PHENOMENA IN OXIDE-COATED FILAMENT ELECTRON TUBES.

BY H. D. ARNOLD.

SYNOPSIS.

Thermionic Phenomena in Wehnelt Oxide Electron Tubes.—The author discusses some of the problems which have arisen in connection with the development of three-electrode vacuum tubes with special reference to the production of a highly active and uniform thermionic source of electrons. The materials and the methods for the preparation of both core and coating are given. Since tubes with these filaments are not self-evacuating by the clean-up effect to the extent found with tungsten filaments, greater care is necessary in the pumping process.

Pure Electron Discharge; the Influence of Pressure and of Bombardment by Positive Ions.—The evidence shows the electron emission from Wehnelt oxides to be purely thermionic. Preliminary measurements on the number of electrons emitted from these filaments under the bombardment of positive ions prove that no appreciable part of their activity can be attributed to this cause. Operation has been studied with pressures of the order of 10^{-10} mm. Hg., but no decrease in activity is found at these low pressures. A plot is given summarizing the constants of Richardson's equation for 4,000 filaments.

Rate of Evaporation of Oxide Coating.—Grams per cm.^{2} per sec. evaporated from a filament coated by the above process are approximately given by

$$m = 4.6 \times 10^8 T^{-1/2}\epsilon - \frac{4.6 \times 10^4}{T}.$$

Thinly Coated Filaments; Coating by Evaporation.—Preliminary results of work now being carried on by Dr. C. J. Davisson show that maximum thermionic activity may be reached with coatings considerably less than one molecule deep. This suggests that of the two important constants determining electron emission, the density of free electrons in the substance and the work function at the surface, the latter is modified by the presence of the oxides while the former may remain essentially that of the core.

THE most generally interesting phenomena in electron tubes are those relating to the flow of electrons through the space, the control of this flow by plate and grid voltages, and the operation of the tubes in the various circuits in which they are used. These phenomena are essentially the same whether the filament is pure metal or is oxide coated, and a considerable literature has already grown up in this field. The phenomena distinctive of oxide-coated filament tubes are those relating to the economic and scientific factors involved in the process of electron emission. I shall therefore confine myself as closely as possible to these factors as they have influenced the design of oxide filament tubes, and as we have been led to investigate them in connection with our development of these tubes during the past seven years. For reference to the scientific literature in this field attention is called to the appended bibliography.

Wehnelt oxide filaments offer the most economical source of electrons at present available for use in three-electrode vacuum tubes, and thus from a commercial point of view they are at present of the greatest interest and importance. On purely scientific grounds they have long been of peculiar interest to physicists and chemists, offering as they have one of the most promising fields for speculations on the possible effect of chemical action in aiding the emission of electrons from hot bodies.

The early work of Richardson, H. A. Wilson, and others, established beyond reasonable doubt that for pure metals the emission of electrons is due to thermal action and not to chemical action in the ordinary sense of the word. Of the early evidence the most convincing was the proof that the emission did not decrease as more and more of the residual gas was removed, and the proof that the emission did obey the law of variation with temperature which would be expected if the effect were purely thermal. Further work[1] showed that the distribution of velocities among the emitted electrons was that which would be computed on the basis of the equipartition of energy between molecules and free electrons in the metal, the faster of the free electrons escaping in spite of the restraining influence of an electric field at the surface of the metal. Still other experiments[2] established that the value of this potential difference, as determined from the cooling of the metal due to the electron emission, corresponded with the value deduced from the observed relation between emission current and temperature. In view of these facts physicists have believed for the past ten years or more that there was no place for a chemical theory of emission as far as pure metals are concerned.

With respect to Wehnelt oxides, however, there was somewhat less certainty as to whether chemical action might not be necessary for electron emission. While it is true that early experiments established that with oxides as well as with pure metals the emission did not depend on the presence of gas in the evacuated chamber, the presence of the oxide itself on the filament seemed to offer sufficient chance for chemical actions, irrespective of any gas. Moreover, the fact that coating metals with these chemical compounds increased their electron emission many fold seemed to invite the hypothesis that this increase resulted from

---

[1] Richardson and Brown, Phil. Mag., Vol. XVI., p. 353 (1908).

[2] Richardson and Cooke, Phil. Mag., Vol. XXV., p. 624 (1913); Vol. XXVI., p. 472 (1913)

chemical action, although there has never been any experimental evidence clearly requiring such an hypothesis.

Data similar to those which established the purely thermal nature of thermionic emission from metals, were accumulated more slowly in the case of Wehnelt oxides, largely because of experimental difficulties which were encountered. The determination of the correspondence of the work function as obtained from the cooling effect, and as found from the exponent in the emission-temperature equation, followed several years behind the similar determination for pure metals, this in spite of the fact that the earliest experiments with the cooling effect were attempted by Wehnelt and Jentzsch[1] using Wehnelt oxides. As for the velocity distribution among the emitted electrons, this, as far as I am aware, has still to be satisfactorily determined for the oxides. Nevertheless, the evidence as it has been verified step by step has in every case supported the opinion of the physicists who believed that emission from oxides as well as metals was in all probability a purely thermal affair and did not require any assumption of chemical action for its explanation.

With the inception of the use of oxide filaments for commercial vacuum tubes, we had to face the same difficulties of technique in producing the filament that had retarded the scientific experimenters in their work, and it was in addition necessary to produce filament in large quantities and with a very high degree of uniformity. To do this a survey was made of the metals available for the core of the filament, and of the materials and methods of coating best adapted to the manufacture of a highly active and uniform filament. Considerations of mechanical strength, electrical resistance, non-oxidizability, availability and reproducibility of commercial supply, etc., led us to choose for the core a wire of platinum-iridium (about six per cent. iridium, with the other impurities usually found in commercial platinum-iridium). This wire was rolled to a ribbon to increase the surface, and the ribbon was twisted to secure a better mechanical structure. This core could be produced in quantity with electrical and mechanical properties sufficiently uniform for our purpose.

In the choice of coating materials we had available the oxides of barium, strontium, and calcium, with thermionic activities in the order given. Experiments with coatings of BaO, however, showed a mechanical disintegration during life which outweighed in importance its superior thermionic activity. Efforts to secure longer life resulted in the use of a mixture of BaO and SrO applied in a number of consecutive coatings.

---

[1] Wehnelt and Jentzsch, Verh. der Deutsch. Physik. Ges., 10 Jahrg., p. 610 (1908); Ann. der Physik, Vol. XXVIII., p. 537 (1909).

In the process which we most commonly used, barium in the form of carbonate, and strontium in the form of hydroxide or carbonate, was mixed with some carrier such as resin or paraffin, which would burn away when heated in the air. In the coating process four applications of the strontium mixture were followed by four of the barium mixture, and this process was then repeated, making a total of sixteen separate applications. After each application the wire was raised momentarily to a temperature of about a thousand degrees, which burned away most of the organic carrier. When the coating was complete the wire was heated to about 1200° for two hours. At the end of this time there remains a fairly heavy coat of BaO and SrO (from 2 to 3 milligrams per sq. cm. surface), while next to the core is a firmly adhering layer which is built up due to chemical reactions between the coating and the core. Analysis shows this coating to consist of barium and strontium combined with platinum, rhodium and iridium, the compound present in largest amount being barium platinate ($BaPtO_3$). The compound with rhodium seems to be more readily formed, but due to the small percentage of rhodium present this compound makes up only a small fraction of the total.

The filament thus formed can be handled without undue precaution so long as it is not exposed to moisture or carbon dioxide. When stored in vacuum containers it shows no signs of deterioration even after a period of several years.

The time required for the proper evacuation of an oxide filament tube is determined almost entirely by the requirement that a large part of the occluded gases must be removed from the metal and glass parts inside the bulb. In case the metal parts can be heated before assembly, or can be heated electrically, either through leads from the outside or by Tesla currents, the evacuating process may be very much shortened. In any event it is desirable to carry the evacuating process considerably further in the case of oxide filament tubes than with tungsten filament tubes, since the clean up effect of the filament itself is not nearly so marked as is the case with tungsten.

During the pumping process the filaments are glowed for several minutes to liberate any gases they may have occluded. At the same time the compounds at the surface of the core decompose to a certain extent, as is evidenced by the fact that filaments taken from tubes after a considerable period of glowing show a marked diminution in the amount of $BaPtO_3$ and similar compounds.

With the exercise of proper care as to the purity of the materials used and with adherence to a definite schedule of coating and heat treatment, filament can be produced with every expectation of uniformity and long life. During the war some half million vacuum tubes were made employing this filament, and the filament was prepared as a part of the regular manufacturing process by practically unskilled labor. Expert supervision was of course necessary to guard against the intrusion of chemical impurities or variations in the coating process.

We have naturally made a very thorough study of this so-called "standard" filament in order to determine its properties and particularly the factors which influence it during life. Having been developed in the first instance, about seven years ago, to meet the needs of telephone repeater service, severe requirements were imposed upon it from the start. Tubes made with it are required to be completely interchangeable. No adjustment of filament or plate voltages is made when tubes are replaced, and no appreciable change in amplification, or in electron current, may result from an interchange. The operation of the tube as an amplifier must remain unchanged when the filament voltage is varied between the limits customarily met with in storage battery service. The operation of the tube must remain sensibly unchanged through a life of several thousand hours, and when it does fail for any reason, it must give sufficient warning to ensure its being removed from service without causing the interruption of a telephone conversation. These and numerous other requirements are rigorously enforced, making it far more difficult to manufacture tubes for telephone repeater service than for the other uses for which they have since been adopted.

What terminates the useful life of an oxide filament is usually the development of local faults or "bright spots" due to the evaporation of the coating. They are practically free from the most common ageing effect of pure metal filaments, namely the gradual increase of electrical resistance caused by the evaporation of the filament. In the case of tungsten filaments used on constant voltage supply evaporation with the resulting increase in resistance causes a lowering in the filament temperature and therefore a decrease of the electron emission, while with a constant current supply the increase in resistance results in an increase of temperature and a progressive increase in rate of disintegration of the filament. With oxide coated filaments it is the coating alone that evaporates, at least until a bright spot is formed, and the temperature and operating characteristics remain unchanged throughout life on either constant current or constant voltage supply.

The cost of electrons in a vacuum tube device is determined by the characteristics of the filament, by the cost of the power used in heating the filament, and by the life and the replacement cost of the tube. The physical factors necessary for computing the cost are the constants in Richardson's equation, the constants of the evaporation equation, and the radiation constant peculiar to the filament. In order to relate the life of the tube to the vaporization constants it is necessary in addition to know to what extent vaporization may proceed, on the average, before the useful life is terminated, and this can, of course, only be arrived at by exhaustive life tests.

For tungsten and molybdenum the physical constants are already available, but for Wehnelt oxide filaments these constants have not as yet been satisfactorily established. Preliminary results have, however, been obtained in our laboratory and Dr. C. J. Davisson is continuing the investigation. We have found that the total thermal emissivity lies between 0.45 and 0.70, for a considerable number of samples of our standard filament. The method followed in determining these limits was to get the resistance power relation for the filament under operating conditions, and later get the resistance-temperature relation by placing the tube in an electric furnace. The latter relation was checked by an observation at the melting point of potassium sulphate. In connection with measurements of filament temperatures it was found by the use of the optical wedge method that these oxides act practically like black bodies in the red region of the spectrum and hence the temperature can be read with a fair degree of accuracy by means of an optical pyrometer using the black body calibration.

The preliminary values of the evaporation constants, obtained by evaporating barum oxide from a tungsten boat, catching it on a platinum shield, and weighing the deposit show that with a fair approximation

$$m = 4.6 \times 10^8 T^{-1/2} \epsilon^{-[(4.6\times 10^4)/T]},$$

where m is the rate of evaporation in grams per sq. cm. per second. A more definite determination of these constants for BaO, SrO and CaO is under way.

As for the determination of the constants in Richardson's equation for oxide filament, this work has covered about 4,000 filaments, and the results are of sufficient interest to warrant more detailed consideration. To simplify the investigation of this matter Dr. Davisson has devised a form of coördinate paper in which the coördinates are power supplied to the filament (abscissæ) and thermionic emission (ordinates). The coördinate lines are so disposed and numbered that if the emission from a filament satisfies Richardson's relation, and the thermal radiation satisfies the Stefan-Boltzmann relation, then points on the chart coördinating power and emission for such a filament will fall on a straight line. For practical purposes the advantage of replacing temperature by power as the independent variable is obvious. From the slope and position of a line on this chart together with the area of the filament, it is possible to calculate $bE^{1/4}$ and $aE^{-1/8}$ where b and a are Richardson's constants and E is the total thermal emissivity of the filament. The lines shown in Fig. 1 give some idea of the characteristics of our standard

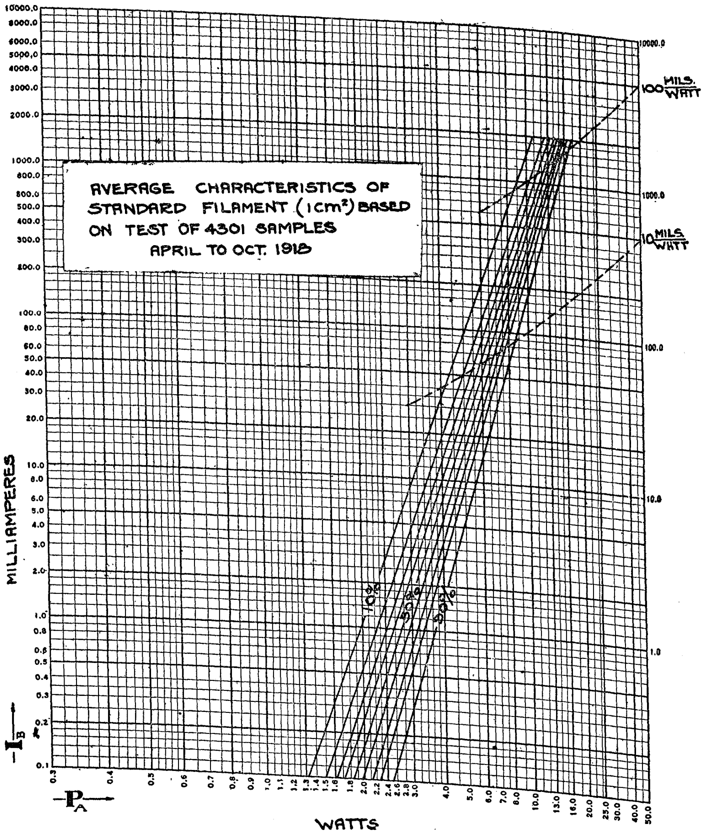

Fig. 1.

filament and the range of variability. Ten per cent. of the filaments have a greater activity than that given by the upper line while the activity for 90 per cent. of the filaments lies above the lowest line. In this connection it should not be overlooked that in the great majority of vacuum tube applications we are concerned only in maintaining the electron emission at a value greater than a certain fixed limit. It is in no way injurious for the emission to exceed this limiting value. In a limited number of cases, however, it is desirable to use tubes with as nearly as possible the same voltage saturation value of emission. For these special problems pure metal filaments offer at present the best solution, since the uniformity of their saturation values can be more readily maintained.

The dotted curved lines on the figure are drawn through points of constant ratio of emission to power, that is, constant efficiency or economy. The customary operating power is from 8 to 9 watts per cm.^{2}, so that the range of efficiencies is seen to lie between 10 mils per watt and 100 mils per watt. Assuming the emissivity of the filament to be 0.6 we obtain from these lines the following values of thermionic characteristics of the filament.

Equivalent volts through surface $\phi = 1.55$ to 1.9,

Richardson's constant b, 19.4×10^3 to 23.8×10^3,

Richardson's constant a, $(0.5 \text{ to } 1.5) \times 10^{24}$ for electrons per sec. per cm.^{2},

$(8 \text{ to } 24) \times 10^4$ for amps./cm.^{2}

In our adaptation of Wehnelt oxide coated filaments to commercial vacuum devices we have found it desirable in a number of instances to carry on investigations which would appear to be more immediately of scientific than of commercial value. One of our early experiments which was reported by Dr. W. Wilson at the Christmas meeting of the American Physical Society in 1914 gave additional data as to the behavior of Wehnelt oxide filaments in very high vacuum. The experimental arrangement used consisted of a cylindrical anode, with suitable guard rings, surrounding a single strand of oxide coated filament placed along the axis of the cylinder. The vacuum was made as good as possible with a Gaede molecular pump and it was established that the electron current in the filament did not diminish even with these extreme vacua. It was expected that the current would vary with the 3/2 power of the voltage according to Child's[1] space charge relation and that from the coefficient K, which involves among other factors the quantity $\sqrt{e/m}$ we might determine whether the carriers in the case of Wehnelt oxide filament were electrons or were in part carriers of greater mass. Wilson found that when proper consideration was taken of the geometrical form and of the voltage drop along the filament, the space charge equation took the form[2]

$$i = k\frac{2}{5}\,\frac{(V - V_0')^{5/2}}{V_0 - V_0'}\left[1 - \left(1 - \frac{V_0 - V_0'}{V - V_0'}\right)^{5/2}\right],$$

---

[1] Child, Phys. Rev., Vol. 32, p. 492 (1911).

[2] See also E. R. Stoekle, Phys. Rev., Vol. VIII., p. 545 (1916).

where V_0' is the potential of the negative end of the filament and V_0 the potential of the positive end. The value e/m obtained from the experimental data by the use of this equation was found under the best conditions to be about 5 per cent. lower than the value obtained for electrons by other methods. This deviation is explicable either by the presence of a very small number of negative carriers of molecular size or by the emission of secondary electrons from the anode under the bombardment of the primary electrons. The deviation is however, no greater than that obtained with tungsten filaments, and the concordance of the results indicates clearly that the discharge from Wehnelt oxides may be considered a pure electron discharge.

By means of the Knudsen absolute manometer, and later by the use of the Buckley ionization manometer,[1] we have measured vacua of the order of 10^{-9} and 10^{-10} millimeters of mercury during the operation of Wehnelt oxide filaments, and have never found any indication of the emission current falling off as the vacuum improved. With the introduction of various gases at pressures of the order of .001 millimeter, or so, the electron emission currents do suffer rather large changes, although not of the degree found with the emission from tungsten filaments under similar conditions. The presence of oxygen and carbon dioxide inhibit the electron emission, while a small amount of hydrogen in contact with a filament of abnormally low emission may result in restoring it to a normal condition. Because of their relatively smaller variations in emission under the action of gases we have found Wehnelt oxide filaments more adaptable for use in Buckley ionization manometers than pure metal filaments, as it is very rare that any blocking effects develop which cannot be overcome by a reasonable increase in the filament temperature.

In another paper[2] before the Physical Society in April, 1917, Wilson gave the results of a series of experiments on the relation between the work function ϕ and the exponent b of Richardson's equation. The method followed was a modification of that first attempted by Wehnelt and Jentzsch for oxide filaments and later used by Richardson and his collaborators in investigating the cooling effect due to the emission of electrons from filaments of osmium and tungsten. Previous experimenters who had attempted to determine the cooling effects with Wehnelt oxides had found it impossible to get consistent results due to the nonuniform behavior of the filament. During Wilson's experiments our standard methods of coating were employed, and the results obtained were remarkably consistent and reproducible. The values obtained were as follows:

[1] O. E. Buckley, Proc. Nat. Acad. Sci., 2, 683 (1916).

[2] Proc. Nat. Acad. Sci., 3, 426 (1917).

	bR/e Volts.	ϕ Volts.
BaO 50 per cent., SrO 50 per cent.	2.02	1.97
	2.16	2.28
BaO 50 per cent., SrO 25 per cent., CaO 25 per cent.	2.34	2.39
	2.59	2.54
CaO	3.28	3.22
	3.49	3.51

We have recently been repeating some of these experiments with a slightly different bridge arrangement and find no difficulty in obtaining consistent results from a given filament over long periods of time.

The close correspondence between b and ϕ, is as pointed out above, one of the grounds for believing that chemical action does not play any part in thermionic emission. The correspondence is, of course, not a proof of the absence of chemical action, but it is certainly more easily explained on the assumption of thermal action than on the assumption of chemical action. The determination of ϕ is also of considerable importance in connection with the theory of photo-emission and of contact potentials.

In connection with our recent experiments Dr. Davisson is finding it of great convenience to use filaments which have been coated by active material evaporated from a standard filament. The standard filament and the wire to be coated are mounted close together in the same tube and the primary is run at a fairly high temperature for various lengths of time according to the purpose of the experiment. Observations are then made on the emission from the secondary filament. One advantage of this method of experimentation is that the core of the secondary filament may be any suitable material, for example, tungsten or iron, without meeting the difficulties of oxidation, which are often troublesome when these materials are coated in the open air.

These secondary filaments have many interesting properties which no doubt will prove of importance in establishing the process of electron emission from Wehnelt oxides. One of the most striking facts is that the secondary filament may show a high electron emission when only a very minute amount of active material has been transferred to it. In certain experiments where the secondary filament was tungsten, the standard filament was glowed for so short a time that only approximately one tenth of the surface of the tungsten filament was covered with active material. While we have not determined in just what form the deposit comes down on the secondary, it seems reasonable to suppose that the material is transferred essentially molecule by molecule, and that the surface of the secondary filament would be found to have on it a considerable number of single molecules of coating separated by distances of the order of one to ten molecular diameters, and in addition a certain number of groups of two molecules, a much smaller number of groups of three molecules, and so on. It is most interesting to note that the electron current obtainable at a given temperature from filament coated in this very tenuous fashion may be only a little smaller than that obtained when the entire filament is covered with a heavy deposit.

It is natural to ask whether this result is due to a difference in the a or in the b of Richardson's equation as applied to these partly coated filaments. Work along this line is not yet completed, but measurements of b taken at intervals while the deposit was forming have never shown an increase with thickness of deposit, and therefore it seems that the result must be due to a difference in a. If we assume that a completely coated filament emits uniformly over its entire surface, while a partly coated filament emits only in the vicinity of the molecule of active material, we compute an a for the partly coated filaments which is much greater than the values (0.5×10^{24} to 1.5×10^{24}) given above for standard filament. The fact that the b obtained for filaments coated merely with a few widely separated molecules is the same as that obtained with a complete coating shows that the reduction of the work function at the metal surface can be brought about by a very small group of molecules. Under these conditions it seems reasonable to suppose that the only important effect of the molecule of active material is to lower the restraining voltage in its own vicinity and thus facilitate the passage of electrons from the metal core. The number of electrons that can avail themselves of such a molecular opening is limited to those presenting themselves with a sufficient outward velocity, and this in turn is determined by the properties of the core material. Since the core materials used have values of a greater than those which we find for the standard filaments it does not seem so strange that the values of a for the partly coated filaments should be found to run higher than those for completely covered filament.

We hope that our present experiments will throw more light on the factors involved in the escape of electrons through these minute activated areas. Our information is at present too meager to warrant an opinion as to whether an electron on its way out remains for some time as a part of the molecule of active material or merely slips past it. The number of electrons passing out through one molecular opening in a second may be of the order of ten thousand, and that this rate may persist for some time is indicated by the rather slow rate of decay of activity. This proves at least that no irreversible chemical change in the active coating is involved in the emission of an electron. Perhaps a more striking proof of this is found in certain of our filaments which through a life of twenty thousand hours have emitted fifteen times more mass of electrons than the mass of their coating.

Another factor of considerable importance in connection with the use of Wehnelt oxides is the facility with which they emit electrons when bombarded by electrons or by positive carriers. The factors governing the emission of secondary electrons are not well understood even in the case of pure metals. Experiments which we have performed with redistilled mercury surfaces indicate that the secondary emission may become very small when an absolutely clean surface is obtained. With Wehnelt oxides the secondary emission may be comparatively large, several electrons being liberated by each one that strikes the surface. Under the bombardment of positive carriers, however, secondary electron emission does not appear to take place so readily, and our experiments have not as yet shown evidence of more than a few electrons emitted per impact. This negatives the idea, which a few people have held, that positive ion bombardment is a controlling factor in electron emission from oxide coated filaments.

In conclusion, it may be remarked that while oxide coated filaments, under the pressure of necessity, have been developed to the state where they can be manufactured and used on an immense commercial scale as evidenced by their employment in more than half a million vacuum tubes, and while they easily hold the field as the most economical, and longest lived, source of electrons available for electron tube devices, we have not as yet by any means reached the limit of their possible development. The physical constants delimiting the operation of pure metal filaments are well known for the metals now available, and there is no apparent avenue by which their efficiency can be materially increased. Marked advance can only be expected when we depart from pure metals by mixing or coating them with other materials. In the case of the oxides, which at present furnish the best material for coating, it is not at all unusual to find sporadic cases of enormously greater activity than the average which we obtain by commercial coating processes. The limit to which improvement may be expected to extend can only be determined when the factors governing electron emission from the oxides are as well understood as are at present those governing electron emission from the pure metals. It is more than probable that in the process of obtaining this knowledge about the oxides we will find new light thrown upon the process of emission from pure metals as well.

Research Laboratories of American Telephone & Telegraph
Company and Western Electric Company, Inc.

BIBLIOGRAPHY FOR THE PHYSICS AND CHEMISTRY OF OXIDE CATHODES.

1. Cooke, H. L. and Richardson, O. W. Absorption of heat produced by the emission of ions from hot bodies. II. Phil. Mag. (6), *26*, 472, 1913.
2. Deininger, F. Austritt negativer Ionen aus einigen glühenden Metallen und aus glühendem Calciumoxyd. Ann. d. Phys. (4), *25*, 258, 1908.
3. Fredenhagen, K. Ueber die Elektronenemission des Platins und über die Wirksamkeit der Oxydelektroden. Leipz. Ber., math.-phys. Kl., *65*, 42, 1913.
4. Fredenhagen, K. Das Verhalten der Wehneltelektrode in verschiedenen Gasen. Phys. ZS., *15*, 19, 1914.
5. Gehrts, A. Die Ursache der Elektronenemission von Oxydkathoden. Verh. d.D.P.G., *15*, 1047, 1913.
6. Germershausen, W. Die Elektronenemission der CaO-Elektrode im Vakuum. Phys. ZS. *16*, 104, 1915. Ann. d. Phys., *51*.
7. Horton, F. Discharge of negative electricity from hot calcium and from lime. Phil. Trans., *A207*, 149, 1907; also Proc. Roy. Soc., *A79*, 96, 1917.
8. Horton, F. Ionization produced by certain substances when heated on a Nernst filament. Camb. Phil. Soc. Proc., *17*, 414, 1914.
9. Horton, F. On the action of a Wehnelt cathode. Phil. Mag. (6), *28*, 24, 1914.
10. Horton, F. Origin of the electron emission from glowing solids. Phil. Trans. *A214*, 277, 1914.
11. Jentzsch, F. Ueber die Elektronenemission von glühenden Metalloxyden. Ann. d. Phys., *27*, 129, 1908.
12. Richardson, O. W. Die Abgabe negativer Elektrizitat von heissen Korpern. Jahrb. d. Rad. and El. *1*, 300, 1904. (Synopsis).
13. Richardson, O. W. The kinetic energy of the ions emitted by hot bodies. II. Phil. Mag. (6), *18*, 681, 1909.
14. Richardson, O. W. The ions from hot salts. Phil. Mag. (6), *26*, 452, 1913.
15. Schneider, H. Die Energie der aus glühenden CaP entweichen den Elektronen. Ann. d. Phys., *37*, 569, 1912.
16. Schottky, W. Bericht über thermische Elektronenemission. Jahrb. d. Rad. and El., *12*, 149, 1915. (Synopsis.)
17. Wehnelt, A. Ueber den Austritt negativer Ionen aus glühenden Metallverbindungen und damit zusammenhängende Erscheinungen. Ann. d. Phys. (4), *14*, 425, 1904.
18. Wehnelt, A. On the discharge of negative ions by glowing metallic oxides, and allied phenomena. Phil. Mag., *10*, 80, 1905.
19. Wehnelt, A. and Jentzsch, F. Ueber die bei der Elektronenemission glühender Korper auftretenden Temperaturanderungen. Verh. d. D. P. G., *10*, 605, 1908.
20. Wehnelt, A. and Jentzsch, F. Ueber die Energie der Elektronenemission. Ann. d. Phys., *28*, 537. 1919.
21. Wehnelt, A. and Liebreich, E. Energie der Elektronenemission glühender Korper. Phys. ZS., *15*, 548, 1914.
22. Willows, R. S. and Picton, T. Notes on the behaviour of incandescent lime kathodes. Proc. Phys. Soc. London, *23*, 257, 1911.

3\. Wilson, W. The loss in energy of Wehnelt cathodes by electron emission. Proc. Nat. Acad. Sci. *3*, 426, 1917.