The Pressure upon the Poles of the Electric Arc

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IV. *The Pressure upon the Poles of the Electric Arc.*

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Suspending one pole of a carbon arc and keeping the other pole fixed it was found that there was an apparent repulsion between them. There is in fact a pressure upon each electrode which tends to separate them. The first part of this paper is devoted to the experimental methods of estimating this pressure, the second to a discussion of its origin.

PART I.—EXPERIMENTAL.

Three series of observations have been made, the original observations and preliminary series by Duffield in 1912,* the second series in conjunction with Burnham, and the third in conjunction with Davis. In spite of the very small forces examined the three series agree within reasonable limits. The general form of the apparatus (fig. 1) was the same in each series, though there were important differences in the dispositions of the carbons in different sets of experiments.

A stirrup was suspended by a torsion fibre, or sometimes by two fibres, F, as in the illustration, in this was placed a copper rod, E, to whose extremity was fixed at right angles a short carbon rod, C, which was balanced by a counterpoise, W, at the other end. The arc was formed between this carbon rod and another, D, fixed either as shown in the figure or in some other manner to be described later.

In its zero position the copper rod swung freely between two stops, S, placed close to one end. The sensitivity of the suspension and the long period of swing necessitated some simple means for bringing the rod back to the zero position, and the V-grip device illustrated in fig. 2 was ultimately adopted in place of the stops, S; the adjustment was made by twisting the torsion head until on turning down the V-grip the suspended wire remained stationary; this control also enabled the arc-length to be maintained nearly constant during an experiment. The difference between the

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* A paper entitled "The Pressure upon the Poles of a Carbon Arc," was read in title at the British Association Meeting, Australia, 1914.

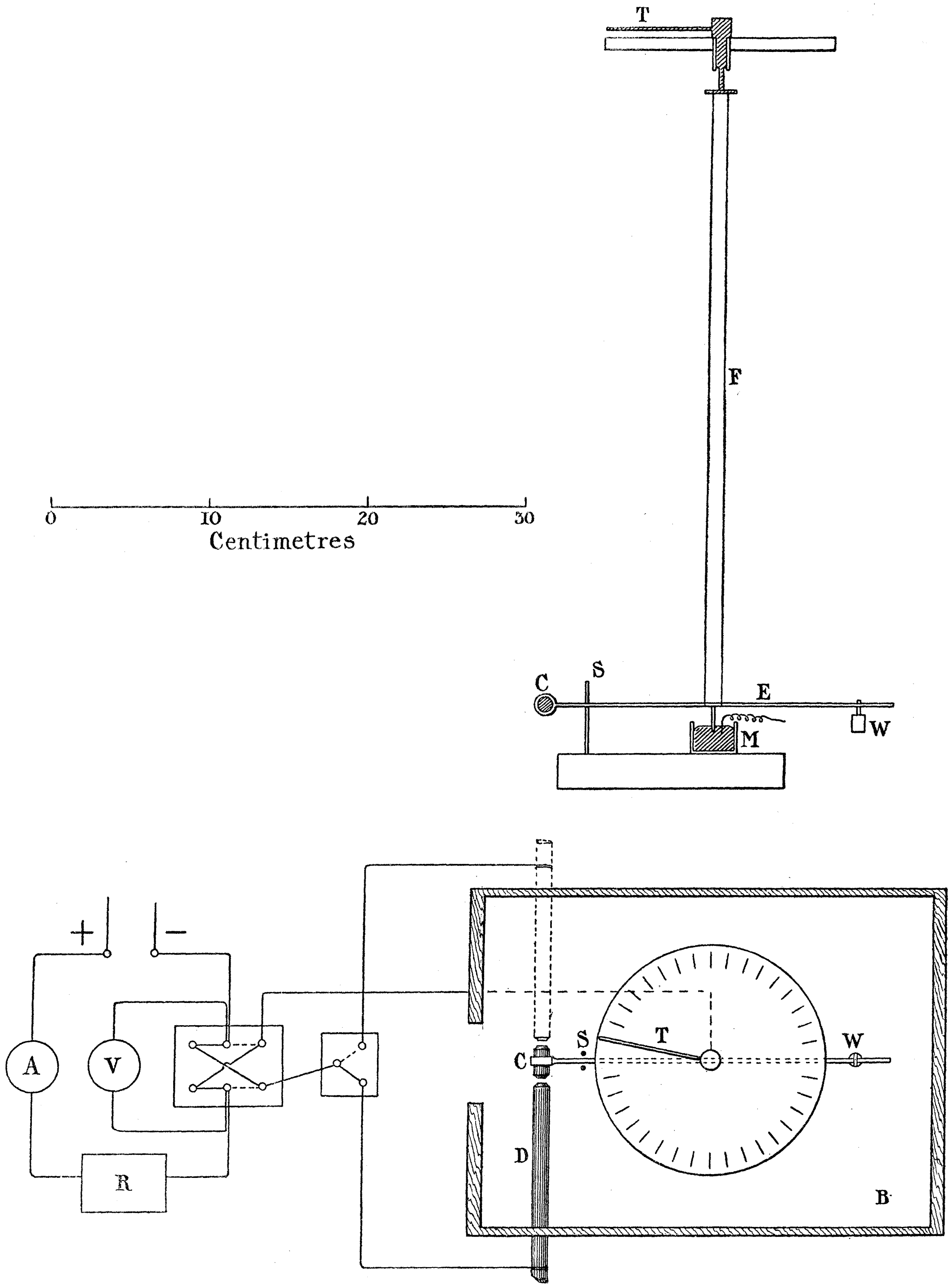

Fig. 1. Plan and elevation of the apparatus.

readings of the torsion head, T, when the current was on and off measures the couple acting upon the suspended copper rod if the constants of the suspension are known.

The movable parts of the apparatus were completely enclosed in a box, B, with a glass top to prevent disturbance from air currents in the room, and appropriate windows and holes were made in it to enable observations to be made. The torsion fibre was enclosed in a vertical tube. A lens focussed an image of the arc upon a screen to facilitate the measurement of the arc-length.

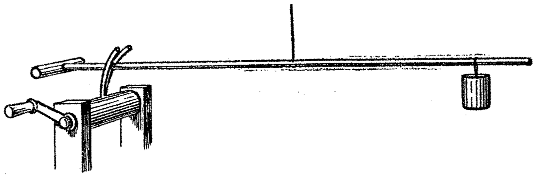

Fig. 2. The **V**-grip.

The observed couple is due to :—

(1) A pressure upon the poles due to forces within the arc, including the effect of convexion currents, electrostatic effects, &c. These will be treated as a whole in the first instance, and called the total pressure ;

(2) The interaction between electric currents in the suspended part of the circuit and the earth's magnetic field ;

(3) Interaction between electric currents in the suspended part of the circuit and the currents in the rest of the circuit, called briefly the electromagnetic effect.

SERIES A. ALTERNATING CURRENT.

Method 1.—The current was conducted to the rod, E, through the mercury trough, M.

Alternating current was used because it at once eliminated the couple due to the action of the earth's magnetic field. The couple due to the electromagnetic effect was estimated by experiments described on p. 124. The values given in the first row of Table I. represent the total pressures upon the pole after allowing for this couple ; the arc length was 3·5 mm. throughout.

TABLE I.—Alternating Current.

Ampères ∼ . . .		3·5	4·3	5·0	5·2	6·5	7·0	8·0	9·0	9·5	10·0	12·0
		Total pressures in dynes.										
Row 1	Method 1	0·01	0·11	·	0·27	0·40	0·60	0·87	0·94	1·02	1·07	·
Row 2	Method 2	·	·	·	·	·	·	·	1·0	·	·	1·7
Row 3	Method 3	·	·	·	·	·	·	0·76	·	·	·	·
Row 4	Method 4	·	·	0·32	·	·	0·59	·	1·0	·	·	·

Method 2.—The disposition shown in fig. 3 was employed, the fixed carbon rod occupied either position A or B. When in position A the arc was vertical and the couple was caused by the electromagnetic action between the movable part of the apparatus and the rest of the circuit. When placed in position B the arc was horizontal and there was an additional couple occasioned by the pressure upon the pole. The difference between the readings gave the couple to be measured and hence the pressure in dynes. The results for currents of 9 and 12 ampères are recorded in row 2 of Table I.

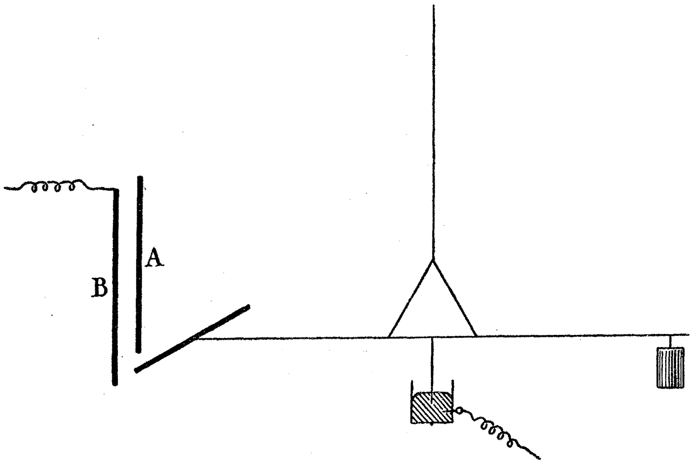

Fig. 3.

Method 3 (*Double Arc*).—The mercury cup was removed and the circuit completed through a second arc shown at C or C′ in fig. 4; as it was vertical it did not add anything to the deflecting couple upon the copper rod. It constituted an extremely flexible electrical joint. As before, A and B were alternative positions for the other carbon, in the latter of which the arc was horizontal and the pressure effective; the differences between A and B measured in a typical experiment are recorded in

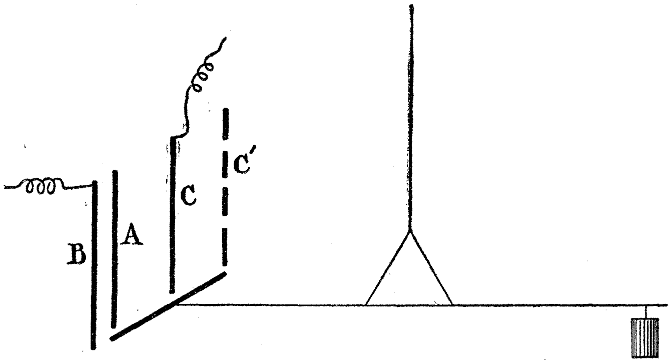

Fig. 4.

Table II., they indicate the nature of the agreement between different readings; when two arcs were used the readings became much more difficult.

TABLE II.—Deflexions. Subsidiary Carbon in Centre. 8 Ampères, Alternating Current.

Zero.	B.	A.	B.	A.	B – A.	Total pressure in dynes.
29°·5	– 5°·0	23°·5	– 3°·5	23°·0	27°·5	0·76

Method 4.—The arrangement was as shown in fig. 5. Carbon rods were fixed axially to the ends of the swinging copper rod, and between these and the sides of two vertical carbons arcs were started. Various dispositions, shown in the same figure, were used, which gave couples which were simple multiples of that due to the pressure upon the pole acting at the end of the swinging arm. For example, for disposition *g* the couple is twice that given by disposition *d*. Save for the small element of current in the arc itself the electromagnetic effects should be eliminated.

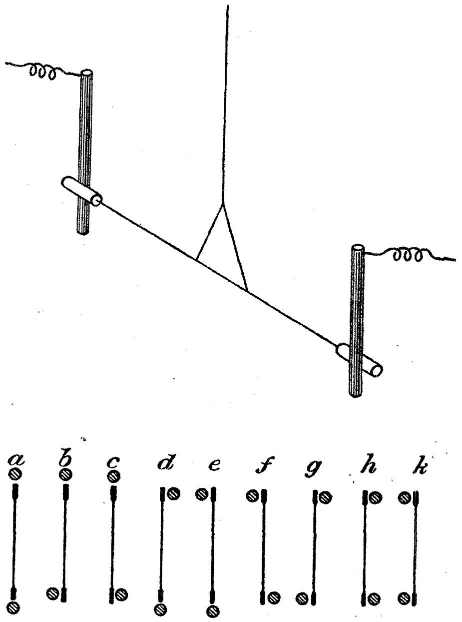

Fig. 5.

Method 4 is a good one save for the effects of convexion currents which are considerable, because they rise over the curved side of the carbon

TABLE III.—Couples Due to a Single Arc.

Current in ampères.	$a-b$.	$a-c$.	$a-d$.	$a-e$.	$\frac{1}{2}(a-f)$.	$\frac{1}{2}(a-g)$.	a_1-b_1.	a_1-c_1.	Mean.	Total pressure in dynes.
	°	°	°	°	°	°	°	°	°	
5	19	29	26	21	26	17	—	—	23	0·32
7	40	47	27	49	50	37	48	50	43	0·59
9	—	>54	76	71	—	—	—	—	73	1·0

Regarding the experiments upon alternating current arcs as a whole the results (Table I.) show a satisfactory measure of concordance for the various methods.

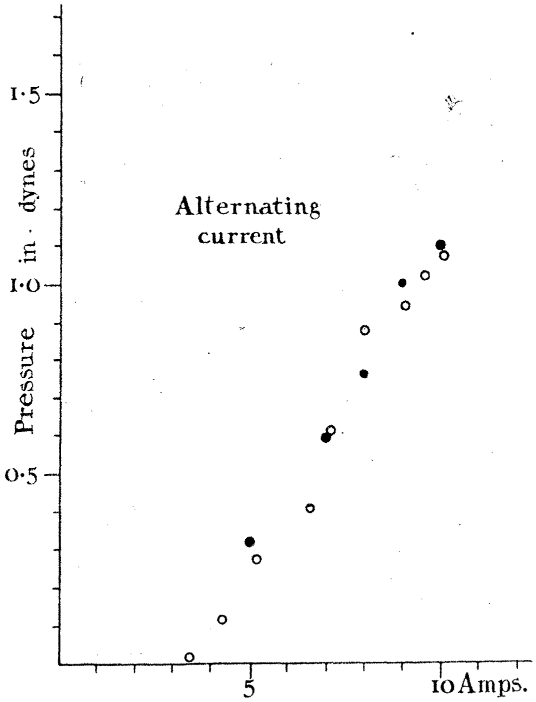

Fig. 6. From Table I.

Method 1 . . . ○. Other methods . . . ●.

Fig. 6 shows the results graphically, open circles representing the observations obtained by method 1, full circles the results of the other three methods.

The Influence of Length of Arc upon the Pressure. Alternating Current.

In the above experiments the arcs were all approximately 3·5 mm. long.

The following experiment was undertaken to determine whether the pressure was increased or diminished by shortening the arc. The disposition was that shown in fig. 7, a current of 9 ampères ∼ was used. The arcs were both horizontal.

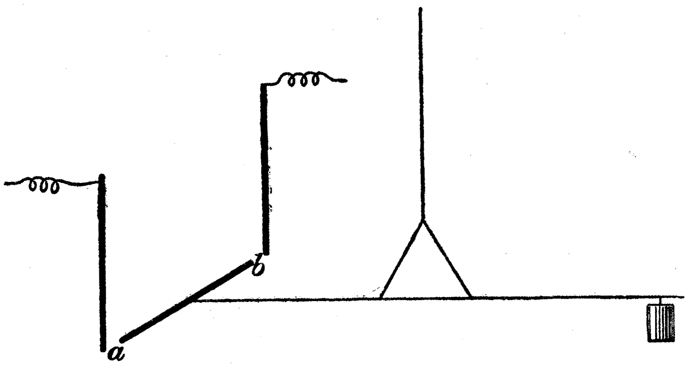

Fig. 7.

When $a < b$ pressure on a greater than pressure on b.

$a > b$,, b ,, ,, a.

Hence for alternating currents the pressure is greater for small arc lengths.

II. Direct Current. Series B.

Observer: Mr. T. H. Burnham.

The disposition of method 1 (fig. 1) was employed. By reversing the direction of the current the pressures upon the anode and cathode were separately determined. In order to eliminate the effect of the earth's magnetic field upon the swinging arm, E, which now carries a current, the fixed pole was placed first on the west and then on the east (dotted position in fig. 1), so that upon one occasion the sum of the pressure upon the pole and the earth's effect was measured, and upon the other their difference. A typical example is shown in fig. 8. The mean of the two curves thus obtained is free from the influence of the earth's magnetism. The values were then corrected as before for the electromagnetic effect due to the rest of the circuit.

The results are given in Tables IV., V., and VI. Discussion of them is reserved until a further method of attack has been described.

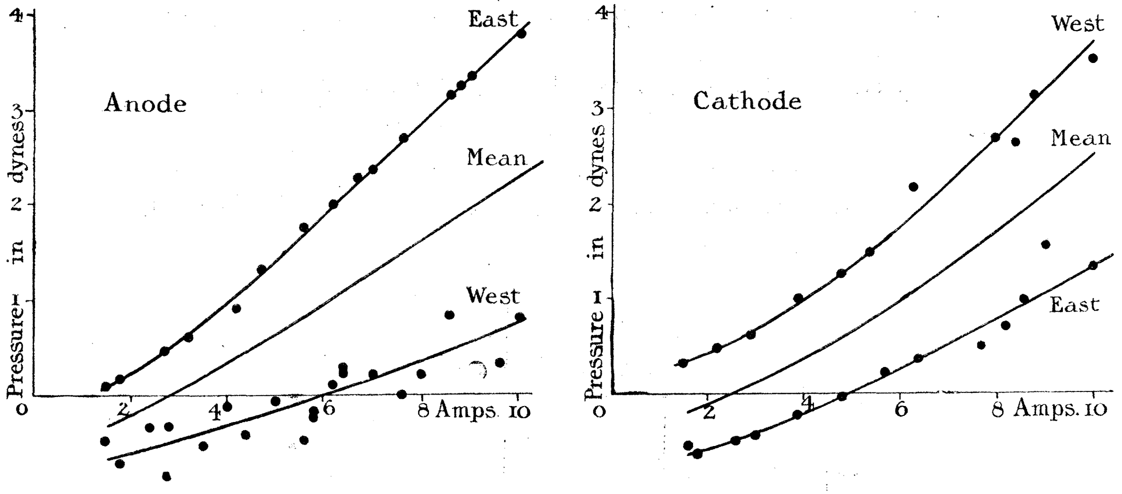

Fig. 8. Direct current, Series B.

Showing the total pressures measured when the fixed carbon was placed East and West of the suspended carbon. The mean curves give the values of the pressure when the effect of the earth's magnetic field has been eliminated.

Table IV. (Burnham).—Direct Current. Variation of Total Pressure with Current. Arc-Length Constant (3·5 mm.). After Correction for the Earth's Field and Electromagnetic Effects.

Current in ampères.	Total pressure on anode in dynes.	Total pressure on cathode in dynes.	Current in ampères.	Total pressure on anode in dynes.	Total pressure on cathode in dynes.	Current in ampères.	Total pressure on anode in dynes.	Total pressure on cathode in dynes.
1·5	−0·32 (2)	−0·22	4·2	0·13	—	7·0	0·74 (2)	—
1·6	—	−0·19	4·4	0·17	—	7·6	0·86 (2)	—
1·8	−0·30 (2)	−0·17	4·7	0·15	—	7·7	—	0·95
2·2	—	−0·12	4·8	—	0·34 (2)	8·0	0·91	1·05
2·4	−0·19	—	5·0	0·29	—	8·2	—	1·12 (2)
2·6	—	−0·05	5·4	—	0·48	8·4	—	1·10 (2)
2·7	−0·17	—	5·6	0·42 (2)	—	8·6	1·01 (2)	1·19
2·9	−0·15	−0·02	5·7	—	0·53	8·8	1·05	1·17
3·0	—	−0·01	5·8	0·45 (2)	—	9·0	1·08	1·31
3·2	0	—	6·2	0·56 (2)	—	9·6	1·19	—
3·5	0·03	—	6·3	—	0·63	10·0	1·26	1·56 (2)
3·9	—	0·20 (2)	6·4	0·58 (2)	0·66			
4·0	0·09	—	6·7	0·66	—			

The figures in brackets indicate the number of observations where more than one were made.

Table V. (Burnham).—Direct Current. Variation of Total Pressure with Current and Arc-length. After Correction for Earth's Field and Electromagnetic Effects.

	Total pressure upon anode in dynes.					Total pressure upon cathode in dynes.					
Current in ampères	3	4	5	6	7	2	3	4	5	6	10
Arc-length. mm.											
0·09	−0·02	0·34	0·60	0·71	·	−0·13	0·30	0·72	0·90	1·13	·
1·3	·	·	·	0·70	·	−0·13	0·08	·	·	0·90	·
1·7	0·17	0·34	0·59	0·66	0·74	−0·25	−0·14	0·34	0·60	·	·
2·2		0·34	·	0·70	·	−0·35	·	·	·	0·83	
2·6		0·26	·	·	·	·	−0·19	0·24	0·49	·	
3·0	·	·	·	·	·	·	0·15	·	·	0·73	
3·5	−0·02	0·32	0·57	·	0·74	−0·45	0·13	0·10	0·36	·	1·55
3·8	·	·	·	0·68	·	·	−0·24	·	·	0·63	
5·2	·	·	0·59	0·65	·	·	−0·40	0	0·30	0·55	
6·0	0·11	0·16	0·56	·	·	·	·	·	0·26	·	
6·9	·	·	·	·	·	−0·53	−0·44	−0·14	·	0·43	
8·6	·	0·27	0·53	0·68	0·74	·	−0·45	·	0·20	·	
9·0	·	·	·	·	·	·	·	·	·	0·45	
10·3	0·11	·	·	·	·	·	·	·	·	·	

Table VI. (Burnham).—Direct Current. Variation of Total Pressure with the Current for two given Arc-lengths.

	Total pressure upon anode in dynes.						Total pressure upon cathode in dynes.							
Current in ampères	2·0	2·8	3·5	5·0	7·0	8·5	2·4	2·8	4·0	5·0	6·0	7·0	8·5	9·0
Arc-length. mm.														
1·7	·	0·22	·	0·45	1·28	1·56	·	0·37	·	0·70	·	1·40	1·82	1·60
7·0	0·11	·	0·13	·	1·15	1·40	0·10	·	0·25	·	0·75	·	1·33	·

Direct Current. Series C.

Observer: Mr. A. H. Davis.

The arrangement shown in fig. 9 was adopted; the moment of inertia of the arm was reduced by moving the balance weight very close to the centre of the swinging arm, and a vane dipping into water was added to damp the oscillations. The double-arc method was adopted because it eliminated the electromagnetic effects upon the movable parts of the circuit due to the earth's field and to the rest of the circuit;

any outstanding effect which might be due to these influences was specially looked for by using two vertical arcs, but it was found to be inappreciable.

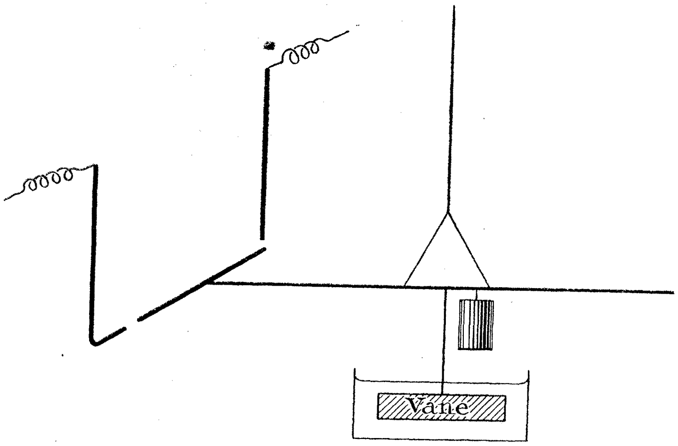

Fig. 9.

Tables VII. and VIII. give the means of a large number of observations obtained by this method.

TABLE VII. (DAVIS).—Direct Current. Variation of Total Pressure with Current and Arc-length.

	Total pressure upon anode in dynes.									Total pressure upon cathode in dynes.								
Current in ampères	2·5	3	4	5	6	7	8	9	10	2·5	3	4	5	6	7	8	9	10
Arc-length. mm.																		
1	0·15	0·26	0·52	0·70	1·16													
2	0·13	0·21	0·51	0·75	0·90	0·98	1·24	1·63	2·07	0·03	0·05	0·18	0·32	0·46	0·85	1·03	1·16	1·75
3 { Set A	·	0·09	0·39	0·37	0·54	0·78	1·17	1·54	1·72		0·08	0·13	0·23	0·39	0·59	0·71	0·74	1·20
Set B	·	0·03	0·24	0·39	0·51	0·61	0·86	1·12	1·58									
5	·	·	0·34	0·65	0·81	0·87	1·21	1·47	1·55			0·23	0·31	0·41	0·59	0·70	0·98	1·15
7			0·52	0·75	0·90	0·90	1·21	1·42	2·02									

TABLE VIII. (DAVIS).—Total Pressures for a Current of 6 Ampères. Variation with Arc-length.

	Anode.								Cathode.				
Arc-length in millimetres	1	2	3	4	5	6	7	8	1	2	3	4	5
Total pressure, set A	0·75	0·62	0·41	0·60	0·67	0·36	0·28	0·35	0·40	0·34	0·43	0·36	0·32
Total pressure, set B	0·95	0·57	0·56	0·52	0·62	0·47	0·50	0·39	·	·	·	·	·

In this table mean values only are given. Fig. 12 shows the individual readings.

Variation of Total Pressure with Arc-length for Constant Current.

This relationship is illustrated by fig. 10, from Table V., for Series B, and by fig. 11, from Table VII., for Series C. Neither set is corrected for convexion-currents.

The Cathode.—The two diagrams agree in showing a rapid drop in the total pressure as the arc-length is increased from very small values; for long arcs the total pressure approaches a constant value which is usually reached at about 10 mm. More weight is attached to the curves of Series B as the experimental method was not so difficult. For very small arcs the curve appears to be asymptotic to the pressure axis, indicating very high values of the reaction for very short arcs.

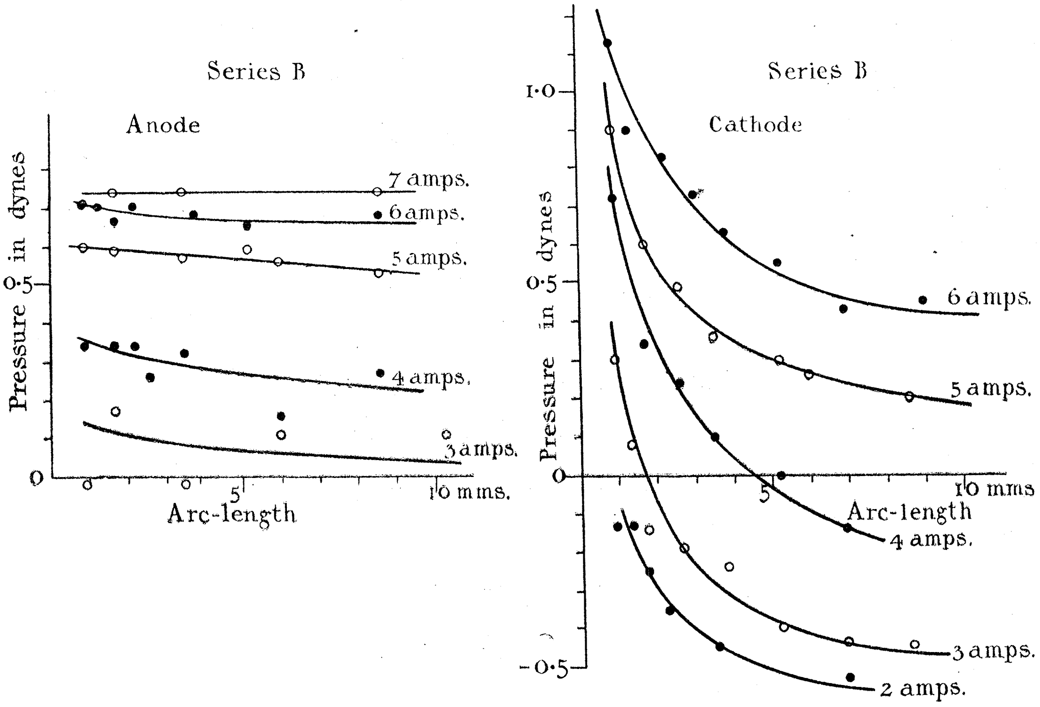

Fig. 10. From Table V.

The Anode.—Fig. 10 differs appreciably from fig. 11 in that the latter shows at first a pronounced fall of total pressure with increasing arc-length, while the former indicates a more constant value. Fig. 11 suggests a minimum value at an arc-length of about 3 mm. for small currents, whereas there is very little indication of this in fig. 10. Two further sets of observations were made with the double-arc method to check this point, and fig. 12, from Table VIII., confirms the accuracy of fig. 10 as far as the constancy of the pressure beyond 3 mm. is concerned, but it also shows that the drop in the value observed for short arcs in Series C is

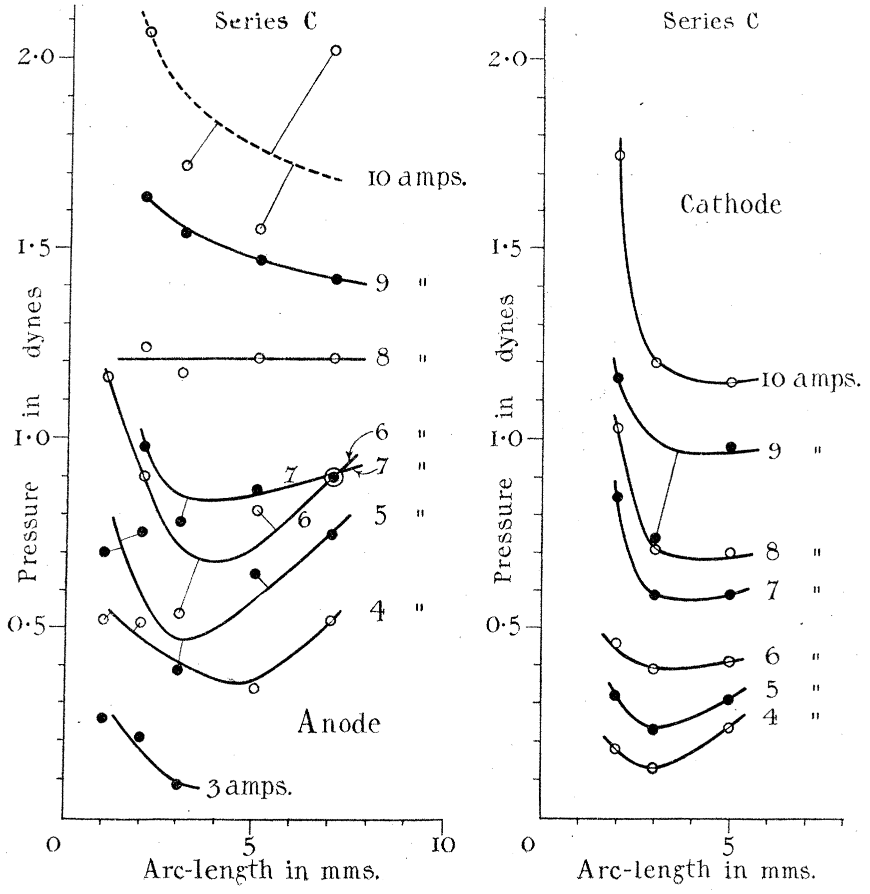

Fig. 11. From Table VII.

probably real; no reason is known for the discrepancy between the two sets of readings in fig. 12.

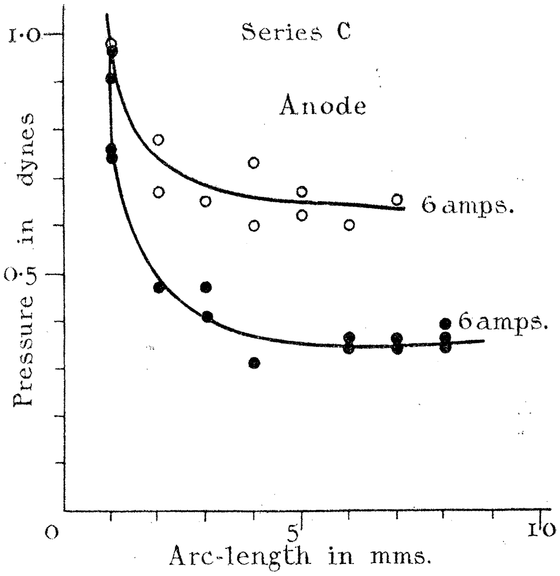

Fig. 12. From Table VIII.

From a comparison of the anode and cathode pressure curves we see that it depends upon the arc-lengths whether one or the other is the greater, but for long arcs there is little doubt that the anode pressure preponderates.

The fact that for direct current the total pressure is greater for short arcs than for long arcs is in agreement with the observation upon alternating current arcs quoted on p. 115.

Variation of Total Pressure with Current for Constant Arc-lengths.

Fig. 13 shows graphically the observations contained in Table IV., Series B, single-arc method, 3·5 mm. arc-length, and fig. 14 depicts the results of Table VII., Series C, double-arc method, 3 mm. and 6 mm. arc-length. The graphs are not straight lines but appreciably convex to the current axis, indicating that the total pressure increases rather more rapidly than with the first power of the current, not, however, as rapidly as the second power. The curves do not pass through the origin but cut the current axis at about 3 ampères. The approximately linear rate of variation is shown for other lengths of arc in fig. 15 for the anode, and in fig. 16 for the cathode, both single- and double-arc methods. For reasons which will appear in Part II., special attention has been given to arc-lengths of 6 mm. We defer further discussion of these curves until convexion-current effects have been eliminated from the total pressure.

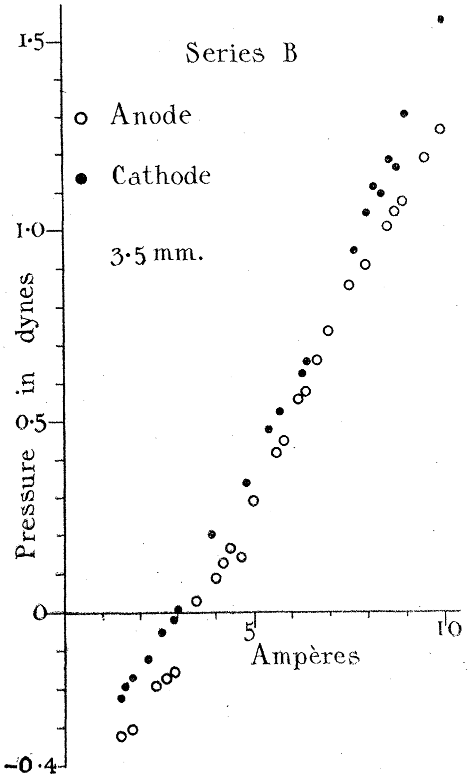

Fig. 13. From Table IV.

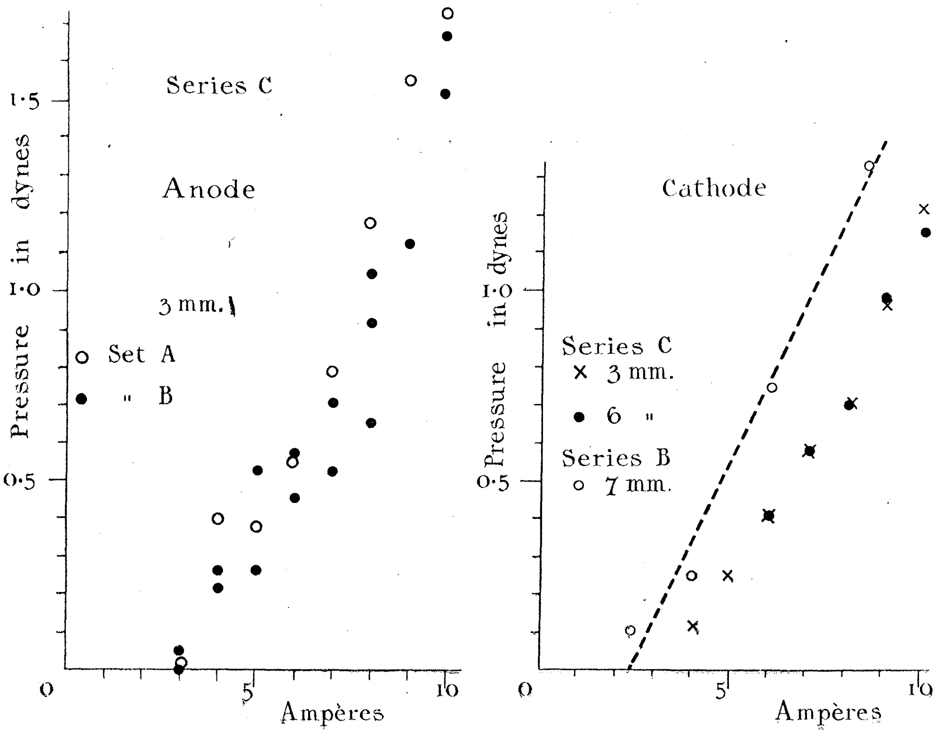

Fig. 14. From Tables VI. and VII.

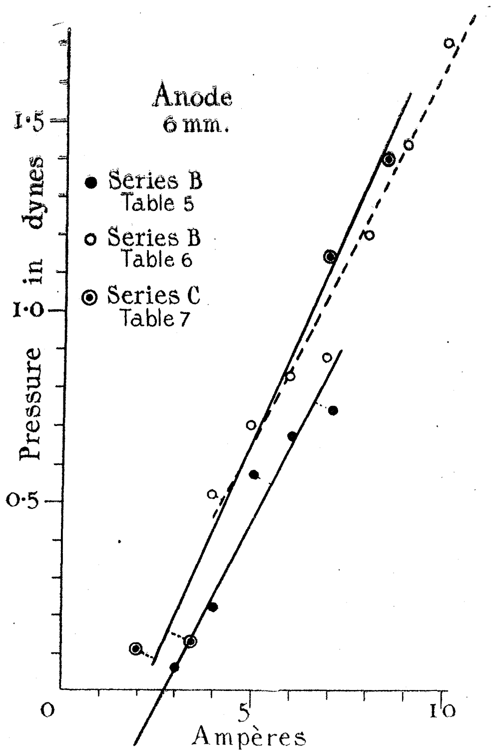

Fig. 15.

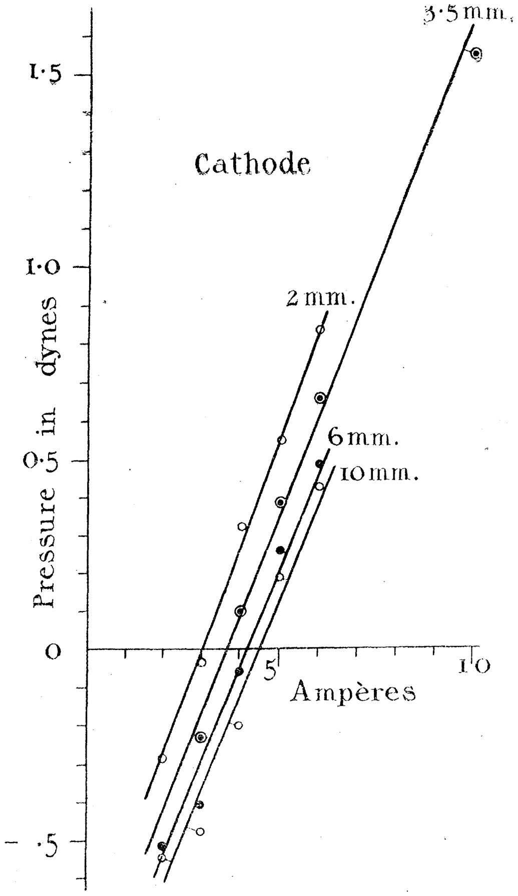

Fig. 16. From Table V.

The Separation of the Pressure from the Electromagnetic Effects.

The evidence contained in the preceding sections proves beyond dispute the existence of a pressure upon the poles of the arc, and shows the general nature of its variation with the current strength. The experiment now to be described provides confirmatory evidence that the electromagnetic effects of the earth's field and of the rest of the circuit have been eliminated, and evaluates these effects.

The current was led to the carbon through a mercury cup as in fig. 1, and the carbon fixed axially at the end of the swinging arm. The dispositions of the poles in the different experiments are depicted in fig. 17. The deflexion may be due to the couple, V, occasioned by the earth's field, or to the electromagnetic couple, E, occasioned by the rest of the circuit, or to the total pressure upon the poles, P, in which category, as before, we include for the present the influence of air currents, &c.

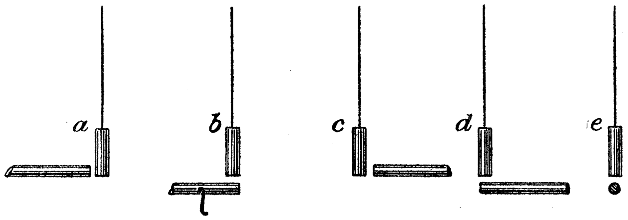

Fig. 17.

In the above arrangements the deflexions were as follows:—

TABLE IX.

Arrangement.	Couple due to	8 ampères, 3 mm.		9 ampères, 5 mm.
		Torsion.		Torsion.
		Set A.	Set B.	
		°	°	°
a	P + E + V	290	312	− 40
b	E + V	235	290	− 87
c	P − E + V	90	60	− 323
d	− E + V	120	104	− 275
e	V	175	126	− 188

The value of V is given by e or $\frac{1}{2}(a+c)$ or $\frac{1}{2}(b+d)$,
E ,, ,, $\frac{1}{2}(b-d)$, $b-e$, $e-d$,
P ,, ,, $a-b$, $d-c$,

whence

	At 8 ampères.						At 9 ampères.			
	°	°	°		°		°	°	°	°
V =	175,	190,	178	Set A	Mean 175	V =	188,	181,	181	Mean 183
	126,	186,	197	Set B						
E =	58,	60,	55	Set A	Mean 75	E =	94,	101,	97	Mean 97
	93,	164,	22	Set B						
P =	55,	30		Set A	Mean 38	P =	47,	48		Mean 47·5
	22,	44		Set B						

The couples due to P, E, and V are thus approximately as 1 : 2 : 4 in the actual arrangement employed, but this is accidental. The pressures, P, at 8 and 9 ampères reduce to 0·91 and 1·03 dynes respectively, values in good agreement with those obtained by other methods.

The Electromagnetic Effect.

In order to evaluate the couple upon the suspended arm due to the electromagnetic effect of the rest of the circuit, and particularly the effect of the fixed pole at right angles to it, the apparatus was arranged as in fig. 17, *b*. The current was led to the centre of the copper rod from the mercury trough and from the fixed carbon by a vertical wire. The couple was measured for different lengths of the fixed pole and was found to reach a maximum at about 11 cm. Alternating current obviated any influence of the earth's magnetic field. The effect of altering the current strength with a fixed length of pole was also examined and the couple found to vary, as was expected, with the square of the current. These data enabled the necessary corrections to be made where method No. 1 was adopted (*loc. cit.*).

Electrostatic Effects.

Previous to striking the arc the electrostatic attractions between the poles amounted to 0·125, 0·031, 0·008, 0·006 dynes for arcs of 1, 2, 3, 4, and 5 mm. respectively. But when the arc is struck the distribution of charges within it entirely alters these conditions.

In Part II. is developed a theory of the pressure which does not appear to be seriously affected by electric effects within the vapour. This view is supported by the observation that the pressure depends upon the nature of the poles.

Convexion Currents.

Hitherto we have dealt with the total pressure upon the poles, it remains to consider to what extent it is caused by convexion currents of hot air and vapour rising from the arc. It will appear that convexion currents tend to cause the poles to move towards one another, and that if they could be eliminated the pressure would be higher.

(1) Using alternating current the arrangement shown in fig. 18 was adopted. No current passed through any of the movable parts of the apparatus. An arc was struck between two vertical carbons below the end of the suspended pole. The torsion head showed a *reduction* of pressure amounting to 0·4 dyne. The effect persisted after the circuit was broken, and until the poles cooled down.

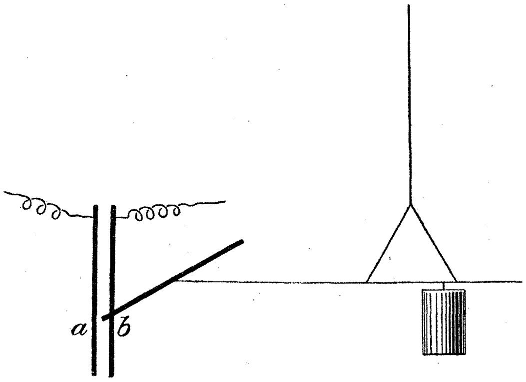

Fig. 18.

This quantity is to be *added* to the observed pressure upon the poles to give the true reaction.

(2) The apparatus was arranged as in fig. 19 for the double arc method. No current flowed through the main apparatus, but an arc was started 1·5 cm. below the arc gap between two carbon rods placed parallel to the suspended carbon; with a direct current of 8 ampères a negative pressure of $-0·32$ dynes was recorded. It is probable that the convexion pressure is actually greater than this, because the arc was necessarily some distance below the suspended poles.

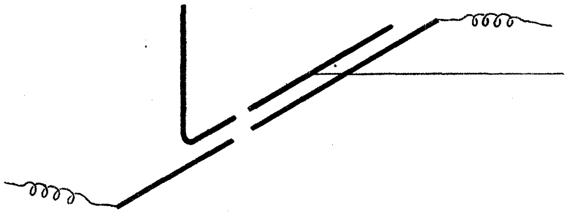

Fig. 19.

(3) In an experiment with 8 ampères direct current (double-arc method) the suspended pole was shaped as shown in fig. 20, with the object of preventing the end from growing pointed, but this was partially defeated by the deposition of a small point of carbon upon its centre, like a boss upon a shield. The disc on the right-hand side was too large (3 cm. in diameter) to be heated over its whole area by the arc above it, hence the convexion currents due to the two sides did not balance. For a

current of 8 ampères and 3 mm. arc length, a deflexion of 30 degrees was recorded. When the current was turned off and the poles were hot, balance was obtained when the deflexion in the opposite direction was 17 degrees. The deflexion corrected for convexion* is therefore 47 degrees, corresponding to 1·22 dynes. The couple due to convexion is in this experiment approximately 36 per cent. of the total couple upon the poles, and it corresponds to a negative pressure of −0·44 dyne.

It had been hoped that the arrangement of an arc at each end of the suspended carbon (double-arc method, fig. 4), besides eliminating the electromagnetic effects, would obviate the convexion current difficulty, but this was not the case, since DAVIS found that moving the vertical arc from the centre to the end did not necessitate more than a minor change in the current strength necessary to produce a given deflexion. No doubt the currents about the vertical arc were very different from those about the horizontal arc at the tip of the carbon rod.

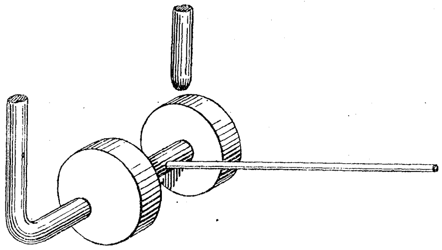

Fig. 20.

The above experiments enable us to fix the lower limit to the effect of the convexion currents rising from a 7–8-ampère arc at −0·5 dynes.

Since it is a matter of considerable difficulty to measure convexion currents in the manner described, a comparative investigation of their value over the range of current strengths used in the main research was made thus:—

A light paper vane was pivotted upon a vertical axis 60 cm. above a horizontal arc, so that the rising convexion currents caused it to turn, the number of revolutions of the vane in 1 minute providing a measure of their velocity. Arcs of constant length and varying current were employed, and the mean curve C in fig. 21 was obtained as the result of a number of experiments, whence it is clear that over the range 2 to 10 ampères there is an increase in the velocity of the convexion currents. For a given curvature of pole the suction upon it is proportional to the square of the velocity of the air moving past it, the curve D has therefore been drawn with ordinates proportional to the square of those of curve C, but on a different scale, it represents, therefore, the pressure effect of the convexion currents. We can approximately fix the scale of curve D from the knowledge that the convexion is approximately 0·5 dynes at 8 ampères, remembering however that this is an underestimate.

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* Also radiometer action if it were effective, see p. 130.

The observation that convexion currents from the poles occasion a reduction of the pressure between them is in accord with the experiments of DEWAR referred to elsewhere. He states that "the effect of hot poles upon the registration of the manometers was to produce a small negative pressure when the arc was stopped, due to the passage of currents of hot air."

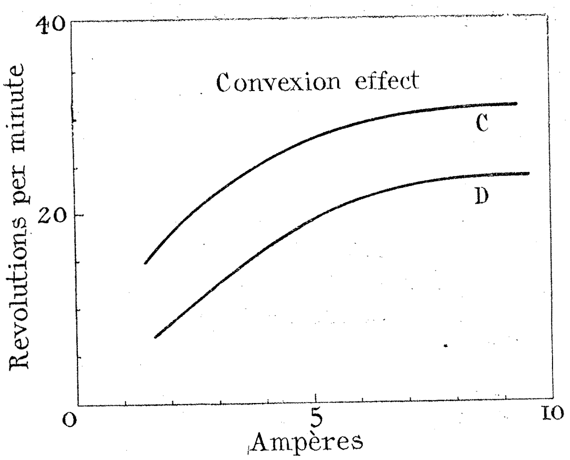

Fig. 21.

The Elimination of Convexion Effects.

The curve D in fig. 22 is the same curve as in fig. 21, but drawn to the appropriate scale, and shown below the current axis instead of above it. A is the curve representing the observed total pressure upon the anode taken from fig. 14. The corrected pressure is given by the curve A referred to D as datum line, or by the curve B referred to the original axes. It will be seen that correcting for convexion results in a rather more linear curve than that obtained from direct observation, and that the curve now more nearly passes through the origin. Remembering that the effects of convexion currents have been underestimated, and therefore that the convexion current curve should have been rather lower, we see that it is probable that the corrected curve is linear, and that the reaction varies directly with the current; it is unfortunate that information is very difficult to obtain in the crucial part of the curve where the current is small; there is no evidence that the pressure when corrected for convexion ever becomes negative. It is clear therefore that, without much error, we may take the origin of the observed curve at the point at which the straight portion when produced backwards cuts the vertical or pressure axis. This provides us with the simplest means for correcting for convexion currents, and all previous diagrams should be so treated, For example, in fig. 15, Series B, instead of 0·45 dynes being the pressure at 5 ampères it is 1·0 dynes, since if produced backwards the curve cuts the vertical axis at −5·5 dynes.

The curves for Series B have been represented by straight lines wherever possible, but it is obvious that the points are often better represented by curves slightly convex to the current axis; they are subject to the same corrections as Series C, and they become more nearly straight after allowance is made for convexion currents.

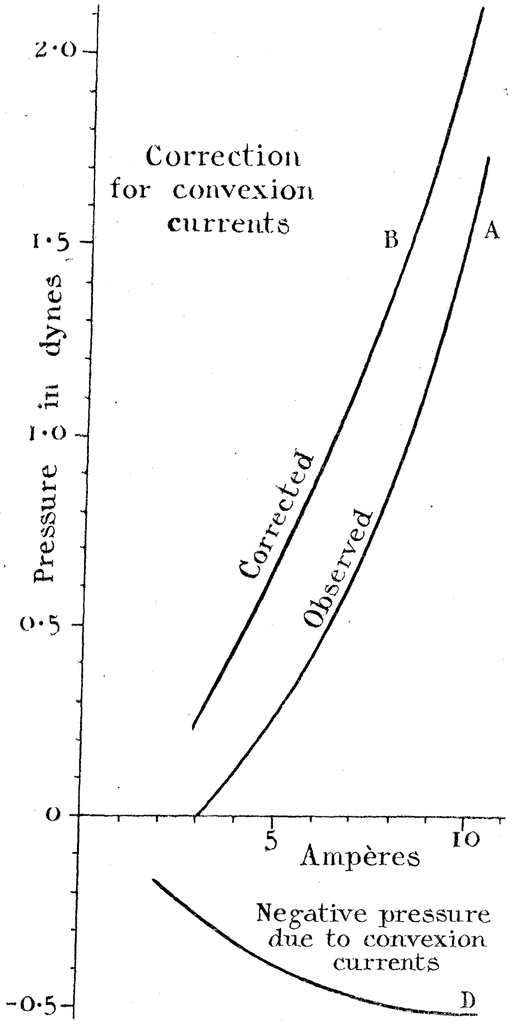

Fig. 22. For "observed" curve, see fig. 14.

In Table X. are shown the values of the pressures corrected for convexion currents for arcs of 10 ampères and 6 mm. length. We shall make further use of these values in a later section.

TABLE X.—The Pressure upon the Poles of an Arc, 6 mm. long, carrying 10 ampères.

Series.	Figure.	Observed total pressure in dynes.	Convexion correction. Dynes.	Corrected pressure. Dynes.	Mean corrected pressure.	Current carried solely by electrons.		Half-current carried by electrons.	
						e/m.	v.	e/m.	v.
1. Cathode.									
B	16	1·60	1·10	2·70	2·18	$6{\cdot}4 \times 10^7$ E.M.U.	$2{\cdot}8 \times 10^8$ cm./sec.	$1{\cdot}6 \times 10^7$ E.M.U.	$1{\cdot}4 \times 10^8$ cm./sec.
B	14	1·69*	0·54	2·23					
C	14	1·11	0·50	1·61					
2. Anode.									
B	15	1·35	0·52	1·87	2·10	$19{\cdot}0 \times 10^7$	$7{\cdot}9 \times 10^8$	$4{\cdot}7 \times 10^7$	$3{\cdot}9 \times 10^8$
B	15	1·79*	0·60	2·42					
C	15	1·68	0·34	2·02					

The values for the observed pressures were taken from the diagrams named in column 2 by drawing a line through the points of observation and noting where it met the vertical axis, and this point taken as the origin. When the graph was not straight the tangent was drawn to touch the curves at 10 ampères and similarly treated.

* Calculated for arc-length of 7 mm.

Previous Investigation.

In 1882 DEWAR† measured the hydrostatic pressure within the arc by using hollow carbons connected to delicate water manometers and found that "during the maintenance of the *steady* arc the manometer connected with the positive pole exhibited a fixed increase of pressure corresponding to 1 to 2 mm. of vertical water pressure in different experiments and under varied conditions. The manometer connected with the negative pole shows no increase of pressure, but rather, on the average, a diminution."

DEWAR gives no data respecting current and arc-length, but we may note that the hydrostatic pressure near the anode is about one hundred times the total pressure upon the poles measured in the present research.

DEWAR suggests that the phenomenon is consistent with "the well-defined boundary of the heated gases acting as if it had a small surface tension," and he suggests as a possible cause "the motions of the gas particles under the conditions of transit of material from pole to pole or a succession of disruptive discharges."

† DEWAR, 'Roy. Soc. Proc.,' xxxiii., 262, 1882.

PART II.—THE ORIGIN OF THE PRESSURE.

By Prof. W. G. DUFFIELD.

In the foregoing pages experimental evidence has been adduced demonstrating (1) the existence of a pressure upon the poles, (2) its variation with arc length, (3) its variation with current strength.

There is reasonably good agreement between the results obtained by different methods in the various series of observations both for direct and alternating current. In view of the delicate nature of the observations, it is satisfactory to find that the rigorous examination given in the section upon the separation of the electromagnetic and pressure effects confirms both qualitatively and quantitatively the existence of the pressure.

Assuming that the corrections for convexion currents have been made with approximate accuracy it remains to attempt to account for the reaction upon the poles.

Radiometer Action and Evaporation.

Before giving the evidence in favour of the reaction being occasioned by electronic projection from the poles, it is necessary to consider whether it is explicable either by radiometer action, produced by the departure with increased velocity of air molecules after impact upon the hot poles, or by the evaporation of carbon atoms.

Against the effect being due to either of these causes we have the experimental evidence that, whereas for a constant current the reaction upon the cathode remains constant or diminishes with increasing arc-length (figs. 10 and 11), the amount of carbon lost from the poles increases rapidly with the arc-length* over the same range. As the amount of carbon consumed depends upon the rate of evaporation or (and) upon the access of air molecules to the poles, it would be expected that, if the reaction depended upon either of these factors, it would increase with the consumption of carbon, which is not the case.

Furthermore, radiometer action is not usually appreciable at atmospheric pressure, though, when the object has been of very small dimensions, it has been observed at about $\frac{1}{3}$ atmosphere. It may be argued that radiometer action is to be expected because the pole face is curved and the intensity of the reaction against the air molecules is not necessarily equal to the reaction upon the poles; against this we have experimental evidence that, starting with a flat pole face, the reaction upon the pole became perceptibly less as it burnt to the usual curved form.

Experiment 3, p. 125, shows that the hot pole is subject to a *negative* pressure when the current is off, indicating that, if any radiometer effect exists, it is very small and is masked by convexion effects.

Again, if we assume that a pressure can arise from the expulsion of carbon atoms

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* "Consumption of Carbon in the Electric Arc," DUFFIELD, 'Roy. Soc. Proc.,' A, vol. 92, p. 122, 1915. See Diagrams 1, 2, 4, 5.

in the process of evaporation, we find marked disagreement between observed and calculated values :—

Any reaction due to evaporation should be calculable from a knowledge of the number n of molecules of mass m which leave the pole in 1 second with a velocity of v cm. per second. The product mn can be measured, but the determination of v presents some difficulty. Assuming that in the arc the carbon is at its boiling-point, and that the carbon atoms are in thermal equilibrium with the air into which they are escaping, *i.e.*, the carbon atom possesses the same kinetic energy as is possessed by an oxygen or nitrogen atom at the temperature at which boiling occurs, we have for the velocity of the carbon atom at 0° C., using the fact that the velocity of H_2 at 0° C. $= 18{\cdot}39 \times 10^4$ cm. per second,

$$v = 18{\cdot}39 \times 10^4 \times \sqrt{\tfrac{1}{6}} = 7{\cdot}5 \times 10^4 \text{ cm. per second.}$$

Since the boiling-point of carbon is about 4000° C., the atomic velocity at that temperature $= 7{\cdot}5 \times 10^4 \times \sqrt{\tfrac{4273}{273}} = 2{\cdot}97 \times 10^5$ cm. per second.

In experiments already quoted the amounts of carbon liberated from the anode and the cathode have been determined under various conditions of arc length and current strength (*loc. cit.*).

In a typical experiment with an arc of 6 mm. length and a current of 10 ampères, 85×10^{-5} grm. of carbon were lost by the cathode in 1 second, a much larger loss being recorded for the anode. Taking the above data the loss of momentum from the cathode per second $= 8{\cdot}5 \times 10^{-4} \times 2{\cdot}97 \times 10^5 = 252$ grm. cm. per second².

On account of the nearly hemispherical curvature of the pole tip for an arc of this length only the components of the momenta along the axis are effective, hence the reaction recorded by the torsion fibre should be one-half of the above pressure—namely, 126 dynes. The observed value of the reaction, after correcting for convexion currents, under the same conditions of current and arc length, is 2·18 dynes, which is not as much as 2 per cent. of the calculated value. It does not appear that we can account for the reaction at the cathode on any simple assumption which regards its cause as molecular or atomic projection.

The Nature of the Particles Projected from the Cathode.

It seemed possible to discover the nature of the particles projected from the cathode from the following considerations :—

If p is the observed pressure corrected for convexion currents, we have, assuming symmetrical projection from a hemispherical pole tip, or random projection from a small area on a flat pole face,

$$2p = mnv, \quad \ldots \ldots \ldots \ldots \quad (1)$$

where m is the mass, v the velocity of each particle, and n the number projected per second.

Assuming in the first instance that each particle carries a single electronic charge, e, and that electrons alone are responsible for carrying the current between the poles, the current C in absolute units is given by

$$C = ne. \qquad (2)$$

The potential drop, V, across the pole face is, on this assumption, due to the projection of these particles, whence their kinetic energy is equal to that derived from the source of current supply, and we have

$$VC = \tfrac{1}{2}mnv^2. \qquad (3)$$

From (1) and (3)

$$v = \frac{VC}{p},$$

whence from (1) and (2)

$$\frac{e}{m} = \frac{Cv}{2p} = \frac{V}{2}\left(\frac{C}{p}\right)^2.$$

DUDDELL* has found the values of V at the anode and cathode of an arc 6 mm. long carrying a current of 10 ampères to be 16·7 and 6·1 volts respectively, both being electromotive forces acting *towards* the poles. These are electromotive forces across the pole faces and are distinct from those within the vapour in the arc-gap.

We have already set forth in Table X. the values of p for a similar arc employed in this series of experiments, and, by substitution in the above formulæ, we derive the values of e/m and of v, which are recorded in the final column of the same table; for the cathode the mean value of e/m is $6{\cdot}4 \times 10^7$ E.M.U. The values of e/m for electrons and for hydrogen atoms are $1{\cdot}77 \times 10^7$ and $9{\cdot}58 \times 10^3$ E.M.U. respectively, and, if carbon is quadrivalent, e/m for that element is $3{\cdot}2 \times 10^3$. Even without further refinement of our assumptions, the experimental evidence is overwhelmingly in favour of the projection responsible for the reaction being electronic rather than molecular.

We expect to find electronic projection from the poles of an arc, because the intense heat may occasion thermionic action, and the richness of the arc light in waves of short length is favourable for photoelectric action.

Electronic emission is thus in accord with expectation, but it is at first sight surprising that it should be capable of producing a measurable recoil.

It has been assumed in the foregoing that electrons carry the whole of the current, but the case for an atomic drift of positively charged atoms on to the cathode has already been considered by the writer (see "The Consumption of Carbon in the Electric Arc—No. 1," 'Roy. Soc. Proc.,' A, vol. 92, p. 122 (1915)). If we assume that half the current in the neighbourhood of the cathode is carried by such atoms (which may be supposed to contribute no more to the pressure than do the gas

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* DUDDELL, 'Phil. Trans. Roy. Soc.,' A, vol. 203, p. 305, 1904.

molecules which they replace), the value of e/m appropriate to these conditions is $1 \cdot 6 \times 10^7$ E.M.U. which approximates closely to the value for the electron derived from other methods, namely, $1 \cdot 77 \times 10^7$ E.M.U.

The corresponding velocity of projection is $1 \cdot 4 \times 10^8$ cm. per second, which is of the order of magnitude to be expected if the emission is due to photoelectric action, though higher than the velocities measured by LENARD from carbon plates. But in the arc the proximity of the luminous vapour to the poles enables light of very short wave-length to reach them, so a correspondingly high electronic velocity is to be expected. Moreover, the condition of the pole, its high temperature, boiling and intense incandescence, are favourable for the liberation of the corpuscles with the minimum loss of energy, indeed, it may be that it is the undiminished momentum of the electron as it leaves the atom which has been measured. If the arguments are sound the experiments constitute the measurement of quanta by a direct mechanical method.

The kinetic energy of the electron as it leaves the cathode is given by $\frac{1}{2}mv^2$, which, from the data of the present set of experiments, amounts to $8 \cdot 6 \times 10^{-12}$ erg. Assuming that this is due to photoelectric action, and taking the radiation constant h as $6 \cdot 55 \times 10^{-27}$ erg seconds, we find λ, the mean wave-length of the light emitted by carbon vapour, which may be regarded as effective in promoting the emission, to be $1 \cdot 22 \times 10^{-5}$ cm.; this is a reasonable result as it is smaller than the threshold wave-length for soot given by HUGHES as $2 \cdot 6 \times 10^{-5}$ cm. We note that the electronic energy is less on emission than the amount $5 \cdot 5 \times 10^{-11}$ ergs, which is the minimum required to produce ionization (RUTHERFORD), but in the arc the further fall of potential beyond the negative pole face rapidly increases the velocity and therefore the kinetic energy of the corpuscle.

The Mechanism of the Arc.

It is clear that the balance of evidence favours the conclusion that the particles responsible for the recoil are electrons. It is doubtful if we can press our results much further than this in view of the very small forces to be measured and the complex conditions under which experiments of this nature must be conducted, but the view of the mechanism of the arc which is most favoured by this research (indeed the agreement with it is remarkable, though it may be accidental) is that an oxygen atom arrives at the cathode with two positive charges of electronic magnitude, and that uncharged CO is formed which removes two of the four electrons, which we have already shown to be associated with the departure of each carbon atom from this pole,* and which are derived ultimately from the source of current supply. The oxygen atoms on arrival and departure contribute no more to the pressure than do the air molecules on the other side of the suspended pole. The remaining two electrons

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* DUFFIELD, *loc. cit.*

are liberated, and their expulsion involves the recoil which has been measured in the present experimental investigation.

Under these conditions the mechanical effect would be least likely to be disturbed by electric forces within the arc, because the oxygen atom approaching with two positive charges would contribute to the attractive force upon the pole an amount not very different from the repulsive force occasioned by the two receding electronic charges.

In a normal arc the effects at the anode are very complicated, there is electronic projection due to thermionic and photoelectric action, and probably access of electrons and negatively charged atoms which carry the current to it. Nevertheless, the values of e/m obtained by the method already described is of the right order of magnitude, though three times higher than it should be, if the recoil is in this case also to be explained by the projection and impact of electrons and if they bear half the current. If we could accept the view that the momentum of the electron derived from the cathode is handed on through the vapour from atom to atom until it reaches the anode, the discrepancy would be reduced. Elsewhere we have shown that it is possible to reduce the carbon consumed by the anode to almost negligible quantities, it would be interesting to determine the changes in the anode recoil under these circumstances, but the experiments would be of very great difficulty.

The writer tenders the above account of the mechanism of the arc with due appreciation of the assumptions underlying it. As far as the details are concerned, a great deal depends upon the accuracy of DUDDELL's results, but any reasonable assumption regarding the magnitude of the potential drop across the cathode pole face would lead to a value for e/m which is of the order of magnitude of that of the electron and far removed from that associated with atoms. If instead of assuming random projection, we assumed normal projection from a small area on the cathode, the values of e/m would be four times those given in Table X., and still in accord with their electronic rather than their atomic nature.

The view I have taken of the mechanism of the arc attributes the fall of potential across the negative pole face to electronic projection there, contrary to the theory which regards the electric force as responsible for the extraction of the electron. POLLOCK,[*] *assuming* electronic projection, took the same view, and from DUDDELL's work calculated the velocities in different parts of the arc in an important contribution to this subject. The discharge of electrons has frequently been assumed, but I do not think that there has hitherto been any mechanical evidence in its favour.

Such action, photoelectric or thermionic, as occasions in the arc a discharge of negative electrons from the poles is probably assisted by the chemical interactions between the poles and the surrounding gas. This point has already been discussed in the paper by the writer, to which reference has been made.

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[*] POLLOCK, 'Phil. Mag.,' vol. XVII., p. 361, 1909.

The method of starting an electric arc by forcing a spark between the separated poles possibly depends as much upon the photoelectric action induced as upon the ionization within the spark gap.

Polar Lines in Arc Spectra.

The original experiment upon the pressure upon the poles on which the above research is based was carried out in 1912, and had been undertaken in the expectation of finding a recoil effect. The writer had previously described a series of spectrum lines which made their appearance near the poles of an iron arc, to which the name "polar lines" had been given,* and in the discussion of their origin something in the nature of an explosion upon the surface of the pole was suggested to account for the potential drop with which they appeared to be associated.

It seems now possible to go further than I did in the original paper and state that the explosion results in the liberation of an electron with high speed, and it is further suggested that the polar line is due to the particular type of vibration which is set up at the instant when an electron is expelled from the atom. The other, or median, lines being due to the secondary action when the electron with its ionizing velocity impinges upon another atom. The feeble intensity of the polar line contrasted with the greater intensity of the median line is in accord with this view.

A feature of the occurrence of polar lines is their predilection for regions of the spectrum of short wave-length. In the case of the iron arc they became increasingly numerous as more refrangible parts of the spectrum were reached. It is quite possible that their preference for this range is due to their photoelectric origin, since such action is limited to regions of high frequency; in the rare case (only as far as I know in the iron arc) in which a small group is found in another part of the spectrum the effect may be a resonance one.

Rossi† has observed polar lines in the spectrum of the copper arc, and it appears that 2714 Å.U. is the wave-length of the least refrangible one. Richardson and Compton‡ give 3000 Å.U. or 3090 Å.U. as the longest wave-length capable of producing photoelectric emission from copper. There is thus further evidence of the polar lines being due to photoelectric action. In the case of iron the polar lines were found to be nearly equally strong at the two poles, but with the copper arc Rossi found that unless the current was strong they were confined to the cathode; this suggests that the attraction of the anode for the electron was sufficient to prevent its expulsion.

The reason why an explanation based upon photoelectric rather than thermionic action is offered is that in the experiments already quoted it was found that the

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* Duffield, 'Astrophysical Journal,' XXVII., 264, 1908.

† Rossi, 'Astrophysical Journal,' XXXV., 279, 1912.

‡ Richardson and Compton, 'Phil. Mag.,' XXIV., 575, 1912.

loss of an atom of carbon from the cathode was associated with the transfer of four electronic charges between the poles, this favours the ejection of electrons from the atom itself rather than from the pole face considered as a whole, but the writer does not wish to rule the possibility of thermionic emission out of account.

One point which emerges from the present research deserves mention. After the discovery of the recoil, and during the endeavour to find a means of disentangling it from the electromagnetic effect due to the rest of the circuit, it was suggested that the two might be identical, that is to say, that the mutual interactions between various parts of a circuit were occasioned by the mechanical effect of the flow of electrons through it. It seemed possible to find a plausible explanation of the motion of a movable wire in the plane of a circuit on this basis. The experiments described on pp. 123 and 124 showed that the two exist simultaneously, and that the electromagnetic effect under the conditions of the experiment was about twice that observed for the recoil. Moreover, the rates of increase of the two with the current strength were different, a fact which effectively disposed of this idea.

The writer has observed a similar recoil upon the suspended cathode within a highly exhausted vacuum tube, but the mechanical effect has not yet been measured.

The experiments were conducted in the Physics Laboratory of University College, Reading, and valuable assistance was given by Mr. J. S. Burgess. Mr. Davis was in receipt of a Research Grant from the Committee of the Privy Council for Scientific and Industrial Research, to whom the thanks of the authors are accorded.