CATHODE MEASUREMENTS WITH GLOW CURRENT IN OXYGEN AND NITROGEN.

By W. Neuswanger.

In a recent paper, Prof. Skinner[1] has developed a theory of the so-called cathode fall in gases which gives a general relation between the fall, the current density, the mean free path of the electron, and the distance from the cathode to the point of minimum potential gradient in the negative glow. A series of experimental results with hydrogen substantially corroborated the theoretical deductions. The purpose of this investigation has been to make a similar experimental study of the cathode fall in oxygen and nitrogen.

Apparatus.

The apparatus consisted essentially of a discharge tube, Fig. 1, connected with a McLeod gauge, a gas generator and storage chamber, and a mercury vacuum pump. The tube, which was similar to the one used by Skinner, was provided with a circular disk cathode K, carried on a threaded shaft S, whereby it could be accurately adjusted, through the ground joint J, to any given distance from the aluminum probe wire P, which served to give the potentials in the gas. The distances were indicated by the graduated drum D. To insure a fixed position of the nut N, the air pressure forced J against a shoulder Q, cemented on the stem of the tube. A glass hood H confined the discharge to the front face of the cathode. The diameter of the probe wire (.125 mm.) was about one half that used by Skinner (.24 mm.) in hydrogen—making it about the same relative to the magnitude of the mean free paths of the electrons in oxygen and nitrogen, as his was to that in hydrogen. This probe was covered by a close fitting glass sheath which was frequently renewed since any metallic deposit would render it conductive and hence give spurious potentials.

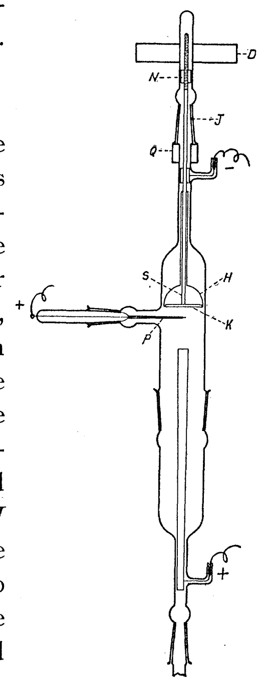

Fig. 1.

[1] C. A. Skinner, Phys. Rev., June and August, 1915.

The electrometer used was a modified Dolazalek fitted with a phosphor-bronze suspension and an aluminum needle. A constant potential difference of 18 volts was placed between the two pairs of quadrants, while that to be measured was placed between the needle and one pair of quadrants. The electrometer was calibrated from time to time by comparison (on a storage battery circuit) with a Weston voltmeter. In order to avoid leakage, the electrometer itself, together with the batteries used to charge the quadrants, were placed on sealing wax—no ground to the electrometer being used. All connecting lines and switches were similarly insulated. The electric current was furnished by a 1,200-volt battery of accumulators and regulated by a liquid resistance of amyl alcohol and cadmium iodide. It was measured by a Weston milliammeter.

Experimental.

Oxygen.

Oxygen was generated by heating a mixture of potassium dichromate and concentrated sulphuric acid. The gas was allowed to stand for several hours in a bulb containing crushed potassium hydrate to remove any acid vapor, and then after being thoroughly dried over phosphorous pentoxide, was stored in a chamber connected to the discharge tube, to be drawn off as desired.

Current Density and Number of Mean Free Paths to the Negative Glow with Normal Cathode Fall.—The general plan followed was to clean and polish the cathode, mount it in the discharge tube, evacuate this and flush with the gas. With the gas reasonably pure, an electric current was then passed through the tube which always increased the pressure by freeing occluded gases from the cathode. This impure gas was then removed and fresh introduced in which the measurements were made, namely: of the gas pressure, the normal cathode fall, normal current density, and the number of mean free paths of the electron from the cathode to the point of zero gradient. This set was then followed by a similar one in fresh gas—the process being repeated until the normal cathode fall rose above what was considered a satisfactory magnitude. The cathode was then removed and again carefully polished with Tripoli composite, and a new clean piece of cheese cloth before further measurements were made.

Series of observations with each of the metals, aluminum, steel, and zinc as cathodes, are given in Tables I., II. and III. respectively. Each gas pressure, column 1 of each table, represents a new gas filling. At pressures below those given, the luminosity was too faint to allow accurate adjustment to normal current density. At higher pressures than those given, the other magnitudes became inaccurate. In column 2 is given the

TABLE I.

Aluminum Cathode in Oxygen. Area of Cathode: 1.35 sq. cm.

Gas Pressure (mm.).	Normal Cathode Fall (Volts).	Normal Current Density (j_n)	Distance to Neg. Glow (x_k-x_0).	Mean Free Path ($\bar{\lambda}^2$)	($j_n \bar{\lambda}^2$)	$\left(\frac{x_k-x_0}{\bar{\lambda}}\right)$
1.06	301	.44 ma.	4.20 mm.	.41 mm.	.074	10.2
1.45	306	1.04	3.30	.30	.090	11.0
1.58	312	1.33	2.50	.28	——	——
1.80	313	1.63	2.50	.24	.092	10.4
1.80	307	1.56	2.60	.24	.092	10.8
1.98	312	1.85	2.30	.22	.087	10.4
2.27	308	2.15	2.10	.19	.076	11.0
2.35	312	2.52	1.90	.19	.090	10.0
2.85	309	3.34	1.60	.15	.074	10.7
2.88	313	3.48	1.65	.15	.079	10.7
3.27	311	4.52	1.50	.13	.076	11.5
3.51	316	5.18	1.25	.125	.081	9.6
3.71	312	5.33	1.30	.12	.076	10.8
3.87	312	5.77	1.30	.11	.070	——
3.93	317	7.18	1.15	.11	.087	10.4
4.16	316	6.81	1.20	.105	.075	11.4
Mean	311			Mean	.081	10.6
Max. dev.	3%			Max. dev.	12%	10%
Mean dev.	1%			Mean dev.	8%	4%

normal cathode fall with its percentage deviation, in all cases surprisingly small. Column 3 gives the normal current density. This was found to decrease rather rapidly below that required to cover the cathode when first starting the current. However, consistent values could be obtained if the time interval required to make the reading was consistent. The method used here was to take the mean of the first two adjustments to the point at which the cathode glow just covered the surface of the electrode with uniform brightness. These were of course made as quickly as careful judgment would allow. The high value of the normal current density in oxygen as compared with hydrogen—six times as large as the same gas pressure—made it advisable to use cathodes of about 1.3 sq. cm. area instead of 3.0 sq. cm., as used by Skinner for hydrogen. The distance, in millimeters, from the cathode to the point of minimum potential gradient, given in column 4, was observed by noting where the potential began to decrease as the cathode was moved toward the probe wire, or, as described by Skinner, by setting the probe wire just in the outer face of the bright striation next to the cathode dark space. The values of the mean free paths of the electron, column 5, corresponding to the given pressure were obtained from the relation given by J. Franck and G. Hertz,[1] namely: $4\sqrt{2}$ times the mean free path of the molecule. Column 7 obtained by dividing the distances in column 4 by the corresponding $\bar{\lambda}$ gives the number of mean free paths from the cathode to the negative glow. This according to theory should be a constant under conditions giving a constant cathode fall. Column 6 is the product of the normal current density by the square of the mean free path of the electron.

TABLE II.

Steel Cathode in Oxygen. Area of Cathode: 1.36 sq. cm.

Gas Pressure (mm.).	Normal Cathode Fall (Volts).	Normal Current Density. j_n	Distance to Neg. Glow. x_k-x_0	Mean Free Path. $\bar{\lambda}$	$j_n\bar{\lambda}^2$	$\frac{x_k-x_0}{\bar{\lambda}}$
1.05	336	.38 ma.	4.30 mm.	.42 mm.	——	10.2
1.37	338	.59	3.70	.32	.060	11.5
1.55	340	.77	3.30	.28	.060	11.8
1.65	343	.81	——	.27	.059	——
1.83	340	1.07	2.80	.24	.063	11.7
2.23	342	1.54	2.20	.20	.060	11.0
2.27	341	1.62	1.91	.19	.058	10.0
2.62	344	2.06	1.77	.17	.061	10.6
2.67	342	2.20	1.72	.16	.056	10.6
2.80	341	2.42	1.65	.16	.061	10.3
3.02	343	2.86	1.50	.145	.061	10.3
3.03	342	2.79	1.56	.14	.055	11.4
3.21	343	3.02	1.52	.14	.059	10.7
3.23	344	3.09	1.47	.135	.057	11.1
3.37	345	3.31	1.52	.13	.056	11.5
3.58	345	3.53	1.37	.12	.050	11.7
3.81	346	3.75	——	.115	.049	——
3.83	345	4.11	1.26	.115	.054	11.3
3.96	344	4.11	1.30	.11	.050	11.8
4.08	344	4.41	1.22	.11	.053	10.9
4.14	346	4.71	1.19	.105	.052	11.4
4.25	347	4.64	1.17	.10	——	——
Mean	343			Mean	.057	11.0
Max. dev.	2%			Max. dev.	13%	10%
Mean dev.	1%			Mean dev.	5%	4%

This too should be constant. Inspection shows for all three metals that throughout the range of gas pressures used, the normal cathode fall, and the number of mean free paths of the electron to the point of minimum potential gradient, are all practically constant. In the case of aluminum, several different samples of metals were used, all giving similar results.

[1] J. Franck and G. Hertz, Ber. d. Deutsch. Phys. Ges., 9, 1913, p. 373.

Comparing the different metals we find aluminum to give, as expected, the lowest cathode fall, 311 volts; next is steel with 343 volts; and then zinc with 354 volts. These values are from two to three per cent. higher than those found by Skinner.[1] The values of the other constants show a

TABLE III.

Zinc Cathode in Oxygen. Area of Cathode: 1.34 sq. cm.

Gas Pressure (mm.).	Normal Cathode Fall, (Volts).	Normal Current Density, j_n.	Distance to Neg. Glow, $x_k - x_0$.	Mean Free Path, $\bar{\lambda}$.	$j_n\bar{\lambda}^2$	$\frac{x_k - x_0}{\bar{\lambda}}$
1.31	353	.46 ma.	3.90 mm.	.33 mm.	.050	11.8
1.45	354	.67	3.14	.30	.060	10.3
1.57	353	.66	——	.28	.052	——
2.13	356	1.19	——	.21	.053	——
2.35	354	1.49	2.31	.19	.054	12.1
2.38	354	1.64	2.05	.18	.052	11.7
2.42	354	1.64	2.19	.18	.052	12.2
2.63	354	1.94	1.96	.17	.055	11.7
2.73	354	2.16	1.75	.16	.056	10.6
2.94	354	2.62	1.66	.15	.058	11.3
3.13	355	2.80	1.54	.14	.055	10.7
3.32	355	3.54	1.38	.13	.059	10.8
3.60	354	4.11	1.32	.12	.059	10.8
3.62	356	3.96	1.33	.12	.056	10.8
3.79	356	4.63	1.38	.115	.061	12.2
3.91	356	4.40	1.34	.11	.053	11.8
3.96	355	4.77	1.20	.11	.058	10.9
4.24	352	5.15	1.18	.10	.052	12.0
4.28	355	5.22	1.22	.10	.052	12.0
4.46	352	6.05	1.11	.10	.058	11.2
4.52	356	5.90	——	.095	.055	——
4.78	354	6.71	1.04	.090	.056	10.9
Mean	354			Mean	.055	11.4
Max. dev.	.6%			Max. dev.	11%	11%
Mean dev.	.3%			Mean dev.	5%	5%

considerably larger variation than the cathode fall, as might be expected when the accuracy of the settings made for these is considered. The values of $j_n\bar{\lambda}^2$ for aluminum and steel are in about the same ratio, 3:2, as found by Skinner for hydrogen—both being about twice as large in oxygen as in hydrogen. Zinc gives about the same value as steel. As with the cathode fall the number of mean free paths to the negative glow differs but little with the different metals. As should be expected, also, the metals are in the same sequence here as with the cathode fall, the metal having the highest fall giving the greatest distance to the negative glow. These results show that the same general relation holds with oxygen as

[1] C. A. Skinner, Phil. Mag., 6, VIII., p. 387.

found by Skinner with hydrogen, namely:—*all gas pressures giving the normal cathode fall have the same number of mean free paths to the point of minimum potential gradient in the negative glow, and, have a normal current density proportional to the square of the gas pressure, i. e., inversely proportional to the square of the mean free path of the electron.*

Potential Curves in the Region between the Cathode and the Negative Glow.—Skinner found with hydrogen that the difference of potential between the cathode and any point at the same number of mean free paths from it is practically the same at various gas pressures, if the current density is the same multiple of the normal current density. The following gives the results of a similar investigation for oxygen.

For obtaining these potential curves an aluminum cathode was used with normal, twice normal and four-normal current densities. The same precautions were observed here as in the other tests, the probe sheath being renewed more often, since any leakage with it in the less conductive space near the cathode would cause greater error than with it in the highly conductive negative glow.

TABLE IV.

Potential Difference in Volts between the Cathode and Points in the Gas at a given Number of Mean Free Paths from it. Aluminum Cathode in Oxygen. For Normal Current Density: $j\bar{\lambda}^2 = .081$

Gas Pressure (mm.).	Number of Mean Free Paths.						
	2	3	5	7	9	10	11
1.34	198	230	272	300	310	312	312
1.39	205	236	278	305	312	312	313
1.49	194	225	272	300	310	312	313
1.56	205	238	279	301	306	306	306
1.92	211	246	290	311	315	315	314
2.02	210	245	292	312	316	316	316
2.04	205	231	268	296	307	308	308
2.24	211	243	283	306	315	318	318
2.27	210	238	270	304	309	312	313
2.28	228	253	282	302	312	313	313
2.45	220	248	282	302	314	315	315
2.50	213	242	282	302	307	307	307
2.54	220	250	282	302	312	314	314
2.64	203	232	272	292	311	313	313
2.67	226	250	278	298	311	313	313
2.72	216	249	282	301	306	306	306
2.82	222	254	286	306	314	315	315
3.04	223	256	287	306	314	316	316
3.08	236	264	290	308	312	312	312
3.08	223	254	287	306	313	315	315
Means:	214	244	281	303	311	312	312

The procedure was to start with a fresh gas filling, and with the probe first in the negative glow, then at positions successively nearer the cathode, the difference of potential between it and the cathode was observed—all with a constant current maintained through the gas. These observations were taken as rapidly as possible to reduce the magnitude of the time changes—indicated by repeating the first observation at the close of each series. In the results given—incorporated in Tables IV., V. and VI.—the time change in the cathode fall was in no case greater than four

Table V.

Potential Difference in Volts between the Cathode and Points in the Gas at a given Number of Mean Free Paths from it. Aluminum Cathode in Oxygen. For Twice Normal Current Density: $j\bar{\lambda}^2$ = .162

Gas Pressure (mm.).	Number of Mean Free Paths.					
	2	3	5	6	7	8
1.52	256	292	322	324	325	325
1.84	240	276	318	323	323	323
2.06	252	286	320	325	325	325
2.25	256	287	317	322	323	323
2.26	256	287	318	——	326	326
2.35	260	292	320	324	326	326
2.39	262	290	320	324	325	324
2.46	260	291	320	324	324	324
2.48	264	294	320	326	327	326
2.94	253	288	320	325	327	327
3.02	258	286	320	325	326	327
3.05	259	291	320	326	328	328
Means:	259	288	320	324	325	325

Table VI.

Potential Difference in Volts between the Cathode and Points in the Gas at a given Number of Mean Free Paths from it. Aluminum Cathode in Oxygen. For Four Times Normal Current Density: $j\bar{\lambda}^2$ = .324

Gas Pressure (mm.).	Number of Mean Free Paths.				
	2	3	4	5	6
1.43	306	338	346	348	348
1.97	302	338	351	356	356
2.07	300	345	359	367	366
2.23	312	343	352	361	362
2.24	312	348	360	361	361
Means:	306	342	353	359	359

per cent.—always an increase and greater for the larger current. An inspection of these tables warrants the conclusion that the potentials are practically independent of the gas pressure; hence their means are taken as representative. These means are plotted in Fig. 2 (circles) using the potential differences as ordinates and the number of mean free paths from the cathode as abscissæ. They show, as in hydrogen, a marked decrease in distance to the point of minimum gradient (at x_0, see Fig. 2) as the current density is increased.

Mobility of the Positive Ions.—To the above data we may apply the theoretical deductions for calculating the upper and lower limits for the mobility of the positive ions. This is defined as the velocity in centimeters per second of the ion in unit field. Skinner gives[1] the two inequalities:

$$V_0 - V < \left[\left(\frac{16\pi j}{9\overset{+}{\mu}} \right)^{\frac{1}{3}} (x - x_0) \right]^{\frac{3}{2}}$$

$$> \left[\left(\frac{16\pi j}{9\overset{+}{\mu}} \right)^{\frac{1}{3}} (x - x_0) - \epsilon^{\frac{2}{3}} \right]^{\frac{3}{2}} + \epsilon$$

where $V_0 - V$ is the difference in potential between the point of minimum gradient at x_0 in the negative glow and any other point x nearer the cathode; j the current density, $\overset{+}{\mu}$ the mobility of the positive ions and ϵ the ionizing potential of the gas all expressed in c.g.s.-e.s. units. The upper and lower limits of $\overset{+}{\mu}$ may be calculated by making equations of the above inequalities and by substituting the observed values in their proper units. For the first we write:

$$V_0 - V_1 = \left(\frac{16\pi j}{9\overset{+}{\mu}} \right)^{\frac{1}{2}} (x_1 - x_0)^{\frac{3}{2}} \tag{1}$$

The second may be transformed as follows:

$$V_0 - V_1 - \epsilon = \left[\left(\frac{16\pi j}{9\overset{+}{\mu}} \right)^{\frac{1}{3}} (x_1 - x_0) - \epsilon^{\frac{2}{3}} \right]^{\frac{3}{2}}$$

$$(V_0 - V_1 - \epsilon)^{\frac{2}{3}} + \epsilon^{\frac{2}{3}} = \left(\frac{16\pi j}{9\overset{+}{\mu}} \right)^{\frac{1}{3}} (x_1 - x_0) \tag{2}$$

$$[(V_0 - V_1 - \epsilon)^{\frac{2}{3}} + \epsilon^{\frac{2}{3}}]^3 = \left(\frac{16\pi j}{9\overset{+}{\mu}} \right) (x_1 - x_0)^3.$$

In the plot (Fig. 2) are indicated the positions of minimum gradient x_0. These are 9.5 mean free paths for "normal"; 6.6 for "twice normal" and 5.0 for "four-normal." The corresponding values of the potential; V_0 were taken from Tables IV., V. and VI. The position x_1 was chosen at two mean free paths from the cathode which also determines V_1 from the tables. The value of ϵ for oxygen is given by Franck and

[1] *L. c.*, June, p. 488.

Hertz[1] as 9 volts. Expressing these quantities and also the current in c.g.s.-e.s. units and substituting in (1) and (2) we have calculated the upper and lower values of $\overset{+}{\mu}$. They do not differ greatly. Their mean for a pressure of 1 mm. was found to be 1.47×10^6 cm. per sec. for a field of 1 c.g.s.-e.s. unit or, in a field of one volt per cm. 4.9×10^3 cm. per sec.—about five times the value customarily obtained. For hydrogen Skinner obtained 2.7×10^4 cm. per sec. for one volt per cm.—about six times the accepted magnitude under ordinary measurements.

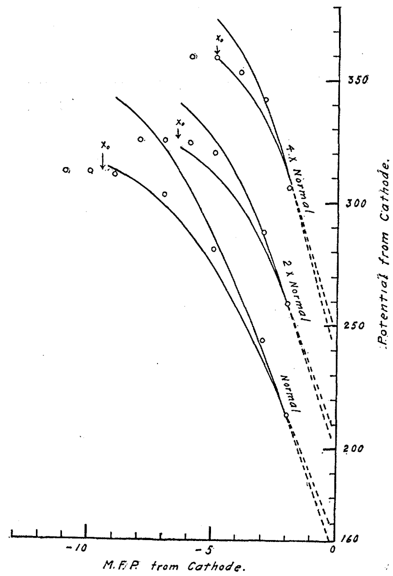

Fig. 2.

Using the above mean for the value of $\overset{+}{\mu}$, the same values for x_0, and the potentials at two mean free paths from the cathode as a starting point, we have determined from (1) and (2) the theoretical curves between which the observed values should fall. The calculated and observed potentials are tabulated in Table VII.—starting points in italics. The corresponding curves with their extensions to the cathode in broken lines are shown in Fig. 2. Referring to this figure, we find the observed

Table VII.

Calculated and Observed Potential Differences between Cathode and Points in the Gas at a given Number of Mean Free Paths from it. Aluminum in Oxygen.

Number of Mean Free Paths.	Calculated from Equation 1.	Calculated from Equation 2.	Observed.
For Normal Current Density: ($j = 1.33 \times 10^6$ c.g.s.-e.s.)			
0.2	163	170	—
2.	*214*	*214*	*214*
3.	240	236	244
4.	264	256	—
5.	285	274	281
6.	305	287	—
7.	322	299	303
9.3	344	314	312

[1] J. Franck and G. Hertz, Ber. d. Deutsch. Phys. Ges., 2, 1913, p. 34.

TABLE VII.

Calculated and Observed Potentiat Differences between Cathode and Points in the Gas at a given Number of Mean Free Paths from it. Aluminum in Oxygen.

Number of mean Free Paths.	Calculated from Equation 1.	Calculated from Equation 2.	Observed.
For Twice Normal Current Density: (j = 2.66 × 10^6 c.g.s.-e.s.)			
0.2	205	210	—
2.	*259*	*259*	*259*
3.	285	281	288
4.	308	299	—
5.	326	—	320
6.4	340	322	325
For Four Times Normal Current Density: (j = 5.32 × 10^6 c.g.s.-e.s.)			
0.2	245	252	—
2.	*310*	*310*	306
3.	339	334	342
4.	362	349	353
5.	374	359	359

values falling fairly consistently between the theoretical limits; but with a gradient (or slope) near the negative glow distinctly lower than either.

The Immediate Cathode Fall.—From the fact that the difference of potential between the cathode and any definite number of mean free paths from it is simply a function of $j\bar{\lambda}^2$ it must follow that the difference of potential between the cathode and the gas immediately adjacent to it, is also a function of $j\bar{\lambda}^2$. The theory assumes this fall to take place over a distance equal to one mean free path of the positive ions from the cathode—approximately .2 mean free path of the electrons. By extending the theoretical curves up to this point, a calculated value for this "immediate fall" at the cathode may be obtained. The following table gives the mean values V_b of this immediate fall. They show that V_b

V_b	Ratios.	$(j\bar{\lambda}^2)^{.30}$	Ratios.
167	1.	.470	1.
208	1.24	.592	1.26
249	1.49	.713	1.52

is closely proportional to $(j\bar{\lambda}^2)^{.30}$. Skinner found with hydrogen that V_b is proportional to $(j\bar{\lambda}^2)^{.38}$.

The Electron Current from the Cathode.—For obtaining the ratio of the electron current to the total current, Skinner has derived the following equation.[1]

$$\frac{\bar{j}_k}{j} = \frac{\bar{\mu}}{\bar{\mu} + \overset{+}{\mu}} \cdot 2^{-\left[\frac{x_k - x_a}{\lambda} + \frac{V_0 - V_a}{\epsilon}\right]} \tag{3}$$

in which $\bar{\mu}$ and $\overset{+}{\mu}$ are respectively the mobilities of the negative and positive ion in the negative glow; $\bar{j}_k$ the electron current density at the cathode; j the total current density; $(x_k - x_a/\lambda)$ the number of mean free paths between the cathode and the point where ionization ceases to take place at every mean free path: $V_0 - V_a$ the fall between this point and the negative glow; and ϵ the ionizing potential of the gas. This relation was obtained by assuming that each electron leaving the cathode resulted in two electrons at the end of the first mean free path, four at the end of the second, eight at the end of the third, and so on for the region in which the potential difference per mean free path was equal to or greater than the ionizing potential; and, in the region where the potential gradient was lower than this, ionization was assumed to occur each time an electron moved through a potential difference equal to ϵ. Assuming $\bar{\mu}$ and $\overset{+}{\mu}$ equal, the ratios of $\bar{j}_k/j$ for the three current densities are as follows:

Current Density.	$\left(\frac{x_k - x_a}{\lambda}\right)$	$\left(\frac{V_0 - V_a}{\epsilon}\right)$	$\left(\frac{j_k}{j}\right)$
Normal	7	1.0	2.0×10^{-3}
2×normal	5	.6	$10. \times 10^{-3}$
4×normal	4	.7	$19. \times 10^{-3}$

Observations on the extent of the cathode dark space in oxygen show that there is no perceptible change with large changes in current density.

Nitrogen.

Atmospheric nitrogen was obtained by passing air slowly over heated phosphorous. The gas was then allowed to stand over crushed potassium hydrate and phosphorous pentoxide to remove the carbon dioxide and moisture. Finally the last traces of oxygen were removed by heating the gas for a time in a tube coated on the inner surface with an electrolytic deposit of sodium which had been previously accumulated by sending an electric current from a sodium amalgam bath through the heated walls of the tube.[2] It is very important that no oxygen be present for as Warburg as shown and I also have observed, even a trace will vitiate results by giving an abnormally high cathode fall.

[1] *L. c.*, August, p. 163.

[2] E. Warburg, Wied. Ann., 40, 1890, p. 1.

Current Density and Number of Mean Free Paths to the Negative Glow with Normal Cathode Fall.—A series of observations with an aluminum cathode in Nitrogen is given in Table VIII. As in the case of oxygen, each pressure represents a fresh gas filling. There was considerable difficulty in obtaining satisfactory observations in nitrogen, because with each new gas filling, the cathode fall was usually distinctly larger than with the preceding filling. At most, only three fillings could be used before it became necessary to remove the electrode and repolish it. Unlike the other gases the cathode fall showed, however, a decrease with duration of the discharge in the same filling—especially noticeable if the electrode had not been previously cleaned. This was attributed to the presence of freed hydrogen. The mean, 218 volts, of the values given in Table VIII., column 2 is about five per cent. higher than the fall as given by Warburg, 207 volts.[1] It agrees closely, however, with Skinner's value,

TABLE VIII.

Aluminum Cathode in Nitrogen. Area of Cathode: 3.04 sq. cm.

Gas Pressure (mm.).	Normal Cathode Fall (Volts).	Normal Current Density, j_n.	Distance to Neg. Glow, $x_k - x_0$.	Mean Free Path, $\bar{\lambda}$.	$j_n\bar{\lambda}^2$	$\frac{x_k - x_0}{\bar{\lambda}}$
1.43	216	.29 ma.	3.30 mm.	.28 mm.	.023	11.8
1.78	——	.39	2.90	.23	.021	11.0
1.81	213	——	2.54	.225	——	11.1
2.30	220	.72	2.32	.18	.023	12.8
2.32	219	.76	2.08	.175	.023	12.0
2.41	219	.76	2.10	.17	.022	12.3
2.53	220	.92	1.80	.16	.024	11.2
2.69	214	.99	1.90	.15	.022	12.6
2.91	218	1.08	1.70	.14	.021	12.1
2.96	220	1.12	1.85	.14	.022	12.8
3.30	216	1.45	1.54	.12	.021	12.5
3.33	212	1.58	——	.12	.023	——
3.59	222	1.81	1.47	.115	.024	——
4.07	218	——	1.22	.10	——	12.0
4.49	223	2.46	1.15	.091	.021	12.1
Mean	218			Mean	.0223	12.0
Max. dev.	3%			Max. dev.	9%	8%
Mean dev.	1%			Mean dev.	5%	4%

217 volts.[1] There was some hesitation in the glow covering the cathode when the current was first started. The normal current densities given in column 3, represent the minimum which would cover the cathode after the discharge had first been forced over the whole face. This minimum sometimes showed a tendency to rise, depending on how much the gas

[1] C. A. Skinner, Phil. Mag., 6, VIII., p. 387.

pressure had been increased by the gases freed from the metal. This pressure increase during a set of readings was never more than four per cent. The normal current density for any given gas pressure of nitrogen is about twice that for hydrogen and about one third that for oxygen; $j_n\bar{\lambda}^2$ (column 6) is approximately one half that in hydrogen and one fourth that in oxygen. The number of mean free paths from the cathode to the negative glow (column 7) lies between the values for hydrogen and oxygen.

Potential Curves in the Region between the Cathode and the Negative Glow.—Table IX. gives observations on the differences of potential between the cathode and successive points in the gas, using an aluminum cathode in nitrogen with the three current densities " normal," " twice normal ", and " four-normal." Each series, except the last (at " four-

TABLE IX.

Potential Difference in Volts between the Cathode and Points in the Gas at a given Number of Mean Free Paths from it. Aluminum in Nitrogen.

Gas Pressure (mm.).	Number of Mean Free Paths.							
	2	3	5	7	9	10	11	12
For Normal Current Density: $j\bar{\lambda}^2=.022$								
1.38	129	151	187	213	221	224	226	226
2.06	117	135	167	195	213	218	222	223
2.17	132	148	178	199	211	215	216	217
2.57	130	151	178	196	206	209	210	211
2.63	131	149	181	207	222	226	229	231
2.65	129	147	177	196	209	212	213	215
2.92	119	136	164	191	210	217	221	222
3.86	130	148	175	195	210	216	220	223
Means	127	146	176	199	213	217	220	221

Gas Pressure (mm.).	Number of Mean Free Paths.					
	2	4	6	7	8	9
For Twice Normal Current Density: $j\bar{\lambda}^2=.044$						
2.22	155	194	219	229	235	236
2.23	148	184	211	220	224	224
2.24	142	180	204	212	217	218
2.55	156	195	222	229	234	234
2.70	153	190	214	223	228	229
Means	151	189	214	223	228	228
For Four Normal Current Density: $j\bar{\lambda}^2=.088$						
2.46	173	214	238	242	242	—

normal") was taken in a fresh gas filling. The large increase in the cathode fall with successive fillings, however, made it impossible to obtain comparative results with four-normal current density with fresh gas fillings as has been the plan followed with other gases. Comparing the different gases, it is found that oxygen and hydrogen both show a greater relative rise in the cathode fall with the same multiple of normal current density. Here as in the other gases, potentials are independent of the gas pressures, and the point of minimum gradient draws in toward the cathode as the current density is increased. The means are plotted as circles in Fig. 3.

Some years ago Skinner found[1] that after passing a heavy current through nitrogen the potential difference between cathode and probe was practically the same for all positions of the probe between the cathode and the negative glow. My observations have shown, however, in all cases a marked gradient in this region. It is very probable that the heavy preliminary current used by Skinner simply served to render (by cathode spray) the insulating sheath of his probe conductive, the potentials indicated being then practically those of the highly conductive negative glow through which the probe passed.

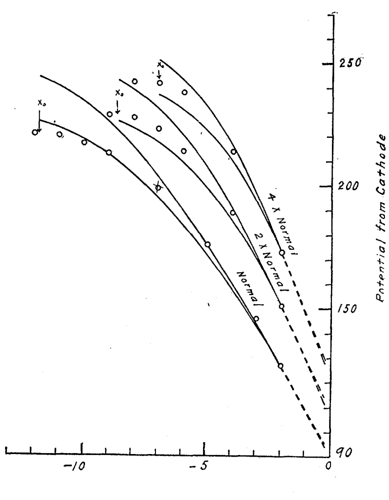

Fig. 3.

Mobility of the Positive Ions.—The mobility $\overset{+}{\mu}$ for the positive ions was calculated from equations (1) and (2) by the same method as used for oxygen. A mean value of 3.1×10^3 cm. per sec. in a field of one volt per cm. was thus obtained. It is rather surprising to find this only about six-tenths that of oxygen—when ordinary measurements show them to be about the same. Using this value, the theoretical curves shown in Fig. 3 were computed. The results are incorporated in Table X.

The Immediate Cathode Fall.—This obtained in the same way as for oxygen (at .2 mean free path from the cathode) is proportional to $(j\bar{\lambda}^2)^{.25}$ approximately; as appears from the table on page 267.

Magnitude of the Electron Current from the Cathode.—The ionizing potential for nitrogen was used as 7.5 volts.[2] Substituting in equation

[1] C. A. Skinner, Phil. Mag., [6], 2, 1901, p. 616.

[2] J. Franck and G. Hertz, Ber. d. Deutsch. Phys. Ges., 2, 1913, p. 34.

Table X.

Calculated and Observed Potential Differences between Cathode and Points in the Gas at a Given Number of Mean Free Paths from it. Aluminum in Nitrogen.

Number of Mean Free Paths.	Calculated from Equation 1.	Calculated from Equation 2.	Observed.
For Normal Current Density: ($j = 4.02 \times 10^5$ c.g.s.-e.s.)			
0.2	94	95	—
2.	*127*	*127*	*127*
3.	144	143	146
5.	177	172	176
7.	204	196	199
9.	226	213	213
10.	235	218	217
11.8	244	226	220
For Twice Normal Current Density: ($j = 8.04 \times 10^5$ c.g.s.-e.s.)			
0.2	111	114	—
2.	*151*	*151*	*151*
4.	190	185	189
6.	220	210	214
7.	232	217	223
8.6	243	226	228
For Four Times Normal Current Density: ($j = 12.06 \times 10^5$ c.g.s.-e.s.)			
0.2	128	129	—
2.	*173*	*173*	*173*
4.	215	210	214
5.	232	221	230
6.	244	230	238
7.	251	237	242

V_b	Ratios.	$(j\lambda^2)^{.25}$	Ratios.
94.5	1.	.387	1.
112.5	1.19	.460	1.19
128.5	1.36	.546	1.41

(3), as before, to obtain the ratio of the electron current at cathode to the total current the results are as follows:

Current Density.	$\left(\frac{x_k - x_a}{\lambda}\right)$	$\left(\frac{V_0 - V_a}{\epsilon}\right)$	$\left(\frac{j_k}{j}\right)$
"Normal"......	7	2.8	$6.\times 10^{-4}$
2 "	7	.7	$24.\times 10^{-4}$
4 "	6	.5	$55.\times 10^{-4}$

These values are somewhat higher than those obtained by Skinner for hydrogen and very much less than those for oxygen.

Observations on the extent of the cathode dark space in nitrogen showed a marked decrease with increasing current density. For example if it extends 6 mean free paths from the cathode at normal current density, it decreases to about 4.5 mean free paths at four times normal current density.

SUMMARY.

To facilitate comparison the various magnitudes measured by Skinner in hydrogen with an aluminum cathode and those obtained in nitrogen and oxygen with the same metal are summarized in the following table:

Gas.	Cathode Fall.	$(j\bar{\lambda}^2)$	$\left(\frac{x_k-x_0}{\bar{\lambda}}\right)$	Immediate Cathode Fall.	Mobility of Positive Ions, at 1 mm. Gas Pres.	$\left(\frac{j_k}{j}\right)$
For Normal Current Density.						
H	197	.038	15.3	78.	27.0×10^3	$4.\times10^{-4}$
N	218	.022	12.0	95.	3.1×10^3	$6.\times10^{-4}$
O	311	.081	10.6	168.	4.9×10^3	$20.\times10^{-4}$
For Twice Normal Current Density.						
H	204	.076	12.	101.	———	$15.\times10^{-4}$
N	228	.044	8.	112.5	———	$24.\times10^{-4}$
O	325	.162	7.	207.5	———	$100.\times10^{-4}$
For Four Times Normal Current Density.						
H	227	.152	10.	130.	———	$42.\times10^{-4}$
N	242	.088	7.	128.5	———	$55.\times10^{-4}$
O	359	.324	5.	248.5	———	$190.\times10^{-4}$

To conclude it is found for each of the different gases, hydrogen, nitrogen and oxygen, that all pressures giving the normal cathode fall have the same number of mean free paths to the point of minimum potential gradient in the negative glow, and have a normal current density proportional to the square of the gas pressure.

With normal current density the cathode fall is a minimum. As the current density is increased the immediate cathode fall also increases, but the fall over the remaining distance to the negative glow decreases. This decrease in the gas is due to the higher ratio of the electron current from the cathode to the total current, which reduces the distance from the cathode to where the negative charge in the gas equals the positive.

Finally, the difference in potential between the cathode and any point at a definite number of mean free paths from it is a function of the product of the current density into the square of the mean free path of the electron, *i. e.*, a function of the ratio of the current density to the square of the gas pressure.

I wish to express my indebtedness to Prof. Skinner, who suggested the problem, and under whose direction it has been my privilege to work, and also to Dr. J. T. Tate for valuable assistance in the experimental part.

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