The Pure Electron Discharge and Its Applications in Radio Telegraphy and Telephony

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Classic Paper

The thermionic current produced by the emission of free negative electrons from the surface of heated metals is described in detail. Its theoretical magnitude is calculated for certain definite cases. The limitation of thermionic currents by space charges around the cathode (in high vacua) is explained. In reviewing the bibliography of the subject, it is shown that the preponderance of opinion before the most recent and careful experiments was to the effect the thermionic currents could not be obtained in a pure vacuum. The incorrectness of this conclusion is experimentally proven. The degree of cleanliness of the electrodes and the completeness of exhaustion required to produce these thermionic currents in regular fashion is unusual. With true thermionic currents, the cathode does not disintegrate, and there is no blue glow in the path of the cathode rays even at the highest voltages. An X-ray tube using thermionic currents is described. A rectifier for high voltage alternating current ("kenotron") is considered, its operating characteristics being given. By inserting a third fine wire grid electrode in a kenotron, an amplifying device ("pliotron") is obtained. Its theory, construction, and characteristics are given. Its use in radio receiving stations as a detector or amplifier is described. The "exponential" method of tuning, involving the use of radio frequency pliotron amplifiers in cascade, is shown to have given remarkable selectivity. The pliotron may also be used as a powerful generator of radio frequency energy; or for the modulation or control of such energy. A 20-W radio telephone transmitter, and a 500-W radio telephone outfit are each described in detail.

I. INTRODUCTION

It has been known for nearly 200 years that air in the neighborhood of incandescent metals is a conductor of electricity. Elster and Geitel studied this phenomenon in great detail, and published the results of their investigations in a series of papers in "Wiedemann's Annalen" during the years 1882–1889.

In most of their experiments, they placed a metal plate close to a metallic filament within a glass bulb, and studied the charge acquired by the plate under various conditions of filament temperature and gas pressure. They found in most gases that the filament tended to give off positive electricity when it was at a red heat, but at very high temperatures it gave off negative electricity more easily than positive. When the vessel was exhausted as completely as was possible in those days, the tendency to give off positive electricity was much decreased and did not persist, whereas the tendency to emit negative electricity was apparently stronger than ever.

A similar discharge of negative electricity from the carbon filament of an incandescent lamp to an auxiliary electrode placed within the bulb was observed and studied by Edison and has since been known as the Edison effect. Fleming, in 1896 [1] investigated and described this effect in detail.

J. J. Thomson [2] showed that in the case of a carbon filament in hydrogen at very low pressures, the negative electricity is given off by the filament in the form of free electrons having a mass about 1/1800th of the mass of a hydrogen atom and constituting in reality atoms of electricity. Owen [3] showed that a heated Nernst filament also gives off electrons, and Wehnelt [4] proved that the electric current from a lime-covered platinum cathode (Wehnelt cathode) is carried in the same manner.

Richardson [5] applied the electron theory of metallic conduction to the electron emission from heated metals, and was thus able to develop a theory of this effect. In order to account for the conduction of heat and electricity by metals, Riecke and Drude had assumed that metals contain electrons which are free to move under the influence of an electric force and which are in constant vibratory motion similar to that of the molecules of a gas. Richardson assumed that these free electrons are ordinarily held within the metal by an electric force at the surface, just as the molecules of a liquid are prevented from escaping by a surface force related to the surface tension. If the velocity of an electron is sufficiently high, it may be able to overcome the surface force and escape. Since the average velocity of the vibratory motion increases with the temperature, the number of electrons which reach the necessary critical velocity to escape will increase very rapidly with the temperature. These considerations are strictly analogous to

This paper is reprinted from the PROCEEDINGS OF THE IRE, vol. 3, no. 3, pp. 261–293, Sept. 1915.

Publisher Item Identifier S 0018-9219(97)06640-1.

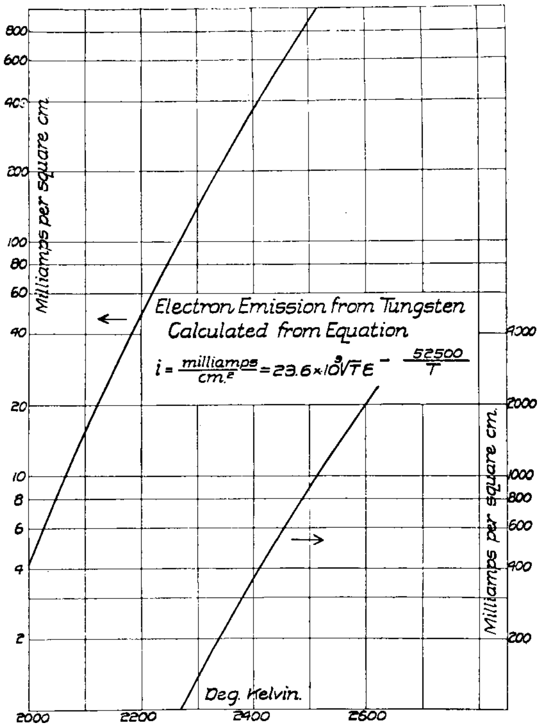

Fig. 1. Electron emission from tungsten in a "perfect" vacuum.

those of the evaporation of a liquid, so that the number of electrons escaping should increase with the temperature according to the same laws as those governing the increase of the vapor pressure of a liquid as the temperature is raised.

It had already been shown that the vapor pressure (p) of a substance varies with the temperature (T) according to a relation of the form

$$p = A\sqrt{T}\varepsilon^{-\frac{\lambda}{2T}}$$

where A is a constant, λ is the latent heat of evaporation of the liquid (or solid), and ε is the base of the natural system of logarithms. Richardson was thus led to conclude that the current from an incandescent metal should increase according to an equation of a similar form, namely

$$i = a\sqrt{T}\varepsilon^{-\frac{b}{T}}.$$

Here i is the current per square centimeter at the temperature T, and b is a constant which should be half the latent heat of evaporation of the electrons.

A curve showing the electron emission from heated tungsten, calculated with the use of appropriate constants from the above equation, is given in Fig. 1.

Richardson suggested that the currents obtained by the emission of electrons or ions from incandescent bodies should be called *thermionic* currents, a term which has since come into very general use.

According to Richardson's theory, an incandescent metal at a given temperature emits a certain number of electrons which is independent of the electric field around the heated body.

If a positively charged body is placed near the heated filament, the electrons will all be drawn away from the filament and will strike and be absorbed by the positively charged body. The motion of these electrons constitutes an electric current, the hot filament being the cathode and the positively charged body the anode of the discharge.

If, however, there is no electric field around the heated filament, or if a negatively charged body be placed near it, the electrons which are emitted from the filament return to it again and are reabsorbed, and therefore no current flows between the two electrodes.

According to this viewpoint, the electron emission is the same whether a thermionic current flows or not. As the potential of the cold electrode or anode is increased, a larger and larger proportion of the electrons emitted are drawn to the anode, so that the thermionic current increases. As the potential is further raised, a point is finally reached at which all the electrons emitted pass to the anode, so that a further increase in voltage causes no increase in current. The current is then said to be "saturated."

Richardson, in 1902, determined the relation between the saturation current from a heated platinum wire and a cylinder around it, and found that i varied with the temperature in accordance with the equation given above. For other substances also he found the relation to hold.

Since 1903, Richardson's theory of thermionic currents has been the subject of much investigation and discussion. H. A. Wilson [6] found that the electron emission from platinum at high temperature was decreased to 1–250 000 of its former value by a preliminary heating of the platinum in oxygen, or by boiling in nitric acid. The admission of a little hydrogen brought the current back to its former value.

Wehnelt [7] discovered that platinum cathodes covered with lime emit vastly more electrons than platinum alone. He proposed using tubes containing such cathodes as rectifiers for alternating current of 100 or 200 V, and described a Braun tube in which very soft cathode rays (100–1000 V) could be produced. Wehnelt worked usually with gas pressures ranging from 0.01 to 0.1 mm of mercury, the lowest pressure recorded being 0.005 mm. Under these conditions the paths of the cathode rays were visible, showing that there was strong ionization of the gas.

Soddy [8] found that the large currents obtainable from a Wehnelt cathode stopped suddenly if the residual gases in the vacuum tube were absorbed by vaporizing some metallic calcium. This work of Soddy attracted considerable attention and made many investigators feel that thermionic currents in general were dependent on the presence of gas.

Lilienfeld [9] however, considered that Soddy's experiments did not show that the electron emission from the Wehnelt cathode had decreased, but suggested that the decrease in current might be caused by the building up of a negative charge in the vacuum because of the large number of electrons needed to carry the current.

Fredenhagen [10] in 1912 studied the electron emission from sodium and potassium, two metals that Richardson had found particularly good sources of electrons, and concluded that the electrons are only emitted as a result of the presence of gas. He suggested that if a perfectly clean metallic surface could be obtained in a perfect vacuum the electron emission would cease entirely.

Pring and Parker [11] in the same year measured the currents from incandescent carbon rods in a vacuum. They found that with progressive purification of the carbon and improvement in the vacuum, the currents decreased to extremely small values. They conclude that "the large currents hitherto obtained with heated carbon cannot be ascribed to the emission of electrons from carbon itself, but that they are probably due to some reaction at high temperatures between the carbon, or contained impurities, and the surrounding gases, which involves the emission of electrons."

More recently Pring [12] repeated these experiments under still better vacuum conditions and finds the former results confirmed. He concludes that "the thermal ionization ordinarily observed with carbon is to be attributed to chemical reaction between the carbon and the surrounding gas." "The small residual currents which are observed in high vacua after prolonged heating are not greater than would be anticipated when taking into account the great difficulty of removing the last traces of gas."

A similar feeling gradually arose in regard to the photoelectric effect, a phenomenon resembling the electron emission from incandescent metals, except that the electrons are emitted by the action of light—usually ultraviolet light, instead of heat.

Pohl and Pringsheim [13] find that the photoelectric effect is very much decreased by improving the vacuum, and suggest that perhaps the whole effect is due to interaction between the gas and the metal. Wiedmann and Hallwachs (the latter the discoverer of the photoelectric effect) [14] go further and state emphatically as a conclusion from experiments with potassium that "The presence of gas is a necessary condition for appreciable photo-electric electron emission."

Fredenhagen and Kuster [15] conclude that the same is true for the photoelectric effect from zinc, and in a still later publication Fredenhagen [16] finds that both the photoelectric and thermionic electron emission from potassium are entirely dependent on the presence of gas.

We see, then, that there were the best of reasons for believing that it would be impossible to get any electric discharge thru a perfect vacuum, because one could not expect to get any electrons from the electrodes. In the operation of ordinary X-ray tubes it was well known that a certain amount of gas was necessary. Porter [17] studied the dynamic characteristics of the Wehnelt rectifier and found that with pressures as low as 0.001 mm there was a tendency for the current to become unstable, fluctuating periodically between zero and a higher value.

With higher pressures, this difficulty was avoided, but the characteristics clearly showed a sort of hysteresis loop, the current with ascending voltage being different from that obtained with descending voltage.

My active interest in thermionic currents began in connection with some experiments on electrical discharges occurring within tungsten lamps. According to Richardson's data on the electron emission from such metals as platinum and osmium, the currents that might exist across the evacuated space in a tungsten lamp would be very large; in fact, the current density, at temperatures close to the melting point of tungsten, might be expected to be several hundred amperes per square centimeter. Of course it is evident at the outset that the current flowing from one part of a filament to the other thru the vacuum must actually be very small in any ordinary lamp. It was known that the vacuum in a tungsten lamp is extremely high, and measurements indicated that in well-exhausted lamps after 100 hours of life the pressure was probably less than one millionth of a millimeter of mercury. Taking these two facts into account, the very existence of a tungsten lamp seems strong evidence that thermionic currents in a high vacuum must be very small, if not entirely absent.

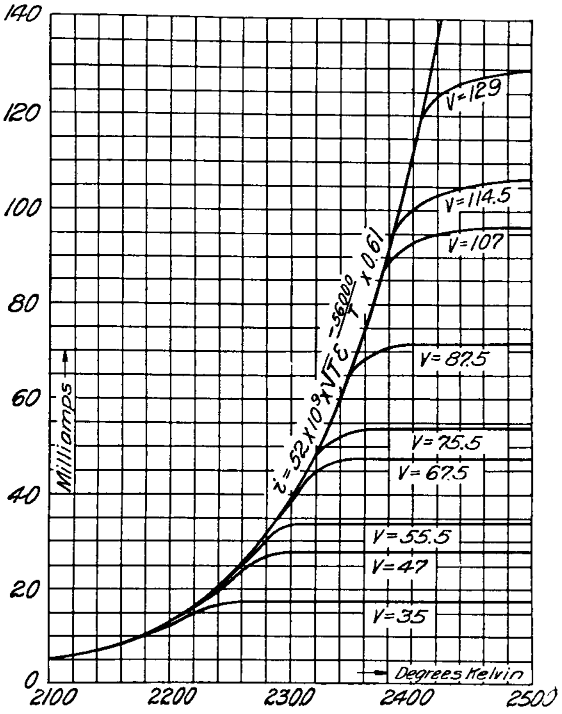

Fig. 2. The effect of space charge on the thermionic currents.

When this effect was studied in more detail, it was found that the smallness of the currents in a lamp was not due to any failure of the filament to emit electrons, but was due entirely to an inability of the space around the filaments to carry the currents with the potential available in the lamp.

In one case, two single loop tungsten filaments were mounted side by side in the bulb. After the bulb was exhausted in the best possible way and the filaments were thoroly aged and freed from gas, one of the filaments was heated while a positive potential was applied to the other thru a galvanometer. The hot filament thus served as a cathode in the discharge occurring in the lamp. As the current thru the cathode was increased, the thermionic current as measured by the galvanometer increased at first, according to Richardson's equation as shown in Fig. 1; but beyond a certain point, as indicated in Fig. 2, the further increase in the temperature of the cathode produced no further increase in thermionic current.

The curve representing thermionic current as a function of temperature therefore consists essentially of two parts: first, a part in which Richardson's equation applies; second, a part in which the current is independent of the temperature. In the first part of the curve, it is found that the current is independent of the voltage, or shape and size of the anode, but in the second part of the curve the current is affected by both of these factors and may also be either increased or decreased by placing the lamp in a magnetic field. It is thus evident that the only reason that the current does not continue to increase, according to Richardson's equation, is that the space between the electrodes is capable to carrying only a certain current with a given temperature difference.

The explanation of this phenomena was found to be that the electrons carrying the current between the two electrodes constituted an electric charge in the space which repelled electrons escaping from the filament and caused some of them to return to the filament.

A further theoretical investigation on the effect of this space charge led to the following formulas by which the maximum current that can be carried thru a space (of certain symmetrical geometrical shapes) may be calculated.

In the case of parallel plates of large size, separated by the distance x, the maximum current per square centimeter, i, is

$$i = \frac{\sqrt{2}}{9\pi}\sqrt{\frac{e}{m}}\frac{V^{\frac{3}{2}}}{x^2}. \tag{1}$$

Here, e is the charge on an electron, m the mass of an electron, and V the potential difference between the plates. If we substitute the numerical value of e/m and express i in amperes per square centimeter and V in volts, then this equation becomes

$$i = 2.33 \times 10^{-6}\frac{V^{\frac{3}{2}}}{x^2}. \tag{2}$$

In the case of a wire in the axis of a cylinder, the maximum current per centimeter of length from the wire is given by the equation

$$i = \frac{2\sqrt{2}}{9}\sqrt{\frac{e}{m}}\frac{V^{\frac{3}{2}}}{r}. \tag{3}$$

If we substitute numerical values as before, we find

$$i = 14.65 \times 10^{-6}\frac{V^{\frac{3}{2}}}{r} \tag{4}$$

where i is the current in amperes per centimeter of length, and r is the radius of the cylinder in centimeters.

These equations have been found to agree accurately with experiments when the vacuum is so high that there is no appreciable positive ionization.

Extremely minute traces of gas, however, may lead to the formation of a sufficient number of positive ions to neutralize, to a large extent, the space charge of electrons and thus very greatly increase the current carrying capacity of the space. For example, a pressure of mercury vapor of about 1/100 000 mm has, under certain conditions, been found to eliminate completely the effect of space charge, so that a current of 0.1 A was obtained with only 25 V on the anode, whereas, without this mercury vapor, over 200 V were necessary to draw this current thru the space.

Besides this enormous effect on the current carrying capacity of the space, many gases have a great influence on the electron emission from the cathode. But in every case where the cathode is of pure tungsten, the effect of gas is to decrease, rather than increase, the electron emission. For example it is found that a millionth of a millimeter of oxygen, or of a gas containing oxygen, such as water vapor, will cut the electron emission down to a small fraction of that in high vacuum.

As a result of this work, we became firmly convinced that the electron emission from heated metals was a true property of the metals themselves and was not, as has so often been thought, a secondary effect, due to the presence of gas.

Further investigation showed that with the elimination of the gas effects, all of the irregularities which had previously been thought inherent in vacuum discharges from hot cathodes were found to disappear. In order to reach this condition, however, it was not sufficient to evacuate the vessel containing the electrodes to a high degree, but it was essential to free the electrodes so thoroly from gas that gas was not liberated from them during the operation of the device. It was also necessary to free the glass surfaces very much more thoroly from gas than had been thought necessary previously. The difficulty thus consists not in the production of the high vacuum, but in the maintenance of this vacuum during the use of the apparatus. As the voltage applied to the terminals was increased and as the current density in the discharge increased, the tendency for the gas residue to become ionized became very much more marked and the difficulties in maintaining a sufficiently high vacuum increased still further. However, by special methods of exhaustion and by special methods of treating the electrodes, these difficulties have been overcome and it has thus been possible to construct apparatus in which a large current density can be obtained and potential differences of much more than 100 000 V may be applied without obtaining effects attributable to positive ionization.

In previous devices which employed discharges thru a vacuum, either with or without a hot cathode, there was always evidence of positive ionization if the current density was increased above an extremely low value, or if potentials over 50 or 100 V were applied while a current of as much as a few milliamperes was flowing. The effects of this positive ionization manifested themselves in many ways. If the ionization was sufficiently intense, a glow thruout the tube was visible. For example, in the Braun tube, with a lime-covered cathode, Wehnelt states that as high a vacuum as possible should be obtained, but he speaks of being able to see the path of the cathode rays. It has apparently always been assumed that cathode rays of sufficiently high intensity can always be seen, but of course such a luminosity is direct evidence of ionization of the gas. One of the most sensitive indications of the presence of positive ionization is the failure of the current to increase with the voltage in a regular manner, as shown in (2) and (4). If much gas is present, and by this I mean a pressure in the order of 1–10 000 mm, the current-voltage curve often shows decided kinks when the voltage is raised above 50 or 100 V. In many cases the discharge is unstable and fluctuates periodically between two values. All these effects tend to be extremely erratic, since they vary with the composition and the pressure of the residual gases, and these, in turn, are altered by the discharge taking place thru them. For example, in the ordinary X-ray tube, the vacuum continually improves, and it is necessary, from time to time, to admit fresh portions of gas.

With the higher voltages, perhaps the most troublesome feature of positive ionization is its tendency to disintegrate the cathode. The positive ions, moving under the influence of the electric field, acquire high velocity, and when they strike the cathode cause rapid disintegration and ultimate destruction of the electrode. With a pure electron discharge, however, there is no disintegration of the electrode caused by the discharge and the filament lasts the same length of time as if no current passed thru the vacuum.

Another effect, produced by positive ionization, is the emission of electrons from the cathode under the influence of the positive ion bombardment. These electrons, which constitute the so-called delta rays, escape from the cathode with considerable initial velocity, and are therefore capable of charging up a third electrode in this space to a potential of ten or fifteen volts negative with respect to the cathode.

With the pure electron discharge, none of these effects are present. The cathode rays are entirely invisible, the current voltage curve is a smooth curve and follows the 3-2 power law, in case the filament temperature is sufficiently high and the shape of the electrodes is such that the small initial velocities of the electrons from the cathode do not play too large a role. It is possible to obtain a very high current density in this type of discharge, but in order to overcome the space charge effects, it is then necessary to use a very strong electric field close to the cathode.

A. Devices Employing a Pure Electron Discharge

Dr. Coolidge [18] has used the pure electron discharge in the construction of a new type of X-ray tube. In this tube the cathode consists of a small, flat spiral of tungsten wire, surrounded by a small molybdenum cylinder which serves as a focusing device, while the anode, or target, consists of a massive piece of tungsten, placed near the center of the tube. With this tube it has been possible to use voltages as high as 200 000 V in the production of X-rays. The current thru the tube is absolutely determined by the electron emission from the filament, which, in turn, depends on the temperature, in accordance with Richardson's equation.

The advantages of this tube over the ordinary X-ray tubes previously used are many. Perhaps the most important feature is that the current and voltage are under complete control at all times, the current being fixed by the temperature of the cathode while the voltage is simply that furnished by the transformer or induction coil used. The tube seems to have an almost unlimited life, the temperature of the filament being so low that no appreciable evaporation occurs and the absence of gas eliminating the cathodic disintegration usually characteristic of high voltage discharges in vacuum. The tube is entirely constant in its action and the erratic effects usually observed in X-ray tubes are eliminated.

Several other types of apparatus have also been developed making use of this pure electron discharge, and these devices possess the same advantages over apparatus formerly used as the Coolidge X-ray tube possesses over the ordinary X-ray tube.

In order to distinguish these devices from those containing gas and in most cases depending upon gas for their operation, the name "kenotron" has been adopted. This word is derived from the Greek *kenos*, signifying empty space (vacuum), and the ending, *tron*, used by the Greeks to denote an "instrument."

B. Kenotron Rectifier

The Coolidge X-ray tube is, of course, a rectifier for high voltage alternating current, but it is not suitably designed for this purpose. In an X-ray tube, the voltage applied must be consumed in the tube itself, whereas in the rectifier the voltage in one direction should be consumed in the load in series with the rectifier, altho the voltage in the opposite direction should be taken wholly by the rectifier. In the X-ray tube, because of the great distance between anode and the cathode and the presence of a focusing device around the cathode, the space charge effects are very much exaggerated, so that it is necessary to apply several thousand volts, in order to get even 10 mA of current. This voltage necessary to overcome the space charge, is completely lost when the tube is used as a rectifier.

To overcome this loss of voltage as far as possible, the anode and cathode in the kenotron are placed close together, and everything is avoided which might tend to screen the cathode from the field naturally produced by the anode. In this way it has been possible to build kenotrons which have supplied pure electron currents of over an ampere, with a voltage drop of about 200 V. This current, however, requires large anodes and cathodes, so that it is usually more convenient to build kenotrons with a current capacity of not over 250 mA, and if it is desired to rectify larger currents than this, to place several kenotrons in parallel.

There seems to be no upper limit to the voltage at which a kenotron can operate. A kenotron has been built capable of rectifying 250 mA at 180 000 V, and there seems to be every reason to think that kenotrons could be used at very much higher potentials if desired.

The design and the characteristics of kenotrons has recently been described in a paper by Dr. Dushman [19] and I will therefore only briefly describe these devices.

Fig. 2 gives the characteristics of a typical kenotron designed for rather large currents. The curves show the current carried by the kenotron for different filament temperatures at given voltages between the electrodes. For example, if the temperature of the filament is 2400° the maximum current that can be obtained with any voltage is about 112 mA.

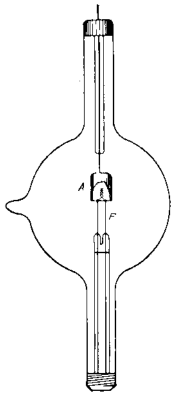

Fig. 3. Molybdenum cap type of kenotron.

If, however, the resistance of the load is able to hold the current down to a value of say 54 mA, then we see from the curves that the voltage drop in the kenotron would be 75.5 V. The remaining voltage, which may be many thousands of volts, is consumed in the load in series with the kenotron.

Figs. 3 and 4 illustrate two forms of kenotrons, one for voltages up to about 10 000, and the other one suitable for use up to 50 000 V. With voltages higher than about 12 000 to 15 000 V, the kenotron of the type shown in Fig. 3 is apt to fail, because the electrostatic attraction of the anode pulls out the helically wound filament and short circuits the device. At the higher voltages, therefore, it is necessary to support the filament and to balance, as far as possible, the electrostatic forces acting on it.

The characteristics of the kenotron are such that the current flowing thru it is always perfectly stable, so that several kenotrons can be run in parallel and each one will take its proper share of the current. This is in marked contrast with the behavior of mercury arc rectifiers, which have negative characteristics and therefore, if several are placed in parallel, one of them takes the whole of the current.

Owing to the absence of gas effects, the kenotron is a perfect rectifier, in that no measurable current flows in the reverse direction, even when voltages of 100 000 V or more are applied. For similar reasons, it is capable of rectifying radio frequency currents, as well as audio frequency, there being not the slightest sign of any lag effects.

C. Amplifying or Controlling Devices—Pliotrons

In a pure electron discharge, as the temperature of the filament is raised, a point is always reached where the current becomes limited by the space charged between the electrodes. Under these conditions, only a small fraction of the electrons escaping from the cathode reach the anode, whereas the majority of them are repelled by the electrons in the space and therefore return to and are absorbed by the cathode. From this viewpoint it is evident that if a negatively charged body is brought into the space between the anode and cathode, the number of electrons which then return to the cathode will increase, so that the current to the anode will decrease. On the other hand, if a positively charged body is brought near the cathode, it will largely neutralize the negative charges on the electrons in the space and will therefore allow a larger current to flow from the cathode. In this way it is possible to control the current flowing between anode and cathode by an electrostatic potential on any body placed in proximity to the two electrodes. This controlling effect may be best attained by having this controlling member in the form of a fine wire mesh, or grid, placed between the electrodes.

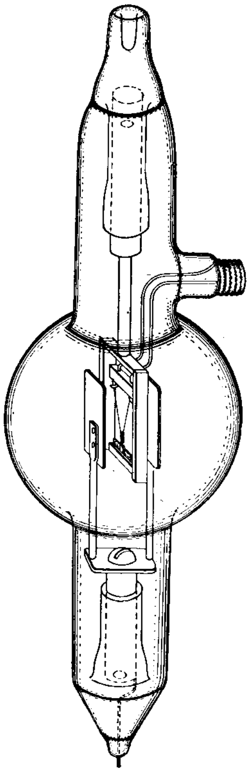

Fig. 4. Kenotron with filament between two parallel plates.

The term "pliotron" has been adopted to designate a kenotron in which a third electrode has been added for the purpose of controlling the current flowing between the anode and cathode. This word is derived from the Greek "*pleion*" signifying "more." A pliotron is thus an "instrument for giving more" or an amplifier. A similar use of the prefix "plio" occurs in the geological term "pliocene."

The three elements, hot filament cathode, grid, and anode, are, of course, similar to the elements of the de Forest audion. However, the operation of the audion is in many ways quite different from that of the pure electron device operating in the way I have described above.

In the audion, as in the Lieben–Reisz relay, the amplifying action appears to be largely dependent on gas ionization, even when the device operates well below the point at which blue glow occurs. The action is probably somewhat as follows. There is normally present a small amount of gas ionization, due to the passage of the electrons between cathode and anode. The presence of the positive ions partly neutralizes the space charge which limits the current flowing between the electrodes. If a small positive

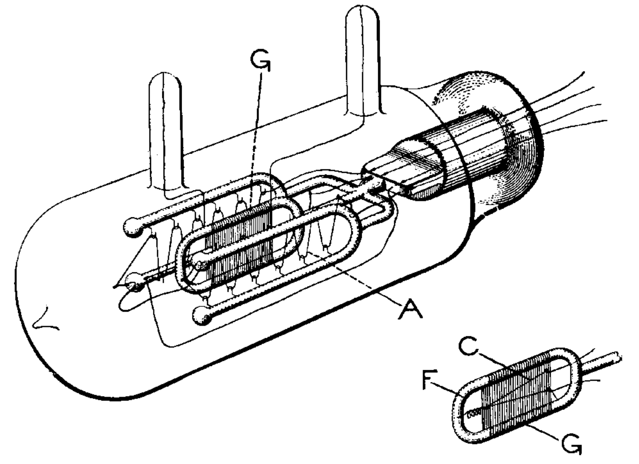

Fig. 5. Small pliotron.

potential is applied to the grid, the velocity of the electrons passing by it is somewhat increased, and they therefore produce more ions in the gas. Besides this, as the potential on the grid is increased, the number of electrons passing the grid is increased, and this again tends to increase the amount of ionization. A very slight increase in the amount of ionization brought about in this way very greatly reduces the space charge, and therefore largely increases the current that can flow between the electrodes. In this way, with a given construction of grid, filament, and plate, the relaying action may be very greatly increased beyond that which would occur if no gas were present. The amount of gas ionization which is necessary, in order to eliminate practically completely the effects of space charge, is often much too small to produce a visible glow in the gas.

If too much gas is present, or if the potential on the plate or the current flowing to the plate is too large, then the amount of positive ionization may reach such values as to neutralize almost entirely the space charge and thus allow a large current to flow. Under these conditions, the relaying action of the audion is lost. This is the case, for example, when the audion gives a blue glow. In the border land between these two conditions, there is a region of instability in which the sensitiveness of the audion may be enormously great, but it is usually not found very practicable to operate the device in this region because of the difficulties in maintaining adjustment, for any lack of adjustment may cause the audion to go over into a condition of blue glow.

The audion is often used with a condenser in series with the grid. Under these conditions, the audion requires the presence of a certain amount of gas ionization so that the positive ions formed may prevent the accumulation of too large a negative potential on the grid. With the pliotron, owing to the absence of positive ions, if it is desired to use a condenser in series with the grid, this condenser must be shunted by a high resistance and often a source of potential must be placed in series with the higher resistance, in order to supply positive electricity to the grid as rapidly as this tends to be taken up from the electrons given off by the filament.

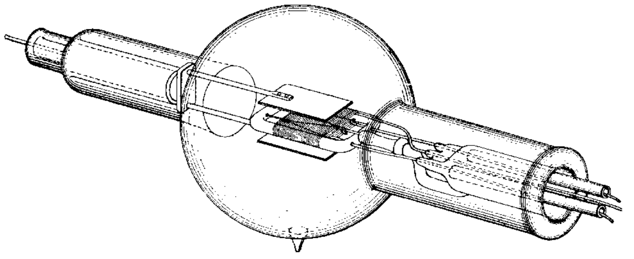

Fig. 6. Large pliotron.

D. Construction of Pliotrons

In the construction of pliotrons, it has been found desirable to make the wires constituting the grid of as small cross section as possible. In this way, even when a positive potential is applied to the grid, the current that flows to the grid may be made extremely small. The use of very fine wire is made possible by using a frame of glass, metal, or other suitable material, to support the grid. Thus, in Figs. 5 and 6, the filament is mounted in the center of a frame made of glass rods, on which the fine grid wire is wound by means of a lathe. The grid may thus consist of tungsten wires of a diameter as small as 0.01 mm and these may be spaced as close as 100 turns per cm, or even more.

In Figs. 5 and 6 are shown two types of pliotron. Fig. 5 shows a pliotron such as is used for amplifying radio signals in a receiving station. Fig. 6 shows a large pliotron which may be used for controlling as much as 1 kW of energy for radio telephony.

The characteristics of the pliotron depend upon the length of filament used, the distance between filament and grid, spacing between the grid wires, diameter of the grid wires, the distance between grid and anode, and the size and shape of the anode. The important elements in the characteristics of a pliotron are: first, the relation between the current flowing between anode and cathode as a function of the potential on the anode and of that on the grid; second, the current flowing to the grid, as a function of the potential of the grid and the potential of the anode.

Fig. 7 gives the characteristics of a small pliotron such as that shown in Fig. 5. Curve A gives the current flowing to the anode for different grid potentials, while the potential of the anode is maintained constant at 220 V. Curve G gives the current flowing to the grid under the same conditions. For different anode potentials, these curves are shifted vertically, by amounts proportional to the change in anode potential. In fact, it is found that these curves can be represented with fair approximation by a function of the form

$$i = A(V_a + kV_g)^{\frac{3}{2}}$$

where i is the current flowing to the anode, V_a is the voltage on the anode, V_g the voltage on the grid, and k the constant which depends on the relative shapes and positions of the electrodes.

Fig. 8 gives similar characteristics for a large pliotron like that shown in Fig. 6. In this case, the anode potential

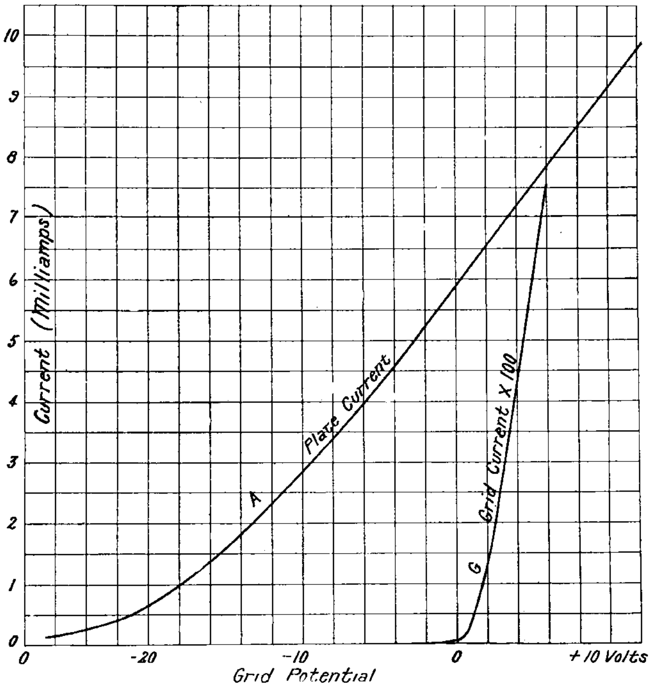

Fig. 7. Characteristics of small pliotron.

was 8500 V. Since the grid is at a negative potential, no perceptible current flows in the grid circuit.

By using a fine grid, the current to the anode can be stopped entirely by even a very slight negative potential on the grid. On the other hand, a rather low positive potential will then be sufficient to draw a large current to the anode. The amount of current taken by the grid would be only a very small fraction of that flowing to the anode, in case the diameter of the grid wires is small compared to the distance between them. On the other hand, with a coarse grid, that is, a grid in which the spacing is large, a rather large negative potential may be necessary, in order to stop the current flowing to the anode. Similar results to those obtained by changing the spacing of the anode, may be obtained by changing the relative distances between the electrodes. The effects produced in this way may be expressed approximately by means of the constant k in the above equation; the effect of fine spacing thus being to increase the value of k, while coarse spacing decreases it.

By using a fairly coarse grid, consisting of fine wire, it is possible to obtain a control of the current to the anode, always using a negative potential on the grid. Under these conditions, since there are no positive ions present, no current flows to the grid, except that necessary to charge it electrostatically to the required potential. It thus becomes possible to control very large amounts of energy in the anode circuit, by means of extremely minute quantities of energy in the grid circuit.

There does not seem to be any upper limit to the voltages that may be used in the pliotrons. With voltages over 30 000 V, it is often necessary to space the electrodes further apart and to use heavier wires for the grid, in order to reduce the danger of breakage of the parts by the large electrostatic forces which then occur.

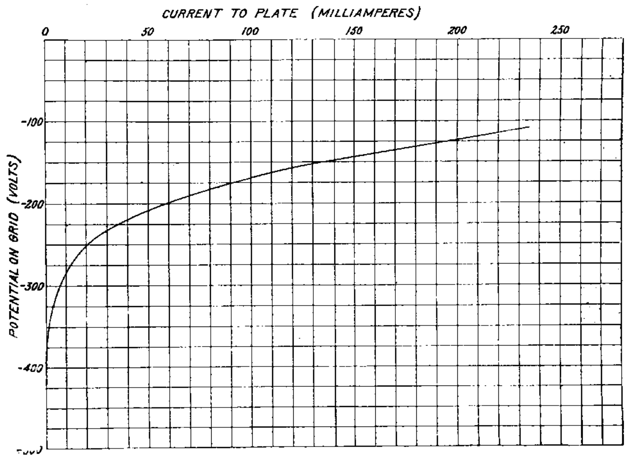

Fig. 8. Characteristics of large pliotron.

The current carrying capacity of the pliotron is limited only by the size of cathodes that it is found convenient to use and by the voltage available. Large currents cannot be readily obtained with low voltages because of the space charge effect described previously. With voltages above 500 V, however, it is found practicable to use currents of 300 or 400 mA for a pliotron of the type shown in Fig. 6. With high potentials, there is no difficulty in using currents as large as this, provided the energy is consumed in some device in series with the pliotron. On the other hand, if the full voltage is applied to the anode while the current is flowing to the anode, the energy liberated in the form of heat may be so great as to volatilize the anode or cause it to radiate so much heat that the glass parts of the apparatus are softened. In a pliotron with a 5-in (12.7 cm) bulb the amount of energy that may be so consumed within the pliotron is about 1 kW. Still larger amounts of power may be dissipated if the bulb is immersed in oil and if the grid frame is made of quartz, or other heat resisting material.

It is evident from the characteristics of the pliotron that any number of these devices may be placed in parallel and that in this way, very large amounts of power may be controlled.

II. Pliotrons in a Radio Receiving Station

A. Pliotron as a Detector

If the antenna of a receiving set is coupled directly to the grid of a pliotron and a telephone receiver is placed in series with the anode, signals may be readily detected, but the results obtained in this way are usually very poor. Under these conditions, the sensitiveness of the arrangement is proportional to the curvature of the curve A, Fig. 7 (or, more accurately, proportional to the second derivative of the anode current with respect to the grid potential). This curvature may be somewhat increased by applying a negative potential to the grid, but even under

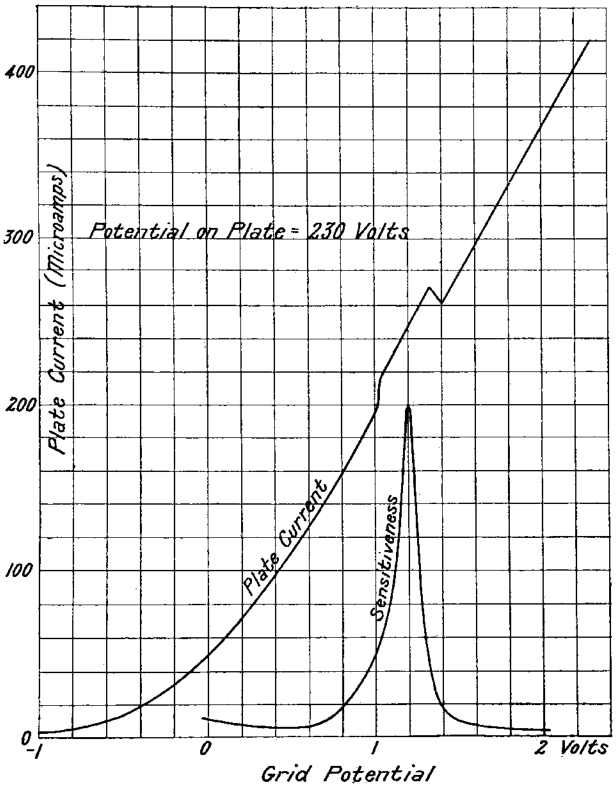

Fig. 9. Characteristics of detector containing a trace of mercury vapor.

these conditions the sensitiveness of the arrangement is usually not very high.

If it is attempted to use a condenser in series with the grid and thus use the pliotron in the way that the audion is often used (as described, for example, by Armstrong [20], it is found necessary to shunt the condenser with the resistance and often to place a battery of a few volts in series with the resistance, in order to present a large negative charge from accumulating on the grid.

It has been found, however, by Mr. White, that a very minute trace of certain gases may very greatly increase the sensitiveness of this device as a detector. For example, by placing within the bulb a small quantity of an amalgam of mercury and silver, the characteristics of the tube show a kink, as indicated in Fig. 9. With a detector of this sort, if the grid potential is adjusted so that its average value is approximately that at which the kink occurs, there is a very marked increase in sensitiveness. This is due to the fact that under these conditions either an increase or a decrease in the grid potential causes a decrease in the anode current. The sensitiveness of this detector is then very high. The quantities of mercury vapor necessary to give this effect are so low that anode voltages of 200 V or more may be used without any indication of glow discharge.

B. Pliotron as Amplifier

The value of a pliotron as an amplifier is dependent primarily on the slope of the curve between anode current and grid potential; for example, curve A, Fig. 7. A second factor of importance is the magnitude of the current taken by the grid. In order to get the greatest amplifying effect it is desirable to have this current as low as possible. In a pliotron of the type shown in Fig. 5, the current to the anode increases at the rate of about 1 mA per volt change in the grid potential.

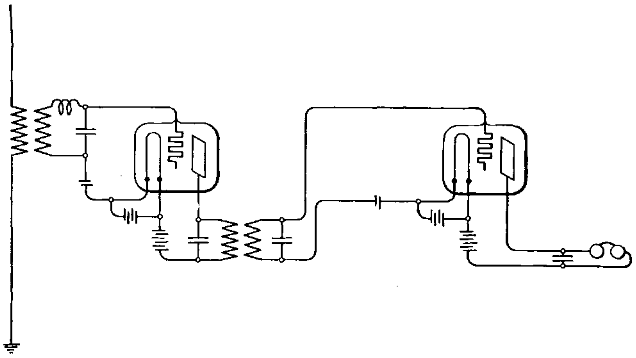

Fig. 10. Arrangement of two pliotrons in cascade, employing "tuning in geometrical progression."

By using larger anode potentials, the slope of the curve can be made very much greater, since it becomes possible to use grids of finer mesh. For example, in Fig. 8 it is seen that the slope of the curve corresponds to about 1.9 mA increase in anode current per volt change in grid potentials.

It has been found that there is no sluggishness in the characteristics of the pliotron, even at the highest frequencies.

By connecting the pliotron as an amplifier, as shown in Fig. 10, the high frequency currents received from the grid may be amplified from 100- to 600-fold. In this arrangement, it is the high frequency or radio frequency that is amplified, and not the audio frequency. This amplification of the radio frequency possesses the marked advantage that the detector circuit may be tuned to the same frequency as the amplifier circuit, and in this way a very marked increase in selectivity is obtained. In fact, it has been shown by Mr. Alexanderson that the resonance curve of an outfit consisting of amplifier and detector, both tuned to the radio frequency as shown in Fig. 10, may be obtained from the resonance curve for the detector alone, by squaring the ordinates. For example, if with a single detector, the signals from one station (A) are received 100 times as strongly as those from another station (B), then, with the above arrangement with the amplifier, the signals from A will be received 100 times more strongly, or 10 000 times as strong as those from station B. If two amplifiers be used in this way, the signals from station A could be obtained one million (or 100^3) times as strong as those from station B.

In practice, this arrangement has been found to give a wonderfully high degree of selectivity.

Of course, a pliotron may also be used for amplifying the audio frequency, coupling the circuits together by means of an iron core transformer. A single pliotron, under these conditions, gives an amplification of current of several hundred fold, when voltages of from 100 to 200 V are used on the anode.

C. Pliotron as Oscillator

By placing inductance and capacity in the grid and plate circuits and coupling these two circuits together, it is possible to use the pliotron as a source of continuous oscillations. Small pliotrons of the type shown in Fig. 5 may produce oscillations of a power up to a few watts, and these may be used in a receiving station, according to the heterodyne principle, for receiving continuous oscillations. One pliotron may be used both for amplifying or detecting, and for producing oscillations.

With the larger pliotrons, using voltages of a few thousand volts, up to a kilowatt of radio frequency oscillations may readily be produced by a single tube.

III. USE OF THE PLIOTRON IN RADIO TELEPHONY

By means of a single large pliotron, it has been found possible to control about 2 kW of energy in an antenna by means of the currents obtained from an ordinary telephone transmitter. There are many arrangements by which this may be accomplished. For example, a 2-kW Alexanderson alternator (100 000 cycles) may be loosely coupled to the antenna and the anode of the pliotron may be connected to a point on the antenna where the potential is normally high. So long as the potential on the grid of the pliotron is strongly negative, no current flows to the pliotron and therefore the full energy is radiated by the antenna. If, however, the negative potential on the grid is decreased, a sufficient current may be drawn from the antenna strongly to damp the oscillations and thus greatly to decrease the energy radiated. With sufficiently high potential on the grid, practically the whole of the energy may be diverted from the antenna.

It is thus possible to control the output of the antenna by varying the negative potential on the grid of the pliotron. Since the grid is always negative, no current flows between filament and grid, and therefore practically no energy is required to maintain the charge on the grid. In this way, therefore, by connecting the secondary of a transformer between the grid and filament, and placing the primary of the transformer in series with a telephone transmitter, it is possible by means of the variations in the currents from the telephone transmitter to obtain potentials on the grid of several hundred volts and thus to control the output of the antenna.

Instead of using an arc or alternator as a source of radio frequency current, the pliotron may also be used as a generator of the oscillations. One pliotron may be used both for producing the oscillations and for controlling the amplitude of the oscillations, in accordance with the variation of pitch and amplitude of the sound waves acting on the telephone transmitter. It is usually preferable, however, to use a large pliotron for producing the oscillations, and to connect a small pliotron in the grid circuit of the large pliotron for controlling the output of the latter.

With the above arrangement an extremely simple and efficient radio telephone outfit can be made. Since the pliotron for producing oscillations requires comparatively high direct current voltages, it has been found convenient to combine the pliotron oscillator with a kenotron rectifier. Two types of apparatus of this type have been in use a considerable time, and it will be of interest to describe these in some detail.

In the first outfit, which is a small outfit having a capacity of about 20 W in the antenna, the source of power is the local city supply, which is 118 V, 60 cycle alternating current. This is connected with the primary of a small transformer, having two secondary windings. One of the secondaries is designed to give about 5 V and furnishes the current used for heating the filaments of the kenotrons and pliotrons. The other secondary of the transformer is wound to furnish a potential of about 800 V. This is rectified by means of a kenotron and serves to charge a condenser of about 6 microfarads. In this way a source of high voltage, direct current is obtained in a very simple manner. The plate of the pliotron oscillator is then connected to one of the terminals of the condenser, while the filament is connected to the other. The plate of the second pliotron is connected to the grid of the first, while the grid of the second is coupled by means of a second small transformer to the microphone circuit. With this small outfit, both pliotrons may be relatively small, and in order to obtain an energy of about 20 W in the antenna, it is found that the current drawn from the condenser is so small that the potential supplied by it does not vary sufficiently to be audible in the signals sent out by this outfit. The different parts of this apparatus may be made very compact and no adjustments are found necessary in operating the system unless it is desired to change the wavelength. In this case, it is only necessary to change the inductance or capacity.

In the second outfit, which is suitable for use up to 500 W or more, the high voltage direct current is obtained from a small, 2000 cycle generator. The current from this is transformed up to about 5000 volts, rectified by kenotrons, and smoothed out by means of condensers. By the use of 2000 cycle alternating current instead of 60 cycle, it is possible to store up large quantities of energy and thus obtain as much as a kilowatt or more of power in the form of direct current with condensers of moderate size. This high voltage direct current is then used, as before, to operate a pliotron oscillator, the output of which is controlled by means of a small pliotron connected to the telephone transmitter.

By means of this system of control the amount of energy in the telephone transmitter circuit need be no larger than that commonly used in standard telephone circuits. It has thus been found possible to connect up this radio telephone outfit with the regular telephone lines so that conversation may be carried on between two people, both of whom are connected with the radio stations by means of the regular land lines. It has also been found possible to communicate both ways over these lines.

IV. DISCUSSION

A. Alfred N. Goldsmith

The material presented by Dr. Langmuir to the Institute of Radio Engineers constitutes one of the important con-

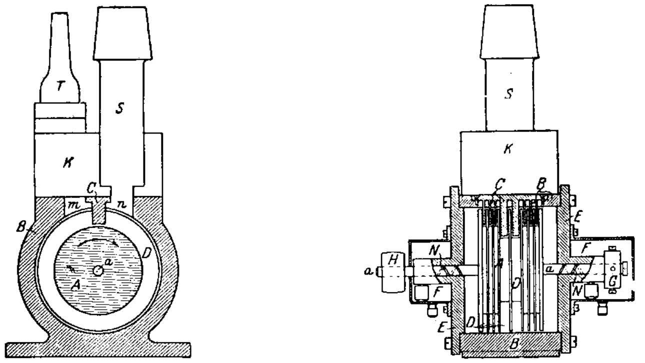

Fig. 11.

tributions to the knowledge of thermionic phenomena in high vacua which have been worked out in the Schenectady laboratory. It may be that certain facts presented in the earlier papers will be of interest.

In a paper by Coolidge [18] the usual defects of X-ray tubes are given. They apply, in general, to tubes in which cathode rays pass. They are a gradual increase in the vacuum as the tube is operated, rapid and erratic changes in the pressure, heating of the electrodes with consequent evolution of gas, deposition of the electrode metal on the tube, the difficulty of obtaining satisfactory pressure regulators, and the dissimilar characteristics of two apparently identical tubes. If, however, the tube be exhausted to a pressure less than 0.00003 mm (and certain other conditions are fulfilled), the above defects can be eliminated. Coolidge used for the cathode a spiral of thin tungsten wire electrically welded to molybdenum supports. The molybdenum was sealed in the tube using a special glass having the same coefficient of expansion. The remainder of the tube was of a German glass. The tungsten filament was heated by a storage battery, well insulated from the ground. Before exhausting the tube, the electrodes were fired in a tungsten vacuum furnace. This latter was a tungsten tube 1 in (2.5 cm) inside diameter and 12 in (30 cm) long. This was placed in a water cooled metal cylinder and exhausted to a few thousandths of a millimeter pressure. The tungsten tube was then connected to a 100-kW transformer. For exhausting the tube, a Gaede molecular pump was used, connected to the tube thru a short large piece of tubing. During exhaustion, the tube was heated to about 470 °C. At the same time, heavy high voltage discharges were passed thru the tube. This procedure was continued for several days. A liquid air trap was used between the Gaede pump and the tube to condense vapors. In the last stages of the exhaustion, very heavy discharge currents were passed thru the tube which was air cooled by the use of a fan.

Inasmuch as sufficiently low pressures to obtain the effects Dr. Langmuir describes can hardly be obtained without the use of a molecular pump, a brief description of this latter is not out of place. This pump is not of the piston type (which cannot pump out vapors) but depends on gas friction. In Fig. 11, the rotating disc is shown. As a consequence of its rotation, the difference of pressures on the two sides will be constant; that is, $p_1 - p_2 =$ constant.

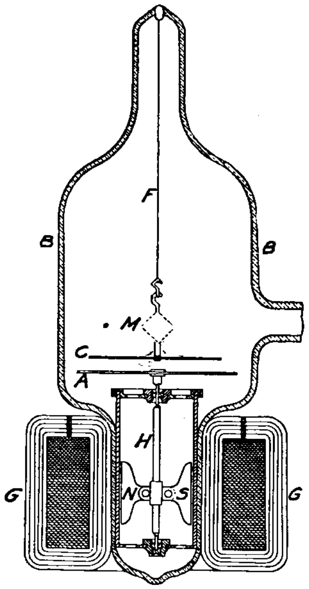

Fig. 12.

The constant is proportional to the speed of rotation of the disc and the internal friction of the gas. This latter has been shown to be constant at all pressures by Maxwell (theoretically). It will be seen that starting at a small pressure, it is theoretically possible to reach an absolute zero of pressure. Actually this cannot be realized since at very low pressures not $(p_1 - p_2)$ but $p_1 \div p_2$ is a constant. It is obvious that an auxiliary pump must be used to begin with. In practice, the peripheral velocity of the disc is high, namely, not far from the molecular velocity. The disc rotates at 8000 to 12 000 R.P.M. With pumps of this type, a 6 liter container can be exhausted to a pressure of 0.000002 mm in 4 min.

Dr. Langmuir has worked out an ingenious pressure gauge for very low pressures based on similar principles [21]. Inside the gauge is placed a thin aluminum disc attached to a steel or tungsten shaft and carrying a magnetic needle, shown in Figs. 12 and 13 (from the *Physical Review*). Outside the tube, but in the plane of the needle, is a Gramme ring which is supplied with current cyclically at six points by means of a motor-driven commutator. The aluminum disc is therefore caused to rotate rapidly. Above it is suspended a very thin mica disc, hanging on a quartz fiber which carries a small mirror. The gas drag resulting from the rotation of the lower disc twists the upper disc thru an angle which is proportional to the pressure of the gas, the number of R.P.M. of the lower disc, and the square root of the molecular weight of the gas. It is, however, practically independent of the distance between the discs. This gauge is of use at pressures below 0.01 mm. Its sensitiveness is high. A light beam reflected from the mirror moves 1 mm on a scale 60 cm (2 ft) away, when the lower disc rotates at 10 000 R.P.M. and the pressure is 0.00000025 mm.

In another paper Dr. Langmuir [22] draws certain important conclusions as to the methods and degree of ex-

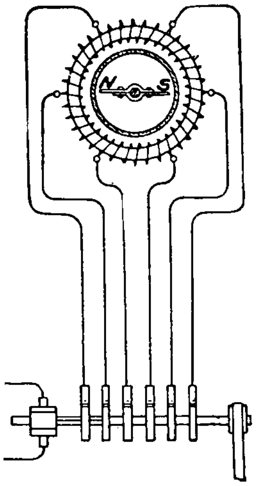

Fig. 13.

haustion of tubes which are to show pure and reproducible thermionic currents. They are:

1) An extremely high vacuum is necessary: less than 0.000 1 mm. No oxygen, water vapor, carbon dioxide or hydrocarbons may be present. During exhaustion all glass parts must be immersed in liquid air, or be heated to 360 °C, for an hour or more.
2) Large anodes are to be avoided. The anode should be heated to 2000 °C. or more *in vacuo*, or else a heavy high voltage discharge should be passed to it during exhaustion. In passing this discharge, the pressure should be so low that no glow is seen (except possibly when inert gases only are present). The electrodes are preferably tungsten which has been heated to 2500° for 10 min in the apparatus.
3) By properly placing the electrodes, the space charge (which limits the thermionic currents) may be kept small. If a cylindrical anode is used, it should be charged to several thousand volts and the filament temperature raised until the thermionic current is 50 to 200 mA.

Dr. S. Dushman has also given some valuable data in relation to the construction of such tubes [23]. In his work, tubes with molybdenum anodes were used. Platinum leading-in wires were employed. From the vacuum tube, a large bore glass tube ran to the liquid air trap, and thence to the Gaede molecular pump, which latter was connected to a "box" pump connected to a 1-cm "rough" vacuum line. A McLeod gauge was placed between the molecular and box pumps. There was also an outlet whereby air dried by passage over phosphorus pentoxid could be admitted to the apparatus. During the exhaustion, an electric oven kept the tube at a temperature of 350°. It was at a temperature of more than 300° for at least an hour. The vacuum was certainly less than 0.0000002 mm. The electrodes were freed from occluded gases and volatile oxids by applying an alternating electromotive force of from 1000 to 5000 V, the thermionic current being 50 to 200 mA. The temperature of the anode was 1000 °C or more. The blue glow gradually disappeared, and the thermionic currents increased. When the anode was finally brought to a white heat, the high voltage discharge was stopped. The temperature of the tungsten cathode was calculated from the following formula, where T is the temperature (in degrees Kelvin), and H is the intrinsic brilliancy of the filament in international candles per square centimeter of projected area

$$T = \frac{11,230}{7.029 - \log_{10} H}.$$

In a recent article, [24] Dr. Dushman gives the details of the design of the kenotron. In particular, the important questions of proportioning the electrodes to the current-carrying capacity, of keeping the internal loss in the kenotron low, and of preventing excessive electrostatic strain on the electrodes are considered.

Passing to the question of the advantage of the kenotron over the mercury arc rectifier in that several of the former may be safely operated in parallel, the criterion for such stable operation is easily expressed. If i is the current passing thru a kenotron, a small change in terminal voltage e must cause a change of the same sign in i. That is,

$$\frac{di}{de} > 0.$$

But for the kenotron, it has been shown that

$$i = ke^{3/2}$$

where k is a constant. Therefore

$$\frac{di}{de} = \frac{3k}{2} e^{1/2} > 0.$$

Also, it can be similarly shown that if two or more kenotrons are operated in parallel, a small change in terminal voltage of all of them will produce changes of current in each of them proportional only to the corresponding constant k of each kenotron.

By reference to Fig. 7 of the paper, it will be seen that the amplification produced by the small pliotron even when the grid is at a positive potential is considerable. Thus a change of grid potential from $+2$ to $+4$ V causes a change of power in the grid circuit of 1.46(10)$^{-4}$ W, but as a result there is a change of power of 1.4(10)$^{-1}$ W in the plate circuit. The amplification is therefore roughly 1000. At lower grid potentials, and especially at negative grid potentials, this must be enormously increased; and especially at lower frequencies.

B. Lee de Forest

Naturally Dr. Langmuir's paper is to me one of the most interesting ever presented before the Institute. It is a tribute to the exhaustive thoroness and scientific care with which such a resourceful corporation as the General Electric Company can attack any problem in which it may become interested.

Philologists, fully as much as physicists or radio engineers, are indebted to Drs. Langmuir and Dushman for coining two fresh new words to add to our modern Greek mythology, along with such contributions as “Cymoscope,” “Cymometer,” etc.

That the two devices thus designated possess a novelty of nomenclature no one can deny. As to just wherein the “Kenotron” differs in principle from the Edison–Wehnelt–Fleming “vacuum valves,” or the “Pliotron” from the audion amplifier and oscillating audion is a somewhat more debatable question.

It is certainly not self-evident that when a large audion is exhausted to a higher degree of vacuum than heretofore, so that conductivity by means of gas carriers enters less and that by thermions enters more into phenomena otherwise identical, long ago discovered, and thoroly characteristic—it becomes (except by an ingenious name) a new device.

Increased utility naturally follows upon enlarged dimensions, increased life, and ability to transform larger amounts of power.

I believe, however, that Dr. Langmuir has, by working into these extremely high vacua and the high potentials necessitated thereby, pursued the less promising of two paths of research.

It is well to remember in this connection that today arc generators developing 75 kW of radio energy are in operation on voltages of less than 1000 V.

An arrangement for controlling the amplitudes of radiated waves by means of an audion side-path to earth, the latter in turn controlled by a microphone, was used by myself as early as 1909. It was found that, with the amount of power I was then experimenting with, the complication of circuits and necessary additional apparatus involved, rendered this method less advantageous than the simple microphone-in-earth-lead connection.

Where however large powers are to be voice-controlled an arrangement operating on this principle offers certain important advantages.

C. Sewall Cabot

I should like to ask Dr. Langmuir to give us some idea as to the constancy of adjustment in using the pliotron as a receiver. In using the audion we have had much trouble in obtaining and holding the voltage at the anode at its proper value, and in keeping the temperature of the filament steady. The pliotron, having no gas in it, and using higher potentials would seem to be a more constant device.

D. Irving Langmuir

The most advantageous feature of the pliotron seems to be its constancy. Even the form using a slight amount of mercury vapor is extremely constant in action. The anode voltage may be increased from 70 V to more than 200 or 300, and as the voltage is increased, the sensitiveness of the device gradually rises. We have had no difficulty whatever in receiving signals using the regular city supply line to supply the plate or anode voltage. This cannot be done with the audion which is too sensitive to slight changes in the voltage of that circuit. The slight fluctuations which occur in the voltage of the city supply line cause, however, no effect at all in the pliotron.

In order to get the greatest sensitiveness in the use of this detector, the potential of the grid is so adjusted that we work on the flat part of the current-voltage curve, thus rendering it possible greatly to increase the current by a slight change in the grid voltage. In fact, the pliotron is always used by us in such a way that most of the electrons emitted from the filament return to the filament when no signals are coming in.

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