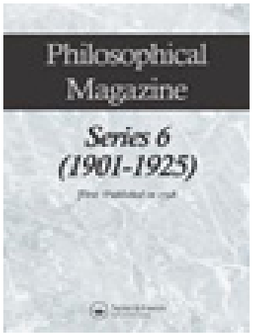

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LXXXIV. Negative thermionic currents from tungsten

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The main object of this paper is to show that the form of quantum-theory which seems necessary to account for line spectra is not really distinct from that originally proposed by Planck, and the subject of its further application to line spectra and other phenomena may be left for a future publication.

In conclusion I wish to express my thanks to Professors J. W. Nicholson and O. W. Richardson for their advice and criticisms.

Wheatstone Laboratory, King's College,
March 1915.

LXXXIV. *Negative Thermionic Currents from Tungsten.*

By K. K. Smith, *A.B., Fellow in Physics, Princeton University* *.

Introduction.

THE emission of negative electricity from an incandescent metal or carbon filament has been the subject of several investigations †. The number of electrons carried from the filament to a neighbouring positively charged electrode increases very rapidly with the temperature. The exact quantitative relation between the number of electrons emitted and the temperature of the filament was established by Richardson, and has been verified by the experiments of others. It was assumed that the emission is determined simply by the number of electrons whose kinetic energy is sufficient to overcome the forces tending to prevent their escape from the metal.

This relation is expressed by the formula

$$i = aT^{\frac{1}{2}}e^{-\frac{b}{T}},$$

where i is the saturation (maximum) current in amperes per square cm. and T is the absolute temperature. The quantities a and b are constants, the latter being proportional to the work done by an electron in escaping from the metallic surface. On this view, a pure metal in a perfect vacuum would give a thermionic current which would be a function of its physical properties only. In any actual case the presence of traces of impurities or gases would presumably

* Communicated by Prof. O. W. Richardson, F.R.S.

† Richardson, Camb. Phil. Proc. vol. xi. p. 286 (1901); Phil. Trans. A, vol. cci. p. 497 (1903); H. A. Wilson, Phil. Trans. A, vol. ccii. p. 243 (1903); Deininger, *Ann. d. Phys.* xxv. p. 304 (1908).

have secondary effects, but would not be required to explain the existence of the current.

In view of some recent experiments *, which seemed to cast doubt upon the above explanation of thermionic currents, the following investigation was undertaken. Professor Richardson has already published the results of the earlier experiments †. The object has been (1) to make a detailed quantitative investigation of the negative thermionic emission from tungsten over a large temperature range, and (2) to discover, if possible, more evidence as to the conditions which determine the emission.

Experimental Arrangements.

The filaments used in these experiments were all taken from a spool of pure ductile tungsten furnished by the General Electric Co., Schenectady, N.Y. They were 0·041 mm. in diameter, and the lengths used in the different lamps varied from 2·5 cm. to about 9 cm. They were electrically welded in hydrogen to copper leads, which, in turn, were welded to platinum wires. Then the wires were mounted axially in cylindrical glass tubes and sealed in. The tubes were 3·2 cm. in diameter, and contained copper gauze cylinders 2·6 cm. in diameter. Separate wires connected these anodes to the outside of the lamps.

Fig. 1.

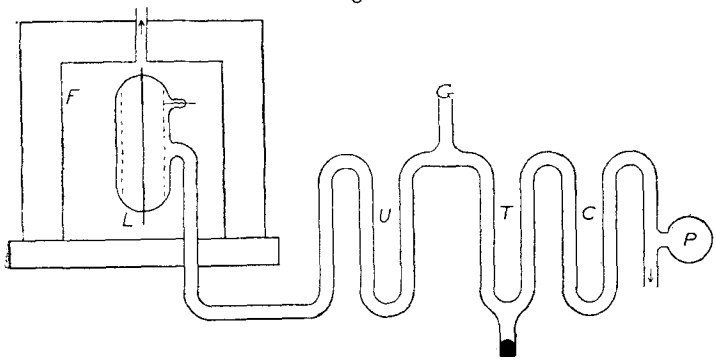


Fig. 1 shows the arrangement for exhausting and heating the lamp L, in the vacuum furnace. The figure is purely diagrammatic and is not drawn to scale. The U-tube, U,

* Pring and Parker, Phil. Mag. vol. xxiii. p. 192 (1912); Pring, Proc. Roy. Soc. London (A), vol. lxxxix. p. 344 (1913); Fredenhagen, *Deutsch. Phys. Gesell. Verh.* vol. xiv. p. 384 (1912).

† Richardson, Phil. Mag. vol. xxvi. p. 345 (1913).

could be surrounded with a Dewar flask containing liquid air. The pressure indications were read on the McLeod gauge, G. By raising or lowering the mercury at T, the lamp and gauge could be shut off from the vacuum-pump, or connected to it. The tube C was half filled with coconut charcoal, and could be surrounded with liquid air when it was desired to reduce the pressure as much as possible. A bulb, P, containing phosphorus pentoxide, was attached between C and the Gaede mercury pump, and auxiliary pump. The furnace itself was evacuated by a separate pump.

The lamp was exhausted and heated at the same time. The furnace reached a maximum temperature of about 600° C., which was maintained for several hours in order to get rid of absorbed gases. At first considerable quantities of gas were given off, but the pressure gradually decreased with prolonged heating, and finally became quite small. The furnace was then allowed to cool slowly, liquid air was applied at U and C, and the filament was heated by an electric current. The cylinder was charged positively, so as to be bombarded by electrons from the filament. At intervals the amount of gas still being driven off was estimated by closing the trap T for five minutes, and noting the increase of pressure, if any. The details of some of these experiments, which have already been published *, show that the observed thermionic currents were too large to be ascribed to the evolution of gas from the filament, or to an action depending upon impacts between the gas molecules and the filament. After the pressure indicated on the gauge had become practically inappreciable, the lamp was either sealed off immediately and removed, or the observations were taken on the unsealed lamp.

Measurement of Currents.

The lamp filament was usually made one arm of a Wheatstone's bridge. The positive terminal of a battery was connected to the receiving electrode, and the other terminal to the positive end of the filament. An electrometer having a sensibility of 790 divisions per volt, and a capacity of 130 electrostatic units, was used to measure the smallest currents. A condenser whose capacity could be varied from 0·001 microfarad to 1 microfarad was used in parallel with the quadrants when necessary. With larger currents, resistances varying from 100 ohms to 1 megohm were put in the

* Richardson, *loc. cit.*

thermionic circuit, and the quadrants were connected to the ends of these resistances in turn. For currents greater than 1 microampere a unipivot galvanometer with variable shunts was used. With these arrangements, it was possible to measure the emission over a range from 10^{-13} amp. up to 1 ampere. Owing to the high melting-point of tungsten, it was possible to obtain thermionic currents of the order of magnitude of the heating currents. In what follows, the thermionic current will usually be expressed in terms of unit area, otherwise it is to be taken as the total current from the filament.

Measurement of the Filament Temperatures.

Through the kindness of Dr. Irving Langmuir, a curve was obtained with the wire, showing the temperature of the filament as a function of the current carried by it. This curve was determined by photometric measurements on a special lamp, using a piece of the same wire that was used in these experiments. As a check on the temperature determinations some small lamps were made from these filaments, and were used in an optical pyrometer of the Holborn-Kurlbaum type, constructed in this laboratory. These lamps were calibrated by observations on a black-body furnace at the melting-points of copper and nickel. The results of the two methods were in satisfactory agreement. In the earlier experiments it was customary to determine the resistance each time an observation was taken, since the bridge galvanometer was of course much more sensitive than the ammeter to small variations in the temperature of the filament.

The effects produced by a thermionic current in the ordinary Wheatstone's bridge circuit have been considered by Richardson and Cooke *. As far as the present experiments are concerned these effects are of no importance, so long as the thermionic current is small in comparison with the heating current. For very high temperatures, however, the large thermionic currents cause the temperature estimations to be much too high. In fact, even if the bridge is not used at all, the temperature of the filament will be overestimated if a large thermionic current is flowing, and, furthermore, the two ends will be unequally heated. For a given current per square centimetre these disturbing effects increase with the length of the filament.

* Phil. Mag. vol. xx. p. 173 (1910).

Experimental Results.

Lamp 1.

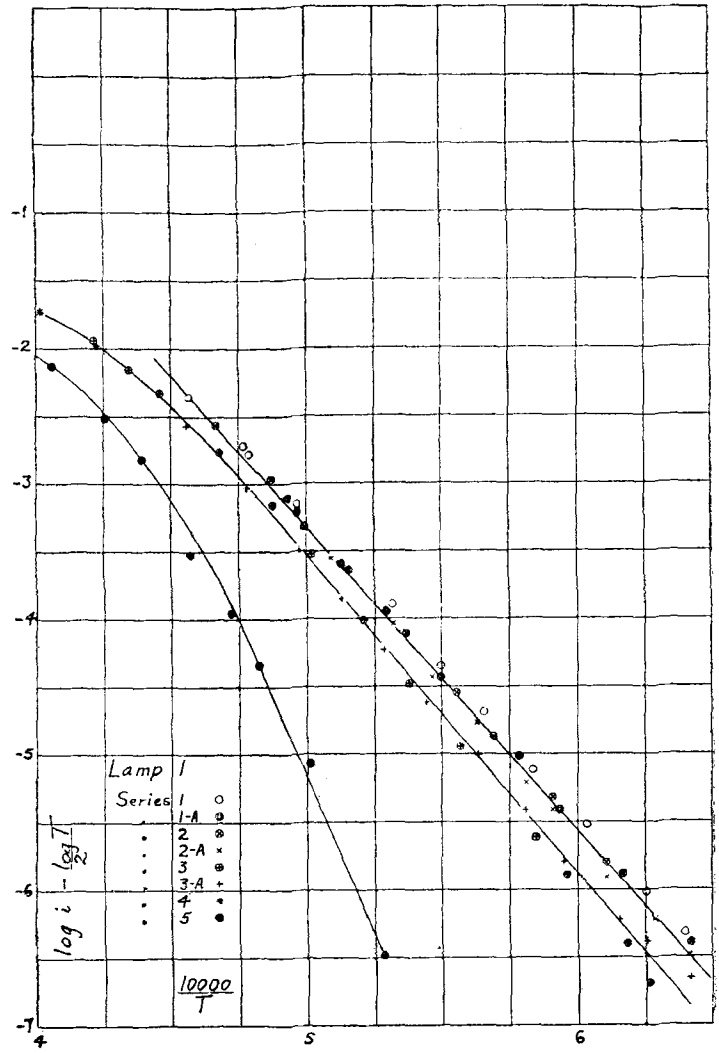
Lamp 1 contained a filament 5 cm. long, and a cylindrical anode. After the lamp had been heated in the furnace for 9 hours, liquid air was applied at U and C, and the filament was glowed for an hour and a half at various temperatures above 2500° K. The thermionic currents varied from 3 to 40 milliamperes. The trap T was closed at intervals, and the increase in pressure during five minutes was noted. In the first period the pressure rose from 0·005 to 0·050 micron; in the last period the increase was from "0" to 0·003 micron. The furnace (still above room temperature) was then opened, and the lamp was sealed immediately. The pressure indicated was "0."

Professor Richardson measured five series of thermionic currents greater than 1 microampere, the potential difference between the anode and the cathode being 120 volts. The results are shown in fig. 2, in which $\log i - 1/2 \log T$ is plotted against 10000/T. Series 1 A, 2 A, and 3 A were taken with decreasing temperatures, the others with increasing temperatures. It will be noticed that the points for the 3rd series are shifted to the left of the preceding ones. At first sight, this would seem to indicate less current at a given temperature as the heating was continued. It is believed, however, that this is not to be ascribed primarily to a change in the emitting power of the surface, but rather to a change in the resistance of the filament, owing to excessive heating. After the first series of readings, the filament was heated for over an hour at a temperature above 2500° K. The thermionic current was turned off to prevent unequal heating, which is likely to burn the filament out at one end. Between the 2nd and 3rd series the filament was heated to a still higher temperature for 20 minutes, and the resistance increased from 1625 to 1670 units, or about 2·8 per cent. The same thermionic current was obtained with R=960 after overheating as with R=945 just before. These resistance changes as the filament evaporates cause the temperatures to be overestimated, and are sufficient to account for the above variations in thermionic current.

In series 4, thermionic currents (not shown in fig. 2) up to 320 milliamps. were obtained, or 8 times as much as had been obtained before the lamp was sealed off. Immediately after this large current was obtained, it was found that at

2480° K. the current was only 22·5 milliamps., whereas it had been 58 milliamps. just before this. Series 5, taken

Fig. 2.



immediately afterwards, shows the effects of this severe heating in a more striking manner. The filament was about

300° hotter than usual before the current was large enough to be read on the microammeter. At this higher temperature, 1890° K., the current was now only 0·014 milliamp. per sq. cm., as compared to 5·36 milliamp. per sq. cm. at the same temperature in series 2. In other words, the thermionic current had been reduced to 1/380th part of what it had been. It began to increase very slowly, although the temperature was constant. The other points of series 5 were determined at once, without waiting to see if the current would become steady at the lower temperature. The current increased with the temperature much more rapidly than before, and approached the preceding series so that at the highest temperature it was 60 per cent. of the current at the same temperature in series 4. About 2500° K. a blue glow appeared after continued heating, and the copper anode became red-hot.

The above experiments were performed before Dr. Langmuir's paper * on thermionic currents was published. They confirm his conclusion that the effect of residual gases is to decrease the thermionic current, especially at low temperatures. The fact that considerably larger currents, at the same temperatures, have been obtained by the writer is undoubtedly owing to better vacuum conditions. According to the above paper, the normal vacuum curve was obtained at a pressure of 0·07 micron, and gives the following values: $a=34\times10^6$ amps. per sq. cm., $b=55{,}500$. By the use of charcoal and liquid air, as described before, it has been possible to keep the pressure as low as 0·001 micron, or less.

In Lamp 1, so long as the thermionic current did not exceed those employed before the lamp was sealed, the vacuum was practically perfect, and very large currents were obtained. At 2000° K. 26 milliamperes per sq. cm. were measured. Later, the excessive heating and bombardment of the anode by electrons liberated occluded gas, which reduced the thermionic current. The presence of gas is proved by the blue glow which appeared. There is no reason to suppose that any appreciable amount of gas was present previous to the excessive heating. Tests have been made at various times with an induction-coil, on similar lamps which had not been overheated, and no indications of gas were ever found. The potential difference and the size and shape of the anode were such as to permit the normal

* Phys. Rev. ii. p. 450 (1913).

current to flow unlimited by any space charge effect *. This is proved by the fact that the currents were practically saturated at 120 volts. Even with a blue glow in the lamp, the points at the upper end of curve 5 fall far to the left of the straight line. Hence this deviation cannot be the result of a space charge effect, but is undoubtedly caused by the large thermionic currents, which were of the order of magnitude of the heating current †.

Lamp 2.

Lamp 2 contained a filament 8·5 cm. in length, and a cylindrical anode of copper gauze. It was heated for 14 hours in all, and liquid air was applied at C, but not at U (at first). The filament was glowed for about 3½ hours, the thermionic current during the last hour being 10 milliamperes. In the first 5 minute test with the trap T closed, the increase of pressure was from 0·001 to 0·050 micron; in the last 30 minutes the increase, if any, was not more than 0·0001 micron from "0." Liquid air was then applied to U to condense the mercury vapour, but no change in the thermionic current could be detected. The lamp was then sealed, and the thermionic currents were measured from 1050° K. up. The results (plotted in fig. 3) show that within the limits of experimental error, the equation

$$i = aT^{\frac{1}{2}}e^{-\frac{b}{T}}.$$

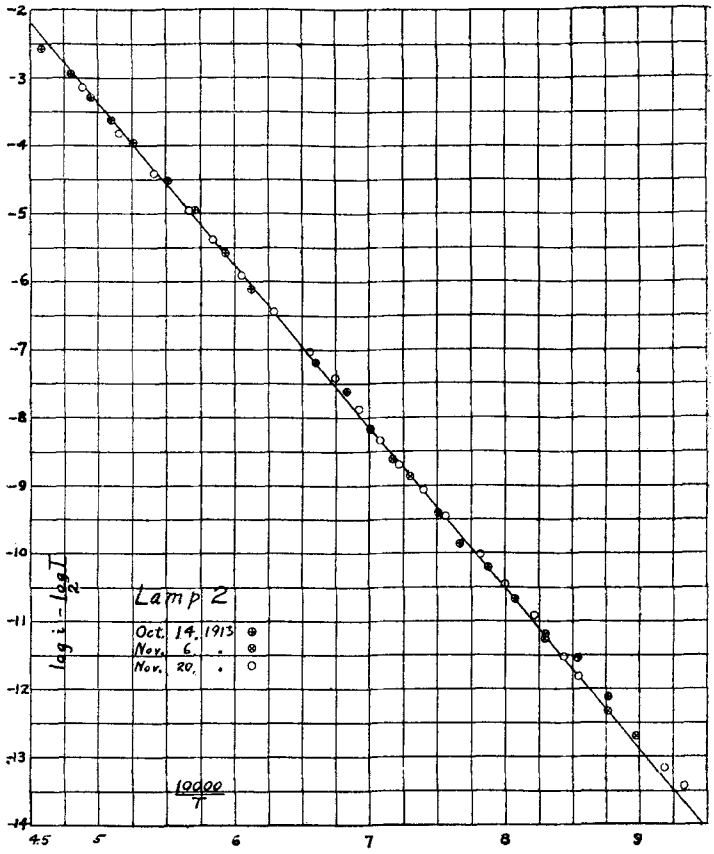
is satisfied throughout. (In all the figures the current is expressed in amperes per sq. cm.)

In order to determine how the thermionic current depended upon the voltage, tests were made at the following temperatures: 1070, 1335, 1465, 1590, 1710, and 1825° K. To reduce the results to the same scale, the current with 200 volts has been taken as the unit measure in each case, and

* Langmuir, *loc. cit.*

† Since these experiments were completed, Dr. Dushman has published (Phys. Rev. iv. p. 121, 1914) the results of some experiments in which he observed the decrease in the thermionic current caused by bombardment of the anode. The temperatures were above 2000° K. and the maximum currents obtained appear to be about the same as those observed by Dr. Langmuir. The values of the currents given for the Coolidge X-ray tube (Phys. Rev. ii. p. 409, 1913) are larger, but not so large as the writer's.

Fig. 3.



the ratios, which were the same for all the temperatures, are shown in the following table:—

Volts.	Current. / Current with 200 volts.
25	0·80
50	0·85
100	0·91
300	1·07
400	1·14
500	1·21
600	1·27

Table I. shows the values of the currents which best represent the emission observed under good vacuum conditions in Lamps 1 and 2. They are given by the values:

$$a = 6{\cdot}7 \times 10^8 \text{ (amps. per sq. cm.)}, \quad b = 54700.$$

TABLE I.

Temperature.	Thermionic Current.
1050° K.	0·000000235 microamps.
1100	0·00000256 per
1150	0·0000227 sq. cm.
1200	0·000169
1250	0·00106
1300	0·00583
1350	0·0282
1400	0·122
1450	0·476
1500	1·70
1550	5·60
1600	17·1
1650	49·0
1700	132·
1750	337·
1800	809·
1850	1880·
1900	4120·
1950	8730·
2000	17800·
2050	35200·
2100	67000·
2150	124000·
2200	224000·
2250	394000·
2300	674000·

Lamp 3.

Lamp 3 contained a filament 5·25 cm. long and a copper gauze anode. It was given the usual treatment and sealed off, but the seal cracked while cooling. The apparatus was then arranged so that the thermionic currents could be measured with the lamp in place in the furnace, and connected to the McLeod gauge, etc. After the lamp had been reheated and exhausted to a low pressure, the furnace was opened, liquid air was applied at U and C, and a series of observations was taken at once, beginning at low temperatures. The potential difference was 190 volts. At several points it was noticed that the current was unsteady, and that it increased with the time. In these cases, readings were taken every minute for 5 minutes or so, and the average reading was taken. The pressure was "0" at the beginning,

and did not exceed 0·002 micron until the current was as large as 0·130 amp. (1·95 amp. per sq. cm.). With this current the pressure increased (with the trap T closed) from 0·002 to 0·060 micron in 6 minutes. Currents as large as 0·350 amp. were observed, while the pressure increased to 0·600 micron, and then decreased to 0·400 micron. The temperature was at least 3000° K., and the filament burned out a few minutes later.

The results are shown in fig. 4. Points in the middle of the curve fall along a straight line from which the value $b = 69{,}500$ is calculated. At the lowest temperature (1950°) the current is about 1/600 of the current observed with Lamp 1 at the same temperature. At 2500° K. the corresponding ratio is about 1/3, while at the highest temperature the two currents are practically identical. These results will be discussed after they have been compared with those of the next experiment.

Lamp 4.

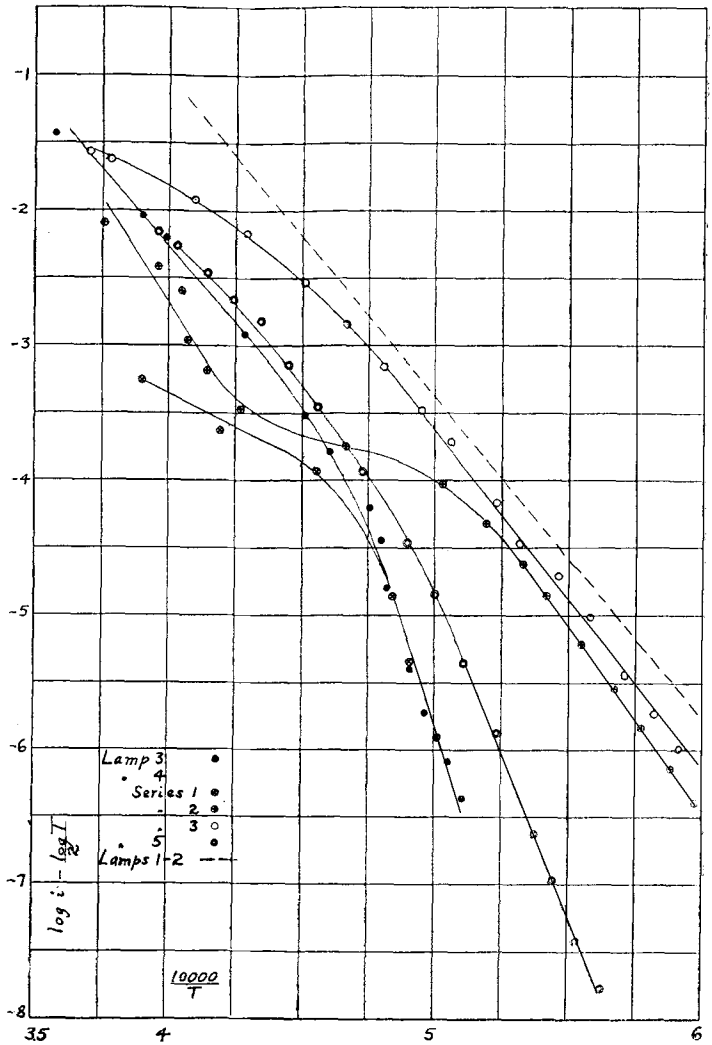
This lamp was an exact duplicate of the preceding one. After the usual treatment the filament was given its initial heating (by a current) at 2100° K. This was continued for $3\frac{1}{2}$ hours, during which time the thermionic current increased from 3 to 133 microamperes. The observations of the last 40 minutes are shown in the following table :—

Time.	Pressure.	Total Current.
10.42 P.M.	0·006 micron.	16
.45		18
.47		21·5
.50		27·5
.52		36·4
.53		42
.54		51
.55		66·5
.57	0·001	
.58		109
.59		114
11.00		116
11.20	0·0001	133

With a potential difference of 210 volts the 1st series of observations at different temperatures was taken, after which the thermionic circuit was broken, and the filament was glowed for 40 minutes at temperatures varying from 2700° to 3000° K. The 2nd and 3rd series were then taken in close succession. During all these series the pressure was "0," according to the gauge, whether the trap T was closed

or not. This was true even after the filament was finally burnt out. All the observations are shown in fig. 4, for comparison with those of Lamp 3.

Fig. 4.



Taken together these two experiments show that the initial negative thermionic current is very much less than that obtained on subsequent heating. The actual difference would be more obvious if the currents, instead of their logarithms,

had been plotted. This conclusion was confirmed in every one of the subsequent experiments. Under some conditions, as in the last experiment with Lamp 1, and in some others to be described later, it is possible that the current may show a decrease, but no emission less than the initial emission has been observed.

The first observations on the two lamps (3 & 4) are in good agreement at low temperatures, but at a certain point the 1st series (Lamp 4) shows that the current is increasing much more slowly with the temperature. The heating of the filament at very high temperatures, with the thermionic circuit broken, was followed (series 2) by much larger currents than before. At 2000° K. curve 2 bends sharply to the left, and then again to the right, while curve 3 is regular. Heating the filament would tend to remove impurities and absorbed gases from the filament. It is known, for example, that the oxide volatilizes in a vacuum without the evolution of gas. On the hypothesis that initially there existed a surface layer which hindered the emission of electrons, we should expect to find larger currents in the second series. The falling off in the rate of increase with the temperature, which occurred at about 2000° in the first two series (Lamp 4), is caused by the bombardment of the anode. At low temperatures, and hence with smaller currents, the latter effect is not apparent. Heating the filament to a high temperature without the thermionic current does not bombard the anode and free it from gas, although it does rid the filament to a large extent of whatever is hindering the normal emission. Heating the filament, and allowing the thermionic current to flow, cleans both anode and cathode.

Lamp 5.

This lamp was like the preceding ones, except that the filament was 6 cm. long. The observations were extended over three days, and during this time there was always a supply of liquid air about U and C. Out of ten series of observations the largest currents are plotted in fig. 4. The smallest currents were found when the filament was first heated, and this agrees with the results of the other experiments. With this lamp complete saturation was obtained, whereas the results already given for Lamp 2 show that the currents always increased somewhat with the voltage. When voltages as high as 600 volts were first applied the results were as follows: at 1800° K. the current was saturated at from 200 to 400 volts, and then decreased with increasing

voltage. The measurements were repeated immediately afterward, and it was found that the current had been reduced one half. At the same time the pressure had increased from 0·010 to 0·014 micron, owing, no doubt, to the evolution of gas from the anode.

The gas pressure, however, was evidently not an important factor in determining the thermionic current. For example, the same pressure (0·001 micron) was indicated in series 1 and 3, although the currents were considerably larger in the latter case. On the other hand, series 3, 8, and 9 agreed quite well, although the corresponding pressures were 0·001, 0·010, and 0·100 micron respectively. Repeated heating did not increase the emission beyond what is shown for this lamp in fig. 4. In view of these facts it was believed that the great reduction in current, as compared with the other lamps, must be caused by condensable vapour, probably water vapour. The lamp had been heated in the furnace to 500° C., or more, but there was the possibility that water vapour had entered afterwards from below the furnace, even though liquid air had been around the U-tube all the time. This was the first lamp which had not been sealed shortly after the furnace was opened. A slight change in the apparatus was therefore made before the next lamp was set up. The glass tube leading to the lamp was bent into a U inside the furnace, so that liquid air could be applied close to the lamp. Any vapour which might arise from the unheated tubing below the furnace would then be condensed before it could enter the lamp.

Lamp 6.

This lamp contained two parallel filaments, 1·7 cm. apart. One filament "A" was 8·5 cm. in length, and the other "B" 7·2 cm. It was then unnecessary to use a cylindrical gauze anode, and thus one possible source of gas was removed. All the platinum and copper connecting wires were completely covered with melted glass before they were sealed in the lamp, so that the only surfaces exposed on the inside of the lamp were of tungsten and glass. At the same time that the lamp was being heated in the furnace, the two filaments were glowed in series for six hours at temperatures varying between 2000 and 2500° K. As soon as possible after the hot furnace was opened, liquid air was placed around the new U-tube next to the lamp. Liquid air had previously been placed around the other U-tube and the charcoal tube as usual.

Using filament "A" as the hot cathode, three series of observations were made, and the results of the first and last are shown in Table II. Following the 2nd series, the cathode had been heated to 2700° K. for twenty minutes. After this the currents were as large, at the same temperatures, as the currents which had been observed in the sealed lamps. The pressure was "0" during the whole time. This experiment shows that the thermionic emission from tungsten is not a secondary effect arising from the presence of gas or condensable vapour, but must come from the metal itself.

TABLE II.

Current.	Temperature.		
(Amps. per sq. cm.)	"A," series 1.	"A," series 3.	"B," series 1.
$1{\cdot}12\times10^{-5}$	1715° K.	1540	1695
2·25 ,, ...	1755	1575	1740
4·50 ,, ...	1795	1615	1785
9·0 ,, ...	1840	1650	1835
18·0 ,, ...	1895	1695	1890

Immediately after the 3rd series with filament "A" as cathode, filament "B" was made the cathode, and "A" the anode. The results of the first series of observations under these conditions are also shown in Table II. It will be seen that the emission under the same vacuum conditions depended upon which filament was used as the cathode. As stated above, both filaments had been glowed in series, and otherwise they had been treated alike, except that "A" had been heated to 2700° K. for twenty minutes. Above 1900° K. the currents were limited on account of the small dimensions of the anode, and after a certain value was reached the currents could not be increased, with constant voltage, no matter how much the temperature was raised.

The liquid air was then removed from the gauge and furnace U-tubes, the trap T being closed. The pressure increased from "0" to 0·25 micron, and the resistance of the glowing filament, "B," began to increase slowly. This was caused by the oxidation of the filament by the water vapour released from the U-tubes. The resulting ionization in the gas neutralized the space charge effect, and the current (T=2180° K.) began to increase. Series 4, taken at once, showed that below 1950° K. the currents had been decreased

by the formation of the oxide, but above this temperature they were larger, for the reason just given. The following table shows how much the currents at 2040° were increased by the removal of the liquid air.

Volts.	Total Current in Microamperes.	
	Liquid Air on. P=0·0001 micron.	Liquid Air off. P=0·250 micron.
20	1·05	...
35	...	18
40	4·1	350
60	9·35	362
80	17·5	365
100	28·2	...
120	40·4	368

Below 2000° K. the currents were steady, but above this it was noticed that they increased with the time. The following table shows one instance of this, as well as the effect of replacing liquid air about the U-tube near the gauge.

Time.	Total Current (T=2010° K.).
0 mins.	350 microamperes.
1	368
1·5	375
2·0	388
3·0	410
3·5 P=0·220 micron.	
4·5	430
Liquid Air replaced.	
5·0	102
5·5	93
6·0	84
6·5	84
7·0 P=0·170	86
8·5	86
9	86
	constant.

The increase was probably caused by the more rapid removal of the oxide at this temperature, or to the increase in temperature due to the filament burning; while the decrease was caused by the absence of ions after the condensation of

the water vapour. The resistance of the filament remained constant when liquid air was about the U-tube, otherwise it increased gradually. The liquid air was removed once more, and repeated measurements showed, as before, that the currents increased rapidly with the voltage when liquid air was around the U-tube; if it was not, the currents were saturated. After the liquid air had once been removed the vacuum conditions were never so good as before, but the pressure was always so low (< 1 micron) that ionization by collision had no effect.

Lamp 7.

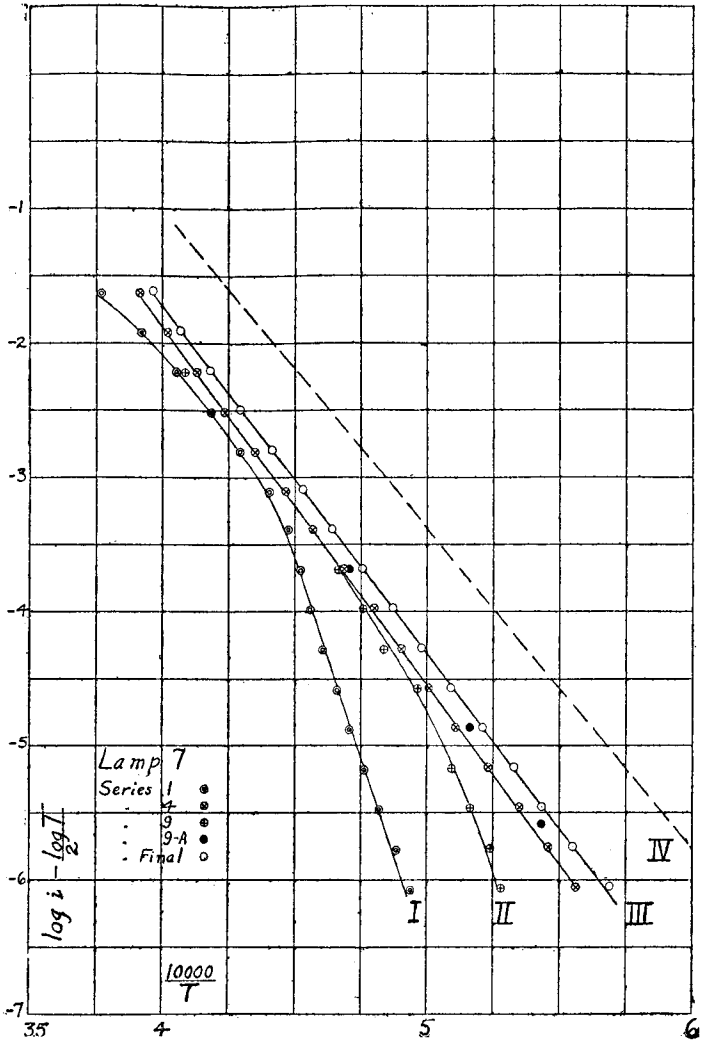
This experiment was undertaken in order to measure the currents before and after the lamp was sealed. The filament was 2·6 cm. long, and the anode was a cylinder of copper gauze. The lamp was heated 10 hours on one day, and 6 hours on the next day. After the first series of observations had been taken, the trap T was closed, and was kept closed until the lamp was sealed 6 hours later. The pressure was "0" before any measurements were taken, and no indication of pressure could be seen up to the time that the lamp was sealed. After sealing, the liquid air was removed from the U-tube, U, and three or four minutes later the pressure in the gauge was 0·370 micron, but it did not increase after that. This was the pressure of the gases that had been condensed.

The results of the typical series are shown in fig. 5. The first currents were less than those that had been observed in the first heating of the other filaments. Afterwards they increased, as can be seen in series 4. This condition was not permanent, however, for after the filament had been kept at a temperature of about 2000° K. for two hours, it was found that the currents were smaller than in series 4, although they were still much larger than in the 1st series. These results (series 6) have not been plotted, since they are represented well enough by series 9. After continued heating the emission was again about the same as in the 4th series, and the lamp was then sealed.

A few days later measurements were taken on the sealed lamp. Without any preliminary heating whatever, series 9 was taken with increasing temperatures, followed immediately by series 9 A with decreasing temperatures. It is evident that a marked change has been produced by simply heating the filament once. The final results have been plotted, and it will be seen that the points lie quite accurately

along a straight line through the whole range of temperature, which was from 1760° to 2520° K. The agreement

Fig. 5.



between the observed and calculated currents can be seen in Table III.

The value of b (59700) is larger and the currents are

smaller for this lamp than for the other sealed lamps. The only known difference in treatment to which this can be ascribed is that this filament was never heated to a temperature so high as 2700° K., and to avoid the risk of burning out the filament, the temperature was seldom raised above 2500° K., except for short periods while observations were being taken. The close agreement indicated in Table III.

TABLE III.

Lamp 7.

T.	Current in microamperes per sq. cm.	
	Observed.	Calculated.
1760° K.	37·5	33·8
1800	75·0	78·0
1840	150·	157·
1875	300·	295·
1920	600·	607·
1965	1200·	1260·
2010	2400·	2460·
2050	4800·	4730·
2105	9600·	9680·
2155	19200·	19300·
2205	38400·	37800·
2265	76800·	76700·
2330	154000·	157000·
2390	308000·	311000·
2455	616000·	597000·
2520	1230000·	1190000·

$a = 4{\cdot}4 \times 10^5$ amperes per sq. cm.
$b = 59700$.

does not, of course, prove that the emission was characteristic of the pure metal alone. An oxide, for example, could remain upon the wire indefinitely if the temperature were not raised too high. Four months after the lamp was sealed, experiments showed that the emission was unchanged. The filament was then heated to 2900° K. for three minutes, with a potential difference applied to prevent the thermionic current from flowing, but this produced little, if any, change in the emission at 1800° K. The temperature was then raised with the thermionic current flowing, but unfortunately the filament was burnt out near one end before any observations could be taken.

Discussion of Results.

Figure 5 may also be used to illustrate the typical results of all the experiments. When the observations are plotted it is found that they fall into four groups, represented by curves I., II., III., IV., as follows :—

I. The first currents in four lamps (3, 4, 5, 7) (*cf.* also fig. 4). The first currents in the other lamps were not measured.

II. (*a*) The last series with lamp 1 (*cf.* fig. 2).
(*b*) The currents after the liquid air was removed from lamp 6.
(*c*) The largest currents in lamp 5 (*cf.* fig. 4).
(*d*) The first currents after lamp 7 was sealed.

III. The permanent emission in lamp 7, which was not heated much above 2500° K. This would also include the currents from filament "B," lamp 6, before the liquid air was removed.

IV. The currents observed after heating the filaments to a very high temperature, 2700° K. or more, under the best vacuum conditions (lamps 1, 2, 6 "A").

These variations in the thermionic emission seem to be the results of progressive changes in the surface conditions *. When the filament is first heated its surface is probably slightly oxidized, and otherwise contaminated by impurities. No special precautions to clean the filament were taken before it was sealed in the lamp. After a good vacuum has been secured, heating the filament for a sufficient time to a temperature above 2700° K. removes the impurities, and then the emission is represented by IV. This condition is permanent thereafter provided the vacuum is maintained, but under the following circumstances the emission changes to II., which is not much larger than the original I.: (*a*) if gas is liberated inside the lamp by excessive heating and bombardment of the anode (lamp 1), or (*b*) if the filament is oxidized by allowing small amounts of water vapour to enter the lamp, as in 6.

The removal of impurities from the surface seems to be indicated quite clearly by the observations made when the filament in lamp 7 was first heated above 2000° K. after sealing. This changed the emission permanently from II. to III. Since the lamp had been sealed under good vacuum conditions there was no fresh supply of gas by which the

* *Cf.* Langmuir, *loc. cit.*

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