THE HOT CATHODE ARGON GAS FILLED RECTIFIER

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The author gives a brief review of hot-cathode phenomena and then shows how through development work these phenomena have been made use of in obtaining practical results. The various types of gas-filled rectifiers are described in detail. — Editor.

It has been known for a number of years that a vacuum tube containing a hot and a cold electrode acts as a rectifier. The problem of applying this principle to a practical rectifier was, however, beset by numerous difficulties. The variation in the magnitude of currents was extremely erratic with a slight variation in the degree of the vacuum. The blue glow phenomenon accompanying the electron emission (indicating the presence of residual gas) caused a very rapid disintegration of the hot electrode, and made the tube inoperative after a relatively short period of life.

Early investigators had assumed that the electron emission was a secondary effect, due to the presence of gas. Dr. Langmuir[1], in his detailed investigation of the whole field of electronics demonstrated that all of the irregularities thought to be inherent in the hot cathode vacuum discharges disappeared with the elimination of all residual gas effects. It has been found possible to produce and maintain vacuums so high that no gaseous discharge occurs with voltages as high as 100,000 volts. This is particularly demonstrated in the kenotron,[2] and in the Coolidge X-ray tube,[3] both of which are commercial devices.

In these types of high vacuum apparatus, the current is more or less limited, due to space charge effect. The electrons emitted from the hot cathode produce an electrostatic field around it, which limits the motion of electrons towards the cold electrode. This space charge, however, is rendered less effective, and the current is increased, by raising the positive potential or by increasing the surface from which the electrons are evaporated. The kenotron, in its present commercial form, is made to supply currents as high as 250 milliamperes, at voltages up to 100,000 volts.

However, owing to the fact that the voltage drop in the kenotron when rectifying currents of the above order of magnitude is relatively high (100-500 volts) it is impracticable to use this device on low-voltage circuits.

In the presence of positive ions the space charge of electrons is partially or completely neutralized. When minute traces of gas are introduced into the kenotron under certain conditions, a sufficient number of positive ions may be formed to completely neutralize the space charge effects, and then the voltage required to draw a given current through the space is reduced many fold. The presence of the gas not only has an enormous effect upon the current carrying capacity of the space between the electrodes, but also may have a very marked influence upon the number of electrons emitted from the cathode. In the presence of oxygen, whether in a free state or contained in a gas (such as water vapor), the electron emission from a pure tungsten cathode is cut down to a small fraction of that in high vacuum. Inert gases and vapors apparently have no effect upon the electron emission from pure tungsten.[4]

In the previous investigations, the work has been confined to the effects of minute traces of gas where the gas molecules are few in number, and where the ionized particles are thus enabled to move with comparative freedom under the influence of electric fields. Under these conditions, the positive ions acquire a very high velocity, and when they strike the cathode actually cause a chipping off of atoms of the metal, until the function of the cathode is destroyed. The disintegration becomes very much more rapid as the voltage is increased.

A very careful investigation was made to determine the effect of gases at higher pressures upon the cathode filament. (By higher pressures is meant pressures exceeding 50 microns). It was found that the nature of the gas had much to do with the rapidity with which the cathode was disintegrated. Certain impurities, even though present in very minute traces, cause the formation of volatile compounds with the cathode material

[1] Dr. Langmuir, Phys. Rev. g. 450-86. 1913.
[2] Dr. Dushman, G. E. Rev. 18, 156-67, 1815.
[3] Dr. Coolidge, Phys. Rev. 3, 409-30. 1913.
[4] Dr. Langmuir. Phys. Zeih. IS. .348-53. 1914.

in the presence of high temperatures, which ultimately effect destruction. At pressures smaller than several millimeters, the effect of positive bombardment is still very troublesome. As the pressure of the gas is increased from vacuum condition the number of molecules increases very rapidly, limiting the free movement of the positive ion, and therefore decreasing the velocity. The energy given up by the individual ion at impact is then very much less than under conditions when it moves at the higher velocities; but there are vastly more positive ions present, so that the effect of bombardment by positive ions is much more

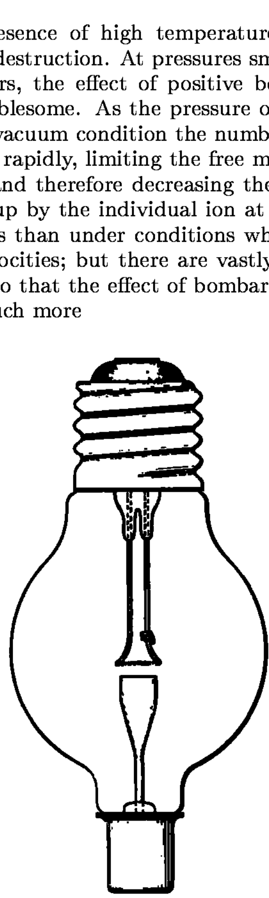

Fig. 1. Low Current Hot Cathode Gas Filled Half-wave Rectifier

disastrous in gases at certain pressures than under conditions where only minute traces of gas are present. In order to prevent disintegration of the hot cathode it becomes necessary to isolate the causes, and produce a condition which would not only eliminate the principal agents of destruction, but also the many secondary effects which are present. During the investigation of conditions covering a period of several years, the properties of many gases at varying pressures have been studied, with particular reference to their adaptability for rectifying purposes. Many electrode materials have been investigated with reference to their size, shape, and indestructibility. By a proper adjustment of the pressure of a selected gas, we have not only been able to reduce disintegration to a minimum (practically eliminating it), but have also been able to secure conditions where the emission of electrons from the cathode has been sufficient to actually cool it when rectifying excessive currents.

As a result of these investigations it has been demonstrated that a rectifier filled with gas at pressures within a more or less definite range can be designed to rectify currents from a few milliamperes to exceedingly high values at voltages varying between several volts and several thousand volts.

The Hot Cathode Argon Gas Filled Rectifier

During the investigation, many observations were made which in themselves are worthy of elaboration.

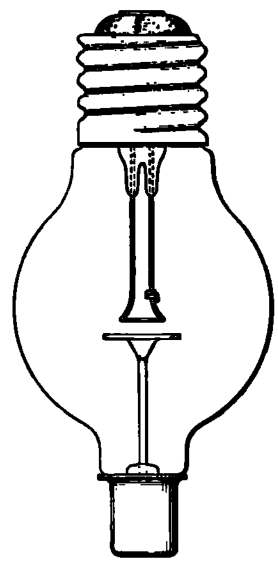

Fig. 2. Low Current Hot Cathode Gas Filled Half-wave Rectifier

The object of this article, however, is not to present any of these noteworthy facts, or even to venture a scientific exposé of any phase of the investigation, but rather to refer to one of the several combinations of conditions which have given us a rather interesting type of low-voltage gas-filled rectifier for rectifying currents within a wide range.

Fig.1 shows a sketch of a rectifier in which the cathode consists of a filament of small tungsten wire coiled into a closely wound spiral, and a tungsten anode of relatively large cross-section, with a comparatively smooth surface. The filament ends are welded to heavy tungsten wires, while the anode lead is swaged from, though is still a part of the anode. All leads are sealed directly through the high heat-resisting glass into 3-inch spherical bulbs of a similar glass. Although the anode of the tube shown consists of tungsten, other materials have been used with good results. Care, however, must be exercised in mounting all anodes, particularly where the material (such as graphite) can not be welded to the tungsten lead.

The rectifier shown in Fig. 2 differs only in the shape of its parts. The cathode is shown as a straight filament of small tungsten wire, which, if properly proportioned and mounted, consumes a minimum of energy for a maximum number of electrons emitted. The anode is shown in the form of a thin disk, made large in diameter, to give a big radiating surface, which is found to be desirable when such metals as copper are used.

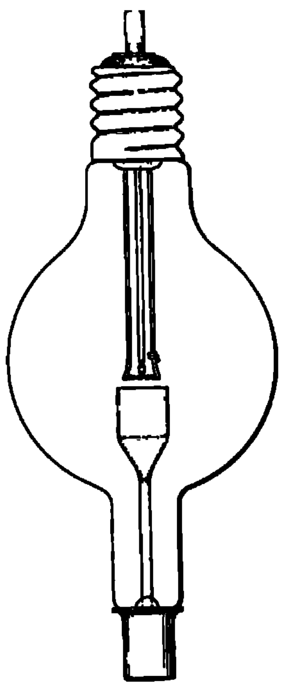

Fig. 3. High Current Hot Cathode Gas Filled Half-wave Rectifier

Fig. 3 illustrates a gas-filled rectifier designed to rectify high currents at low voltages. Two cathodes are shown; one is in filament form identical to that shown in Figs. 1 and 2, used for starting; the other is a tungsten rod cathode with beaded tip, used during the operation of the tube. The construction between the bead and the lead suffices to prevent conduction of heat from the tip. The object of using such a cathode is to secure a long operating life. Any disintegration, unless very severe, has no appreciable effect upon the life and operation of a rectifier of this design. A graphite anode mounted on a heavy tungsten lead is shown, as graphite has been found to be a very desirable anode material for rectifying high currents. As before, all leads are sealed directly through the glass and, for currents between 20 and 45 amperes, into a 5-inch spherical bulb of a similar glass.

The rectifiers just described are constructed of high heat-resisting glass, since it is possible to seal the tungsten parts directly into the glass, and bulbs of small volume can be used for tubes of large energy consumption. Soft glass bulbs are used with very good results. It is then necessary, however, to use special sealing-in wires, or blended seals.

All tubes, whatever the material of which they are constructed, are carefully exhausted and filled with a gas in a high state of purity. As has already been stated in the introduction, certain impurities, even though present in small quantities, produce a very rapid disintegration of the cathode, and also have a very marked effect upon the voltage characteristics of the rectifier.

It is advisable in certain types of gas-filled rectifiers to introduce substances which react chemically with such impurities as are introduced with the gas, or are given off by the parts during the operation of the rectifier. The reaction which occurs keeps the gas in a pure state. It is found convenient in certain types of the low-current rectifier to introduce the purifying agent in the form of an anode.

As the impurities are distilled from the anode or cathode, or from the overheated glass parts, the arc drop increases. The increased energy consumption automatically causes evaporation of the anode material until the high state of purity is re-established, when the evaporation ceases. In Figs. 1, 2 and 3, the purifying agent is shown as a coil wound around one of the leads. During aging it is evaporated, and redeposits on the sides of the bulb, carrying with it the impurities in their respective chemical combinations. The experimental work with argon indicates that rectification is possible in all pressures of gas. With an increase in the gas pressure the potential at which the arc is established increases. At the higher pressures, the temperature of the filament is also a factor in determining the starting voltage. After the arc is formed, the arc drop increases very gradually for big increases in gas pressures. Between gas pressures of 10 and 15 centimeters, the nature of the arc changes from a sharp concentrated arc to one diffused in character, which at very low pressures assumes the characteristics of the blue glow. At the lower pressures, the filament temperature above 2200 deg. K. has little effect upon the characteristics of the arc.

For the low-voltage tubes of all current capacities a pressure is selected at which the effects of disintegration are a minimum and where the voltage condition for starting and operating are desirable. A pressure of argon between 3 and 8 centimeters (measured cold) gives very good results and is, therefore, the pressure used in this type of rectifier.

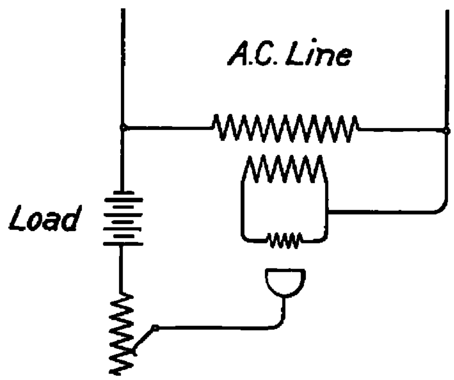

Fig. 4 Diagram showing Method of Connecting a Half-wave Rectifier in Circuit

Characteristics and Operation

The principles already briefly discussed are applied equally well to half-wave or full-wave rectifiers. The half-wave type shown in Figs. 1, 2 and 3, is very desirable, because of the simplicity of its construction and installation. A typical circuit for the half-wave rectifier, consisting of a 40-watt transformer for filament excitation, a load, and a means of regulation, is shown in Fig. 4. Where efficiency is not a serious consideration, regulation can be secured by placing resistance in series with the load. If efficiency must be considered, however, the line voltage is transformed to values where no regulation is required, so that the load can be placed directly between the terminals of the transformed source. Unless a sufficiently great number of these units controlling relatively large amounts of energy are placed in a power circuit in such a way as to badly distort its wave shape, the use of this type of tube is permissible. As a matter of fact, the half-wave unit of low-current capacity if generally installed will have no appreciable effect upon the power-supplying circuit. Should this feature, however, become objectionable to the central station when high current units are used, two half-wave rectifiers can be placed in circuit, as shown in Fig. 5. The compensator is designed to transform the voltage to values required for regulation, and to supply current for exciting the filament. It possesses as much or as little reactance as the characteristics of the load require for proper operation. Where it is possible to split the load into equal parts, or where the total load is divided into units, as for example the vehicle battery of a central charging station, the half-wave units, each with its individual battery load, are connected into the circuit in such a way that half of the tubes are

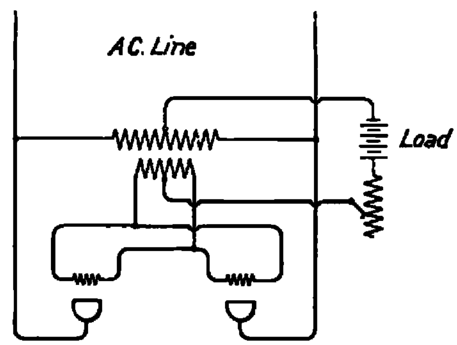

Fig. 5. Diagram showing Method of Connecting Two Half-wave Rectifiers in Circuit

rectifying one loop of the wave, while the other half rectify the remaining loop. The resultant effect upon the wave shape of the main circuit is similar to that when the full-wave rectifier is used.

The full-wave gas-filled rectifier shown in Fig. 6 consists of a tube into which are sealed two anodes and a common cathode. This type of rectifier is connected in a compensator circuit, Fig. 7, very much in the same way as the two half-wave units shown in Fig. 5. The energy consumed by the two cathodes in the former arrangement is somewhat greater than that consumed by the one filament of the full-wave unit. The effect upon the general efficiency is, however, relatively small, and is offset by other features, depending upon the service for which the rectifier is used.

A particularly desirable characteristic of the hot cathode gas-filled rectifier shown in Figs. 1 and 2 is the self-starting feature. When the alternating-current circuit switch is closed, the cathode filament is heated very much in the same manner as is the filament of an electric lamp by the turning of the snap-switch. A supply of electrons is liberated from the filament, and through the mechanism of ionization positive ions arc produced, which, with the electrons, carry the unidirectional current of the arc. Normally the arc forms very rapidly upon the closing of the switch. This characteristic is particularly attractive to communities where the power-circuits are frequently broken during the night. The rectified current service is re-established automatically immediately after the power-circuit is completed, and continues to give service as long as desired.

In the low-current unit the cathode filament is excited continuously during operation. The apparent loss of energy, due to the excitation, is compensated for by a low loss of energy in the arc when the filament is excited from an external source, under which condition we have repeatedly observed arc potentials as low as 1 volt d-c. Once the arc is formed, the tube continues to operate as a rectifier even though the filament circuit is broken, except in instances where the rectified current is very low. The electrons are not so freely liberated from the unexcited cathode, and the deficiency of electrons results in the formation of a positive space charge. The voltage required to overcome this positive space charge and cause the electrons to be emitted by bombardment mav be sufficient

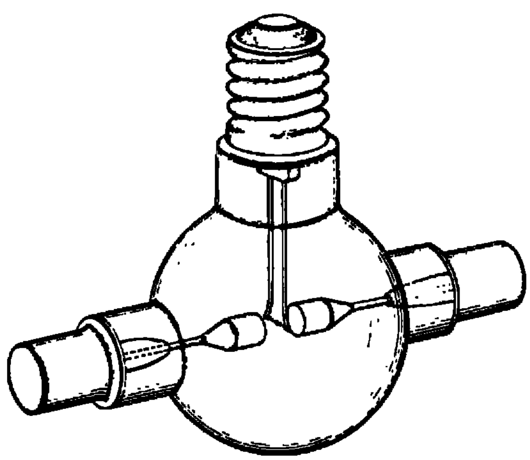

Fig. 6. Hot Cathode Gas Filled Full-wave Rectifier

to make the total loss within the tube greater than when the filament is excited by external means. With no filament excitation, the spot concentrates on a few turns and there is a tendency to shorten the life of the cathode by evaporation. It is therefore feasible in tubes of low-current and low-voltage capacity to continuously excite the cathode by external means. In the high current rectifier, the intensity of the bombardment is sufficient to produce electrons from the cathode with remarkable ease and the energy consumed

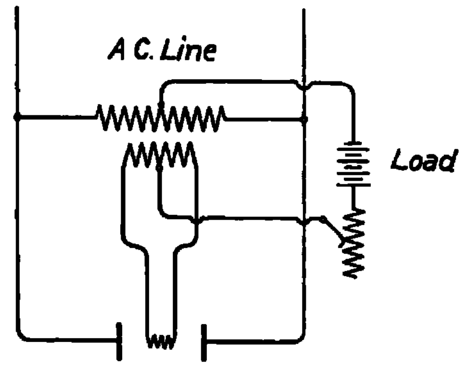

Fig. 7. Diagram showing Method of Connecting a Full-wave Rectifier in Circuit

is small. The filament is no longer necessary during operation. It functions in such tubes only as a starting cathode. A three-pole switch closes the filament-circuit, and also connects it with the anode. The gas is immediately ionized and the current begins to flow to the operating cathode, which is acting temporarily as anode until it becomes hot enough to emit electrons at which point the rectifying arc is established between it and the anode.

If conditions warrant, the tube is made to start automatically by placing a directcurrent relay in the rectified current circuit. When the arc forms between the operating cathode and anode the three-pole switch is opened and is closed when the power-circuit is broken.

When a constant purity of the gas can be relied upon, the filament is used both as a starting and as an operating cathode even in the high current rectifier. Rectified currents as high as 80 amperes have been drawn from a tungsten filament 20 mils in diameter for short periods without any appreciable harm to it. The filament remains relatively cool and the spot moves toward the filament lead connected into the main circuit, as the current increases. The 20-mil tungsten filament in a low-pressure atmosphere of argon normally fuses at 31 amperes. Unless extreme precautions are taken to free all parts of the rectifier from gases which are later given up during operation, or unless purifiers are incorporated in the rectifier, it is advisable to use the point cathode. This is not noticeably affected by the irregularities inherent in a poorly treated tube.

In this as in all types of gas or vapor rectifiers, it is necessary to ionize the gas before the arc can be started.

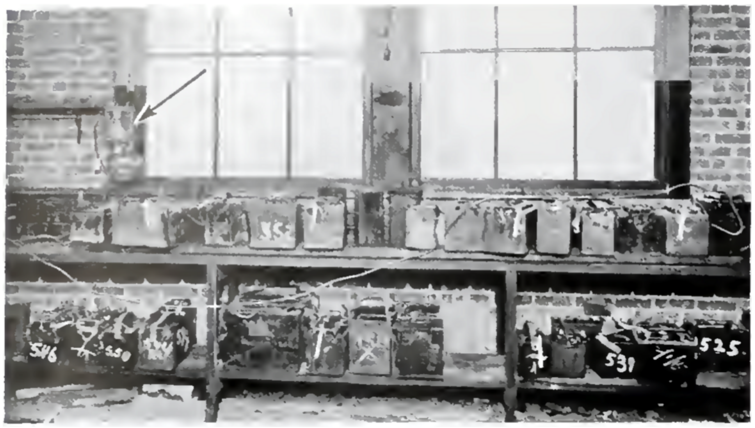

Fig. 8. Typical Half-wave Hot Cathode Gas Filled Rectifier Installation

Furthermore, in order to prevent the arc from going out permanently it is necessary to maintain the cathode spot and re-establish ionization at comparatively low voltage. As long as the arc exists it supplies its own ionization. During that portion of the cycle when the voltage is too low to maintain the arc, and is zero, the cathode cools only slightly due to its heat capacity, and with the aid of the residual ionization the arc reforms at low voltage without the starting anodes and other devices for overlapping the voltage waves. The rectifier is not only self-starting but also self-maintaining. The persistency of ionization in argon seems to be particularly marked and this makes it possible even without filament excitation to use the rectifier for supplying current for very low frequencies. For the same reason, it is possible to operate the tube on very low current when the cathode is not externally excited.

No auxiliary starting load is required when beginning a battery charge. The supply switch is closed and the charging current picks up immediately, giving a slightly tapering charge as the battery voltage increases. On a resistance load, the current is very constant due to the fact that the cathode spot does not wander. The efficiency of the tube depends upon the supply voltage, increasing with it as the voltage become higher, and upon the energy consumed in the arc indicated by the arc drop. The arc drop of the low-current low-voltage rectifier in which the filament is externally excited is between 4 and 8 volts measured on a direct-current circuit. The energy consumed in keeping the filament cathode hot enough to produce initial ionization is less than 40 watts. Therefore for a 6-ampere tube the energy consumed by the arc and filament is equivalent to that of a rectifier having an arc drop of 10.66 to 14.66 volts. The actual drop in this tube without filament excitation is however somewhat higher than indicated by these values. The tube operates satisfactorily on current ranging from a fraction to many amperes. With a properly excited cathode, the rectifying arc is started on alternating current supply voltages as low as 20 volts and is maintained on voltages as low as 14 volts.

The life of the low-current low-voltage rectifier, upon which the greater part of the work has been done, varies from nine-hundred hours to over three-thousand hours. Some of the high current half-wave tubes have a life of over a thousand hours and many others have a life of five-hundred hours or more. Most of the life runs have been made with resistance loads. Many of the low-current tubes have been in actual service for over eighteen months in several of the local central charging stations. Here they have been used to supply current for charging batteries. The life and characteristics in such service have proven to be very satisfactory. A typical central charging station installation is shown in Fig. 8. The outfit consists of a half wave rectifier screwed in a fuse block and a 50-watt filament transformer supported by a small bracket screwed to the window post to the left of the photograph. The direct-current meter placed in the load circuit is screwed to the sill just beneath the tube. The supply circuit is a 60-cycle, 236-volt alternating-current city power main. To secure flexibility, a variable resistance was placed in series with the battery load. In practice where efficiency must be considered, a variable transformer should be used

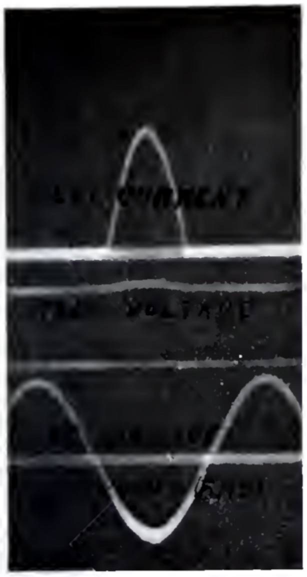

Fig. 9. Rectifier Charging Ignition Cells at 6.1 Amperes Direct-Current Voltage Across Battery

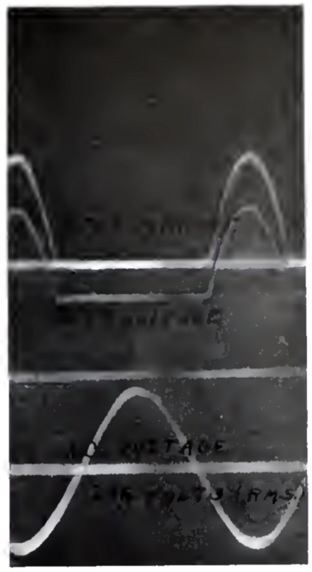

Fig. 10. Rectifier Charging Ignition Cells at 6.1 Amperes Direct-Current Voltage Across Battery and Regulating Resistance

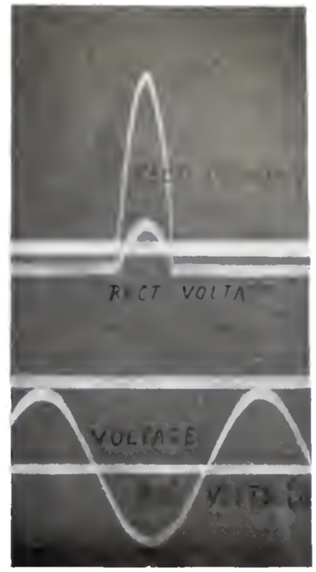

Fig. 11. Rectifier Charging Ignition Cells at 6.2 Amperes Direct-Current Voltage Across Battery and Regulating Resistance

Fig. 12. Rectifier Containing no Purifying Agent. Voltage Across Arc Gap 21 Amperes Direct-Current Flowing

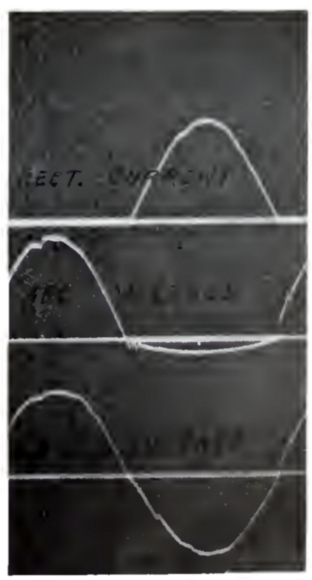

Fig. 13. Rectifier Containing an Active Purifying Agent. Voltage Across Arc Gap 29.6 Amperes Direct-Current Flowing

Fig. 14. Rectifier Containing a Purifying Agent as Anode Voltage Across Arc Gap 6.6 Amperes Direct-Current Flowing

in place of resistance. When the photograph was taken the rectifier was supplying a 6-ampere charging current to 15 batteries or 54 cells of miscellaneous character. At one period during the life run of this particular tube, all of the available batteries in the garage were coupled into a series circuit and the characteristics and oscillograms taken. During this period eighty-nine cells were in circuit being charged with a direct current of 6.2 amperes. The direct-current voltage over the total number of cells was 224 volts (average value) and the alternating-current voltage at this instant was 236 volts (root mean square value). The total direct-current voltage measured over the battery and variable series resistance was 236 volts (average value). It is evident that even a larger number of batteries can be charged by reducing the regulating resistance to zero value. The characteristics indicated above are typical.

Oscillograms

In order to study the characteristics of the rectifying arc, frequent oscillograms have been taken under varied conditions. Figs. 9, 10, 11, 12, 13 and 14 are typical of the half-wave low-voltage rectifiers. In all of the films, the lower curves represent the voltage of the supply circuit, while the upper curve gives the current passing through the rectifier. The middle curve represents the voltage measured either over the load where the curve does not cross the reference line. Figs. 9, 10 and 11, or over the arc gap where the curve traces below the reference line. Figs. 12, 13 and 14.

In Fig. 9, the middle curve represents the voltage taken at the battery terminals.

The rises in the rectified voltage line are due to a voltage factor which is the product of the battery resistance and the charging current. Where a smaller number of cells are being charged, these rises are barely perceptible.

In Fig. 10. the voltage is taken over the batteries and regulating resistance; therefore these voltage rises are very much more pronounced due to the increased value of the resistance. As the regulating resistance of the charging circuit is replaced by a larger number of batteries, the counter electromotive force is increased and the time during which the current flows is accordingly decreased. Therefore for the same r.m.s. value of the current, the wave becomes very peaked, as shown in the upper curve of Fig. 11.

The middle curve of Fig. 12 represents voltage across the arc gap of a tube in which there are no gas purifiers. Note that the voltage for starting is rather high, but decreases as soon as the arc forms. There is a tendency for it to increase at the end of the half cycle. This is more pronounced at the lower current values. The middle curves of Fig. 13 represent the arc voltage of a tube which contains an active purifying agent, and Fig. 14, a tube in which the purifying agent is used as an anode.

In all of the oscillograms the current graph shows that the rectification obtained is absolutely perfect and that, by a proper use of purifying agencies, a very desirable voltage condition is established.

In conclusion, the writer wishes to express his indebtedness to Mr. J. H. Clough, who has assisted throughout these investigations, also to acknowledge the generous co-operation of Mr. G. M. J. Mackay and others of the Research Laboratory staff.