THE SAGA OF THE VACUUM TUBE

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Part 13. Covering the developments by the General Electric Co. of higher power-output alternators for use in the fields of telegraphy and telephony.

THE development of the comparatively crude Audion into a satisfactory high-vacuum telephone repeater element was undertaken and carried through by the engineers of the Western Electric Company because of an urgent need. The problems of wire telephony in general do not involve the use and control of large powers, and the Audion, as submitted for their consideration by de Forest, was limited to low power applications. The General Electric Company, on the other hand, dealt essentially in comparatively high-power devices. Why then did they become interested in the low-power Audion? Paradoxically enough it was because they had need of a high-power device—but one with the type of characteristics exhibited by the Audion at low power levels.

Although in the popular mind the name of the General Electric Company is associated with power equipment in the early 1900's, the engineers of this Company had for some years been engaged in an attempt to develop a radio-frequency alternator for long-distance communication. The work was begun about 1904 at the request of Mr. Reginald A. Fessenden of the National Electric Signalling Company. At that time Fessenden was working at Brant Rock, Massachusetts, trying to develop a method of obtaining a continuous flow of high-frequency energy, and had requested the General Electric Company to undertake the development of an alternator to operate at 100,000 cycles. He was familiar with the work done previously at the General Electric laboratory by Thompson and Steinmetz along this line. Fessenden was using an arc transmitter, the only satisfactory generator of continuous waves of that day. He experienced many difficulties in this work because the arc was tricky to handle and not entirely free from self-modulation. When Fessenden appealed to the General Electric Company to undertake this work, E. F. W. Alexanderson was assigned the job of developing such an alternator. The result of the next few years' work on his part was what became known as the Alexanderson Alternator. The real significance of this development was realized in 1919, when the General Electric Company, after having spent millions of dollars to make such a device practicable, refused to sell to its only customer, the British-controlled Marconi Company, and in so doing helped return the control of transatlantic radiotelegraph stations to the United States.[186] By this act also, the General Electric Company paved the way for the founding of the Radio Corporation of America.

Therefore, it might be said that in the early 1900's the General Electric Company was trying to build a machine—a mechanical device—to do the job of the vacuum-tube transmitter of the present day.

By 1913 Alexanderson had been able to construct satisfactory alternators of several kilowatts output at frequencies up to 200,000 cycles.[187, 188] They were satisfactory, that is, for use

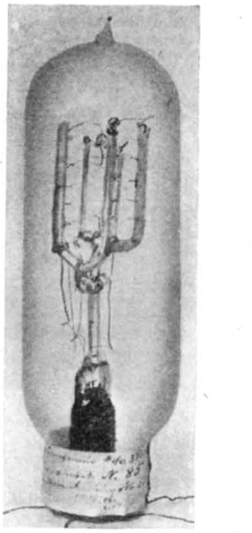
Fig. 149.

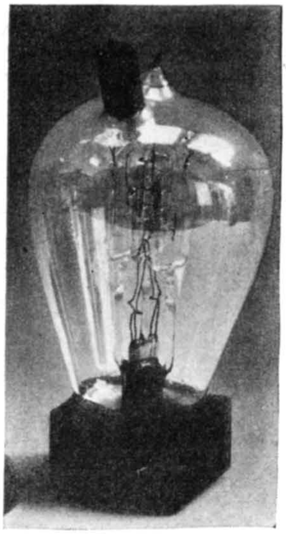
Fig. 150.

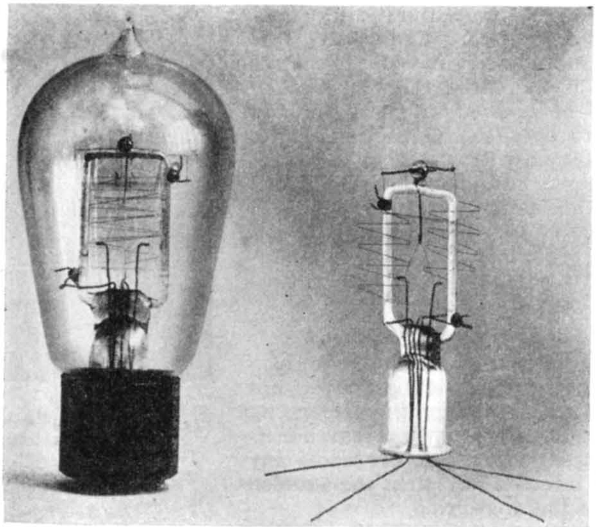
Fig. 151.

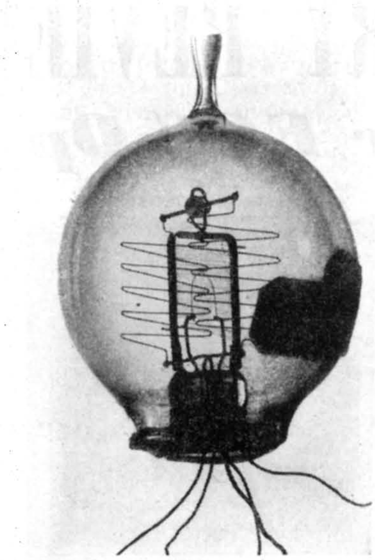

Fig. 152.

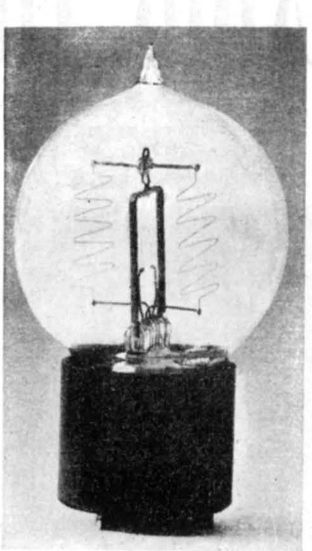

Fig. 153.

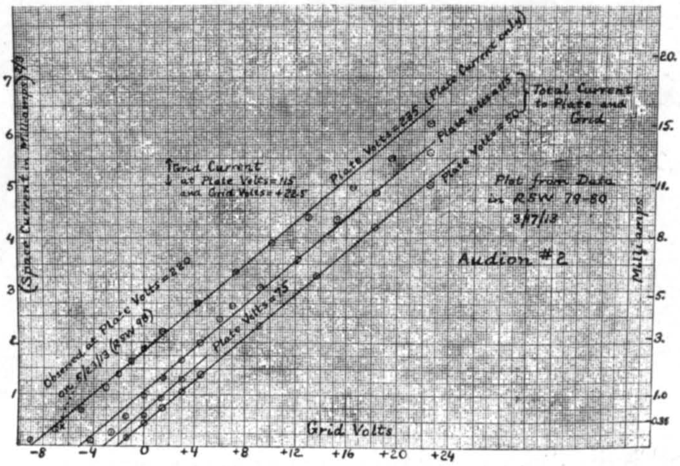

Fig. 154.

in continuous-wave telegraphy, but could not be used for satisfactory radiotelephonic communication since no method of adequate modulation of their output was available. Alexanderson had tried various methods of modulation with varying degrees of success. One method utilized a generator with its field excited by the telephone current. Another involved the use of the so-called "magnetic amplifier" or magnetic modulator.[189] A third was the use of a three-electrode mercury arc tube, in which an attempt was made to control the arc current by the use of the third electrode. None of these methods was completely satisfactory, and Alexanderson continued his search for a better modulator.

In 1912 the General Electric Company sold to John Hays Hammond, Jr., two high-frequency alternators for use in his experimental work on radio-controlled devices. In October of that year Alexanderson discussed with Hammond, at the latter's laboratory in Gloucester, Mass., the problem of obtaining the necessary modulation. While there, Alexanderson was told of some receiving apparatus, designed and constructed by Benjamin F. Miessner, one of Hammond's assistants, in which Audions were used. Alexanderson, who had never seen an Audion, felt from the description of the Audion and its characteristics that it might be promising as a high-frequency relay. He thought that it was in many ways defective but considered that the defects might be overcome. He therefore arranged to obtain a sample of the Audion from Hammond, to see if it might be made into a suitable device for the application he had in mind.

At Schenectady he showed the Audion to Drs. W. D. Coolidge and Irving Langmuir, with whom he often discussed problems. The discussion with Langmuir was fruitful. Langmuir said that he could develop a high-vacuum device of the three-electrode type which would function satisfactorily as a high-frequency relay. Alexanderson felt that such a device as Langmuir described could be used not only for modulation of the transmitted wave from his alternator, but also could be used in a new system of reception on which he was working. Accordingly, Langmuir set about the development.

Irving Langmuir had been in the employ of the General Electric Company since 1909. He was graduated from Columbia University in 1903, and had done postgraduate work at the University of Göttingen under Nernst, receiving his Ph.D. in 1906. When he entered the employ of the General Electric Company he attacked some of the problems still to be solved in connection with the tungsten filament incandescent lamp. The Coolidge process of making drawn tungsten wire had recently been introduced into commercial manufacture and had given rise to a number of problems, as does any new process.

One of the problems which Langmuir studied in connection with tungsten filament lamps was the blackening of the bulbs in service. This same problem in connection with carbon filament lamps, it will be remembered, led to the discovery by Edison of the "Edison Effect." It was the common idea in the General Electric laboratory that this blackening, in the case of the tungsten filament lamp, was due to secondary causes, among them electric discharges. It had been observed that the "blue glow," characteristic of insufficiently exhausted lamps, caused very rapid blackening. Also the presence of water vapor in the lamp bulb accelerated the blackening. From this it would seem that better vacuums were desirable.

Others had attempted to solve the problem by increasing the vacuum. Langmuir adopted a different approach. He attempted to determine the cause of the blackening by increasing the amount of the impurities introduced into the bulb. Particularly he studied the effect on the filament of gases introduced. Some of these, such as hydrogen, would disappear if introduced in limited amounts. Others, such as nitrogen, would react with the tungsten vapor given off by the hot filament.

In this work Langmuir had to differentiate between the effects due to evaporation of the filament—because of its high operating temperature—and the effects due to electric discharges within the bulb. To accomplish this he used low-voltage filaments to study the evaporation phenomena, and high-voltage (50-250 volt) filaments to study the effect of discharges. From all this he began to get a picture of what would happen in a perfect vacuum. He concluded that the blackening of the bulb was due to normal evaporation of the filament, not to electric discharges. He found the reason why the presence of water vapor accelerated the blackening. He found that even if the vacuum were perfect the blackening still would occur.

From his studies he concluded that

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the presence of pure gases was not harmful, and from this work came the high-efficiency, gas-filled incandescent lamp.

During the period just before Alexanderson brought the Audion to his attention, Langmuir had been studying the properties of filaments as a function of their length. It was thought at the time that with long filaments, requiring a comparatively high voltage for their operation, there might be a considerable amount of current flowing through the vacuous space and hence, for the same total current into the lamp, the actual filament current might be less and the lamp less efficient. Langmuir looked for this effect but could not find it. That is, in well-exhausted lamps there was a negligible space current, regardless of the length of the filament. Others had worked along this same line and were of the opinion that in a perfect vacuum there would be no space current.

One of these others was Dr. Coolidge, who was working on X-ray tubes. In the old-fashioned X-ray tube of high power most of the electrical energy supplied to the tube appeared at the anode, which would operate sometimes at white heat. Coolidge used tungsten for the anode and in some cases tried tubes with tungsten cathodes as well. In the case of the tungsten cathodes he found that after the tube had been in operation for some time the cathode also became white hot, and shortly thereafter the tube ceased to pass current and became inoperative. Coolidge was aware of the "clean-up" effect of white-hot tungsten and believed that the stoppage of the tube was caused by its becoming too "hard," that is, the vacuum had become too high to permit the passage of current. Langmuir's own experimental work indicated that these currents would become very small when the highest vacuums, obtained by thoroughly baking the lamps to free them from occluded gases, were attained.

On the other hand, Langmuir was familiar with the work of O. W. Richardson on thermionic emission, which showed that thermionic emission increased with temperature.[190] Calculations based on Richardson's equations indicated that at the temperature at which Langmuir was operating his tungsten filaments the thermionic currents should have been hundreds of amperes per square centimeter of filament surface. He checked the discharge from a hot filament to a cold anode in the presence of mercury vapor and found that the space current followed Richardson's law up to very high filament temperatures. Hence, he concluded that there was nothing abnormal about tungsten and that the filaments actually were emitting electrons in accordance with Richardson's law.

The ordinary tungsten lamp of that time had a long zigzag filament of six loops, with two leads brought out and connected to a base for use in a standard screw type socket. Langmuir had made some experimental lamps in which two additional leads, connected to intermediate points on the filament, were brought out. These leads were placed so that between any two consecutive leads there were two loops of filament. These lamps were exhausted by the ordinary procedure, but Langmuir then proceeded to raise the middle two loops of the filament to a very high temperature and vaporize the tungsten, so as to "clean-up" the vacuum. The act of vaporizing the tungsten assists in the removal of some of the residual gases. The tungsten vapors will combine with nitrogen, oxygen, carbon monoxide, and carbon dioxide, and these are the gases which are likely to be present in the bulbs. When this was done, and the middle portion of the filament burnt out, there were left two sections of filament electrically separated from each other, between which a voltage could be applied.

Langmuir then heated one filament by passing a current through it, and applied a voltage between that filament and the other which was cold. He measured the space current as a function of temperature for various filament temperatures and compared the results obtained with values calculated according to Richardson's law. He found that at first the space current followed the law, but as the temperature increased the space current tended toward a constant value. This always occurred, although the limiting value was different for different voltages between the hot and cold electrodes. He found that this limiting current was approximately proportional to the voltage difference between the hot and cold electrodes, and to the area of the anode.

He discovered also that a potential applied to the bulb externally affected the space current. If, for example, he placed one hand on the bulb and with the other hand touched the terminals of the d.c. power circuit in the laboratory, the space current increased or decreased.

By November 22, 1912, Langmuir had accumulated enough data to enable him to formulate a qualitative theory concerning the space current. This theory, as entered in one of his notebooks under that date, was as follows:

"New Theory of Edison Current. The velocity of electrons in a conductor corresponds to that produced by a fall through a potential diff. (sic) *of only a few tenths of a volt. Electrons leaving a filament will leave irrespective of the presence of a field, but they will only travel a very short distance if there is an electric field of only 0.1 volt per centimeter against them. Hence, around filament there is an atmosphere of electrons in equilibrium with the filament. Below a certain temperature the potential is determined by wires* (i.e. electrodes) *only.*

"Above a certain temperature the concentration of electrons becomes so great that they determine the field. Hence, two laws: Richardson's at low and some other at high temperature.

"Cooling bulb has no effect when no gas molecules present, but if gas is there the molecules collide with electrons (which have the same velocities as those of the filament) and slow them up and make them more readily absorbed by the anode wires."

This last paragraph was an attempt to explain the fact that the presence of gas caused an increase in the space current. This, we know now, was not the correct theory. The increase in current when the gas is present at high voltage is due to the fact that the positive ions formed, neutralize the space charge and allow the space current to rise toward the temperature saturation value.

These experiments threw an entirely new light on the theory of discharges from hot electrodes in very-high vacuums. It showed why, in the past, such small space currents were found under conditions where large currents were indicated by Richardson's equation.

Langmuir attached great importance to this explanation and theory, and proceeded to make a detailed study of the laws governing the phenomenon under high-vacuum conditions. His first step was to have constructed another lamp in which were placed two independent filaments, both of which could be heated during the process of exhausting the bulb. The bulb of this lamp was baked at high temperature during exhaust and a liquid air trap was used to remove traces of water vapor and carbon dioxide. Thus Langmuir removed as much of the occluded gases as possible, and pushed the vacuum to the limit attainable with the available equipment.

Tests run on this new bulb were made using anode voltages up to 250 volts d.c. and about 500 volts a.c. When the test data was plotted in a curve, the shape of the curve indicated that the space current varied as the 1.5 power of the voltage.

This, then, was the background of knowledge born of experience that enabled Langmuir to tell Alexanderson, in January of 1913, that he could improve the gadget which Alexanderson had obtained from Hammond, and make of it a device which would enable Alexanderson to do what he wanted. In order to do so Langmuir needed another assistant, and William C. White was assigned to this work. White studied the characteristics of the Audion and discussed the results of his tests with Langmuir.

While White was studying the

Audion, Langmuir had made up a tube similar to the Audion but with leads widely separated in order to enable him to apply high voltages during the exhausting process, and thus heat the electrodes by bombardment and free them from occluded gases. The results obtained were unsatisfactory and Langmuir decided to alter the construction of the tube in such a way as to facilitate the evacuation.

In order to accomplish this he abandoned the conventional Audion construction and made a three-electrode tube in which all three of the electrodes (filament, grid, and anode) were made of wire. The filament was made of 2.7 mil tungsten wire and was about 5½ inches in length. The grid was of 1.5 mil wire, hand wound on a glass frame. The anode was a zigzag wire 5 mils in diameter. The filament operated at about 2.5 amperes. This tube was known as "Tungsten Wire Audion No. 2" and is shown in Fig. 149.

This type of construction was adopted so that the electrodes could be heated by current from an external source during exhaust, in order to expel the occluded gases. This form of construction was used from March, 1913 until well into 1914 for all small tubes for operation at or below 250 volts, and somewhat longer for special tubes. Samples of tubes using this construction are shown in Figs. 150, 151, 152, and 153.

After this tube had been exhausted and sealed off the pump at a pressure of 0.05 micron it was subjected to numerous tests. In one case the anode voltage was held constant at 250 volts and the anode current measured as a function of grid voltage. Curves plotted of total space current showed that the space current obeyed the 3/2 power law. These curves are reproduced in Fig. 154.

This tube was also tested and functioned satisfactorily as a detector of wireless signals. Others made up shortly thereafter were also operated successfully when tested, in May of 1913, by Alexanderson for use as radio-frequency amplifiers.

While these experiments were under way, Coolidge was continuing his work on X-ray tubes. In December, 1912, Langmuir had discussed with Coolidge the results of his experiments and suggested that Coolidge try a tungsten cathode which could be heated by electric current from an external source, for the purpose of getting electrons in his X-ray tube. He told Coolidge that electrons were emitted from such filaments even in the highest vacuum, and that controlling the heating current would control the electron emission and the space current, independently of the applied voltage. Coolidge immediately proceeded to build an X-ray tube using an independently heated tungsten cathode of the type suggested. He used a tungsten anode, which he degassed by electron bombardment while the tube was still on the pump. He found it necessary to add a focussing shield around the cathode, and with this addition obtained a tube which was steady in operation, with none of the crankiness of the old type of cold-cathode tube, and one with which he could obtain reproducible results. By December, 1913, Coolidge had developed this tube to the point of commercial use, and described it in a paper before the American Physical Society.[191]

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CAPTIONS FOR ILLUSTRATIONS

Fig. 149. Langmuir's "Tungsten Wire Audion No. 2". Reproduced from Interference Record, Interference No. 40,380.

Fig. 150. Early type of wire element Pliotron, now in Science Museum, South Kensington, England. Photograph copyright by H. M. Stationery Office.

Fig. 151. Left—early Langmuir Pliotron complete. Right—element assembly on stem. Photograph courtesy General Electric Company.

Fig. 152. Early Langmuir Pliotron, before exhaust. This Pliotrom has a grid of tungsten wire 0.4 mil in diameter, wound on a metal frame, with a pitch of 120 turns per inch. The anode is of 7 mil tungsten wire. Note the 5 leads, two filament, one grid, and both ends of wire anode. Exact date uncertain, but prior to 1917.

Fig. 153. Completed, based Pliotron, Type CA. Vintage of 1917. This is a high-mu triode. The filament takes 1.0 ampere at 3.5 volts. The usual plate voltage was 180 volts. Photograph courtesy General Electric Company.

Fig. 154. Characteristic curve of Langmuir "Tungsten Wire Audion No. 2". Reproduced from Transcript of Record, General Electric Company vs. De Forest Radio Company, U.S.C.C. of A., Nos. 3799, 3800, 3801, March Term, 1928.

(To be continued)