



LXXIV. The discharge of electricity through gases and the temperature of the electrodes

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LXXIV. *The Discharge of Electricity through Gases and the Temperature of the Electrodes.* By J. A. CUNNINGHAM, B.A. (R.U.I. & Camb.), A.R.C.Sc.I., 1851 Exhibition Scholar, Cavendish Laboratory, Cambridge*.

Introduction.

THE conduction of electricity through hot gases and vapours has been the subject of investigations by Becquerel, Blondlot, Grove, Maxwell, and Hittorf. In 1890 Prof. Thomson† reinvestigated the whole subject, and showed that the heating of the electrodes was an essential part of the phenomenon. Recently Dr. H. A. Wilson‡ has investigated the conductivity of air and salt vapours up to about 1300°. His electrodes were, of course, also hot, and from his previous experiments on flames he had concluded that the ionization of the air took place quite close to the hot electrodes.

It has long been known that hot bodies possessed the property of discharging electricity§. The experiments of Elster and Geitel|| are fundamental, and the subject has been taken up at the Cavendish Laboratory by Prof. Thomson¶, who showed that the carriers were charged particles, Prof. McClelland**, Mr. O. W. Richardson††, and Prof. Rutherford‡‡. The result of all these experiments is to show that a hot metal gives off positive ions at a red heat and negative ions at a white heat, and that this negative current increases very rapidly with further rise of temperature, the potential-difference being much less than is necessary to produce a discharge in the ordinary sense.

When we pass to the discharge in a vacuum-tube the phenomena become more complicated, and the results more difficult to interpret. Hittorf§§ carried out a very extensive series of experiments on the temperature effects at various parts of the discharge. He found that the luminosity in the positive column was extinguished in the neighbourhood of a heated platinum spiral, or if the anode itself were made white hot. On heating up the cathode he found no marked diminution in the total potential-difference until a yellow heat

* Communicated by Prof. J. J. Thomson, F.R.S.

† Phil. Mag. [5] xxix. pp. 358, 441.

‡ Phil. Trans. cxvii. p. 415 (1901).

§ Guthrie, Phil. Mag. [4] xlv. p. 257 (1873).

|| Wied. Ann. xxxviii. p. 27 (1889).

¶ Phil. Mag. [5] xlv. p. 203 (1897).

** Proc. Camb. Phil. Soc. x. p. 241 (1900), and xi. p. 296 (1901).

†† Ibid. xi. p. 286 (1901).

‡‡ Phys. Rev. xiii. p. 321 (1901).

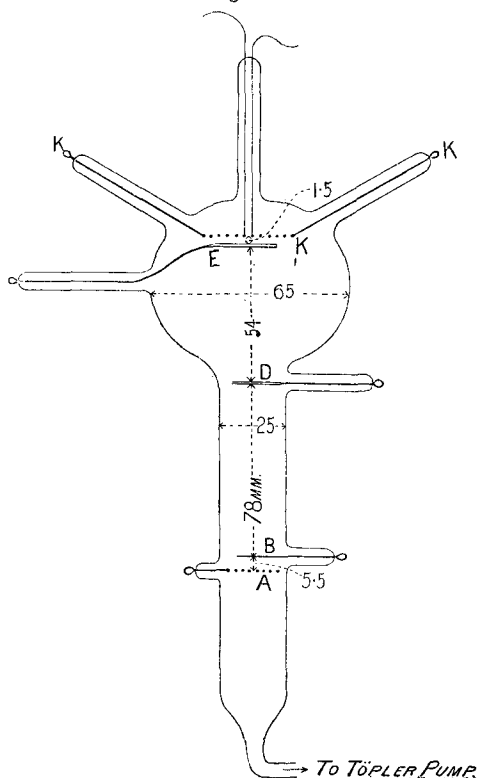
§§ Wied. Ann. xxi. p. 90 (1884).

was attained, after which it began to diminish rapidly. The differences were more marked at reduced pressures. Hittorf also found that the potential gradient in the positive column was independent of the current, but diminished with the pressure. The "cathode fall" remained practically constant until the cathode was covered with the negative glow, after which it increased with increasing current. It also increased very rapidly with diminishing pressure.

Apparatus.

The form of vacuum-tube used in the present series of experiments is shown in the diagram (fig. 1). The electrode

Fig. 1.



(KK) consisted of a platinum wire bent backwards and forwards on itself so as to form a plane grating. Four strands of wire of the same thickness fused into each of two side

tubes served to lead the heating current through the grating without undue heating of the blue-glass joint. The grating could thus be included in the circuit of a carefully insulated secondary wound on a ring transformer. The current for the primary was taken from the Cambridge town (alternating) supply, and was regulated by means of a rheostat.

The opposite electrode (A) was made of a similar grating, but could not be artificially heated. The three intermediate electrodes (E, D, & B) were made of fine platinum wires whose free ends inside the discharge-tube were hammered out flat, and the edges then trimmed off parallel, so that the width of the blade was only about double the diameter of the original wire. They were fused into side tubes perpendicular to the bars of the gratings, and so that the plane of the blade was parallel to the axis of the discharge-tube. Professor Thomson has pointed out that, especially when working at low pressures, an ordinary wire placed in front of the cathode would be subjected to a bombardment of negatively charged corpuscles, from which it would derive a negative charge and acquire a potential which might have nothing much to do with the potential of the surrounding gas. Prof. Thomson's scheme of using a transverse pencil of cathode particles whose deflexion would measure the electric intensity at the point was not easily applicable in the present case, since when the cathode was at a high temperature the illumination from it would render a phosphorescent spot practically invisible. It was thought that the flat-bladed electrodes here adopted would expose only a very thin edge to particles moving rapidly along the axis of the tube, and a maximum surface to the ionized gas whose potential it was desired to ascertain.

This tube was connected by means of a short glass tube with the Töpler-pump, P_2O_5 bulb, and McLeod gauge, so that the whole system rapidly came to one uniform pressure. A three-way tap served to admit fresh supplies of air, and by being closed at night prevented an excessive diffusion of mercury-vapour into the discharge-tube. The discharges below described always presented a rich red colour without any apparent traces of the blue due to mercury.

The current from a battery of 1000 small secondary cells, used for generating the discharge, passed through two variable liquid resistances, and was measured by means of a low resistance d'Arsonval galvanometer of the Ayrton and Mather type. A telephone in series served to check the steadiness of the discharge.

A German voltmeter of simple construction (with an aluminium needle suspended about a horizontal axis a little

above its centre of gravity) served to measure the total potential-difference between the electrodes, and at very low pressures (Table XIV.) also for the cathode fall. Its scale was carefully calibrated by direct comparison with the Kelvin multicellular voltmeter, which was used for measuring potential-differences between the other electrodes ranging from 250 to 1000 volts. The German instrument was a little sluggish in its movements, and its indications were used mainly as a check on those of the other instruments, except when special precautions were taken to tap it before each reading. For potentials between 100 and 300 volts an Ayrton and Mather direct-reading voltmeter (with vertical cylindrical quadrants) was employed.

The temperature of the hot electrode (KK) was measured by means of a platinum-platinum-rhodium thermo-couple. The wires (0.1 mm. in diameter) were attached to adjacent bars of the grating. They were fused through the end of a small glass tube at the top of the discharge-tube, and passed over into two glass tubes immersed alongside a mercury thermometer in a bottle of water. These glass tubes were partly filled with mercury, which served to make good contact with the copper wires leading to the galvanometer. This was also a d'Arsonval of the Ayrton and Mather type. To reduce the deflexions of the galvanometer to degrees centigrade use was made of Messrs. Heycock and Neville's determination of the melting-point of potassium sulphate*. The thermal junction was attached to a strip of platinum-foil which was heated up as in the course of the experiments. The deflexion of the spot of light on the scale was then read off just when the K_2SO_4 began to melt. The observation was repeated with very slow increments of current through the foil. From the final value thus obtained a curve of temperatures against deflexions was plotted in the manner described by Callendar†, and verified by a determination of the melting-point of sodium sulphate. The deflexions of the spot at all distances of the galvanometer from the scale were readily reduced to this standard distance.

There is a little doubt attaching to some of the highest temperatures recorded owing to a sagging of the wire-grating which left the portion to which the thermo-couple wires were attached slightly out of the plane of the grating, and so made them rather cooler than the rest.

With this apparatus, where there were only glass joints and there was therefore practically no leak until very high

* Chem. Soc. Journal, lxxvii. p. 160 (1895).

† Phil. Mag. [5] xlviii. p. 519 (1899).

temperatures were reached, it was often thought desirable to vary the temperature backwards and forwards so as to try and isolate the temperature effect as completely as possible. It was also possible to raise the temperature of the platinum grating by more gradual steps than would actually appear from the numbers recorded in the accompanying tables. Where in such cases a gradual change of temperature was accompanied by a gradual and continuous change in the distribution of potential, it was often thought sufficient to record the measurements of successive maxima and minima. And in nearly all cases plenty of time was allowed to elapse for the instruments to settle down to perfectly steady readings.

A few general remarks on some of the appearances observed may not, perhaps, be out of place here before proceeding to a detailed record of the actual measurements made.

The temperature of the cathode was observed to rise gradually by the action of the discharge. At moderately high pressures (0.5 to 2 mm.) and with small currents, on first starting the discharge the negative glow was seen to wander about in an unsteady manner over the surface of the cathode, accompanied by a noise in the telephone which only ceased after a very considerable lapse of time. This unsettledness was most marked on starting the discharge for the first time with a new wire.

When the cathode was now gradually heated up the negative glow was observed to move away from the central hottest portion of the grating and wander up into the side tubes, where the wire was cooler. On further heating the discharge would come back again and proceed from the hottest part of the cathode. This phenomenon is consistent with the measurements recorded below, which show a more or less well-marked maximum "cathode fall" at temperatures below a yellow heat varying with the pressure; and it seems natural to suppose that the discharge will pass where it can do so with the greatest ease.

It will be seen at a glance from all the tables where the cathode was taken through a cycle of temperature changes that a sort of *hysteresis* becomes apparent. This may be partly due to an error of observation. The cooling was nearly always more rapid than the heating up. The method of observation adopted was to keep an eye fixed on the voltmeter after each successive reduction of current in the primary of the transformer, and at successive readings of the voltmeter to look up quickly at the corresponding reading on the conveniently placed scale of the galvanometer connected with the thermo-couple. Particular attention was paid to recording maxima and minima on the voltmeter with

their corresponding temperatures. As in all recorded cases, the potential indicated on the voltmeter was changing but slowly, and as the coil of the d'Arsonval galvanometer was inclosed in a silver cylinder and was very dead beat, it was thought that the error of observation could not really be very great. Some such lag is, after all, only to be expected.

Results.

In Tables I. to VIII. are shown the measurements of the fall of potential along the discharge at different pressures, the temperature of the cathode being kept constant.

TABLE I.

Temperature of Cathode.		Potential Difference, Volts.					Pressure, mm. of Mercury.
Deflex-ion.	° C.	K-A.	K-E.	E-A.	K-D.	K-B.	
0.90	35	815	300	(515)	...	665	1.18
0.90	35	780	240	(540)	...	520	0.88
0.90	35	720	214	(508)	...	500	0.66
0.90	35	650	228	(422)	...	396	0.51
0.95	38	600	259	(341)	...	345	0.38
0.90	35	538	320	218	340	(350)	0.29
0.90	35	522	352	170	...	...	0.221
0.90	35	519	370	149	...	...	0.168
0.65	27	558	395	163	...	...	0.105
0.90	35	580	418	162	...	...	0.104
0.90	35	654	478	176	...	...	0.079
0.95	38	705	503	202	...	...	0.050
0.95	38	1100	770	>310	...	...	0.031

TABLE II.

Temp. of Cathode.		Potential Difference.			Current.		Pressure, mm. of Hg.
Defln.	° C.	K-A.	K-E.	E-A.	Defln.	Amp. $\times 10^9$.	
32.8	820	1150	293	860	6.60	3.96	2.67
33.3	832	960	268	680	7.40	4.44	1.92
33.3	832	800	292	512	8.35	5.01	1.42
33.3	832	755	290	(465)	(8.6)	(5.16)	1.03
33.3	832	730	293	(437)	9.0	5.40	0.76
33.3	832	660	230?	(430)	9.15	5.49	0.563
33.3	832	625	290	(335)	...	...	0.507
33.3	832	580	387	181	9.25	5.55	0.294
33.3	832	625	430	190	9.65	5.79	0.210
33.3	832	650	465	192	8.45	5.07	0.155
33.3	832	710	537	197	7.95	4.77	0.108
33.3	832	690	482	212	7.85	4.71	0.079
33.3	832	730	520	255	7.40	4.44	0.058
		840	527	313	6.55	3.93	0.041
33.3	832	1070	540	(530)	...	...	0.029

TABLE III.

Temp. of Cathode.		Potential Difference.			Current.		Pressure, mm. of Hg.
Defn.	° C.	K—A.	K—E.	E—A.	Defn.	Amp. $\times 10^3$.	
43·7	1040	1200	300	900	5·45	3·27	2·70
43·9	1043	955	272	682	6·70	4·02	1·95
43·9	1043	810	292	518	7·60	4·56	1·43
43·9	1043	780	300	490	7·70	4·62	1·35
43·9	1043	(725)?	(200)	(525)	...	...	1·00
43·9	1043	750	215	...	(7·4)	(4·5)	0·74
43·9	1043	690	260	430	(7·8)	...	0·53
43·9	1043	565	367	199	8·3	4·98	0·39
43·9	1043	565	377	184	8·15	4·89	0·280
40·4	986	630	440	201	7·7	4·62	0·196
42·7	1020	625	432	199	7·7	4·62	0·196
43·3	1030	(680)	(490)	207	(7·3)	...	0·143
43·1	1028	670	468	200	7·6	4·56	0·096
43·7	1040	710	487	226	(7·1)	...	0·068
43·9	1043	800	522	282	6·70	4·02	0·054
43·9	1043	865	502	(363)	6·05	3·63	0·042
43·9	1043	970	464	(506)	(5·5)	...	0·031
43·9	1043	1045	435	(610)	5·0	3·00	0·027
43·9	1043	1340	437	(900)	3·3	1·98	0·020

TABLE IV.

Temp. of Cathode.		Potential Difference.			Current.		Pressure, mm. of Hg.
Defn.	° C.	K—A.	K—E.	E—A.	Defn.	Amp. $\times 10^3$.	
50·2	1163	960	275	661	5·9	3·54	1·90
50·3	1165	810	300	512	(6·6)	...	1·40
50·4	1167	730	(317)	413	7·1	4·26	1·05
50·4	1167	730	296	(430)	7·0	4·20	0·74
50·4	1167	685	285	(400)	7·2	4·32	0·55
50·4	1167	570	366	204	7·5	4·50	0·40
50·4	1167	570	372	195	7·45	4·47	0·30
50·2	1163	630	426	206	7·2	4·32	0·206
50·4	1167	680	432	204	(6·7)	...	0·151
50·4	1167	780	565	220	6·3	3·78	0·108
50·4	1167	770	560	210	6·1	3·66	0·079
50·4	1167	795	508	284	...	...	0·055
50·4	1167	900	500	(400)	5·4	3·24	0·039
50·4	1167	1080	690	(390)	4·2 ?	2·52 ?	0·037
50·4	1167	1450	950	(500)	...	...	0·025

TABLE V.

Temp. of Cathode.		Potential Difference.			Current.		Pressure, mm. of Hg.
Defln.	° C.	K - A.	K - E.	E - A.	Defln.	Amp. $\times 10^5$.	
55.4	1256	1010	277	720	(5.2)	...	2.15
55.4	1256	860	293	538	6.1	3.66	1.53
55.4	1256	790	(337)	453	6.4	3.84	1.10
55.5	1259	740	300	(440)	(6.6)	...	0.82
55.4	1256	660	220	(440)	...	...	0.60
55.4	1256	570	345	224	(7.2)	...	0.43
55.4	1256	570	350	214	...	...	0.314
55.4	1256	575	360	196	7.0	4.20	0.224
55.4	1256	640	390	241	(6.6)	...	0.171
55.4	1256	680	480	199	(6.3)	...	0.130
55.4	1256	750	558	196	...	...	0.106
55.4	1256	780	(566)	214	5.75	3.45	0.082
55.4	1256	780	521	259	(5.65)	3.39	0.066
55.4	1256	810	500	(310)	5.7	3.42	0.057
55.4	1256	880	545	(335)	5.1	3.06	0.050
55.4	1256	920	612	(310)	5.1	3.06	0.054
55.4	1256	1120	715	(405)	...	...	0.037
55.4	1256	1310	860	(450)	3.1	1.86	0.034
55.3	1254	1420	930	(490)	3.1	1.86	0.029

TABLE VI.

Temp. of Cathode K.		Potential Difference.				Current.		Pressure, mm.
Defln.	° C.	K - A.	K - E.	E - A.	K - D.	Defln.	Amps. $\times 10^5$.	
59.8	1335	1160	(330)	830	...	(4.5)	...	2.10
60.3	1340	960	(360)	602	...	(5.4)	...	1.40
63.3	1394	790	(340)	450	...	(6.0)	...	1.02
60.3	1340	700	(343)	357	...	6.7	4.02	0.75
60.2	1340	665	(342)	323	...	6.8	4.08	0.55
60.4	1344	575	340	235	...	7.1	4.26	0.39
60.4	1344	565	350	215	...	7.0	4.20	0.29
60.4	1344	570	370	202	...	6.85	4.11	0.22
60.4	1344	640	425	215	...	6.6	3.96	0.174
60.4	1344	710	500	206	...	(6.2)	...	0.116
60.4	1344	770	573	196	...	...	...	0.088
60.4	1344	820	563	250	...	...	...	0.065
60.4	1344	840	580	258	700	(5.4)	...	0.058
60.4	1344	990	(590)	(400)	840	4.5	2.70	0.041
60.4	1344	1150	725	(425)	1020	...	...	0.035
60.4	1344	1220	800	(420)	...	...	...	0.032
60.4	1344	1200	775	(425)	...	3.55	2.13	0.033
60.46	1346	1300	860	(440)	...	...	...	0.032

TABLE VII.

Temp. of Cathode.		Potential Difference.					Current.		Pressure, mm. of Hg.
Defn.	° C.	K-A.	K-E.	E-A.	E-D.	D-A.	Defn.	Amps. $\times 10^5$.	
65.5	1432	1350	360	990	280	720	...	(2.6)	2.13
65.5	1432	1020	328	692	190	500	5.1	3.06	1.53
65.3	1429	850	(280)	(570)	120	450	...	(3.2)	1.13
65.5	1432	770	300	470	100	380	5.9	3.54	1.07
65.5	1432	650	302	348	< 90	...	...	(3.8)	0.604
65.55	1434	587	328	259	...	...	...	(3.8)	0.431
65.5	1432	583	370	213	...	...	6.3	3.78	0.226
65.5	1432	680	470	210	...	...	...	(3.4)	0.122
65.5	1432	780	510	270	...	...	...	(3.2)	0.078
65.5	1432	1110	565	545	> 310	90	3.9	2.35	0.035
65.3	1429	1480	430	1050	920	150	...	...	0.023
65.5	1432	2000	...	...	...	...	0	0	0.017

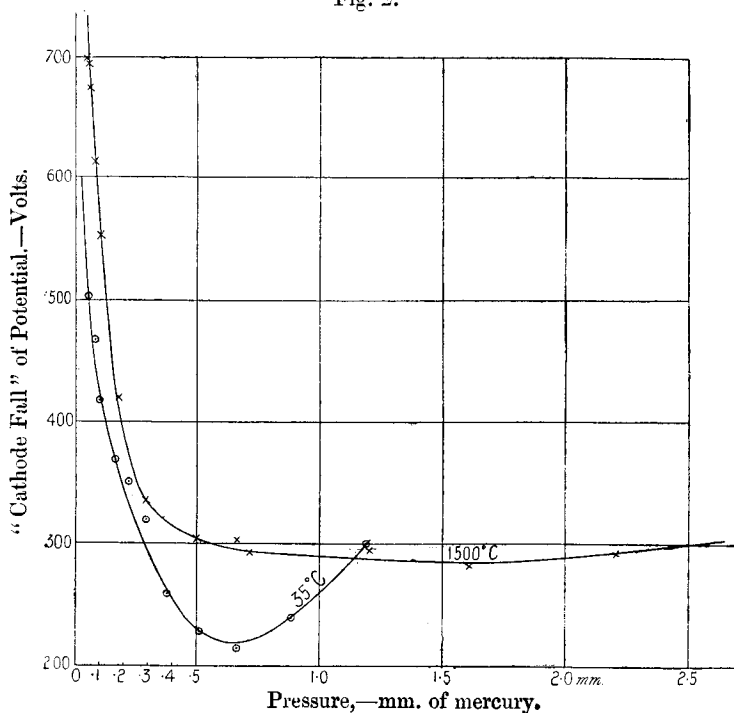
TABLE VIII.

Temp. of Cathode.		Potential Difference.					Current.	Pressure, mm. of Hg.
Defn.	° C.	K-A.	K-E.	E-A.	K-D.	K-B.	Defn.	
69.4	1500	1650?	305	1190	(760)	...	6.09	2.95
69.4	1500	1220	293	930	340	930	10.54	2.20
69.5	1502	970	283	670	333	720	(16.4)	1.60
69.4	1500	800	295	490	...	610	(22.0)	1.20
69.4	1500	690	295	380	310	500	(28.0)	0.71
69.4	1500	635	304	326	305	435	27.7	0.66
69.5	1502	580	304	280	335	...	29.34	0.50
69.4	1500	575	(335)	240	352	472	32.44	0.29
69.4	1500	630	420	203	508	585	34.44	0.18
69.4	1500	750	554	194	640	700	34.04	0.103
69.4	1500	860	614	220	740	820	(31.8)	0.078
69.4	1500	960	674	262	850	905	30.54	0.058
69.4	1500	1030	695	335	900	980	30.00	0.056
69.4	1500	1050	700	350	920	1010	...	0.048

At low temperatures of the cathode the "cathode fall" (K-E) shows a well-marked minimum at a pressure of about 0.65 mm. of mercury. At higher temperatures this minimum tends to become less marked, and to occur at a greater pressure. In fact the cathode fall becomes almost independent of pressure above 0.5 mm. The cathode fall at the highest (1500° C.) and at the lowest (35° C.) are plotted in fig. 2.

The potential-differences between the fixed electrodes A, B, D, E, and K when the cathode is at a temperature of

Fig. 2.



about 1500° C. are shown in fig. 3 (p. 694) and Table VIII. The fall of potential close to the anode (B—A) decreases steadily with diminishing pressure. The potential-gradient in the positive column (D—B) is approximately proportional to the pressure above 0.5 mm. The gradient at the negative end of the positive column, and including the Faraday dark space (E—D), is very much less than anywhere else in the discharge, and seems almost to vanish at a pressure of about 0.65 mm.

In Tables IX. to XIV. we pass on to the results obtained by pumping down to any required exhaustion and then gradually heating up the cathode, the actual pressure being measured and recorded at intervals. As the volume of the discharge-tube bore but a small ratio to that of the pump cylinder, McLeod gauge, and P_2O_5 bulb, the heating of the cathode only produced trifling changes of pressure, and it has been shown already that the cathode fall is hardly affected by

slight changes of pressure except at very high exhaustion. At very high temperatures and low pressures the slight leak did, however, produce quite appreciable effects, as is well illustrated by the latter part of Table XIV.

Fig. 3.—(Temperature=1500° C.)

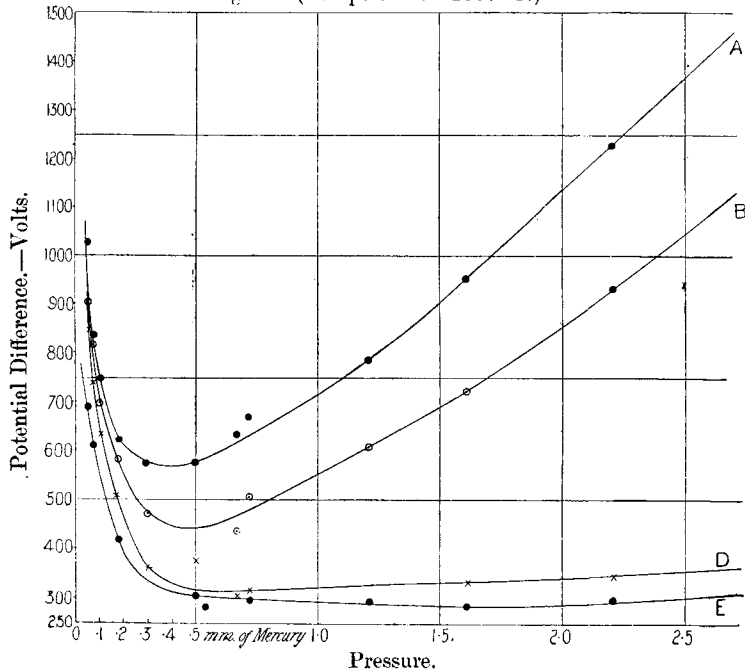


TABLE IX.

Temperature of Cathode K.		Potential Difference.			Current.		Pressure, mm. of Mercury.
Defn.	° C.	K - A.	K - E.	E - A. (calculated)	Defn. of Galvanr.	Amps. $\times 10^4$.	
16.8	468	793	336	457	25.2	8.4	1.8
5.8	195	...	320	...	25.2	8.4	
2.7	102	804	324	480			
7.8	248	...	318	...			
16.3	455	804	330	474			
19.7	532	...	340	...	26.9	8.97	
20.2	545	...	337	...			
46.3	1112	...	306	...			
55.3	1255	747	302	445			
59.3	1325	752	300	452	26.5	8.83	
67.3	1463	793	296	497			
70.3	1514	798	294	504			

TABLE X.

Temperature of Cathode.		Potential Difference.			Current.		Pressure, mm. of Hg.
Defln.	° C.	K - A.	K - D.	D - A.	Defln.	Amps. $\times 10^4$.	
80.3	1681	787	350	437	1.9
78.6	1653	798	358	440			
73.4	1566	793	362	431			
53.3	1220	770	366	404			
52.3	1202	770	360	410			
24.8	650	782	373	409	24.9	8.30	
19.8	535	...	390				
19.3	524	804	400	404			
10	305	815	455	360			
7	227	...	420				
5	173	...	410		24.1	8.03	
4	142	...	420				
2.8	105	...	450	...			

TABLE XI.

Temp. of Cathode.		Potential Difference.					Current.		Pressure, mm. of Hg.
Defln.	° C.	K - A.	K - D.	D - A.	D - B.	B - A.	Defln.	Amp. $\times 10^4$.	
3.7	133	720	410	(310)	262	(48)	20.4	6.80	1.07
17.4	480	710	398	(312)	259	(53)	20.9	6.97	
18.0	495	700	390	(310)	258	(52)	21.9	7.30	
37.7	920	665	368	(297)	250	(47)	19.9	6.63	1.14
37.7	920	665	358	(307)	253	(54)	23.0	7.67	
44.9	1063	665	365	(300)	252	(48)	19.85	6.62	
52.0	1196	665	365	(300)	252	(48)	19.65	6.55	1.14
53.8	1230	663	352	(311)	262	(49)	19.90	6.63	
56.1	1270	660	351	(309)	265	(44)	19.80	6.60	
60.9	1352	660	353	(307)	271	(36)	19.3	6.43	1.16
67.9	1475	665	357	(308)	277	(31)	18.5	6.17	
71.4	1533	673	362	(311)	282	(29)	18.6	6.20	
72.4	1550	675	360	(315)	284	(31)	19.0	6.33	1.17
73.5	1570	680	359	(321)	287	(34)	17.5	5.87	
62.5	1380	675	356	(319)	275	(44)			
24.1	635	700	402	(298)	273	(25)	12.4	4.13	1.12
23.4?	610?	...	412						
22.4	597	740	445	(295)	278	(17)			
21.4	575	742	453	(289)	279	(10)			1.14
20.1	542	735	434	(301)	275	(26)	15.7	5.23	
18.7	510	742	450	(288)	278	(10)	15.0	5.00	
2.9	108	...	...	...	285			
2.4	90	...	525	...	290	...	11.0	3.67	

TABLE XII.

Temp. of Cathode.		Potential Difference.				Current.		Pressure, mm.
Defln.	° C.	K—A.	K—D.	D—A.	D—B.	Defln.	Amp. $\times 10^4$.	
1.9	75	525	370	148	...	22.8	7.60	0.376
1.95	76	...	376	...	119			
9.0	280	...	382	...				
16.2	451	...	388	...	121			
19.2	520	535	392	152	122	20.4	6.80	
21.7	580	535	394	152	...	19.7	6.57	
24.7	648	535	393	152	...	19.7	6.57	
28.0	720	545	395	153	...	19.2	6.40	
40.7	980	(555)	400	155	...	18.8	6.27	
41.2	990	(548)	393	155	...	18.8	6.27	
61.7	1367	(545)	390	155	...	18.6	6.20	0.406
66.4	1450	545	392	154	...	18.5	6.17	
71.4	1533	(553)	392	161	...	18.3	6.10	
71.0	1525	550	392	160	128			
74.2	1580	555	394	158				
77.4	1634	(545)	388	157	...	17.8	5.93	
79.0	1660	(528)	375	153	...	18.0	6.00	
81.2	1696	...	240					
77.7	1638	(523)	372	151				
85.0	1750	320	190	151	...			0.392
78.0	1642	470	343	148	...	17.2	5.73	
76.4	1617	525	389	150				
75.1	1594	560	407	150				
72.2	1547	570	415	150	...	17.0	5.67	
		565	420	150				
53.0	1213	565	412	150				
34.2	850	580	426	152	...	16.8	5.60	
24.2	637	(575)	423	152				
8.0	250	(542)	390	152	...	16.8	5.6	
3.7	133	560	400	151	...	19.2	6.4	0.374
3.6	130	565	404					

The results of Tables IX. and X. are plotted in fig. 4, curves E and D respectively. The one was obtained while the cathode was being warmed up, while the other was a cooling curve, which may account for the shifting of the initial minimum and maximum along the axis of temperature. The curve D shows the potential-difference between the cathode and a point in the top of the positive column (K—D).

The results obtained at a rather lower pressure (about 1.1 mm.) are given in Table XI. and plotted in fig. 5, where the cathode (K) is supposed to lie along the line of zero-potential below the diagram, and the P.D. between it and each of the electrodes A, B, and D is measured by the ordinate drawn to the respective curve at any given temperature. Here the initial variations (at a temperature below 600° C.)

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Fig. 4.

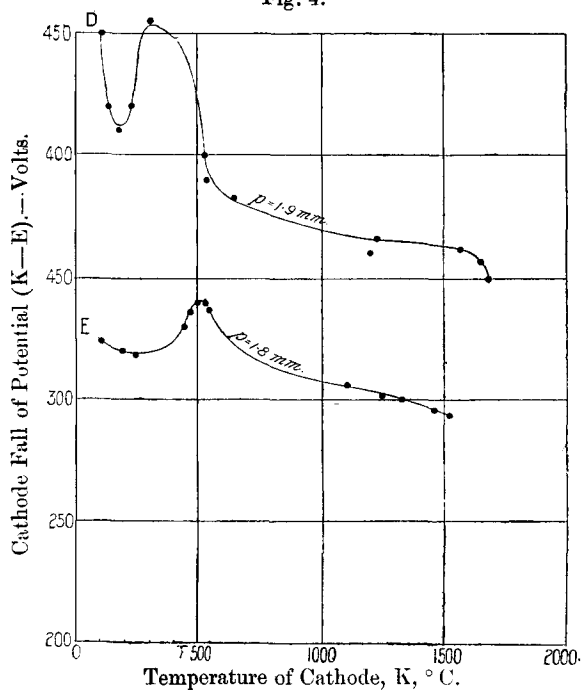
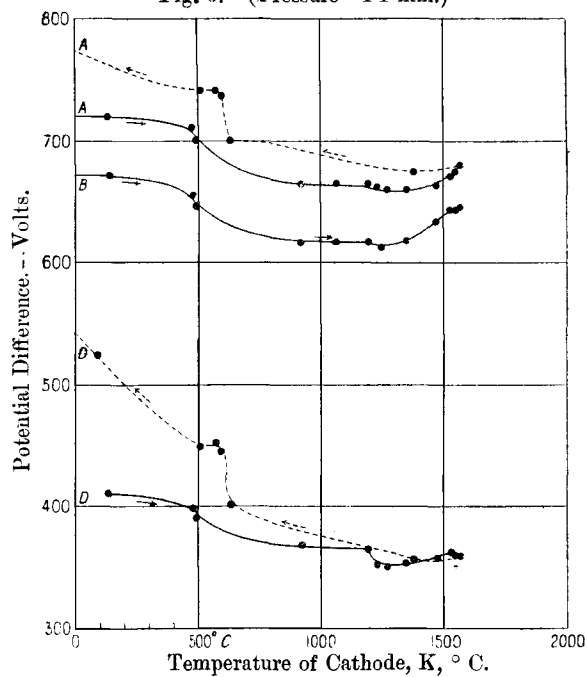


Fig. 5.—(Pressure = 1.1 mm.)



have become less marked though still apparent. The difference of potential between the cathode and the top of the positive column (K—D) shows a distinct tendency to a maximum above 1500°C . The potential-gradient in the positive column (D—B) is pretty nearly constant with a slight minimum about 920° , after which it increases uniformly up to the highest temperature attained. The curves for heating up and cooling down are indicated by the arrows, cooling curves being dotted.

In Table XII. and fig. 6 the pressure is still further reduced to 0.4 mm. The initial minimum and maximum of potential-difference at the negative end of the discharge have broadened out, so to speak, along the axis of temperature, and contracted parallel to the axis of potential. There is a gentle maximum about 800°C ., and a second above 1500°C . before the final very rapid diminution.

Table XIII. and fig. 7 :—In this series of experiments, made soon after admitting a fresh supply of air, so far from the apparatus showing any tendency to leak, the pressure steadily diminished during the course of the experiments. This could only be accounted for as being due to the constant

TABLE XIII.

Temp. of Cathode.		Potential Difference.					Current.		Pressure, mm. of Hg.
Defln.	$^{\circ}\text{C}$.	K—A.	K—E.	E—A.	K—D.	K—B.	Defln.	Amp. $\times 10^5$.	
1.9	74	540	355	187	430	510	29.0	17.40	0.172
20.5	550	580	410	185	490	560	32.1	19.22	0.173
28.6	732	600	429	178	510	587	33.2	19.92	0.171
33.5	837	615	453	177	530	602	35.6	21.36	0.167
49.7	1153	640	474	172	552	623	...	...	0.167
60.9	1350	670	515	169	586	654	41.1	24.66	0.156
69.5	1500	710	542	169	...	...	42.7	25.62	...
70.5	1518	705	(530)	173	620	...	...	...	...
71.6	1536	710	(546)	164	640	...	...	...	...
72.6	1552	710	(549)	161	641	...	...	...	...
73.3	1566	710	(549)	161	630	...	45.0	27.00	...
73.8	1574	705	(550)	155	615	...	...	...	...
74.2	1580	700	(546)	154	598	...	...	...	0.150
		665	(515)	150	560	...	...	...	...
		655	(502)	153	565	...	...	...	...
71.0	1526	740	(583)	157	660	...	...	...	...
75.0	1593	700	(546)	154	624	...	...	...	...
76.1	1612	680	(528)	152	600	...	...	...	...
76.7	1620	670	(520)	150	590	...	...	...	...
74.5	1585	740	(585)	155	655	...	...	...	...
72.0	1540	760	605	155	670	...	...	...	...
67.5	1468	...	...	...	670	...	...	...	...
57.2	1290	755	598	157	660
		740	583	157	655
38.5	937	720	562	158	637
5.5	188	670	514	156	573	...	57.6	34.56	0.140

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Fig. 6.—(Pressure 0.4 mm.)

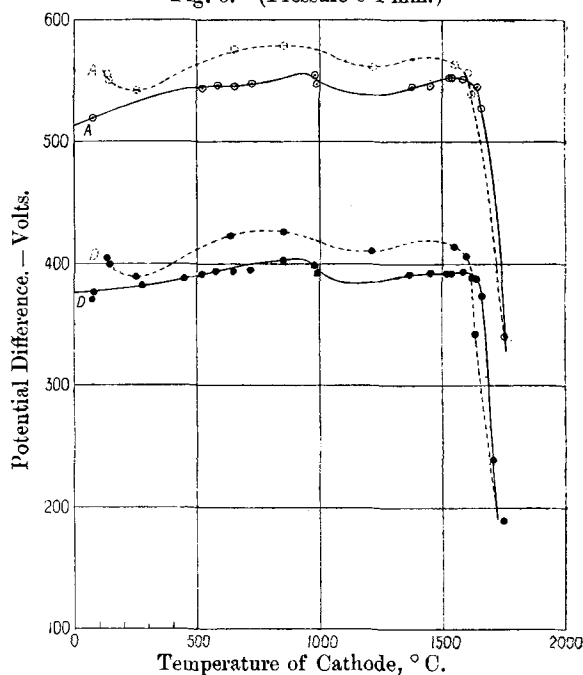
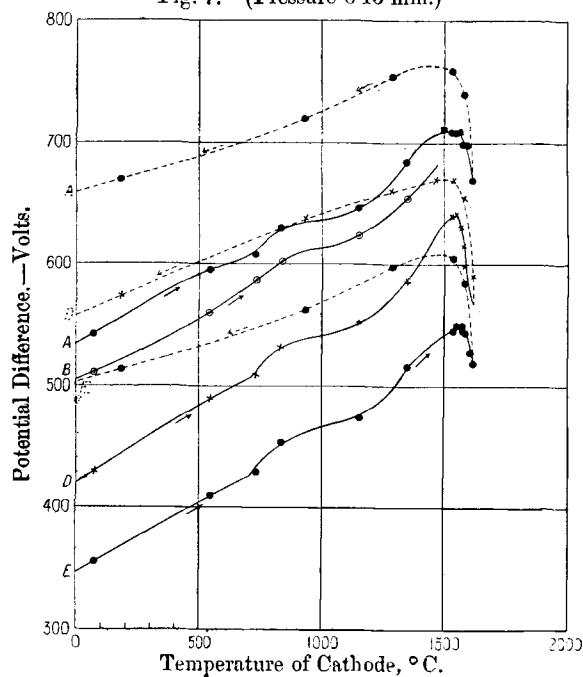


Fig. 7.—(Pressure 0.15 mm.)



raising and lowering of the mercury in the McLeod gauge causing a movement of the heated and ionized air to and fro between the discharge-tube and the P_2O_5 bulb, and so bringing about a more perfect drying which would, perhaps, also partly explain the cathode-fall being so much greater after the cathode had cooled down than it was before heating. We have, however, already noticed a progressive increase of this "lag" as the pressure was diminished. At this low pressure (0.15 mm.) the whole curve is, as it were, tilted up and there is only one real maximum value of the cathode-fall a little below $1600^\circ C$. The previous maximum is here only represented by a change of curvature. Above 1600° the diminution of cathode-fall becomes very rapid.

The potential-gradient in the rest of the tube (E—A) remains practically unchanged with temperature.

TABLE XIV.

Temp. of Cathode.		Potential Difference.				Current.		Pressure, mm. of Hg.
Defln.	$^\circ C$.	K—A.	K—D.	D—A.	D—B.	Defln.	Amps. $\times 10^4$.	
2.7	103	...	1460	< 90	...	10.4	3.47	0.030
2.8	105	...	1420	"	...	8.6	2.87	
15.2	430	...	1490	"	...			
20.2	545	...	1490	"	...			
26.2	682	...	1460	"	...			
26.8	693	...	1420	"	...			
49.9	1158	...	1400	"	...			
64.2	1410	...	1470	"	...			
65.2	1428	...	1490	"	...	10.6	3.53	
73.8	1573	...	1560	"	...			
79.7	1670	...	1490	"	...	10.6	3.53	0.040
79.7	1670	...	1500	"	...	10.0	3.33	
79.9	1675	...	1510	"	...			
80.4	1683	...	1510	"	...			
80.7	1688	...	1500	100	...	...	...
80.0	1676	...	1420	145	...			
80.8	1690	...	1410	185	...			
80.4	1683	...	1380	240	...			
80.4	1683	...	1385	> 310	> 310	6.6	2.20	
80.2	1680	...	1250	90	...	17.8	5.93	0.052
74.7	1589	...	1200	"	...	19.1	6.37	
66.9	1458	...	1140	"	...	20.6	6.87	
57.2	1290	...	1100	"	...	21.5	7.17	
34.2	850	...	1080	"	...	22.2	7.40	
32.2	809	...	1030	"	...			
13.7	395	...	970	"	...			
11.2	335	...	960	"	...			
10.6	320	1030	940	"	...	24.5	8.17	0.061
3.9	140	925	830	"	...	11.6	3.87	
3.1	115	890	790	"	...	10.5	3.50	
2.8	105	870	770	"	...	9.8	3.27	
			725	220	...	5.1	1.70	
2.2	85	1030	720	> 310	...	0.8	0.27	

On reducing the pressure to 0.04 mm. (Table XIV.) the potential-gradient becomes so steep that only the German voltmeter was available for measuring the cathode-fall, and even it was working at a very unsensitive part of its scale. The electrode D was right in the middle of the negative glow, and the whole of the rest of the tube was practically dark. But as soon as the cathode became white-hot the pressure began to rise so much that the measurements on cooling down were not strictly comparable.

The most interesting part, however, of this table is that which shows the effect of variations of current on the potential-gradient in different parts of the discharge. For all values of the current greater than about 2.5×10^{-4} amperes the potential-difference across the whole 83.5 mm. (D-A) at the positive end of the discharge remained too small to be measured by any of the available instruments; and, as has

TABLE XV.
A = Cathode; K = Anode.

Temp. of Anode.		Potential Difference.					Current.		Pressure, mm. of Hg.
Defln.	° C.	A-K.	A-B.	B-D.	A-D. (calc.)	D-K. (calc.)	Defln.	Amps. $\times 10^4$.	
1.8	70	875	352	255	607	268	24.2	8.07	1.83
1.8	70	850	366	214	580	270	24.5	8.17	
		...	370	210	580	...	24.9	8.30	
		850	366	231	597	253	24.3	8.10	
15.5	438	780	367	194	561	229	24.2	8.07	
17.4	482	775	368	194	562	213			
18.1	498	775	368	198	566	209	24.1	8.03	
17.9	492	775	370	192	562	213	24.0	8.00	
44.8	1060	770	370	202	572	198	23.9	7.97	
50.4	1167	770	369	208	577	193	23.6	7.87	
60.3	1340	768	367	213	580	188			
71.4	1533	765	365	220	585	180	22.6	7.53	
71.4	1533	768	368	230	588	180	23.6	7.80	
71.4	1533	765	362	217	579	186	24.1	8.03	
77.5	1635	765	362	225	587	178	23.95	7.98	
82.4	1716	770	370	232	602	168	23.2	7.73	
			370	224	594	...	24.5	8.17	
83	1725	...	375	220	595	...	25.1	8.37	
63.4	1397	793	380	208	588	205	24.9	8.30	
51.4	1185	793	383	198	581	212	24.9	8.30	
19.4	525	793	383	190	573	220	24.6	8.20	
17.6	485	800	383	187	570	230	24.5	8.17	
2.4	91	...	383	220	603	...	23.5	7.83	
2.4	91	845	383	207	590	255	24.8	8.27	
2.3	89	810	385	166	551	259	34.5	11.50	1.82
		810	383	160	543	267	41.7	13.90	

TABLE XVI.

A=Cathode ; K=Anode.

Temp. of Anode.		Potential Difference.					Current.		Pressure, mm. of Mercury.
Defln.	° C.	A-K.	A-B.	B-D. (calc. *obs.)	A-D. (calc. *obs.)	D-K.	Defln.	Amps. ×10 ⁴ .	
0.55	20	632	407	90*	497	135	25.1	8.37	0.602
0.55	20	632	410	90*	...	...	25.3	8.43
0.55	20	632	409	90	499	133	25.1	8.37	
17.5	484	620	400	97	497	123	21.6	7.20	
17.7	488	623	410	91	501	122	25.1	8.37	
19.5	530	...	413	0.650
20.9	562	623	410	92	502	121	25.0	8.33	
26.8	693	623	410	93	503	120	25.5	8.50	
30 ?	...	623	413	...	...	...	25.7	8.57
46.5	1093	623	409	99	508	115	25.1	8.37	
52.5	1205	623	408	99	507	116	25.0	8.33	
63.0	1390	623	408	101	509	114	24.8	8.27	
73.2	1563	623	407	103	510	113	24.3	8.10	
			409	...	...	...	25.1	8.37
76.4	1617	623	410	101	511	112	25.5	8.50	
80.1	1680	(630)	414	(104)	(518)	112	25.1	8.37	0.633
80.6	1685	630	430	89	519	111	25.1	8.37	
81.0	1693	640	440	90*	530*	(110)	...	...
65.3	1430	640	...	...	530*	112	25.5	8.50
		(640)	452	(72)	(524)	116	25.5	8.50	
53.3	1220	640	452	71	523	117	26.5	8.83	0.619
20.8	560	640	458	60	518	122	28.9	9.63	
20.65	555	640	450	65	515	125	24.7	8.23	
20.7	556	640	444	70	514	126	23.5	7.83	
9.0	280	640	446	64	510	130	23.9	7.97	
2.0	78	645	446	64	510	135	24.1	8.03	
1.2	49	645	447	63	510	135	24.6	8.20	

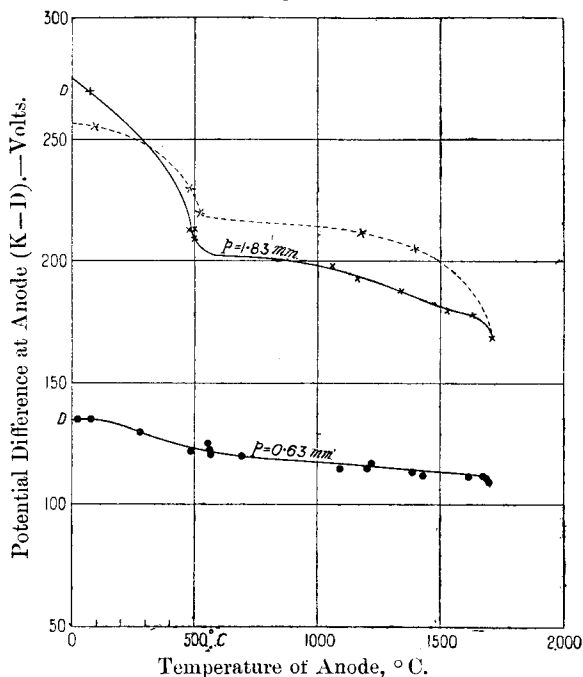
already been mentioned, the gas in this part of the tube remained quite dark. But on allowing the current to fall gradually below the above value a brilliant yellow positive column began to rise up from the anode, and the potential-gradient in this part of the discharge increased very rapidly. It was at first thought that the tube had begun to leak rapidly until a direct measurement with the McLeod gauge disproved this. The cathode-fall had also only shown a very slight diminution. And on increasing the current the potential-difference (D-A) fell off again instantly to its former immeasurably small value.

While confirming the old well-known observation that at ordinary temperatures the cathode-fall increases with increasing current-density, this table also shows that, on the other

hand, at high temperatures the cathode-fall diminishes with increasing current.

The measurements of the fall of potential along the discharge at different temperatures of the anode are collected in Tables XV. and XVI. at pressures of 1.83 and 0.63 mm. respectively. The effects of temperatures on the fall of

Fig. 8.



potential close to the anode are shown in fig. 8. This "anode-fall" ($K-D$) shows a steady diminution with rising temperature. The changes of potential-gradient near the cathode were probably mainly due to its slow warming up, the amount of which could not, however, be measured.

It will be noticed that though the total potential-difference across the electrodes diminishes, yet the "anode-fall" ($K-D$) increases with increased current at all temperatures of the anode, though, perhaps, less markedly at high temperatures. The potential-gradient in the positive column, as we have noticed before, diminishes with increasing current.

I am glad of this opportunity to express my indebtedness to Professor Thomson for many encouraging suggestions during the progress of the work.

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