SECONDARY ELECTRON EMISSION FROM COPPER SURFACES.

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SYNOPSIS.

Secondary Electrons from a Copper Surface Bombarded by Electrons.—The method used was to measure the current flowing to the bombarded plate as a function of the grid potential. By using sufficiently low pressures the ionization effect was made negligible. (1) *The coefficient of secondary emission* was found to increase somewhat with the energy of the primary electron *up to* 500 *volts* but never exceeded 1.5 per electron; the coefficient was increased by *heat treating the plate*, and was greatly decreased by raising the *temperature of the plate*. (2) *The energy* of the secondary electrons was always less than that corresponding to a fall through 5 volts, yet owing to the roughness of the surface an accelerating potential of about 10 volts is required to release most of the secondary electrons from the plate. (3) As to the *origin* of these rays, the fact that their maximum energy is always less than the energy of the primary rays and the shape of the curves obtained both indicate that the secondary electrons are not reflected electrons.

Reflection of electronic rays with energy below 500 *volts, from a copper surface* seems to be zero, or at least small.

INTRODUCTION.

WHEN α rays, positive rays, or free electrons fall on a metal surface it has been found by various investigators that if the energy of impact is high enough there results a reemission of electrons from the surface. These emitted electrons have been termed δ rays when they are produced by α rays, but in view of their corpuscular nature they will be referred to as secondary electrons throughout this paper no matter what is the cause of their excitation. The number of these secondary electrons has been found by O. van Baeyer,[1] Gehrts,[2] A. W. Hull[3] and others to exceed the number of primary electrons striking the plate when the velocity of impact is sufficiently great. This is evidenced by the fact that with increasing velocities of the primaries a point is reached at which the electron current flowing into the plate begins to decrease, and finally reverses in direction, provided there is present another collecting electrode to which the secondaries may flow. So far as measurements of current alone are concerned when the number of these secondary

[1] O. von Baeyer, "Verh. der deutsch. Phy. Gessel.," 10, 1908, p. 903.
[2] A. Gehrts, "Ann. der Phy.," 36, 1911, p. 995.
[3] A. W. Hull, "Proc. Instit. Radio. Engineers," Feb., 1918.

electrons is less then the number of primaries the effect might as conveniently be explained by assuming a true reflection of a portion of those incident as by assuming a secondary emission. However measurements of the velocity of the emitted electrons appear to show that this velocity is practically independent of the method of excitation,[1,2] of the nature of the metal, and of the speed of the incident electrons provided this is greater than about 30 volts. Most observers find also that the bulk of the secondary electrons have velocities of about 5 volts while a small proportion may have as great a value as 30 volts but may never exceed this. These facts as to velocity have resulted in the adoption of the point of view that the emission is due to penetration of the atom by the electron and its subsequent absorption so that the atomic stability is in some manner disturbed and a secondary emission occurs. Below the "ionizing potential" of the surface atoms the effect has generally been regarded as a true reflection and this viewpoint was apparently substantiated by the fact that velocity distribution curves found by von Baeyer and Gehrts changed form at a certain potential.

The present paper gives the results of a study of the number of secondary electrons produced per primary for various velocities of impact of the latter on a copper surface which was so arranged that its surface condition and temperature could be changed. Determinations of the velocity were also made in order to see if any relation existed between the maximum velocity of emission and the energy of impact, as well as to see if the conclusions of other observers could be substantiated. The approximate critical velocity below which no secondary electrons are produced, has also been found, and evidence obtained for the view that there is no true reflection of electrons from metal surfaces. These investigations were initiated by Professor Millikan because it was thought especially desirable at the present time, first, to apply modern methods of high vacuum technique to the elimination of all spurious effects due to residual gases which might have inhered in some of the earlier work; second, because with the rapid increase in our knowledge of the ionizing potentials of gases, the relations to these of the ionizing potentials of liquids and solids has become important; and third, because no one had made any conclusive study of the effect of adsorbed gas films on secondary emission, nor of the effect of changing the temperature of the bombarded surface.

[1] Fuchtbauer, Phy. Zeit., 7, 1906, p. 748.

[2] N. R. Campbell, Phil. Mag., 22, 1911, p. 276; 24, 1912, p. 527.

The Experimental Arrangement and the Method of Making the Observations.

In order to eliminate any effects which might be due to gases where ionization would mask the effects sought the experiments were performed in very high vacua. In order further to make it possible to determine the exact potential at which secondaries begin to be emitted an equipotential filament was used, whereas most of the other experimenters have been limited by the drop of potential along their hot wire source of primary electrons. A hot platinum tube coated with a Wehnelt oxide served as the source of primary electrons. The use of this oxide was found to be necessary because a pure platinum tube gave too small a supply of thermions to produce currents which were large enough to be accurately measured with a galvanometer, unless very large filament heating currents were used. The platinum tube was 6 cm. long, about 3 mm. in diameter and .01 cm. in wall thickness. It was heated by a coaxial No. 22 tungsten wire which carried all the current. The insulation between the wire and tube was a thin layer of alundum cement. The No. 22 wire was fastened mechanically just beyond the ends of the platinum tube to heavier No. 18 tungsten wire leads. These did not become incandescent for filament currents sufficient to heat the No. 22

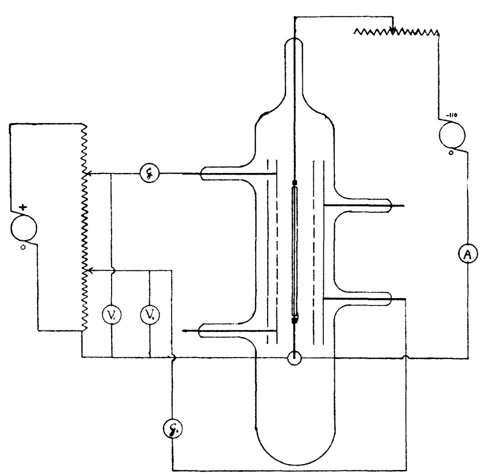

Fig. 1.

wire to a bright red heat. The platinum tube is fastened by a platinum strip to the lead at one of its ends.

The experimental tube which was used in the preliminary experiments is shown in cross section in Fig. 1. The filament is situated in the axis of two coaxial copper cylinders. The outer cylinder which will hereafter be spoken of as the plate, was 10 cm. long and 3 cm. in diameter. The other cylinder, which will be called the grid, is of the same length as the plate cylinder and has a diameter of 2 cm. The grid is perforated symmetrically for a length of 6 cm. with 1 mm. holes whose centers are 8 mms. apart. These holes were made small in an endeavor to eliminate the "stray field" effect. The wall thickness of both the plate and the grid was about .015 cm. Each of the cylinders was supported by two No. 18 dumet wires which screwed into lugs on them, so that the assembling of the tube was easily effected. Platinum leads were used for conveying the filament current through the seals of the surrounding soft glass envelope. The whole tube was mounted vertically, so that any expansion of the filament when it became hot would not let it sag out of center.

The tube through which the exhaustion is effected connects to the side of the glass envelope half way between the ends of the cylinders. The system used for exhausting consisted of a water aspirator, a McNeill oil pump and two mercury condensation pumps in series. This system of pumps connected to the experimental tube through a liquid air trap which served to freeze out any mercury or organic vapors. No stopcocks were used on the high vacuum side of the condensation pumps. The pressure was roughly indicated by Geissler tubes. It could be accurately measured by a Western Electric Co. ionization gauge which was sealed on close to the experimental tube. Both the gauge and the experimental tube were so mounted that an oven could be lowered over them. They could thus have any adhering gas driven from their walls by the process of baking out.

The experimental arrangement that has been described above provided no means of altering the condition of the surface of the plate or its temperature. It may be remarked in this connection that it was found to be impossible to get sufficient energy across to the plate to raise its temperature much by bombardment and thus rid it of any adhering gas. This was because the solid portions of the grid intercepted the greater part of the primary electron stream. Moreover the preliminary arrangement was subject to the objectionable feature that when the grid was positive with respect to the plate, the grid current was a measure of both the secondary emission from the plate and the primary current from the filament intercepted by the solid portions. This latter current was so much larger than the secondary current which it was desired to study that it nearly masked it. Accordingly on the hope of remedying these defects a new tube as depicted in Fig. 2 was designed. It differed from the first tube by having a copper cylinder S which was 1.8 cm. in diameter and 10 cm. long. This was perforated symmetrically for 6 cm. of its length with 1 mm. holes. The copper grid-cylinder *g* was 2 cm. in diameter and coaxially situated with respect to the shield *s*. It was perforated symmetrically with 3 mm. holes which were situated directly above the corresponding smaller holes of the shield. These two cylinders were rigidly held together at each end by rings made from the best grade of porcelain. These rings were so arranged that a 4 mm. surface of

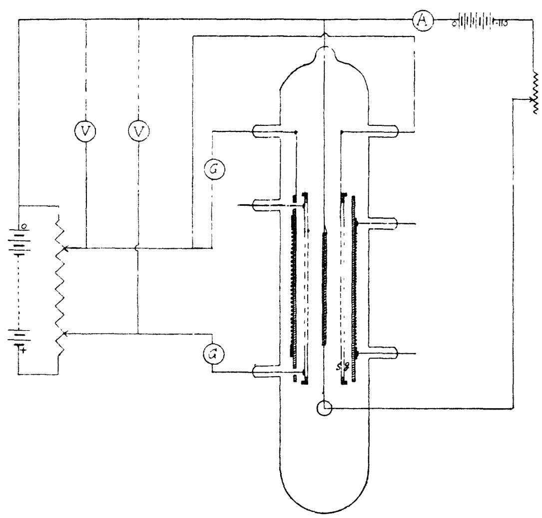

Fig. 2.

insulation existed between the cylinders. In order to alter the surface and temperature of the plate it was surrounded by an insulating cylinder of soapstone which had a wall about 2 mm. thick. On this cylinder was wound several turns of No. 36 nichrome resistance wire. All parts were mounted by No. 18 tungsten wires in a Pyrex glass tube as indicated. The filament current was led into the tube by means of very heavy No. 11 tungsten wires. By adopting Pyrex it was found to be much easier to construct the tube than when it was made of soft glass.

The usual method of experimenting was to bake out at about 400° C. for three hours and have the pumps running all the time. The pressure during this whole process was quite low as no visible discharge appeared in the Geissler tubes. After this exhaustion the gauge-filament was glowed and the gauge-plate was bombarded to a cherry red heat to rid it of gas films adhering to its surface. After the gauge-plate was well bombarded in this manner all traces of blue glow disappeared. The tube filament was freed of gases by heating to incandescence. It was not necessary to bake out and bombard every day as it was found in the case of the gauge-plate that, after it was once thoroughly bombarded, it absorbed little gas unless the apparatus was opened to the air. This same thing is undoubtedly true for the glass walls. Accordingly when the system was clamped off and liquid air was kept continuously on the trap, after the tube and gauge had been well exhausted, baked out and bombarded once, it was found that the pressure was still low the next day. It was only necessary to start the pumps and exhaust in order to produce as good a vacuum as had been obtained just after bombardment. As the pressures obtained in these experiments were always of the order of 5×10^{-6} cm. of mercury, a simple calculation shows that the ionization current does not on the average amount to more than one tenth of one per cent of the electron current getting through the holes of the grid to the plate.

The observations consisted of noting the currents flowing to the plate and grid both as to magnitude and direction when various positive potentials with respect to the emitting platinum cylinder were applied to them. Curves were taken in two distinct ways. In the first type of curve, which will hereafter be referred to as a curve taken at constant grid voltage, the positive potential applied to the grid was maintained at an arbitrary fixed value while the potential applied to the plate was varied from zero up to potentials larger than that applied to the grid. In the second type of curve, which will hereafter be referred to as a curve taken at constant plate voltage, the potential applied to the plate is held constant while the potential applied to the grid is varied. The pressure was measured by means of the ionization gauge just before and just after each set of observations and the mean value was taken as correct. The currents recorded below are reduced to amperes from the corresponding galvanometer deflections and sensibilities. The zero of the galvanometer was taken after each reading so as to correct for any "drift" or other cause of its shifting if it were present. The currents were generally measured for increasing potentials and then for decreasing.

For the last tube the shield S in Fig. 2 was always maintained at the potential of the plate. Any electrons liberated from the plate were then all attracted to the grid if the latter was positive with respect to the plate. The measurements of the grid current for the last tube had to be discarded as experiments showed that the porcelain insulation allowed a leakage current of the same order of magnitude as that of the secondary emission from the plate to flow between the shield and the grid when it became hot due to heat radiated from the filament. This however was not so serious as it seemed, for the variations in the current flowing to the plate were of themselves able to give most of the information desired on the number and velocity of the secondary electrons. This latter factor might have been better investigated, however, by means of the grid current if the porcelain had retained after the filament was lit the splendid insulating properties it possessed while cold. The shield was not however superfluous as a comparison of Fig. 4 with Fig. 5 below shows that its use practically did away with the "stray field" effect which was present in the first tube. This enabled the method of finding the number of secondaries per primary to be applied to lower velocities of impact of the primary electrons than was possible with the first tube.

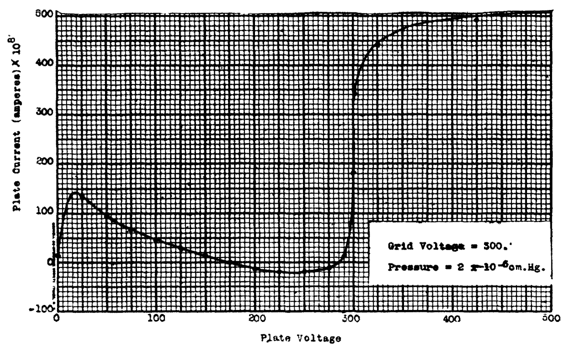

Fig. 3.

After the curves at constant plate voltage and at constant grid voltage had been taken for the untreated surface of the plate the furnace on the tube was slowly heated up until the plate was at a cherry red heat. It was allowed to run this way for 14 hours continuously. The pumps were running all the time. This treatment visibly changed the appearance of the surface of the plate in that it reduced most of the oxide and undoubtedly drove off practically all the adhering gas films. Curves were taken as before for this new surface. This treated surface is not, however, claimed to be a perfectly clean pure copper surface, especially as the tube from which the plate cylinder was manufactured was made of commercial copper.

In order to investigate the effect of temperature on the secondary electron emission it was only necessary to pass a current through the outside furnace. This raised the temperature of the plate and readings analogous to those described above were taken. As it was surmised that the soapstone insulation might break down and cause a leakage current to flow at high temperatures, preliminary measurements of this leakage current were made when the filament at the center of the tube was cold. There are then no primary electrons coming to the plate from the filament so that the whole current flowing in the plate-circuit is due to leakage. These measurements showed that the leakage current was relatively small in comparison with the primary electron current for furnace current less than .5 amperes. Accordingly curves at constant plate voltage were taken at furnace currents of .4, .25 and 0 amperes for various potentials of the plate. It is estimated the corresponding temperatures of the plate are about 110° C., 45° C., and 25° C. For a given plate voltage these readings at various temperatures were taken right after one another, so that the surface of the plate was the same at all the temperatures. In order to correct exactly for the leakage it was only necessary to eliminate the primary electron current coming to the plate by cutting off the filament current. All the applied voltages and the furnace currents are of course left the same as when the filament is lit in this determination of the correction due to leakage.

The Experimental Results Obtained.

A. *Curves Taken at Constant Grid Voltage.*

The form of these curves was the same with both of the tubes. Fig. 3 is typical of the series of curves which was taken under these conditions. The ordinates represent the current in the plate circuit, reckoned positive for electrons passing from the filament to the plate, that is, in the direction which is equivalent to positive electricity flowing from high potential to low across the vacuum. These plate current-plate voltage curves all have the following characteristics.

1. When the plate voltage is zero there is always a small electron current flowing into the plate from the filament. This is due to the primary electrons which do not pass through the very intense field near the boundaries of the holes of the grid but pass through the weaker fields at the center of these holes with a velocity corresponding to the potential of the grid. This velocity is so high that some of them shoot right through the holes into the retarding field between the grid and plate and finally hit the plate with an energy corresponding to their energy of emission from the filament.

2. The plate current assumes larger values as the plate voltage is increased until a maximum is attained. This is believed to be due to the fact that a greater proportion of these primary electrons, which get through the holes of the grid, go to the plate as the retarding field is diminished. It is only when the rate of increase of the primary electron current flowing into the plate in this manner is just compensated by the rate of increase of the electron current due to secondary reemission which flows from the plate to the grid that the maximum is attained.

3. For plate-voltages greater than that corresponding to the maximum of the curve, the current flowing into the plate assumes continually smaller values as the plate-voltage is increased until a plate-voltage slightly lower than the prevailing grid-voltage is reached. The numerical value of the smallest current flowing into the plate is found to become less as the grid-voltage is increased. If the grid-voltage exceeds about

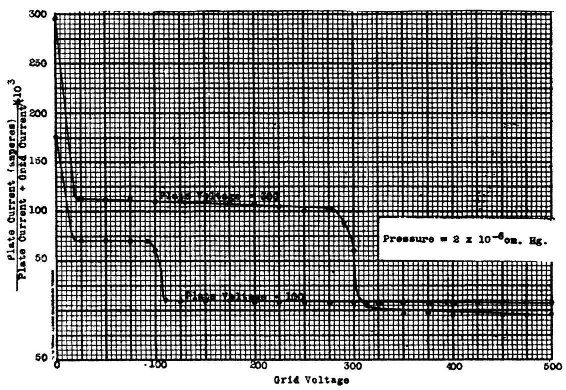

Fig. 4.

200 volts the current flowing into the plate reverses in direction and assumes small negative values. This means that more electrons are leaving the plate than are hitting it, so that there is some true secondary reemission certainly present.

4. The current flowing into the plate begins to assume larger values again for plate-voltages greater than a voltage which is about 25 volts

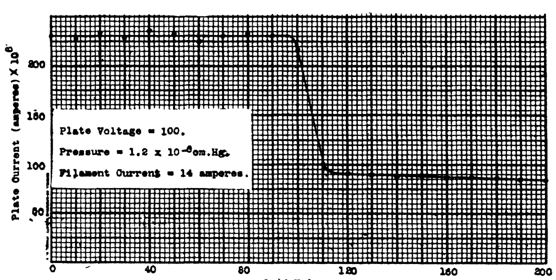

Fig. 5.

less than the potential of the grid. This current increases rapidly in numerical value between plate-potentials that are about 5 volts less and about 10 volts greater than the grid-voltage. After this the rate of increase is much slower and there is the appearance of saturation setting in. This saturation current is a measure of the total number of electrons getting through the holes of the grid. The difference between it and the lowest value of the current flowing into the plate is an approximate measure of the number of secondary electrons reemitted by the plate. The ratio of this difference to the value of the saturation current is moreover an approximate measure of the average number of secondaries emitted by a primary electron that strikes the plate with an energy corresponding to the grid-voltage. The number of secondary electrons emitted by one primary electron will hereafter be called the coefficient of secondary emission. The curves showed that this coefficient increased with the velocity of impact. For a given velocity of impact a comparison of curves taken under similar conditions before and after treating the surface showed that the coefficient of secondary emission was everywhere increased by the heat treatment.

B. *Curves Taken at Constant Plate-Voltage.*

The forms of the curves taken under this condition are different for the two experimental tubes because of the fact that the "stray field" is largely eliminated in the second tube. This means that varying the grid-voltage for the last tube has practically no influence on the number of primary electrons that shoot through the holes of the shield. Fig. 4 represents two curves taken with the first tube while Fig. 5 and Fig. 6

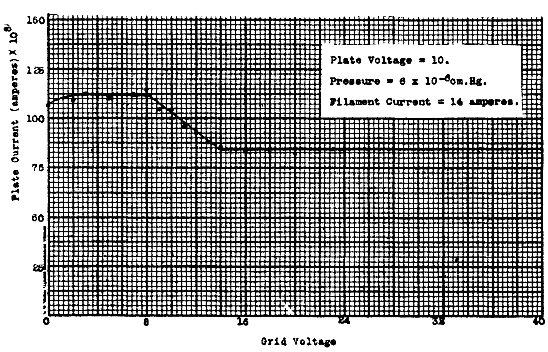

Fig. 6.

show two curves typical of those taken with the second tube. The principal facts to be noted in connection with these curves are as follows:

1. Increasing the grid-voltage from zero (cf. Fig. 4) causes the ratio of the current flowing into the plate to the sum of the currents flowing into the grid and plate to decrease quite rapidly until a final constant value is attained for a grid potential of 25 volts, provided a potential greater than about 50 volts is applied to the plate of the first tube. Any further increase of the grid voltage does not change this ratio until a

potential slightly less than the applied constant plate voltage is reached. At this voltage Fig. 4 shows that the ratio drops suddenly to a value which is constant for all higher grid voltages. The fact that there exists a constant ratio above 25 volts indicates that the "stray field" is independent of the grid voltage above this point. This constant value is a measure of the number of primary electrons incident on the plate. The second decrease in the ratio is due to the fact that for grid voltages greater than the plate voltage the secondary electrons are attracted to the grid. The difference in the two constant currents is thus a measure of the number of secondary electrons. The ratio of this difference to the original constant plate current gives an accurate measure of the coefficient of secondary emission.

2. The curves taken with the second tube can be extended to much lower plate voltages than was possible on account of the "stray field" with the first tube. Fig. 6 shows how beautifully the method works at 10 volts primary velocity. Table I. gives the coefficients of secondary

TABLE I.

Coefficient of Secondary Emission.

Plate Voltage.	Before Treating Surface.		After Treating Surface.	
	Increasing Voltage.	Decreasing Voltage.	Increasing Voltage.	Decreasing Voltage.
5	—	—	0	0
7	—	—	.08	—
10	—	—	.21	.23
15	—	—	.30	.29
20	—	—	—	.34
25	—	—	.39	.41
50	.38	.46	.46	.45
75	.59	.58	—	—
100	.64	.64	.68	.61
150	—	—	.85	.86
200	.70	.70	1.00	1.00
250	—	—	1.08	1.10
300	.85	.85	1.26	1.26
400	.91	.92	1.28	1.25
500	—	—	1.23	1.25

emission as calculated from a series of such curves before and after treating the surface. The principal limitation that is imposed on obtaining the number of secondaries per primary in this manner is the fact that the strength of the source of primary electrons may not stay constant.

It is estimated that the means of the two values of the coefficient of secondary emission in the table are not subject to an error exceeding

3 per cent. This is doing as well as could be expected, since the filament was supplied by the 110-volt power line whose voltage fluctuations sometimes caused the temperature and hence the emission to change by about 5 per cent. The form of the curves and the sharpness with which they fall off indicate however that the coefficient could be obtained to a much higher degree of accuracy with sufficiently constant primary sources.

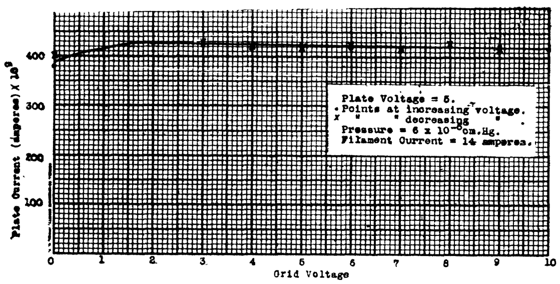

Fig. 7.

3. Figure 7 represents a curve taken when the primary electrons hit the plate with a velocity of 5 volts. It is to be remarked that there is no drop in the current flowing to the plate when the grid voltage exceeds the plate voltage such as Fig. 6 shows is present for energies of impact of 10 volts. *This means that at 5 volts there is neither a true secondary emission nor a reflection of electrons.* This is contrary to what has always previously been considered to be the case.

C. *The Velocities of the Secondary Electrons.*

The curves at constant plate-voltage show that the current does not drop appreciably from its constant value for voltages of the grid less than those of the plate until this voltage-difference is smaller than

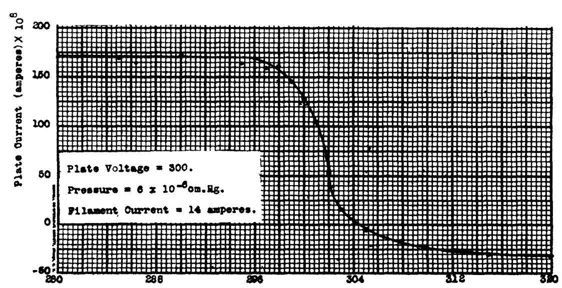

Fig. 8.

about 5 volts. Fig. 8 shows how these curves fall off when the velocity of impact of the primary electrons is 300 volts. The principal facts to be noted in this connection are as follows:

1. A comparison of Fig. 6 with Fig. 8 shows that the maximum velocity of emission of the secondary electrons is about 5 volts when the velocity of impact of the primary electrons is 300 volts, while it is 2 volts when the velocity of impact is only 10 volts. This shows that the maximum velocity of emission increases *but slightly* when the energy of impact of the primary electrons is raised. The fact that the velocities of the secondary electrons are small is in accord with the results of other observers.

2. The fact that the velocity of the secondary electrons is always considerably less than the velocity of the primary electrons indicates that the secondary electrons have been truly reemitted rather than reflected. This holds even for primary velocities as low as 10 volts.

3. If this conclusion that there is no such a thing as a "reflection" of electrons is true, Figs. 6 and 7 indicate that the critical velocity for the reemission of secondary electrons lies between 5 and 10 volts. A few attempts at locating this "ionizing potential" of the surface atoms more accurately were unsuccessful because of the fact that the variations caused by the fluctuations of the filament-current were of the same order of magnitude as those differences which it was desired to detect.

4. Fig. 8 shows that it requires an accelerating field of nearly 10 volts to pull the greater portion of the secondary electrons from the plate to the grid, that is, in order to reduce the current flowing to the plate to its final nearly constant value. All of the other curves showed similarly that these accelerating fields were required. The magnitude of these fields decreased however as the velocity of impact of the primary electrons diminished. These facts are readily explained by considering that the surface of the plate is not smooth but rough and irregular. With such a surface the secondary electron liberated by an impinging primary electron may be freed in a "pocket" or depression formed by the atoms of the surface. As the attractive forces exerted by the grid do not readily "penetrate" into these depressions, the secondary electron which is liberated in such a place may not have any attractive forces exerted on it by the grid until the latter has attained a considerable positive potential above that of the plate. The fact that the strength of the accelerating field required to pull all of the secondary electrons to the grid varies directly with the velocity of the primary electrons is explained by the assumption that the faster primary electrons liberate secondary electrons in "pockets" that are deeper or more perfectly shielded from the attraction of the grid than do the slowly moving electrons. It might be thought that the space charge effect of the secondary electrons would also be a factor which would require a considerable grid potential

to overcome it. Calculations which are based on the magnitude of the secondary electron current and the dimensions of the apparatus show however that this effect is probably less than one half a volt. The assumption of the irregular surface is then the most plausible explanation of the effect.

D. *The Effect of Temperature on Secondary Electron Emission.*

The curves at constant plate-voltage that were obtained when the plate was hot were of the same form as those obtained and already described when it was cold. The effect of the correction caused by the leakage current is simply to displace every point of the curve by a constant amount parallel to the current axis. Table II. gives the corrected

TABLE II.

Coefficient of Secondary Emission.

	Furnace Current=0.		Furnace Current=.25.		Furnace Current=.40.	
Plate Voltage.	Increasing Voltage.	Decreasing Voltage.	Increasing Voltage.	Decreasing Voltage.	Increasing Voltage.	Decreasing Voltage.
25	.34	.36	—	.34	.21	.24
100	.67	.68	.71	.71	.50	.51
200	1.09	1.09	.97	.95	—	.56
300	1.26	1.265	.88	.88	—	.31
400	1.41	—	1.12	1.12	.51	.525

values of the coefficient of secondary emission as obtained from the corrected curves taken at constant plate voltage for various temperatures of the plate. The table shows the extraordinary fact that the secondary emission appears to be greatly diminished by increasing the temperature of the plate. This was especially true for the primary electrons possessing the highest velocities.

This decrease is not due to the magnetic field which is caused by the current in the furnace. This was shown to be the case by applying a magnetic field of the same strength as that which was due to the furnace by means of a large solenoid which was slipped over the experimental tube. Fig. 9 shows a curve obtained when no current was flowing in the furnace and no magnetic field was applied. Fig. 10 shows a curve taken under the same conditions when a magnetic field which was equal in intensity to that which would be set up by passing a current of .40 amperes through the furnace was applied by means of the exterior solenoid. It is to be noted that the coefficient of secondary emission is *not decreased* in the second case, as would be the case if the results in Table II. were due to the magnetic field instead of to the temperature of the plate. The main effect of the magnetic field seems to be that it causes the drop in the current to be much less abrupt than when it is not applied. Curves which were taken when the plate was hot showed similarly that the application of the exterior magnetic field did not de-

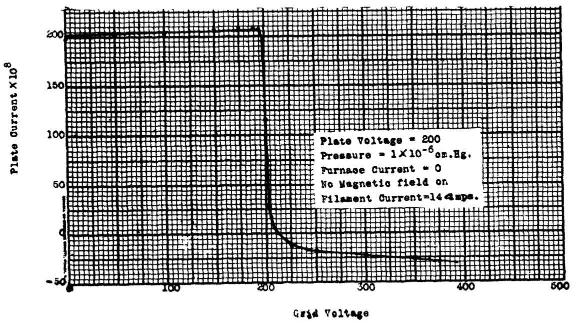

Fig. 9.

crease the coefficient of secondary emission corresponding to the temperature of the plate.

Discussion of the Results.

O. von Baeyer and A. Gehrts stated in their papers that the two most important sources of error in their experiments were ionization and "tragerbildung." The first error only occurred for velocities of the primary electrons greater than the ionization potential of the residual

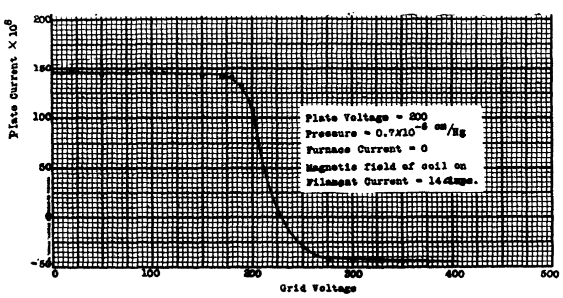

Fig. 10.

gas. The second error occurred only with the very slow primary electrons which attached themselves to gas molecules and formed slowly moving ions. These on account of their large mass did not hit the plate hard enough to cause a reemission. The tables given in the papers of both of these authors show this last effect is undoubtedly present. Any of their conclusions for velocities of the primary electrons less than 10 volts are probably then without any great significance as they themselves point out. On account of the high vacuum prevailing throughout the present experiments it is certain that these two sources of error are of negligible importance.

Dr. A. W. Hull in his paper on the dynatron explains the initial rise in his curves taken at constant grid voltage on the ground that there is a voltage drop along the hot filament. As the voltage is increased thermions first reach the plate only from the negative end of the filament, and then gradually from the whole filament. This to be sure explains part of the rise but it can not explain it totally as this same initial rise was found in the present experiments where an equipotential filament was used. The curves in Hull's paper are moreover not extended to plate voltages much higher than the prevailing grid voltage, *i.e.*, to the final saturation values obtained in these experiments. It is accordingly not evident on what grounds the statement is based that as many as twenty secondary electrons may be produced per primary. *It is certain that copper surfaces such as were used in this investigation do not give more than* 1.5 *electrons per primary.* It is expected that molybdenum and other metals will be tested in the future to ascertain to what extent the effect depends on the nature of the metal.

The results found in this investigation do not indicate a maximum emissive power at a primary velocity of about 250 volts. Gehrts found the coefficient of secondary emission diminished beyond this point while the results shown in Table I. of this investigation show that there is a final constant value, or one that increases very slowly.

Summary and Conclusions.

The principal conclusions which may be drawn from this investigation are as follows:

1. A method for obtaining the average number of secondary electrons emitted by a single primary electron when the latter bombards a copper surface has been developed. This method is independent of the geometrical dimensions of the apparatus. No appreciable errors are introduced due to ionization or attachments on account of the high vacua used.

2. The coefficient of secondary emission was found to increase with the velocity of impact for all velocities of the primary electrons which exceeded the ionizing potential of the metallic surface. This coefficient is nearly constant above 300 volts primary velocity for a copper surface from which the adhering gas films and other impurities have been removed by heating.

3. By heating the copper surface in vacuo the surface condition is

changed. The effect of this is to increase the coefficient of secondary emission for any given velocity of impact of the primary electrons above the value it possessed before the heat treatment.

4. The maximum velocity of emission of the secondary electrons varies from 2 volts, when the velocity of the primary electrons is 10 volts, to about 5 volts when the velocity of the primary electrons is 300 volts.

5. There is apparently no reflection or secondary emission of electrons when the velocity of the primary electrons is 5 volts. This fact coupled with the small value of the maximum velocity of emission of the secondary electrons indicates there is no such a thing as true "reflection" of electrons.

6. The approximate critical velocity of the primary electrons necessary to produce a reemission lies between 5 and 10 volts.

7. The coefficient of secondary emission was found to be quite considerably reduced by raising the temperature of the plate. This was especially true for the higher velocities of impact.

In conclusion the author wishes to express his indebtedness to Professor Millikan for suggesting the problem and for continuous assistance during its progress. Mr. Julius Pearson, the mechanic at the Ryerson laboratory, is responsible for several important mechanical suggestions in connection with the design of the tubes. The assistance that Mr. L. E. McAllister has rendered by helping to take the observations of the latter part of this work has been of very great value.

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