America's Oldest Radio School

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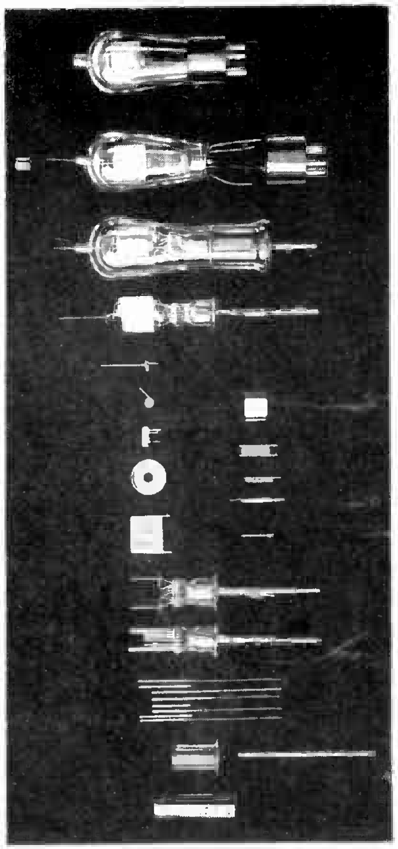
CLASS ROOMS AND LABORATORIES
75 Varick Street, New York

A 5-Prong, 3-Electrode, Uni-Potential,
Heater-Cathode Vacuum Tube

VACUUM TUBE THEORY

VOL.13#3



Parts Assembly of the '24-A Type Tube

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VACUUM TUBE THEORY

We now come to the study of the Vacuum Tube, a device which is the very heart of the radio receiver. The student will, at this point, have to give his undivided attention to that which follows and proceed with an open mind and active imagination. In order to understand the action of the vacuum tube we should review the action of the electron in a vacuum. To imagine an electron is one thing, but to follow the actions of electrons is quite another. The study of the electron theory as applied to the vacuum tube is comparatively easy if the student will concentrate, otherwise it is a difficult study and only results in a state of confusion. It is intensely interesting and, when understood, gives a clear idea of the relation between radio circuits and vacuum tubes.

The vacuum tube is not confined to radio alone; it is used in any number of other scientific fields, especially those in which high frequency rays are involved.

Let us consider for the time being that in the vacuum tube we have a device which will not only rectify an alternating current but will also reproduce, in amplified form, the most feeble variations of E.M.F. applied to it regardless of the frequency.

The tube may be employed as a rectifier of alternating currents of any frequency. The term rectifier is sometimes used to indicate the detector action.

It is termed a radio frequency amplifier when it is used to amplify the high frequency currents induced in the antenna by the incoming signal wave.

Further, the tube is used to amplify the output currents of the detector and when so used it is known as an audio frequency amplifier.

When used as a generator of high frequency undamped oscillations in an oscillatory circuit it is called an oscillator.

Before these various functions can be explained it is necessary to have a knowledge of the characteristics of the vacuum tube and to what extent these characteristics can be controlled. Until recent years no satisfactory explanation was offered concerning many phases of electrical phenomena known to science. As the application of electricity developed, however, there was a great amount of data secured which enabled scientists to formulate some of the laws governing the flow of electricity. For example, the relation between electromotive force, current, and resistance was explained by Dr. Ohm and put into the form of a law, the law being known universally as Ohm's Law.

Discoveries were also made regarding the generation of electrical pressure by chemical action between certain liquids and metals. This led to the development of the battery, and then came the evolution of the dynamo. No satisfactory explanation was offered at the time concerning the electrical phenomena of these discoveries yet they were of great practical value in determining from the results obtained, experimentally, many of the present laws of electricity. It also became necessary to settle upon certain arbitrary standard units by which electrical force and energy could be measured and computed, these being known as Universal Electrical Units which were explained in a previous lesson.

It was also found necessary to assume a certain direction in which electricity flowed through a conductor. Scientists decided to call the copper or carbon plate of a primary cell the positive terminal, and the zinc plate the negative terminal, and considered that electricity flowed in an external circuit from the positive electrode to the negative electrode. It must be understood that this direction given to the current flow was entirely an arbitrary one and was agreed upon only as a matter of convenience in understanding certain phenomena.

For many years the atom was regarded as the smallest unit into which matter could be divided and still retain its chemical and physical properties and the phenomenon was then explained by the atomic theory. In recent years many scientists have accepted the general belief that the atom is itself subdivided into many thousands of particles termed electrons and that these electrons carry with them a charge of electricity. It has been found that under certain conditions these electrons or particles of negative electricity can be made to move. Their movement is from a negative to a positive electrode and when in motion they constitute a current flow. This new theory is known as the "Electron theory of matter".

THERMIONIC CURRENTS

Thermionic current is the name given to electricity which is the result of electrons thrown off or emitted from hot bodies. A discovery made by Thomas A. Edison in 1884, known as "The Edison Effect", gave rise to an investigation of thermionic currents which leads up to the vacuum tube of today. Edison, in his work with the electric lamp, found that after a lamp had been in use some time a dark coating formed on the inside of the lamp, becoming in some instances nearly black with long continual use. He became interested in this effect and further research brought out the fact that when a metal plate was placed inside the lamp and connected to one side of a sensitive galvanometer and the other terminal of the galvanometer then connected to the positive terminal of the battery supplying current to the filament of the lamp, the galvanometer would show a deflection when the filament of the lamp was heated.

The effect at the time seemed to indicate that an electric current flowed from the positive side of the filament through the galvanometer to the plate inside the lamp, through the vacuum of the lamp, returning to the filament. Edison also discovered that, when the galvanometer terminal was removed from the positive side of the filament and connected to the negative side, practically no deflection of the galvanometer followed. After the discovery of this phenomenon experiments were carried out by several scientists. J. A Fleming, after considerable experimenting and research on the Edison effect, came to the conclusion that NEGATIVE electricity passed from the filament of the lamp to the plate when the plate was relatively cold with respect to the filament and the plate was charged to a positive potential.

Conclusions of the experiments of J.J. Thompson led to the belief that what is now called the electron existed and that negative electricity consisted of masses of these electrons which were forced away from the filament of an electric lamp when the filament was brought to incandescence. In other words the filament itself consisted of these infinitely small particles called electrons. It has now been generally accepted that it is by means of the electron that electricity is carried through a conductor or through a vacuum.

There are always large numbers of electrons in an atom and normally this quantity amounts to a given number just sufficient to neutralize the effect of the positive nucleus. Generally but one electron can be detached from an atom even though it may have a great many associate electrons. Under normal conditions the atom possesses no electrical charge because a perfect state of neutralization exists between the positive charge and the electrons. When, however, one of the free electrons is forced away by some cause or other this perfect balance is destroyed and the atom predominates in positive charge because it is now deficient in its complement of electrons.

ELECTRON EMISSION

The emission of electrons is dependent upon the temperature of the filament, the size (area) of the filament, the nature of the substance employed as the filament, and the medium in which the filament is heated. The number of electrons emitted will be proportional to the area of the filament. For example, if you have two filament lengths, one twice as long as the other, by heating one filament to a given temperature a certain electron emission occurs. With the same heat applied to the filament of twice the length, double the emission occurs. This happens however only when the same heat is applied to both filaments.

The temperature of the filament is very important in that, with each increase of filament heat, there will be an increase in electron emission. This increase in electron emission increases as the temperature increases until the maximum emission takes place which is just below the melting point of the filament. Heating the filament to excessive temperature is of no advantage as you will later learn.

The composition of the filament, that is, the material employed in its manufacture, will have a bearing upon the electron emission. Some metals, when heated, do not emit as many electrons as others. Carbon, for example will emit a certain quantity of electrons but not nearly in as large quantities as tungsten. Tungsten is materially helped in electronic emission when another metal called thorium is combined with it. It is the Thoriated Tungsten filament that is used in many types of tubes because at low temperatures it has a very high rate of electron emission.

There is still another factor which has a great influence on electron emission and that is the medium in which the emission occurs. In the first place it must be in a vacuum, or at least a partial one. It is quite impossible to obtain a complete vacuum and small traces of gas left in the tube will decrease the electron emission. Most of the gases in the tube, with few exceptions, are inert gases. The presence of gas in the vacuum presents a resistance to the emission of electrons unless ionization takes place. (This particular subject will be taken up later in more detail).

The most important factor in the rate of emission is the temperature of the filament for, upon the rate of emission alone in a certain tube, will depend the number of electrons emitted. It must be understood at this point that the term "Emission" refers only to the emerging of the electrons from the filament and not to the passage of the electron through the vacuum.

Suppose now we attempt to visualize that which takes place in the filament when it is heated. As heat is applied the whole atomic structure is set into a violent agitation and the free electrons about the atoms of the filament are set into rapid vibration. With each increase of heat this vibration increases and the electrons finally gain a velocity in their movements great enough to carry them beyond the positive force of the atom which normally holds them within the filament. As this velocity is attained they emerge from the filament in clouds much as does steam from a pan of boiling water. This happens only after they have acquired a speed which is able to project them beyond the influence of the atom to which they belong.

Once beyond the attractive force of the parent atom they are subject to collisions which are continually occuring as they move about in the filament. Their velocity, on leaving the filament, varies according to the retarding effect these collisions have had upon the electron in its attempt to escape. Once outside the filament they again have difficulty due to the gas molecules which may be present within the vacuum, and with which they continually collide until their energy is exhausted whereupon they are drawn back to the filament.

SPACE CHARGE

The electron constitutes a negative charge of electricity and, on emerging from the filament, leaves the filament positive in respect to the projected electron. The tendency, therefore, is for the electron to be attracted back to the filament. Any gas in the vacuum also presents a resistance to be overcome by the electron. There is also another repelling effect which must be overcome. This is the repelling effect of electrons which are moving at a greater distance from the filament than the newly emitted electrons.

As stated before, the electrons fill the space about the heated filament much as steam fills the space over a pan of boiling water. The electrons, in their countless thousands, may be considered as actual particles of negative electricity, and they constitute in reality an actual negative charge in the space they fill. It is this condition that is called "The Space Charge".

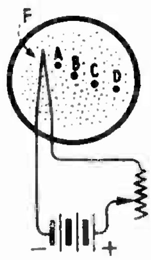


Figure 1

Let us now consider the effect this space charge has upon electrons leaving the filament and, for example, we will consider a single electron. In Figure 1 the filament is shown emitting electrons which are represented by the black dots. The electron A, which is represented by the enlarged dot, is shown a short distance from the filament F and we will assume its velocity carries it to the point shown, first, by overcoming the tendency of the filament to draw it back, second, its velocity carries it against whatever resistance is offered by any gas present and, third, it is carried against the repelling force exercised against it by the electrons which are moving about ahead of it.

At the point shown at "A" the velocity of the electron is spent and it has no further energy to carry it ahead. It is then easily influenced by the repelling action of the electrons beyond it,- also by the attractive force of the filament and it finally returns and is absorbed by the filament.

We will consider Electron "B" as having gained a greater velocity on leaving the filament. It reaches point B before it is drawn back to the filament.

Electron "C" has left the filament at a still greater velocity than either A or B and has reached the point C as shown. This electron has reached a point in the space charge where there is a greater number of electrons behind it than ahead of it and, since like charges repel, electron "C" is actually assisted on its course further away from the filament to point D.

The foregoing will serve to acquaint you with at least a working knowledge of the forces acting upon the electron, this being important because it accounts for certain phenomena which will be encountered later on in our detailed study of the tube.

THE PLATE

In addition to creating a supply of electrons in the vacuum tube it is necessary that we also create some attraction which will cause these electrons to move from their point of origin. This is accomplished by sealing a second element called the plate in the vacuum space. This is shown in Figure 2. It is to be noted that the plate has a connecting lead brought out for a purpose which we will soon explain. For the time being we shall consider the plate as shown in Figure 2 to be sealed in the tube but not connected in any way.

Electrons being emitted will accumulate on the plate and charge it to a negative potential, the negative charge will increase until the plate repels any further electrons moving in its vicinity. Let us now give the plate a positive charge by connecting it to the positive side of a battery, called the "B" battery, as shown in Figure 3. Since this makes the plate positive its natural tendency, in order to restore the state of balance, is to attract any negative charge possible. This it does by drawing to it the electrons being emitted by the filament.

When the plate is connected in the circuit as shown in Figure 3, and is given a positive charge, electro-static lines of force immediately are set up between the plate and terminate at the filament. It is along these lines of force that a positive charge of electricity, as formerly understood, would travel. The electron being a negative charge would move along the same lines of force but from filament to plate which simple means, when expressed differently, that the positive plate will attract to it the negative electrons (unlike charges attract). The attractive force the plate has for the electrons will depend upon the potential of the plate relative to that of the filament

The original tube, known as the Fleming Valve, consisted of only two elements, the filament and plate, as shown in Figure 3.

CHARACTERISTICS OF THE FLEMING VALVE

The phenomenon of a vacuum tube can best be understood by making a preliminary study of the Fleming Valve.

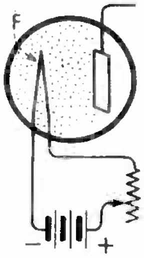


Figure 2

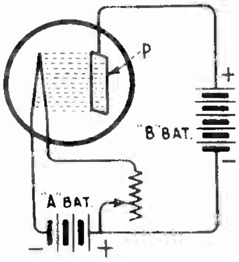


Figure 3

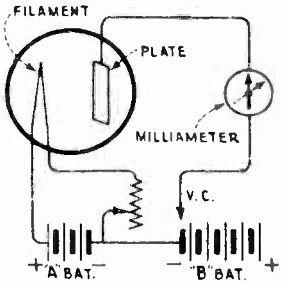


Figure 4

The circuit consists of a source of current, known as the "A" battery to heat the filament. The E.M.F. applied to the filament is made variable. A source of E.M.F., known as the "B" battery, is used to charge the plate and this should also be variable. Such a circuit is shown in Figure 4.

If the plate has a very small positive potential placed on it as shown in Figure 5 a very weak current will flow through the plate circuit, P, M, A, F, because. under these conditions, only a limited number of electrons will reach the plate and the greater majority of them are drawn back into the filament.

It is to be noted here that the plate will have a potential about equal to the filament. Let us, however, connect a battery in the plate circuit as shown in Figure 5A, giving the plate a high positive potential with respect to the filament. Under these conditions nearly all the electrons emitted from the filament will be attracted to the plate resulting in a flow of a comparitively large plate current, as indicated by the milliameter reading. If the B battery is connected as shown in Figure 4 thus placing a negative potential on the plate, the meter will show no deflection because the emitted electrons are negative and they will be repelled by the negative plate. This clearly indicates that electricity cannot flow from the plate to the filament due to the fact that no electrons are passing in the direction of the filament.

As we stated before the rate of emission will depend upon the material of which the filament is made, the size of the filament, and the temperature at which the filament is heated. In the vacuum tube the temperature of the filament is a variable factor. We cannot change the position nor size of any of the elements within the tube, but we can change the filament temperature by a variation of the current passed through it. For a given filament current there will be a corresponding temperature and this temperature will remain constant, providing the current is not varied. At a certain temperature a definite number of electrons will be emitted.

If the circuit as shown in Figure 6 is set up with the filament switch F S open filament current will not flow and no electrons are emitted· hence no plate current will flow, which is indicated by zero reading of the milliameter, M.A. When switch FS is closed current will flow through the filament from battery A. Electrons will then be emitted and as the current increases through the filament its temperature will be increased with a corresponding increase of electron emission.

If the rheostat is set at a point where less than normal filament current flows through the filament and the plate voltage is varied from

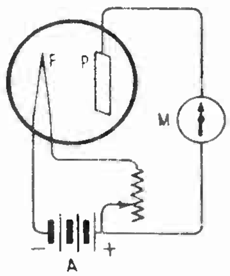


Figure 5

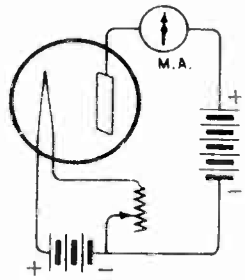


Figure 5A

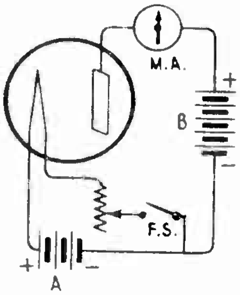


Figure 6

zero upward by changing the taps on the "B" battery a curve as shown in Figure 7, A,B,C,D, is obtained. This shows that plate current increases as the plate voltage is increased. An examination of this curve shows that as the plate voltage is increased at first there is a rapid increase in plate current (A). After a certain value of plate voltage is applied there is no appreciable increase produced in plate current by increasing the plate voltage. This is shown by the horizontal portion D of the curve. If the filament current is now increased and the plate voltage again is varied from zero upward the change in plate current takes place along the curve AEFG. Here the plate current coincides with the lower filament current along part A, but continues to increase above the bend B obtained with the lower filament current. After a certain plate voltage is applied the plate current again fails to increase for further increase in plate potential. This is indicated by the horizontal portion G which however is higher than D, obtained with the lower filament current. If other similar curves are drawn, each corresponding to a definite filament current, the same characteristics would be noted in each, namely a part where the plate current increases as the plate voltage increases. and a part were the plate current is constant even though the plate voltage increases.

From these curves it is evident that with a definite filament current there is a definite plate current that cannot be exceeded. Moreover these curves show that as the filament current increases the maximum value of plate current also increases. This shows that a condition exists in the tube itself which limits the amount of current that can be obtained from the filament. Furthermore it seems certain that this limiting factor depends on the filament temperature which in turn depends on the filament current. Thus we can say that the maximum plate current obtainable depends on the filament. But for each filament temperature there is a definite maximum value of plate current.

A further study shows that the proportion of electrons attracted to the plate depends on the magnitude of the plate potential. When the filament temperature is kept constant and the plate voltage gradually increased the number of electrons attracted to the plate, and therefore the current in the plate circuit, will gradually increase as shown at (A) and (B) of Figure 8. This will continue until a condition is reached where all the electrons are drawn over to the plate as shown at (C). A further increase of plate potential will not result in any increase of plate current. This maximum plate current, beyond which there is no increase for increased plate voltage is known as the saturation current of the tube. For each filament temperature there is a different value of saturation current. Saturation for any definite temperature of the filament occurs when the plate attracts the electrons at the same rate as they are being emitted by the filament. In order to increase the plate current beyond this point it is necessary to increase the filament temperature. The modern tube must be so designed that its filament will be able to emit electrons at a high enough rate so that saturation will not occur at the normal filament current and plate voltage. This means an electron emitter having an ample supply of electrons.

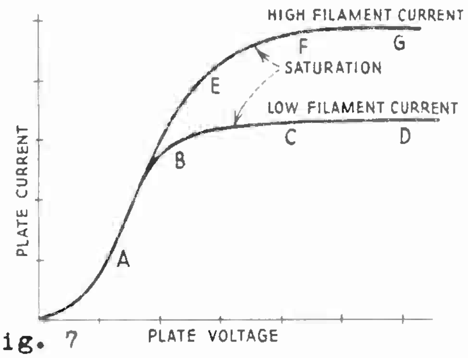


Fig. 7

Characteristic Curves of a Two-Electrode Tube at Two Different Filament Temperatures

GAS EFFECTS

The subject matter just given applies to tubes which are theoretically perfect in vacuum, allowing the electrons to pass in the space between the filament and plate without interference.

When, however, small traces of gas are left in the tube the electron current, which flows when a positive potential is applied to the plate, is increased over that obtained under the same conditions with tubes highly evacuated. The increase in electron current takes place, however, on the condition that ionization takes place.

IONIZATION

Ionization is the effect produced when electrons, on their path from the filament to the plate, collide with the molecules of gas in the tube. The molecule of gas is disrupted by the collision and it frees detachable electrons which then flow with the main body of electrons originating at the filament.

As the "B" voltage is increased the attraction of the plate for the electrons is increased. This, of course, affects the speed of the electrons and when they strike the gas molecules with greater speed the number of electrons freed from the molecules of gas will be increased. It is the liberated electrons from the gas molecules joining the main stream of electrons that increases the plate current.

When the electrons being emitted from the filament have attained a speed great enough they break up the gas molecule into free electrons leaving the gas molecule positively charged. In other words the gas molecule has been ionized and is now what is termed a positive ion. When this takes place in a vacuum tube to any great extent it is made evident by a blue glow which fills the space about the plate because at this point the greatest velocity of the electron occurs. The positive ions thus formed cannot flow to the plate because the plate is positively charged, and like charges repel, and the ions will then move toward the filament. Upon striking the filament they break loose more electrons, which again increases the quantity of electrons available to bombard the plate.

Ionization, therefore, is the splitting or breaking up of gas molecules into free electrons which are always negative and positive charged ions. The freed electrons forming with the main stream of electrons, and the ions shaking more electrons free from the filament which at once start on their journey to the plate, produces increased current in the plate circuit.

THE THREE-ELEMENT VACUUM TUBE

The three-electrode tube differs from the two-element tube only in the introduction of a third element, called the grid.

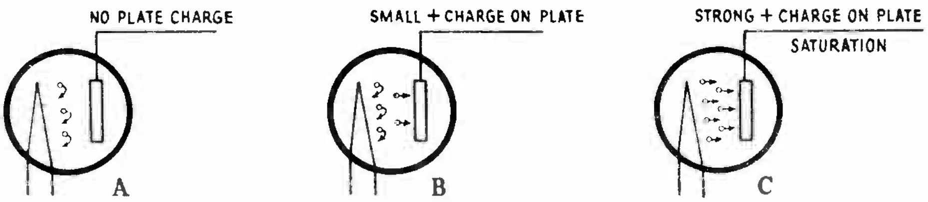


Fig. 8—Action of Electrons in a Two-Element Tube

The introduction of the grid brought about a change in radio that has had a far reaching effect. In fact it was the most important contribution made in the advancement of radio communication since the Fleming Valve was perfected. It greatly increased the sensitiveness of all receiving apparatus used in radio and is directly responsible for all the uses of the modern vacuum tube in transmitting and receiving apparatus.

The grid is capable of controlling the electrons which fill the space between the filament and plate. It exercises a directive power over the cloud of electrons which are racing with tremendous speeds toward the plate. The grid allows certain quantities of the electrons to proceed to the plate or it may prevent them in some cases from striking the plate at all.

By making the grid alternately positive and negative the quantity of electrons flowing from the hot filament to the plate can be increased or decreased. It can thus control large powers of plate current. The amazing feature here is that very small power applied to the grid will exercise this control. How this is accomplished will now be considered

THE USE OF THE GRID

The theory of the two-electrode tube, relative to the electron flow, the space charge, etc., will now be applied while explaining the effects produced by the introduction of the third element, the grid.

The grid is placed in the tube to control the electron flow from filament to plate. For this reason it is often compared to the trigger action of a gun, or the valve control over water, steam lines etc. In the grid, however, we utilize electricity to effect this control. You will remember in our study of the two-electrode tube that the space between the filament and plate was filled with minute negative charges, the electrons. You also know that like charges of electricity will repel and unlike charges will attract.

Now let us refer to the three-electrode tube shown in Figure 9. The grid will then be right in the middle of the cloud of electrons constituting the space charge. If we now connect the negative terminal of a third battery "C" to the grid as shown in Figure 9 we place a negative charge on the grid which will assist the negative space charge.

Since the space charge is already negative an additional negative charge on the grid will repel the greater number of electrons which otherwise would have traveled directly to the plate. As soon as this happens the plate is robbed of electrons and a drop in plate current results. If we have the grid potential battery in Figure 9 arranged so that it is variable, allowing us to gradually increase the negative charge on the grid, a point will finally be reached when the repelling force caused by increasing the negative potential will become great enough to effectually block and turn back all the electrons emitted by the filament.

In this case no current will flow in the plate circuit because electrons are not now reaching the plate. In other words we have made the grid equal in negative force to the positive attraction of the plate and neutralization is the result.

Now let us reverse the battery "C" so the positive terminal is connected to the grid as shown in Figure 10. This will give the grid a positive charge and, since unlike charges attract, the grid will have the effect of attracting the electrons and also conteracting, to a certain extent, the negative space charge. The plate current will be increased because the grid, being made positive, has now added an attractive positive force to that of the plate and consequently assists the plate in attracting electrons to it. By this added positive force in the electron paths the electrons gain a much greater velocity and pass between the fine grid wires striking the plate in greater quantities.

Some of the electrons strike the grid and cause a current to flow therein. This current is usually small and later on methods will be introduced to keep it at a minimum because large grid current is undesirable. If this grid battery C is made variable as in the case of Figure 9, and then gradually changed so that an increasing positive charge is placed on the grid, more and more electrons will be assisted to the plate, but there will be a point reached where further increasing the positive potential of the grid will not draw more electrons from the filament. When the saturation point has been reached further increasing the grid potential will not increase the plate current.

When we consider the repelling effect the space charge has on electrons being emitted it is easily understood how the electron flow is effected when we introduce any element that will either increase or decrease this action of the space charge. The grid has the power to exercise this control as you have observed.

The radio wave is alternating current, rapidly changing from positive to negative. This current is led directly to the grid in the radio receiver and changes the grid rapidly from positive to negative thereby controlling the flow of electrons which, in turn, determine the plate current flow. The plate current flowing through the telephone receivers is made to change in this way. The tube action in the receiving set will bring this explanation out in more detail.

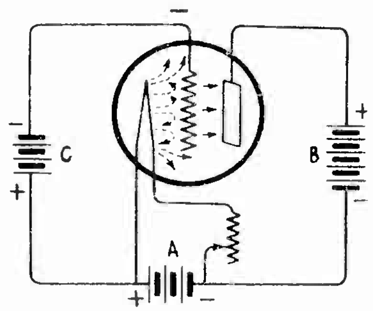


Figure 9

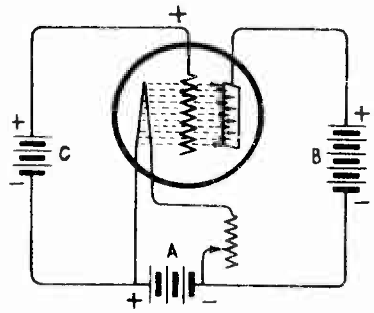


Figure 10

EXAMINATION QUESTIONS

1. What are Thermionic Currents?

2. Of what importance was the discovery of the "Edison Effect"?

3. Does the atom normally possess an electrical charge?

4. Upon what does electron emission depend?

5. Tell what you know about "space charge".

6. (a) In a vacuum tube what is the function of the plate?
   (b) The filament?

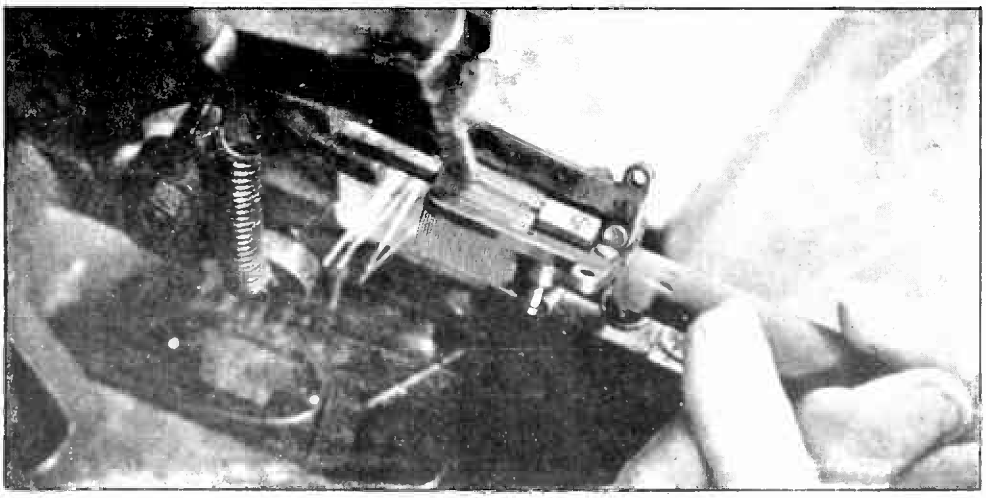
7. What is the effect of ionization?

8. How does the three-element tube differ from the Fleming Valve?

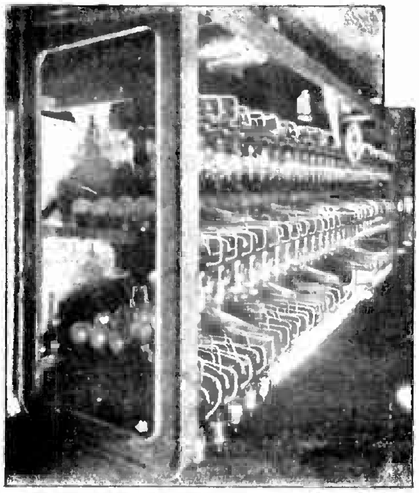
9. Of what importance is the grid element?

10. When the heat applied to the filament is increased is there an increase in the electron emission?

DATA SHEET



Method of Welding the Screen Grid



Radiotrons in the
Seasoning and Degassifying
Process

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