic structure of the control grid. By isolating the control grid in this manner, both preconduction grid current and the likelihood of damaging post-conduction grid current are minimized. Protective series resistors are not normally needed in the grid circuit of a shield-grid thyratron. Series grid resistors in both control and shield-grid circuits improve tube life in some thyratron applications.

Small shield-grid thyratrons like the 2050 are generally used with their shield grids connected to their cathodes, thus placing the shield grid at zero potential. In this connection with 150 volts be-tween anode and cathode, the 2050 will fire when the grid potential

reaches the vicinity of −2 volts. Figure 28 shows a 2050 connected as a non-latching switch that requires infinitesimal grid power. The circuit owes its non-latching property to the use of ac for anode power. To convert it into a latching relay, dc may be used for the anode circuit in place of the ac.

The shield grid can serve as a control grid. Some applications utilize the fact that circuits can be designed so that the shield-grid thyratron will conduct only when both grids are above a critical voltage value.

31. Two Direct Applications of Industrial Thyratrons

A thyratron is essentially a grid-controlled rectifier which can replace a vacuum-tube rectifier in any circuit in which control of output voltage is desired. It is natural, therefore, that one would think of this as its primary application. As a matter of fact most thyratrons are not used as rectifiers at all since most industrial applications require a device that will control a-c output *without* rectifying

THYRATRON 2050

Fig. 28. The 2050 connected as a non-latching switch.

POSITIVE INITIATING PULSE

RELAY
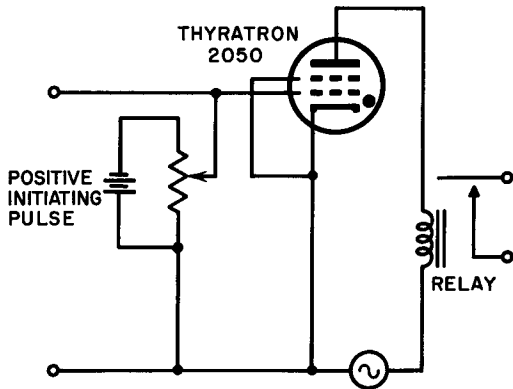
it. Control of resistance welding machines and large a-c motors are examples. On the other hand, current control *and* rectification are often necessary characteristics. Hence, thyratron circuits fall into two broad classifications: controlled ac and controlled dc.

Figure 29 illustrates a full-wave thyratron power supply designed for the production of pulsating dc into a filter. Output current is made variable by quantity control in this case, but phase-shift meth-

ods may easily be substituted by using circuits described earlier in this chapter.

For the operation of transformers or a-c motors under controlled current requirements, a pair of thyratrons may be connected *back-to-back* as shown in Fig. 30. In this circuit, each thyratron conducts for one half of the a-c input cycle, providing a full sinusoid at the output of the system. Two separate control voltages are necessitated
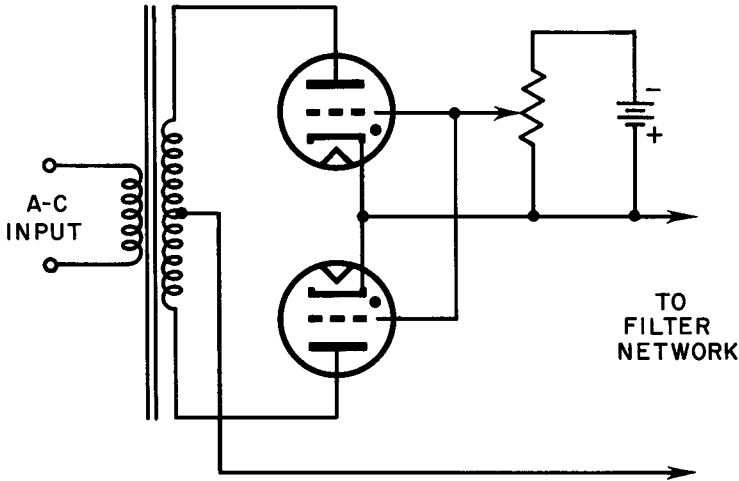

Fig. 29.   A full-wave thyratron power supply.

by this configuration as indicated in the schematic diagram, because there is no common point for the return of the positive side of the grid voltage source. When the tubes are cut-off they act like open switches and the full line voltage appears between the two cathodes. With modern thyratrons, it would be impossible to supply both heaters from a common filament transformer since the cathode-to-heater insulation is not effective enough to prevent possible arcing from one electrode to the other. The limitation on heater-cathode voltage in thyratrons is due to the fact that a few microamperes of leakage current can produce ionization that leads to breakdown between heater and cathode. This effect is generally negligible in vacuum tubes. This necessitates two entirely separate heater voltage sources, each insulated for the full line voltage between each other and between the windings and frames. Many industrial devices make

use of this arrangement with phase-shift grid control providing smooth, continuous output current from zero to the maximum rating of the system.

32. Thyratrons in High Current Circuits

The structure of a thyratron, like that of a vacuum tube, makes it more suitable for high-voltage low-current circuits than for low-voltage high-current applications. Even large industrial thyratrons can handle little more than 10 to 15 amperes continuously. Suppose, for example, that a pair of large thyratrons are to be used as theater dimmers in an arrangement where 50 500-watt lamps are involved. Taking the current for each lamp at approximately 5 amperes (on a
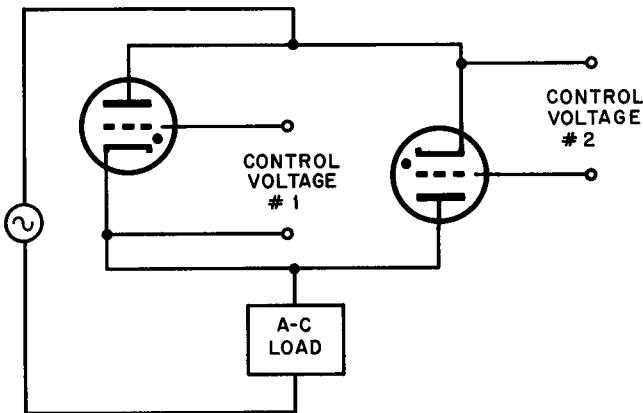
Fig. 30. Method of connecting two thyratrons back-to-back for the operation of a-c loads.

nominal 115-volt circuit), this means that the lamps must be provided with a total current of about 250 amperes at 115 volts.

This current is far above the rating of the thyratrons; at the same time, the tubes are capable of handling much higher voltages than 115 volts. This immediately suggests the use of a pair of transformers, one for raising the applied voltage and the other for dropping it back to its initial value. A circuit that might be used is shown in Fig. 31. At 100% efficiency, the power in the primary windings of both transformers must be exactly equal to the secondary-winding powers. In actual operation, where 90% efficient trans-

formers are employed, the primary power would be 10% greater than the secondary power in T1. The same would be true of T2. Hence, the current in the thyratrons would be somewhat greater than that indicated in the figure but would still be substantially below their current ratings.

33. Additional Thyratron Circuits

Countless circuits in which thyratrons play an important role may be found in engineering reviews and industrial handbooks. Two arrangements in which the thyratron is used neither as a con-
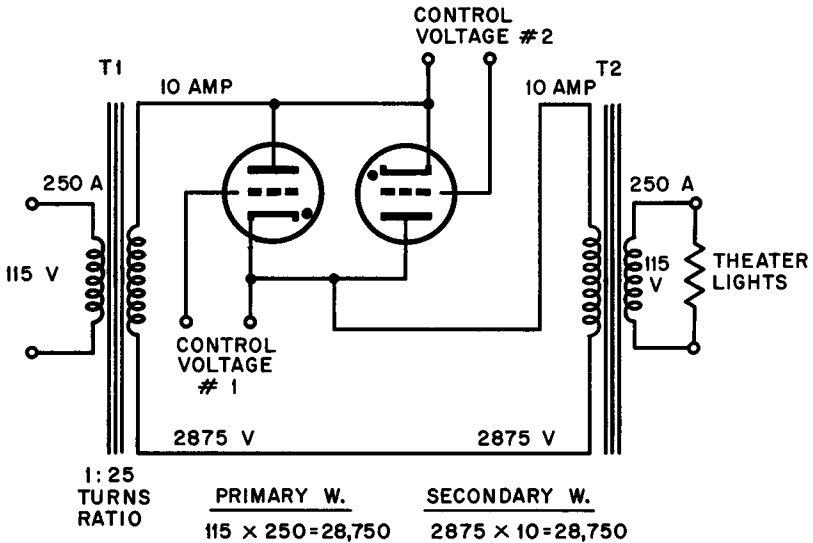
Fig. 31. A method of using high-voltage, low-current thyratrons for controlling a low voltage, high-current load.

trol element nor as a trigger are described below: these circuits are interesting because the tubes are handled in a different manner and because the circuits are widely used in modern electronics.

Time Delay Circuit (Fig. 32). When the double pole switch is in position 1, the anode circuit is open (section A) and the grid voltage is appreciably more negative than the critical value (i.e. the critical value for this tube when the given anode voltage is applied later). Capacitor C is charged negatively on the side since it is

connected across points C and D on the bias potentiometer R1. There is no current in the load R4 under these conditions.

When the switch is moved to position 2, anode voltage is immediately applied but anode current remains zero as a result of the over-critical voltage applied to the grid-cathode circuit by the charge on C. This charge gradually drops toward zero as C dis-

Fig. 32. A practical time delay circuit.
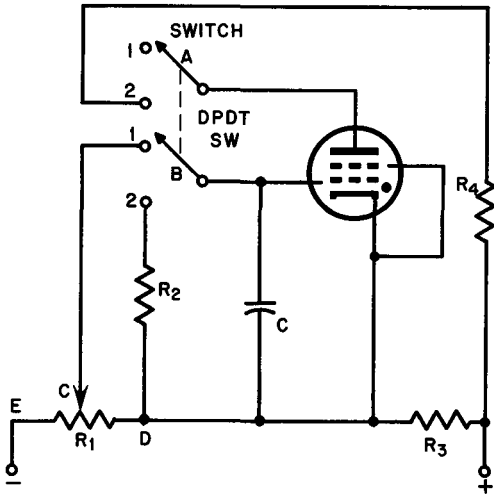
charges through section 2 of the switch and resistor R2. The tube fires when the grid potential approaches the cathode voltage; that is, ignition occurs as soon as the grid voltage reaches critical potential. The time-delay interval between operation of the switch and the triggering of the thyratron is determined by the original charging voltage as selected by R1 and the R-C time constant of R_2C. The timing interval may be increased, for example, by moving R1 toward point E, or by increasing the resistance of R2 and/or the capacitance of C.

Binary Counter Circuit (Fig. 33). A binary counter is a type of 2:1 frequency divider in which every alternate input pulse is mechanically counted. In many industrial and scientific operations, the recurrence rate of the output pulses is too high to be measured by electro-mechanical digital counters. Mechanical counters of the digital variety seldom are reliable at pulse rates higher than about 10/sec whereas substantially higher frequencies are common in sort-

ing, counting and allied control operations in manufacturing plants. A pair of thyratrons can easily be set up as 2:1 dividers; these may be followed by a second and third pair, if desired, to achieve a geometric frequency division of 4:1, 8:1, and so on.

The two tubes are biased beyond conduction by the negative voltage from E_c applied to their grids. T_2 may now be made to fire by momentarily short-circuiting its grid to its cathode. Assume now that a positive pulse having a very fast rise-time (steep leading
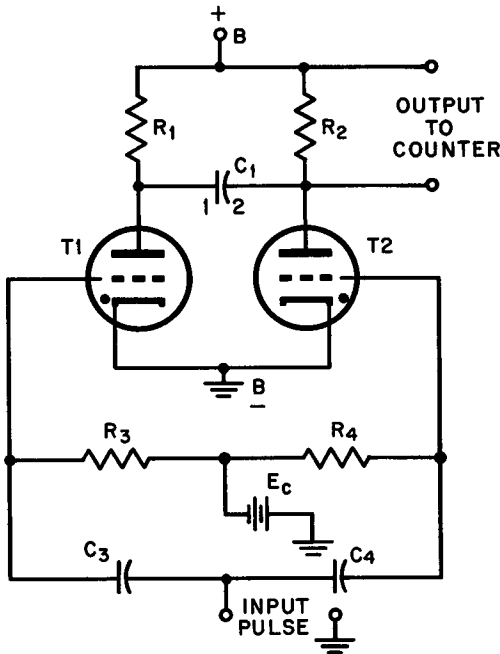
Fig. 33. A binary counter circuit based on thyratron action.

edge) is fed to the input terminals. The pulse will be transferred to both grids simultaneously through C_3 and C_4, but since T_2 is already conducting, its operation will not be affected. T_1, on the other hand, will trigger if the pulse is large enough to overcome the negative bias of E_c, but as it does so, T_2 immediately extinguishes. Conductivity has thus been transferred from T_2 to T_1.

Extinction of T_2 at the instant of transfer occurs as follows: while T_2 is conducting, C_1 is charged to within about 15 volts of the supply voltage and is polarized with side 2 negative and side 1 positive. (While T_2 conducts, it behaves like a closed switch with

an internal voltage drop of approximately 15 volts. C_1 side 2 is connected to the anode of T_2 and C_1 side 1 is connected to B+ through R_1. Since T_1 is not conducting at this instant there is no voltage drop across R_1 and C_1 must charge to a value equal to the applied voltage minus the drop in T_2).

The firing of T_1 with the incoming positive pulse is virtually an instantaneous action. When it happens, the anode voltage of T_1 drops about 15 volts. A capacitor cannot instantaneously change its charge, so that as side 1 of C_1 also drops to 15 volts the cathode of T_2 (T_1 too) instantaneously assumes a potential of about 15 volts through the conductivity of Tube 1. But the anode of T_2 is heavily negative (as a result of the stored charge on C_1) with respect to its cathode under the conditions imposed upon it by this new situation, hence it must extinguish. Within a very short time, C_1 charges again, this time with opposite polarity; but if T_2 has deionized before this commutation of polarity occurs it will not fire again since its grid continues to be more negative than the critical potential.

Upon the arrival of a second pulse, commutation again takes place. Thus, Tube 2 conducts only on alternate pulses and the counter forming part of its plate load registers every second signal.

Review Questions

1. What is the major difference between a gas diode and a thryatron?
2. Give the reason for the necessity of a plate load in a thyratron circuit.
3. Why does temperature affect the firing point of a mercury-vapor thyratron?
4. Name three gases used in thyratrons.
5. What is the function of the capacitor in Fig. 21?
6. What is the purpose of the shield grid in a thyratron?
7. Name two devices that use thyratrons to control current flow.
8. How do we hook up thyratrons to get full wave operation?
9. What type circuit will give us control over the average current flow, when the thyratron is used in an a-c circuit?
10. Name at least two circuits where the thyratron is *not* used as control element nor as a trigger.

Chapter 5

OTHER TYPES OF GAS TUBES

34. Gas-filled Phototubes

The term phototube as used in this book refers to a light-sensitive device which consists of two electrodes in a glass envelope. One electrode, the cathode, emits electrons when its sensitive surface is acted upon by radiant energy of the wavelength or wavelengths for which it is designed. The second electrode termed the anode is operated at a positive potential with respect to the cathode and sets up an electro-static field which causes the emitted electrons to move toward it. The number of electrons involved in the transfer is determined by the specific sensitivity of the cathode surface to the wavelength of radiation being used and by the quantity of radiant energy reaching the surface. For a given phototube operating with a specific wavelength of radiation, the magnitude of the anode current is thus a function of the amount of energy it receives.

The envelopes of many modern phototubes (Fig. 34) are evacuated to very low pressure. When characteristic curves of anode voltage vs. anode current with constant iluumination are taken, the tube does not operate under conditions of space charge at all. In this way, the phototube differs from a thermionic diode. Absence of space charge is explained by the fact that so few electrons are emitted from the cathode (even under strong radiation) that it requires very little anode-to-cathode potential to attain the equivalent of thermionic diode temperature saturation. That is to say, a very small voltage applied between the two elements will result in the attraction of all the emitted electrons to the anode.

The presence of a small amount of some inert gas like helium or argon produces an increase in the anode current of a given phototube without change of illumination. This increases the sensitivity of the tube as compared with corresponding vacuum types. The

CATHODE
ANODE

I"

Fig. 34. Cutaway view of a 1P29 gas phototube (photoemissive).
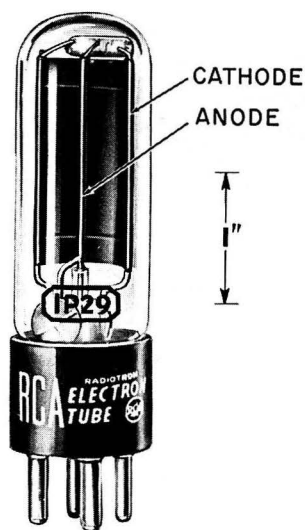
mechanism of this improvement is quite similar to those previously discussed relative to the passage of small currents through gases:

1. The flow of primary or photo-electrons from the cathode produces ionization of the gas;

2. The collision electrons now become available as charge carriers and add to the photo-electrons to increase the total number in the tube;

3. Positive ions reaching the cathode may produce secondary electrons which further swell the total number of electrons moving between the cathode and the plate. The total current flowing in a gas-filled phototube may be several times larger than that of the corresponding vacuum-type operated with the same illumination and anode voltage.

We can draw many interesting conclusions from the curves in Fig. 35. The flattening of the vacuum phototube characteristic beyond about 40 volts of applied potential shows that the equivalent of temperature saturation in a thermionic diode has been reached

at this point and that increasing the anode potential has little effect upon the anode current. At low anode voltages the available current from the vacuum type is greater, but the superiority of the gas
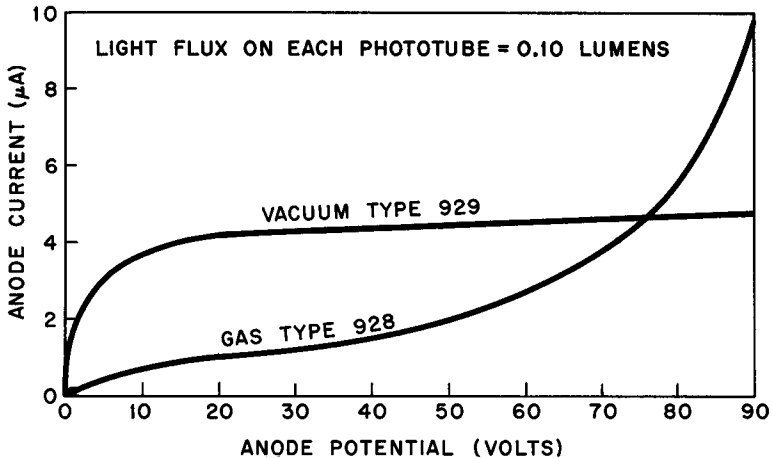
Fig. 35. Comparison of characteristic curve of gas phototube with equivalent curve of vacuum type.

tube in this connection becomes evident as the anode potential is raised above approximately 75 volts. At 90 volts, the gas tube current is about twice as great as that of the vacuum tube. The curved incremental of the gas type between 60 and 90 volts of anode potential indicates increased ionization and accounts for the rapid rise of anode current.

Phototubes of the 929 type (868, 918, 923, etc.) are rated at a maximum anode supply voltage of 90 volts. Since the glow discharge in the gas tube must at all costs remain non-self-sustaining, any attempt to increase the voltage above the recommended value may result in a self-sustaining discharge which would quickly ruin the cathode by sputtering.

35. Cold-cathode Gas Tubes (Grid Glow Tubes)

Gas-filled cold-cathode triodes are known as trigger tubes or *cold-cathode gas tubes* (Fig. 36). Sometimes these are classified as grid-glow tubes, although the third element is more properly referred to as a starter anode or control electrode rather than a grid.

The cathode may be a nickel-iron element coated with a barium and strontium mixture. The anode is usually pure nickel in the form of a wire shielded from the other electrodes by a glass cylinder; the end of the nickel wire protrudes above the end of the cylinder and is spaced from the other elements by a distance which depends upon the gas, gas pressure, and general design of the rest of the tube. The starter anode may be a surface or a wire loop placed near the cathode. The gas used is either neon, argon, or a mixture of the two.

The spacing between the control electrode and cathode is substantially smaller than the spacing between the anode and cathode so that a discharge can occur at a lower voltage between the first two. At the instant of this primary discharge, ionization occurs and the

Fig. 36. Structure of a cold-cathode gas tube (grid glow tube).

CATHODE

STARTER ELECTRODE

PLATE (ANODE)

MICA INSULATOR

GLASS ROD INSULATOR
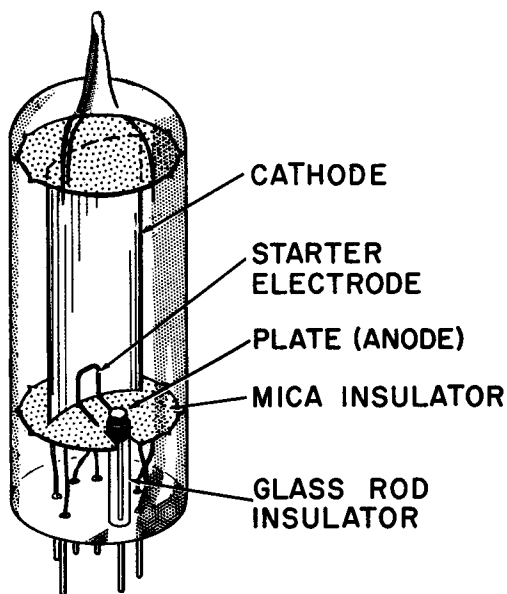
discharge transfers to the main anode. In order for the transfer to occur, the anode-cathode voltage must be adjusted to a specific value, the voltage required being determined by the cathode-starter anode current or *transfer current*. The curve shown in Fig. 37 illustrates how the required anode voltage varies with transfer current. It should be noted that the required anode voltage at zero transfer current is the same as the potential required to start the discharge

if the starter anode is not in the circuit. In practice, of course, the anode voltage is therefore always lower than this self-initiating level — less than 250 volts in the case of the 0A4-G. The necessary anode voltage falls more and more rapidly as the transfer current is raised, indicating increased ionization. Figure 38 gives a basic circuit for using the cold-cathode tube as a relay. The voltage E_a is greater than the self-sustaining voltage of the tube but less than the breakdown voltage; the voltage E_s is applied to the starter anode through the input coupling device and is slightly less than the potential required to initiate the action. A positive pulse applied to the upper input terminal adds to E_s bringing the voltage above the breakdown point for the starter circuit. The starter-cathode dis-
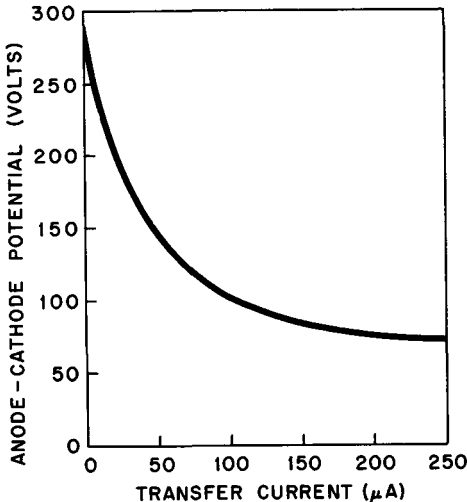
Fig. 37. How required anode voltage varies with transfer control in the 0A4-G.

charge then initiates the main discharge and the load is energized. It should be noted that this is a self-latching action which can be opened only by reducing the anode potential so that it falls below the voltage required to maintain the discharge. In this connection we might mention that cold-cathode gas (grid-glow) tubes can be classified in the same general group as small thyratrons such as an 884 or a 2050 on the basis of current handling ability. These tubes are capable of passing approximately 100 milliamperes on continuous service and are suitable for use as small controlled rectifiers, voltage regulators, relaxation oscillators, relays or switching devices.

36. Mercury Pool Rectifier

Although large thyratrons can handle up to 200 kilowatts of rectified power, they are essentially high-voltage-low-current devices because the average current does not exceed 12 amperes and the large amount of power mentioned can be obtained only with voltages around 15,000 volts.

From the industrial point of view — particularly in low voltage applications (200 to 500 volts) — the *mercury-pool cathode* rectifier is much more suitable. The earliest pool rectifiers were constructed in tube form as shown in Fig. 39. A cold mercury pool does not emit electrons, but a plentiful supply of electrons can be obtained from it if a stream of the liquid that has a current passing through it can be quickly broken to start an arc. The tube in Fig. 39 is operated this way. To initiate the arc, the tube is tipped to the right so that a stream of mercury flows from the main pool into the well along the side arm. Current then flows through the stream as
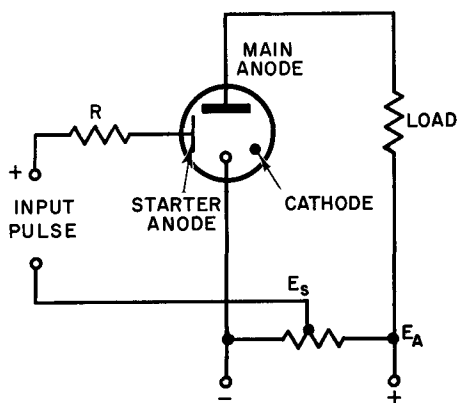
Fig. 38. The cold-cathode gas tube used as a relay.

a result of the potential applied between the starting electrode and the pool. As the tube is returned to the upright position, the stream breaks and an arc begins between the auxiliary electrode and the pool surface. This results in the formation of a *cathode* spot at the surface of the pool from which enormous numbers of electrons are liberated. Situated as it is in the strong electric field of the anode, the pool supplies the electrons to the anode to initiate a self-sustained arc.

Electrons enter the arc through the cathode spot which moves freely about the surface as a result of the forces exerted on it by the returning ions and the vaporizing liquid around it. Mercury ions formed in the body of the tube are either returned to the pool by electrostatic action where they pick up the necessary electrons to re-form into atoms of liquid mercury, or they are neutralized on
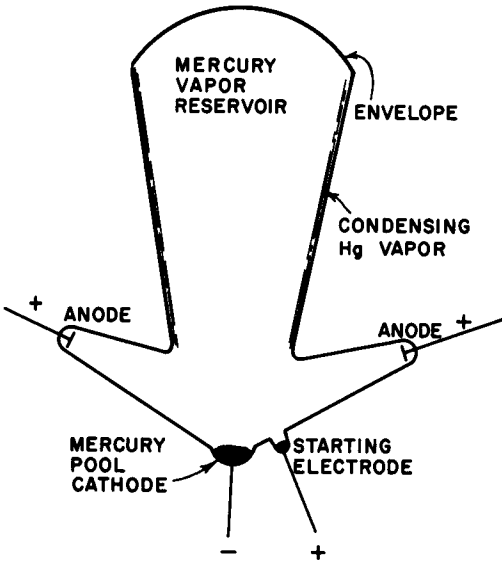

Fig. 39. An early form of mercury-pool rectifier.

the glass walls where they condense as a result of cooling. The condensed mercury drops down the walls and returns to the pool in this manner. Thus, cathode material is constantly being replenished; an electrode of this kind is virtually indestructible.

Modern multiphase mercury-pool rectifiers are manufactured in the form of cylindrical steel tanks from 1 to 2 ft. in diameter and about 4 ft. high. Each tank rectifier contains a single pool and a single anode together with its starting mechanism. (Multianode rectifier tanks are fast becoming obsolete and will not be discussed here.) One of the disadvantages of the older forms of mercury-pool rectifiers was that some form of manipulation was required to restore the arc each time it was lost. To make the pool rectifier just as convenient as thermionic types, a continuous supply of electrons is required whether the arc is struck or not. This is accom-
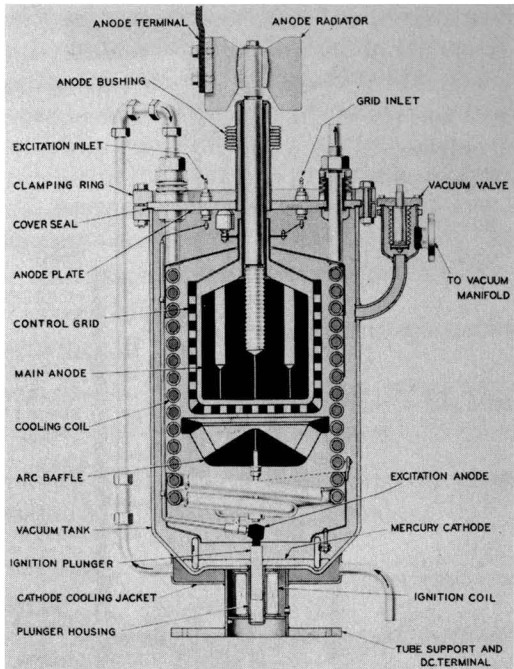
Fig. 40. Vertical cross-section of an excitron rectifier tube. *Allis-Chalmers*

plished by maintaining at all times an auxiliary arc between the pool and a special excitation electrode located just above the cathode. To start the arc, a fine stream of mercury is hosed from the pool to the excitation electrode, short-circuiting the two elements momentarily to initiate the arc. The voltage applied between the starting device and the cathode is approximately 35 volts dc obtained from a separate source so that the excitation arc is maintained continously.

The sustained excitation mercury-pool rectifier is often commercially called an "excitron." This unit also includes a grid which exercises the same type of control over the anode current as the equivalent element in the thyratron (Fig. 40).

37. The Ignitron

The ignitron differs from the excitron in that initiation of the arc is based upon a completely different principle. Once an arc is struck in the excitron it is maintained by the excitation electrode connected across a source of separate dc. In the ignitron, however,

(A)

RADIATOR

ANODE LEAD

BUSHING-GLASS

GRID ENTRANCE BUSHING

KOVAR

WATER OUTLET

DEGASSING STEM

HEADER-STEEL

ANODE-GRAPHITE

INNER CYLINDER STAINLESS STEEL

WATER JACKET STAINLESS STEEL

GRID-GRAPHITE

BAFFLE-GRAPHITE

AUXILIARY ANODE

IGNITOR

MERCURY POOL

WATER INLET

HEADER-STEEL

IGNITOR CONNECTION

CATHODE TERMINAL

(B)

ANODE RADIATOR AND TERMINAL

VACUUM MANIFOLD CONNECTION

ANODE PORCELAIN INSULATOR

ANODE PLATE

ASBESTOS GASKET

ALUMINUM GASKET

TANK VACUUM VALVE

TANK COOLING COILS

SHIELD ENTRANCE BUSHING

ANODE HEAD

IGNITOR ENTRANCE ASSEMBLY

ANODE SHIELD

BAFFLE

INTERIOR COOLING COILS

IGNITOR

ALUMINUM GASKET

MERCURY

CATHODE COOLING COILS

Fig. 41. Sectional views of typical ignitrons; (A) Sealed type; (B) Pumped type. *Westinghouse.*

the main arc is permitted to extinguish completely on every non-conducting half-cycle and is reinitiated at the beginning of the following conducting half-cycle. The energy for ignition is supplied through the action of a bar of semi-conductor refractory material such as carborundum which dips into the main mercury pool, as illustrated in Fig. 41. When a current of 5 to 20 amperes flows from the ignitor rod to the mercury, tiny arcs form between the surface of the semi-conductor and the surface of the pool, initiating the arc. Transferral from the ignitor to the main arc is almost instanta-
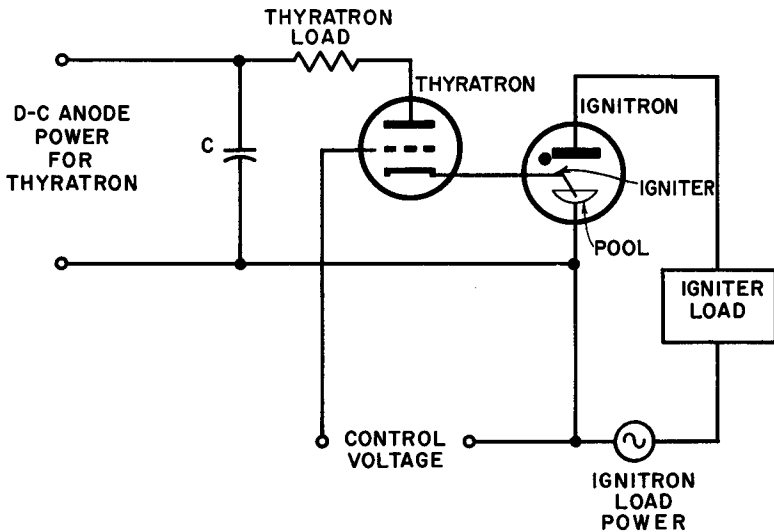
Fig. 42.   How a thyratron can be used to control the firing angle of an ignitron.

neous, hence current can flow in the main arc circuit over virtually all of the conducting half-cycle. The ignitor itself is pulsed periodically at exactly the right instant making the power consumption of the auxiliary circuit relatively small.

One of the most important features of the ignitron is its suitability for current control via the ignitor circuit. Here again, *firing angle* enters the picture: the average output current of any controlled rectifier is a function of the portion of the half-cycle over which it conducts.

One of the best ways to control the firing angle of an ignitron is to use a thyratron as an ignitor trigger. Figure 42 illustrates one

of the many ways this might be done. A phase shift control circuit, such as that described earlier, determines the firing angle of the control thyratron; as this tube fires, its anode current passes through the ignitor circuit striking the main arc of the ignition. Anode potential for the thyratron is provided by the charge across C so that as soon as C is discharged by the conducting thyratron, the latter extinguishes and the grid circuit regains control. Thus, the portion of the cycle for which the ignitron conducts is determined by the firing angle of the thyratron which, in turn, may be varied by the grid control voltage. This kind of system is very economical on ignition power and extremely dependable.

Ignitrons are used for heavy duty rectification being capable of handling very large currents continuously. Another important application is control switching in welding and similar operations.

In conclusion, there is a very basic difference between the grid-control action in a thyratron and ignitor-rod action in an ignitron. The grid of the thyratron *inhibits* ignition while the ignitor rod of the ignitron *initiates* the duty cycle. In the former case, electrons are always present owing to thermionic emission and the electro-static action of the grid prevents the electrons from reaching the anode until firing occurs; in the latter, the tube does not have free electrons which might produce ionization of the gas until the cathode spot is formed.

Review Questions

1. What controls emission in a phototube?
2. Why is there no space charge in a phototube?
3. What is the maximum rated anode voltage in a 929 tube?
4. Name five uses of the cold-cathode gas tube.
5. What device is used to make the mercury-pool rectifier equal to a thermionic emission tube?
6. Explain the basic difference between the ignitron and the excitron.
7. How do we control time of current-flow in an ignitron?
8. What is the basic difference in the action between the grid of a thyratron and the ignitor in an ignitron?
9. What is the life of the cathode in a mercury-pool tube?
10. Name some uses of the ignitron.

INDEX

Abnormal glow, 9, 11
Anode, 2
Arc discharge, 9, 10
Argon, 41
Atom 1, 2
  neutral, 1, 2
Auxiliary arc, 67

Back-to-back, 54 55
Binary counter, 57, 58

Carborundum, 69
Cathode, 2
Cathode arc, low-boiling-point, 10
Cathode spot, 65, 66
Cold-cathode gas tube, 62, 63, 64
Commutating capacitor, 42
Critical grid curve, 39

Discharge, 4-10
  arc, 9, 10
  gaseous, 10-11
    summary, 10-11
  non-self-maintaining, 5, 6, 7
  self-maintaining, 7, 8, 9, 27
Disintegration voltage, 22

Elastic collision, 11
Electric field, 14
Electron avalanche, 6, 7
  formula, 7
Electrostatic charge, 13, 14
Excitation electrode, 67
Excitron, 67
Extinguish state, 39
Extinction angle, 46

Filament, 13
Filters, 24, 25
  choke input, 24, 25
  capacitance input, 25
Fired state, 38
Firing angle, 69, 70
Force equation, 3
Full-off condition, 47
Full-on condition, 47

Gas amplification, 6, 7
Gas conduction, 4, 5
Gaseous tube, characteristics of, 10, 11
Glow discharge, 7, 27
Gradual control, 47
Grid-glow tubes, 62, 63, 64

Hydrogen, 41

71