Technical and Bibliographic Notes / Notes techniques et bibliographiques

The Institute has attempted to obtain the best original copy available for filming. Features of this copy which may be bibliographically unique, which may alter any of the images in the reproduction, or which may significantly change the usual method of filming, are checked below.

L'Institut a microfilmé le meilleur exemplaire qu'il lui a été possible de se procurer. Les détails de cet exemplaire qui sont peut-être uniques du point de vue bibliographique, qui peuvent modifier une image reproduite, ou qui peuvent exiger une modification dans la méthode normale de filmage sont indiqués ci-dessous.

- [x] Coloured covers/ Couverture de couleur
- [x] Covers damaged/ Couverture endommagée
- [ ] Covers restored and/or laminated/ Couverture restaurée et/ou pelliculée
- [ ] Cover title missing/ Le titre de couverture manque
- [ ] Coloured maps/ Cartes géographiques en couleur
- [ ] Coloured ink (i.e. other than blue or black)/ Encre de couleur (i.e. autre que bleue ou noire)
- [ ] Coloured plates and/or illustrations/ Planches et/ou illustrations en couleur
- [ ] Bound with other material/ Relié avec d'autres documents
- [x] Tight binding may cause shadows or distortion along interior margin/ La reliure serrée peut causer de l'ombre ou de la distorsion le long de la marge intérieure
- [ ] Blank leaves added during restoration may appear within the text. Whenever possible, these have been omitted from filming/ Il se peut que certaines pages blanches ajoutées lors d'une restauration apparaissent dans le texte, mais, lorsque cela était possible, ces pages n'ont pas été filmées.

- [ ] Coloured pages/ Pages de couleur
- [ ] Pages damaged/ Pages endommagées
- [ ] Pages restored and/or laminated/ Pages restaurées et/ou pelliculées
- [x] Pages discoloured, stained or foxed/ Pages décolorées, tachetées ou piquées
- [ ] Pages detached/ Pages détachées
- [x] Showthrough/ Transparence
- [x] Quality of print varies/ Qualité inégale de l'impression
- [ ] Continuous pagination/ Pagination continue
- [ ] Includes index(es)/ Comprend un (des) index

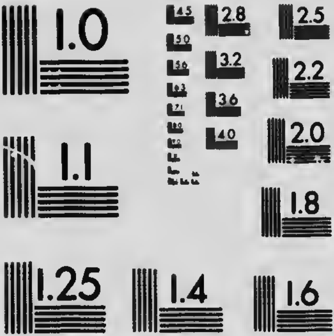
Title on header taken from:/ Le titre de l'en-tête provient:

- [ ] Title page of issue/ Page de titre de la livraison
- [ ] Caption of issue/ Titre de départ de la livraison
- [ ] Masthead/ Générique (périodiques) de la livraison

- [x] Additional comments:/ Commentaires supplémentaires: Pagination is as follows: p. 161-182.

This item is filmed at the reduction ratio checked below/
Ce document est filmé au taux de réduction indiqué ci-dessous.

10X	12X	14X	16X	18X	20X	22X	24X	26X	28X	30X	32X
							✓				



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS

STANDARD REFERENCE MATERIAL 1010a

(ANSI and ISO TEST CHART No. 2)

FROM THE TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA

SECOND SERIES—1902-1903

VOLUME VIII SECTION III

MATHEMATICAL, PHYSICAL AND CHEMICAL SCIENCES

ON THE POTENTIAL DIFFERENCE

REQUIRED TO PRODUCE

Electrical Discharges in Gases at Low Pressure

AN EXTENSION OF PASCHEN'S LAW

By W. R. CARR, B.A.

FOR SALE BY

J HOPE & SONS, OTTAWA; THE COPP-CLARK CO., TORONTO

BERNARD QUARITCH, LONDON, ENGLAND

1902

XX.—*On the Potential Difference required to produce Electric Discharge in Gases at low pressures—An Extension of Paschen's Law.*

By W. R. CARR, B.A.

(Communicated by President Loudon.)

(Read May 27, 1902.)

I. INTRODUCTION.

The researches of recent years have conclusively settled the general connection between the spark potential and the pressure of a gas. It is now well known that as the pressure of a gas diminishes the difference of potential necessary to produce a discharge between electrodes in the gas, a fixed distance apart, also diminishes until at a critical pressure the spark potential reaches a minimum value. It is further established that below the critical pressure the potential difference required to produce discharge rapidly increases as the pressure is lowered.

This connection between the spark potential and the corresponding pressure of a gas has been well illustrated in a series of curves drawn by Peace,[1] who investigated the sparking potentials between a pair of parallel plates at pressures ranging from one-half an atmosphere down to a little below the critical pressure.

Among others, Strutt[2] and Bouty[3] have carried on the investigation at pressures considerably below the critical point and the results show that, once the critical pressure has been passed, the rise in potential difference necessary to produce discharge is exceedingly rapid.

The effect of varying the distance between the electrodes was first determined by Paschen,[4] who observed the existence of a simple law connecting the pressure at which discharge took place with the corresponding spark potential and the distance between the electrodes.

Paschen's results showed that when a given potential difference was applied to two spherical electrodes whose distance apart could be varied, the maximum pressure at which discharge occurred varied inversely with the distance between the spheres.

---

[1] Peace, Proc. Roy. Soc., Vol. 52, p. 99.

[2] Strutt, Phil. Trans., Vol. 193, p. 377.

[3] Bouty, Comp. Rend., Vol. 131 (2), p. 443.

[4] Paschen, Ann. d. Phys., Vol. 37, p. 69.

The range of pressures over which he found the law to apply, while considerable, did not extend below 2 cm. of mercury, and his results do not in any case indicate that the critical pressure had been reached. It is evident then that Paschen's conclusions are confined to pressures higher than the critical pressures.

Since the statement of this law by Paschen, Peace[1] alone seems to have published results which could throw any additional light on the conditions holding for discharge in a gas at very low pressures. Peace experimented in air, with parallel plates as electrodes, at various distances apart and found that the value of the critical pressure increased greatly as the distance between the electrodes was lessened, but his results at points below the critical pressure give no evidence of the existence of any such law as had been enunciated by Paschen.

This can be readily seen from the numbers recorded in his paper, a few of which, selected from readings taken below the critical pressure, are given in the following table. These results admit of easy comparison since the potential difference in the cases chosen are very nearly the same. The product of pressure and spark length should be a constant quantity, if Paschen's law held.

TABLE OF PEACE'S RESULTS.

Applied potential difference in volts	Pressure in mm. of mercury.	Distance between electrodes in inches.	Product of pressure and spark length.
649	2·5	·082	·205
660	6	·005	·030
670	5	·021	·105
731	2·5	·030	·075

If we compare the first and second of these results where the difference in spark potential is only 11 volts, we find the product in the first case nearly seven times that in the second. Again, the product corresponding to the spark potential, 660 volts, is less than one-third that corresponding to 670 volts, a large difference in the opposite direction. The same irregularity is exhibited by the product corresponding to the spark potential, 731 volts, and it seems difficult to understand how experimental errors could be made to explain such a wide divergence of results.

At the critical pressure Peace's results point to the existence of the law, but, as stated above, it would appear that as soon as lower pressures were approached the indications were uniformly against

[1] Peace, Proc. Roy. Soc., Vol. 52, p. 99.

the existence of the relation which Paschen found to hold at high pressures.

Owing to the special precautions taken by Peace to obtain accurate values for the spark potentials, it is possible to arrive at but one of two conclusions regarding the departure from Paschen's law indicated by Peace's numbers. Judging by the results, either the law ceases to hold when the critical pressure is passed or else the apparatus used by him in his experiments did not admit of an accurate measurement of the actual spark lengths corresponding to different spark potentials.

A short discussion of the apparatus will reveal one considerable defect. The object of the investigations of both Paschen and Peace was to determine the electromotive intensity requisite to cause discharge in a gas. Throughout the range of pressures investigated by Paschen the discharge always took place along the shortest distance between the spherical electrodes, and the electromotive intensity requisite to break down the gas was, therefore, directly proportional to the spark potentials obtained by him. At points below the critical pressure, as Peace's results indicate, discharge occurs more easily over a longer distance than over a shorter one, and if the values of the electromotive intensities necessary to break down a gas at different pressures are to be compared, it is necessary to know in each case not only the potential difference applied to the electrodes, but also the path between the electrodes along which the initial discharge occurs.

To insure passage of the discharge over the same length of path Peace used plane parallel plates of very large diameter as electrodes; but while in this way he obtained a uniform field of considerable extent, and so was able to obtain an accurate measure of the electromotive intensity between the electrodes, he failed to make certain that the path along which the gas initially broke down was always confined to the uniform part of the field. As mentioned in his paper, there was considerable tendency at low pressures to a brush discharge from the edges of the plates and this indicated a defect in his apparatus which apparently he did not completely eliminate.

In the present paper an account is given of an investigation on the potentials necessary to produce discharge in a gas, with a form of apparatus which insured the passage of the discharge in a uniform electric field.

With this apparatus the discharge potentials have been determined for different distances between the electrodes over a range extending considerably above and below the critical pressure. The results of the investigation not only confirm the truth of the law enunciated by Paschen for discharges at high pressures, but also demonstrate beyond doubt the applicability of the same law to the critical pressure and to all pressures below it.

The existence of the same relation has been sought in each of the gases, air, hydrogen, and carbon dioxide, and the result of the investigation has been the establishment with equal certainty of the same general law for all pressures, viz., that with a given potential difference, the field being uniform, the product of the pressure at which discharge occurs, and the distance between the electrodes, is constant.

II. Description of Apparatus.

The form of the discharge chamber is shown in Fig. I.

The electrodes consisted of two plane brass plates *a*, *a*, 3·6 cm. in diameter, embedded in ebonite as shown in the figure, the outer

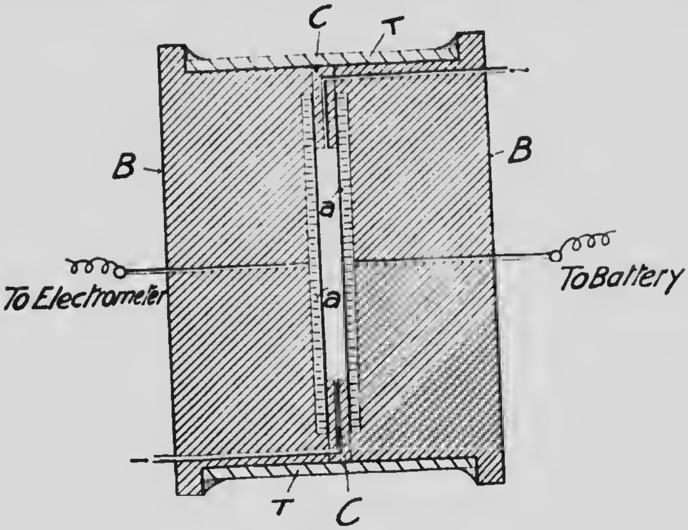


Fig. 1.

faces of the electrodes being flush with the surface of the ebonite. These pieces of ebonite which carried the electrodes served also to close the glass tube *T*, *T*, which thus constituted a discharge chamber. In order to confine the gas in this chamber to the region where the electric field was uniform, a ring of ebonite *C*, *C*, which projected over the edges of the brass plates, was inserted. In the construction of the apparatus special precautions were taken to insure that the plugs *B*, *B*, pressed tightly against the ebonite ring. As a result of this device, that portion of the electric field which was not uniform was entirely confined to the space occupied by ebonite, so that in this way it was rendered impossible for a discharge to occur through the gas in any but a uniform field. The thickness of the ebonite ring, which could be made accurate to $^1/_{1000}$ mm., determined the distance between the electrodes and consequently the length of the discharge. The length of the discharge could be varied at will, therefore, by inserting rings of different thicknesses.

The gas was admitted and removed from the chamber by glass tubes sealed into the ebonite plugs, and these tubes were connected with the air space by two very fine channels leading through the ebonite ring.

Before closing the discharge tube, which was made air-tight with ordinary commercial soft wax, the inner surface of the ebonite ring was carefully rubbed with glass paper to remove any conducting material from its surface.

The potential differences used in these experiments were obtained from a series of small storage cells, similar to those used in the Reichsanstalt, Berlin. As these cells have a large capacity their voltage remained constant over long intervals of time, and as a consequence it was possible to make the readings with the greatest accuracy. The potential differences were measured by a Weston voltmeter which was carefully calibrated by means of a potentiometer furnished with a standard Weston cadmium element.

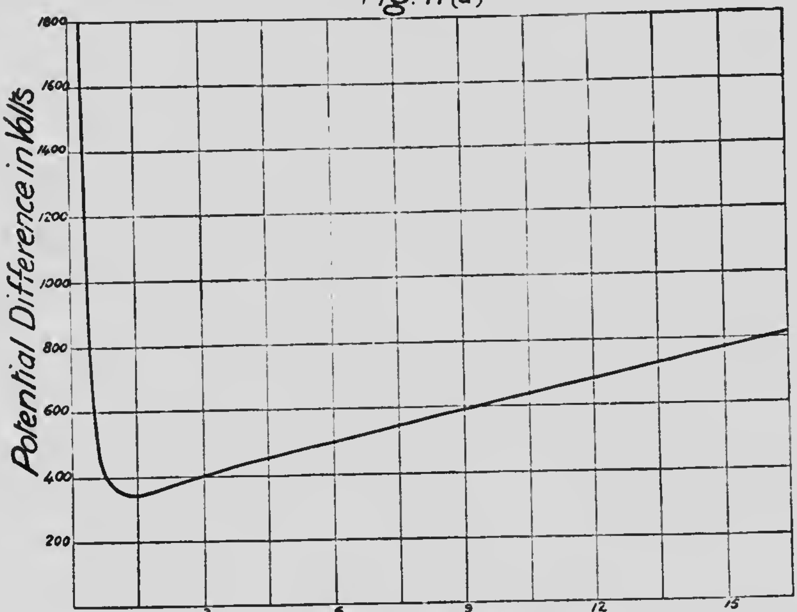
Throughout the investigation the discharge chamber was connected in series with a drying tube containing phosphoric pentoxide, a glass reservoir about two litres in volume, a McLeod pressure gauge giving readings accurate to $^1/_{1000}$ of a mm., and a mercury pump of small capacity. By using this reservoir and the pump of small capacity it was possible to diminish the pressure in the discharge tube by such exceedingly small amounts that it was easy to obtain a series of discharge potentials over the whole range of pressures investigated without the necessity of admitting fresh gas to the chamber.

In making measurements one terminal of the battery was joined to earth and the other terminal was connected through a resistance of xylol to one of the electrodes of the discharge tube. The other electrode was permanently joined to one pair of quadrants of a quadrant electrometer, the second pair of which was kept to earth. In determining the potential difference necessary to produce discharge at a given pressure, the electrometer electrode was first earthed, a given potential applied to the battery electrode and the earth connection of the electrometer electrode then removed.

If, after waiting some minutes, no discharge passed, the operation was repeated with a slightly higher potential applied to the battery electrode. This procedure was followed until a potential sufficiently high was reached to break down the gas and cause a discharge. The passage of the discharge could be readily noted as it was accompanied by a violent deflection of the electrometer needle.

The well known phenomenon of delay in the passing of the discharge, which has been investigated at length by Warburg,[1] was observed throughout the experiments. It was especially marked in

Fig. 11 (a)



Pressure in Millimetres

the neighbourhood of the critical pressure, discharges being frequently obtained ten or even fifteen minutes after the requisite voltage had been applied.

In every case, therefore, as the minimum sparking potential for any pressure was approached, a considerable time was allowed to elapse, with a given applied potential difference, before any increase was made.

III. Experiments in Air.

In the experiments on atmospheric air the whole discharge apparatus was first exhausted to a very low pressure and then refilled by fresh air, which bubbled in very slowly, first through a wash-bottle of sulphuric acid and then through a tube tightly packed with phos-

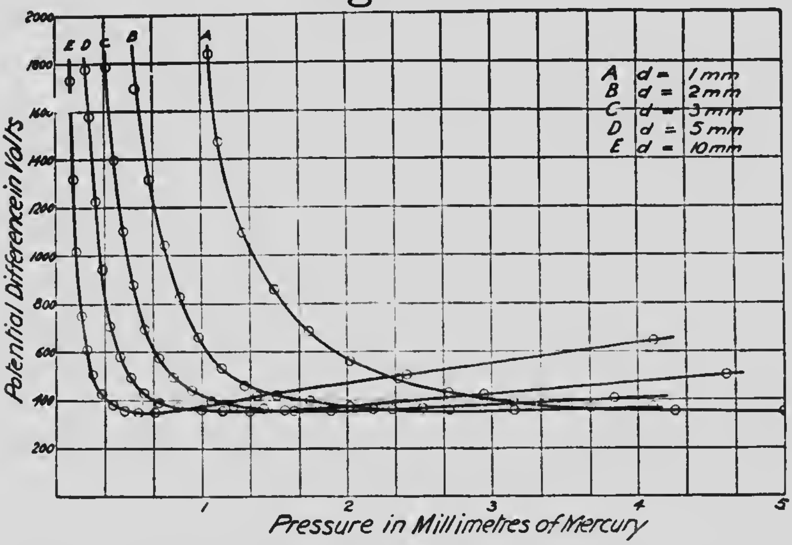
[1] Warburg, Ann. d. Phys., Vol. 62, p. 385.

phoric pentoxide. The discharge chamber was then exhausted to about 20 mm. of mercury and allowed to stand at this pressure for a period of from eight to twelve hours.

During this time the air was always in contact with phosphoric pentoxide in the drying tube, and was, therefore, entirely free from moisture when the measurements were taken.

The first measurements were made with the electrodes 3 mm. apart, and the spark potentials were determined over a range of pressures extending from 51 mm. down to ·35 mm. of mercury. The

Fig. 11 - Air



spark potentials corresponding to the various pressures are recorded in columns 5 and 6 of Table I., and the results are represented graphically in Fig. II., a.

In making these determinations the precaution was always taken of allowing eight or ten minutes to intervene between consecutive readings in order to make certain that the air was in its normal condition when the discharge occurred. As can be seen from the figure the curve is quite regular and exhibits all the peculiarities already noted by Peace,[1] Strutt,[2] and Bouty[3]. The curve, however, is carried much higher than those drawn by any of these experimenters, discharges corresponding to potential differences of over eighteen hundred volts being recorded.

[1] Peace, Roy. Soc. Proc., Vol. 52, p. 111.

[2] Strutt, Phil. Trans., Vol. 193, p. 384.

[3] Bouty, Comp. Rend., Vol. 131 (2), p. 446.

TABLE I. AIR.

Spark length = 1 mm.		Spark length = 2 mm.		Spark length = 3 mm.		Spark length = 5 mm.		Spark length = 10 mm.	
Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts
150·	1510	20·	620	51·	1480	7·34	600	7·09	831
120	1265	13·2	527	41·5	1275	4·61	504	4·12	645
90·	1025	8·73	455	31·5	1015	2·95	418	2·39	504
61·	784	5·52	400	21·4	790	1·85	368	1·39	420
40·8	631	4·11	373	14·1	630	1·57	356	·982	372
21·6	489	3·16	355	9·31	526	1·34	349	·805	355
19·4	477	2·71	351	5·99	452	1·14	352	·679	348
12·4	417	2·32	357	3·84	405	·982	359	·562	351
7·77	367	2·02	371	2·51	371	·839	370	·466	359
6·66	357	1·75	389	2·18	361	·711	388	·381	377
5·80	352	1·52	419	1·89	356	·607	427	·312	425
4·98	349	1·30	460	1·64	358	·517	484	·259	504
4·27	355	1·13	531	1·42	364	·440	575	·219	605
3·67	368	·982	654	1·22	375	·375	705	·180	757
3·15	392	·857	826	1·06	397	·321	935	·152	1020
2·70	429	·750	1042	·928	441	·276	1223	·125	1315
2·35	481	·643	1312	·801	494	·232	1585	·105	1730
2·02	558	·549	1695	·710	576	·216	1774		
1·71	681	·536	1829	·616	691				
1·51	855			·536	863				
1·29	1090			·465	1092				
1·12	1463			·411	1395				
1·05	1826			·357	1784				

The distance between the electrodes was then varied and five different sets of readings were taken in air with the electrodes 1, 2, 3, 5, and 10 mm. apart, respectively. The complete set of numbers for these different spark lengths is given in Table I., and curves showing the readings taken over that portion of the range of pressure below 5 mm. of mercury are exhibited in Fig. II.

It is apparent from the relative positions of these curves in the figure, that at points at and below the critical pressures, with a given potential difference applied to the electrodes, the pressures at which discharges occurred regularly decreased as the distance between the electrodes was increased. But a critical examination of the curves and also a reference to the numbers which they represent show that Paschen's law is rigidly applicable over the whole series of discharge potentials recorded.

For example, the pressures at which discharge took place with an applied potential of 1800 volts were, for the different distances between the electrodes, approximately:—

Distance between electrodes in mm.	Discharge pressures in mm. of mercury.
1	1·05
2	·536
3	·351
5	·216
10	·105

and it will be seen that the numbers in column 2 are almost exactly in inverse proportion to the numbers in column 1.

Again, with an applied potential of 500 volts (say), the approximate pressures at which discharge occurred were:—

Distance between the electrodes in mm.	Discharge potential in mm. of mercury.
1	2·35
2	1·30
3	·804
5	·517
10	·259

where the pressures are in the ratio 1·00: ·55: ·34: ·22: ·11, numbers which are again very nearly inversely proportional to the distance between the electrodes.

Further, we notice that the spark potential corresponding to the critical pressure in all cases was practically the same, 350 volts, and the values of the critical pressures for the different spark lengths were, from Table I.:—

Distance between electrodes in mm.	Discharge pressures in mm. of mercury.
1	4·98
2	2·71
3	1·89
5	1·34
10	·679

and these numbers while not exactly in the ratio 10: 5: 3: 2: 1, are still very close to it.

In finding the values for portions of the curves around the critical pressures he results given in Table I. show that a small variation in potential difference was associated with a relatively very large change in the pressures, so that a very small error in reading the potential difference would result in a large error in the pressure readings. It is interesting to note, however, that even under these unfavourable conditions a striking agreement is presented between the results obtained at critical pressures and the results demanded by Paschen's law.

In order to make the agreement between the numbers demanded by Paschen's law and those obtained in these experiments still more evident, the results recorded in Table I. are again given in a slightly different form in Table II., where each potential difference is associated with the product of the pressure at which discharge took place and the corresponding spark length. Paschen[1] found that at high pressures these products were constant for different distances between the electrodes, as long as the applied potential difference was the same.

The numbers recorded in Table II. show that the same law is rigidly applicable to all pressures both high and low.

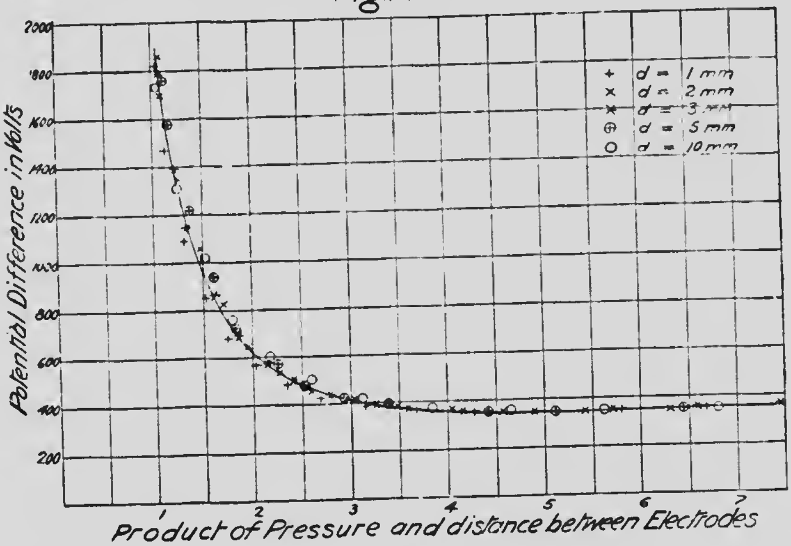
[1] Paschen, ..n. d. Phys., Vol. 37. p. 69.

TABLE 11. AIR.

Spark length = 1 mm.		Spark length = 2 mm.		Spark length = 3 mm.		Spark length = 5 mm.		Spark length = 10 mm.	
Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts
150·	1510	40·	620	153·	1480	36·7	600	70 9	[illegible]
120·	1265	26·4	527	124·5	1275	23·0	504	41·2	645
90·	1025	17·4	455	94·5	1015	14·7	418	22·9	504
61·	784	11·0	400	64·2	790	9·25	368	13·9	420
40·8	634	8·22	373	42·3	630	7·85	356	9·82	372
21·6	489	6·32	355	27·9	526	6·70	349	8·05	355
19·4	477	5·42	351	17·9	452	5·70	352	6.79	348
12·4	417	4·64	357	11·5	405	4·91	359	5·62	[illegible]
7·77	367	4·04	371	7·53	371	4·19	370	4·66	350
6·66	357	3·50	389	6·54	361	3·57	388	3·84	377
5·80	352	3·04	419	5·67	356	3·03	427	3·12	425
4·98	349	2·60	460	4·92	358	2·58	484	2·59	504
4·27	355	2·[illegible]	534	4·26	364	2·20	575	2·19	605
3·67	368	1·96	654	3·66	375	1·87	705	1·80	757
3·15	392	1·71	826	3·18	397	1·60	935	1·52	1020
2·70	429	1·50	1042	2·78	441	1·38	1223	1·25	1315
2·35	481	1·28	1312	2·41	494	1·16	1585	1·05	1730
2·02	558	1·09	1695	2·13	576	1·08	1774		
1·74	681	1·07	1829	1·84	691				
1·51	855			1·60	862				
1·29	1090			[illegible]	1092				
1·12	1463			[illegible]	1395				
1·05	1826			[illegible]07	1786				

A like conclusion must be drawn from the curve shown in Fig. III., which graphically represents the numbers in Table II. In plotting this curve the products of spark lengths and discharge pressures were taken as abscissæ and the sparking potentials as ordinates. The regularity of the curve which represents the products for the five

Fig. III—Air



different electrode distances shows clearly that there can be no doubt regarding the applicability of Paschen's law to electric discharges in air at pressures at and below the critical point as well as to pressures above it.

IV. Experiments in Hydrogen.

In order to demonstrate, if possible, the generality of the law which has just been proven to hold for discharges in air, a series of measurements were made on the spark potentials in the gases hydrogen and carbon dioxide.

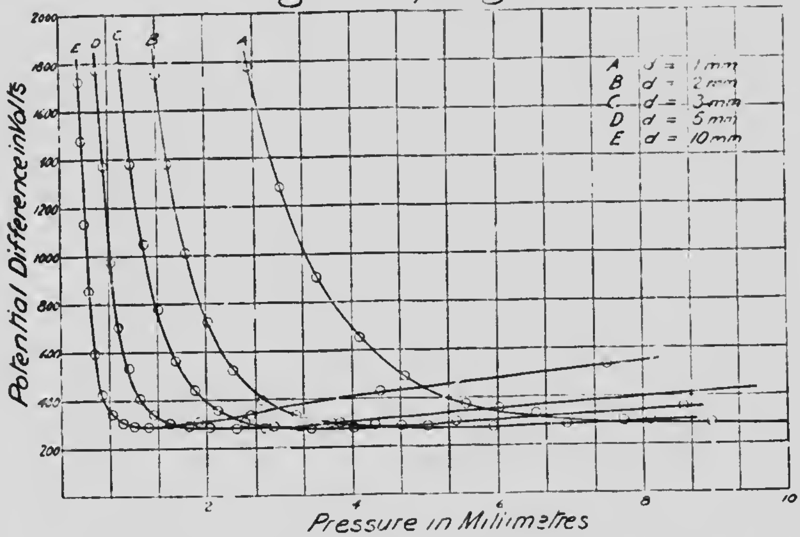
In these experiments exactly the same apparatus was used as in the previous experiments in air.

Preparatory to making the measurements in hydrogen the apparatus was first exhausted of air to a pressure of 1 mm. of mercury or less, and then filled with hydrogen to atmospheric pressure. It was then exhausted and refilled with hydrogen several times to make certain that all air was removed.

The hydrogen was prepared from zinc and sulphuric acid in a Kipp apparatus, and, in order to insure purity and freedom from moisture, was passed through wash-bottles containing potassium permanganate and caustic potash and through a tube tightly packed with phosphoric pentoxide, before being led into the discharge chamber.

Also, just as in the experiments in air, the gas was always allowed to stand for several hours at a pressure of about 20 mm. of mercury in the presence of phosphoric pentoxide, before any readings were recorded.

Fig IV - Hydrogen



In the experiments with this gas readings were taken for the same electrode distances, 1, 2, 3, 5, and 10 mm., and the values of the spark potentials and their corresponding pressures are given in Table III. These numbers are also graphically set forth in Fig. IV.

We see from this table that the readings corresponding to the spark potential 1800 volts are:—

Distance between electrodes in mm.	Discharge pressure in mm. of mercury.
1	2·60
2	1·33
3	·861
5	·518
10	·264

which pressures are in the ratio 9·9 : 5·0 : 3·2 : 1·9 : 1.

TABLE III. HYDROGEN.

Spark length = 1 mm.		Spark length = 2 mm.		Spark length = 3 mm.		Spark length = 5 mm.		Spark length = 10 mm.	
Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts
21·7	328	23·	435	13·6	415	13·6	469	7·53	526
16·2	300	14·8	360	8·54	356	9·35	415	4·37	427
11·9	281	11·0	323	5·40	301	6·02	350	2·55	335
10·3	278	8·08	299	4·66	286	3·80	300	1·77	299
8·94	287	6·95	285	4·02	278	3·28	287	1·46	283
7·74	306	5·93	279	3·44	282	2·80	281	1·22	287
6·52	335	5·04	284	2·93	292	2·41	282	1·01	295
5·57	374	4·30	293	2·52	310	2·05	285	·846	313
4·73	487	3·72	305	2·15	356	1·76	293	·700	343
4·11	649	3·23	333	1·85	440	1·51	305	·575	426
3·54	905	2·77	399	1·50	564	1·26	345	·470	595
3·04	1275	2·36	523	1·35	780	1·09	410	·390	850
2·60	1781	2·03	727	1·16	1054	·928	539	·330	1142
		1·73	1010	1·04	1382	·808	706	·276	1477
		1·48	1380	·861	1789	·700	975	·264	1710
		1·33	1746			·600	1373		
						·516	1775		

TABLE IV. HYDROGEN.

Spark length = 1 mm.		Spark length = 2 mm.		Spark length = 3 mm.		Spark length = 5 mm.		Spark length = 10 mm.	
Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts
21·7	328	46·	435	40·8	415	68·	469	75·3	526
16·2	300	29·6	360	25·6	356	46·7	415	43·7	427
11·9	281	22·0	323	16·2	301	30·1	350	25·5	335
10·3	278	16·1	299	13·9	286	19·0	300	17·7	299
8·94	287	13·9	285	12·0	278	16·4	287	14·6	283
7·74	306	11·8	279	10·3	282	14·0	281	12·2	287
6·52	335	10·0	284	8·79	292	12·0	282	10·1	295
5·57	374	8·60	293	7·56	310	10·2	285	8·46	313
4·73	487	7·44	305	6·45	356	8·80	293	7.00	343
4·11	649	6·46	333	5·55	440	7·55	305	5·75	426
3·54	905	5·54	399	4·77	564	6·30	345	4·70	595
3·01	1275	4·72	523	4·05	780	5·45	410	3·90	850
2·60	17[illegible]	4·06	727	3·48	1054	4·64	539	3·30	1142
		3·46	1010	3·00	1382	4·04	706	2·76	1477
		2·96	1380	2·58	1789	3·50	975	2·64	1710
		2·66	1746			3·00	1373		
						2·58	1775		

Again, with a spark potential of 500 volts, the readings give:—

Distance between electrodes in mm.	Discharge pressure in mm. of mercury.
1	4·7
2	2·4
3	1·7
5	·94
10	·51

the pressures being in the ratio 9·3: 4·8: 3·3: 1·9: 1.

The minimum spark potential in hydrogen was about 280 volts and the critical pressures corresponding to the different spark lengths were: —

Distance between electrodes in mm.	Discharge pressures in mm. of mercury.
1	10 3
2	5·93
3	4 02
5	2·80
10	1·46

where the various discharge pressures are once more nearly inversely proportional to the distance between the electrodes.

To indicate further that the law is applicable at all points, a table of products similar to those recorded for air was calculated, and is given in Table IV. A single curve, Fig. V., represents these five sets of readings, and again the close grouping of the different results about this common curve shows that the law is equally applicable above and below the critical pressure to all spark potentials.

It is evident, then, that with hydrogen just as with air, Paschen's law is rigidly applicable over the whole range of pressures.

V. Experiments in Carbon Dioxide.

These further experiments were made with a view to corroborate the results already obtained in air and hydrogen. The same apparatus as had been used with these two gases again served for the experiments in carbon dioxide and the distance between the electrodes was varied as before, so that readings were obtained at the five different

Fig V - Hydrogen

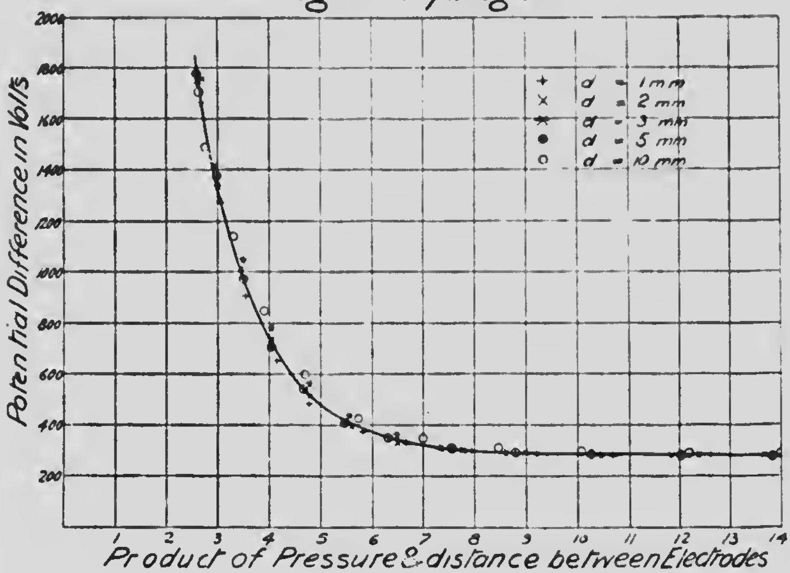
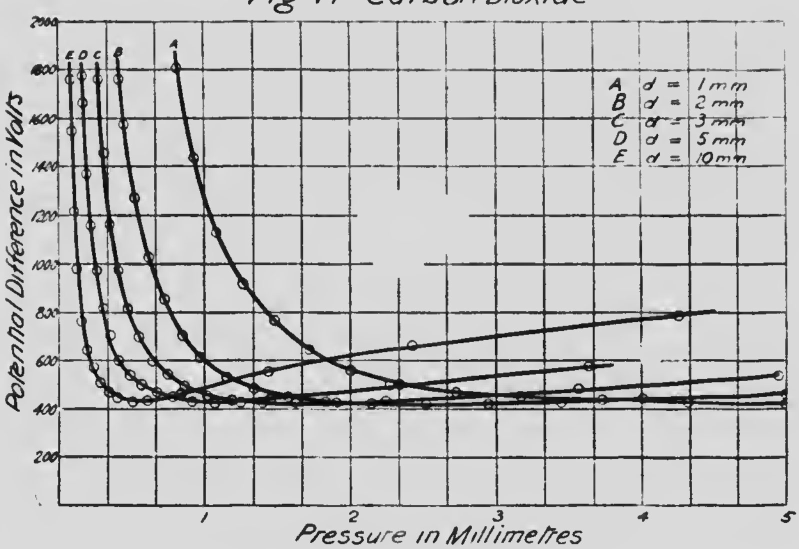


Fig VI Carbon Dioxide



distances, 1, 2, 3, 5, and 10 mm. The carbon dioxide was prepared by treating marble with hydrochloric acid and was purified and dried by being bubbled through a wash-bottle of water and passed through a tube tightly packed with phosphoric pentoxide before reaching the discharge apparatus. In each case the operation of exhausting the whole discharge apparatus to 1 mm. or less, of mercury, and then refilling with carbon dioxide, was repeated five or six times, and finally the gas was allowed to stand, as in both previous cases, in the presence of a bulb of phosphorus pentoxide for several hours.

The complete set of results is given in Table V. and the corresponding curves set forth in Fig. VI., and if we again compare the discharge pressures and spark lengths corresponding to any value of the applied potential, the same law is seen to hold here also with even greater rigidity than in the other cases.

For 1800 volts the figures are approximately:—

Distance between electrodes in mm.	Discharge pressures in mm. of mercury.
1	·817
2	·421
3	·274
5	·164
10	·0892

where the pressures are almost in the required ratio, being 9·2: 4·8: 3·0: 1·9: 1.

For 500 volts the numbers are:—

Distance between electrodes in mm.	Discharge pressures in mm. of mercury.
1	2·34
2	1·23
3	·84
5	·57
10	·28

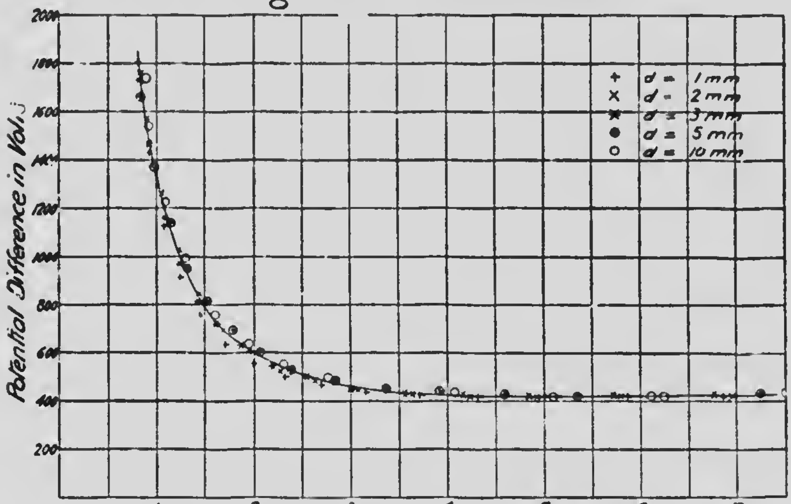
where the pressures are as 8·4: 4·4: 3: 2: 1.

And at the minimum discharge potentials which are again constant, 420 volts, the readings given are:—

Distance between electrodes in mm.	Discharge pressures in mm. of mercury.
1	5·02
2	2·52
3	1·61
5	1·07
10	·510

Special attention is directed to these latter results, inasmuch as the exactness of the ratio indicated by the pressures is very remarkable The ratios of the pressures are practically 10: 5: 3·1: 2: 1, the nearest approximation to the numbers demanded by Paschen's law which has been shown by any of the comparisons, and this result is all the more convincing in that these figures were obtained at the critical points where in the other two gases the results obtained indicated the law in a somewhat less marked degree.

Fig VII Carbon Dioxide



Though it would appear that further evidence was unnecessary, the table of products was again calculated and is given in Table VI. Also the corresponding curve is shown in Fig. VII.

Once more the regularity of the curve shows that as in air and hydrogen so in carbon dioxide Paschen's law is rigidly applicable to all spark potentials both above and below the critical pressure.

VI. Spark Potentials with Different Electrodes.

It has now been shown, using brass electrodes of constant size, that for discharges in a uniform field in any gas, the values of the spark potentials are determined solely by the product of the pressure of the gas and the distance between the electrodes. From this result it appeared that if the size or material of the electrodes did not affect the results, the spark potentials were dependent only upon the quantity of the gas per unit cross section between the electrodes.

In order to determine this point the brass electrodes which had been used up to this time were replaced in turn by electrodes of iron, zinc and aluminium of exactly the same size. The results of the experiments showed that there was no variation in the different sets of readings and it was evident that there was not the slightest effect produced in any case by a change in the material of which the electrodes were made.

In order to see if the size of the electrodes affected the values of the spark potentials for the different pressures, provided the discharge took place in a uniform field, a reduction was made in the surface of the electrodes exposed to the gas. This was done by replacing the ebonite rings *C*, *C*, Fig. I., which had an inner diameter of 3 cm., by others whose inner diameter was but 1 cm. By this device the areas of the electrodes exposed to the gas were reduced to about $^1/_{10}$ of their value in the early experiments, and the condition that the discharge could only take place in a uniform field still held. Using this apparatus, with air, no difference could be observed in the values of the discharge potentials corresponding to the different pressures, and it was therefore certain that the value of the spark potential was in no way influenced by the size of the electrodes.

It is therefore clearly established that the only factors that affect the spark potentials are pressure and the distance between the electrodes, and hence Paschen's law is most accurately expressed by saying: " That, with a given applied potential difference, discharge in a uniform field, in any gas, at pressures both above and below the critical pressures, is dependent solely on the constancy of the quantity of matter per unit cross section between the electrodes."

Every assistance towards the carrying of my research to a successful issue has been given me throughout by President London, and I gratefully accept this opportunity of thanking him. I also wish to record my appreciation of the many kind suggestions of Professor J. C. McLennan, in whose laboratory the experiments were performed and to whom I owe much for their success.

TABLE V. CARBON DIOXIDE.

Spark length = 1 mm.		Spark length = 2 mm.		Spark length = 3 mm.		Spark length = 5 mm.		Spark length = 10 mm.	
Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts	Pressures in mm. of mercury	Spark potential in volts
19·8	516	21·3	802	8·75	674	9·10	730	7·27	993
12·6	480	13·8	645	5·57	563	5·77	671	4·26	790
9·41	443	8·76	519	3·55	477	3·64	579	2·43	656
6·83	425	5·41	464	2·25	427	2·33	498	1·44	553
5·86	421	4·02	439	1·91	420	1·45	438	·860	473
5·02	419	3·46	426	1·63	419	1·25	423	·612	428
4·31	420	2·95	421	1·11	425	1·07	421	·510	423
3·73	427	2·52	419	1·20	432	·919	428	·409	440
3·18	443	2·15	420	1·02	449	·786	441	·340	470
2·73	475	1·81	427	·875	487	·678	464	·280	506
2·34	503	1·58	443	·758	542	·572	495	·239	563
2·00	559	1·31	473	·651	599	·492	533	·196	639
1·72	636	1·16	525	·558	699	·419	599	·162	761
1·47	763	·980	605	·482	815	·360	704	·134	973
1·26	916	·848	702	·420	971	·310	820	·111	1219
1·08	1127	·728	847	·362	1162	·266	960	·091	1550
·946	1432	·625	1026	·314	1115	·232	1159	·089	1730
·817	1801	·536	1258	·274	1756	·196	1373		
		·455	1574			·169	1662		
		·421	1762			·164	1770		

TABLE VI. CARBON DIOXIDE.

Spark length = 1 mm.		Spark length = 2 mm.		Spark length = 3 mm.		Spark length = 5 mm.		Spark length = 10 mm.	
Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts	Product of pressure and spark length	Spark potential in volts
19·8	516	42·6	802	26·2	674	45·5	790	72·7	993
12·6	480	27·6	645	16·7	563	28·8	674	42·6	790
9·41	443	17·5	519	10·6	477	18·2	579	24·3	656
6·83	425	10·8	464	6·75	427	11·6	498	14·4	553
5·86	421	8·01	439	5·73	420	7·25	438	8·60	473
5·02	419	6·92	426	4·89	419	6·25	423	6·12	428
4·31	420	5·90	421	4·23	425	5·35	421	5·10	423
3·73	427	5·01	419	3·60	432	4·59	428	4·09	440
3·18	443	4·30	420	3·06	449	3·93	441	3·40	470
2·73	475	3·68	427	2·62	487	3·39	464	2·80	506
2·34	503	3·16	443	2·27	512	2·86	495	2·39	563
2·00	559	2·68	473	1·95	599	2·46	533	1·96	639
1·72	636	2·32	525	1·67	699	2·09	599	1·62	761
1·47	763	1·96	605	1·44	815	1·80	704	1·34	973
1·26	916	1·69	702	1·26	971	1·55	820	1·11	1219
1·08	1127	1·45	847	1·08	1162	1·33	969	·946	1550
·946	1432	1·25	1026	·942	1445	1·16	1159	·892	1730
·817	1801	1·07	1258	·822	1756	·98	1373		
		·910	1574			·845	1662		
		·842	1762			·820	1770