

## ON THE THEORY OF THE COHERER.

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## INTRODUCTION.

NO satisfactory explanation has as yet been advanced of the phenomenon of the lowering of the resistance of a loose contact when electromagnetic waves are set up in the surrounding medium, in spite of the numerous investigations made thereon. Of the existing theories, those of Branly, Lodge and Auerbach are the most important. Branly<sup>1</sup> supposes that the medium between the conducting particles of the coherer undergoes a modification under the influence of the electromagnetic waves and that thus the whole becomes conducting.

Lodge<sup>2</sup> tries to explain the phenomenon chiefly on electrostatic principles. He supposes the particles to be separated by films—for instance, oxide films. These films he calculates to be under enormous pressures, due to electrostatic attraction. Under these circumstances the surfaces may be welded together “especially if the electric stimulus simultaneously acted in any way as a flux, by reducing the infinitesimal tarnish of oxide or other compound which must be supposed normally to cover them.”

The fact that Lodge compares the coherer phenomena to the welding of metallic spark gaps due to lightning discharges of leyden jars has led to an interpretation of his theory by later observers, that the spark plays the all-important rôle in producing an intimate contact between the particles, by the formation of metallic bridges.

Auerbach<sup>3</sup> advances what he calls a mechanical theory. He showed that by periodic vibrations of a mechanical nature a lowering of the resistance of a coherer takes place. He explains this as follows :

<sup>1</sup>C. R., **111**, p. 785, 1890; **125**, p. 939 and **1163**, 1897.

<sup>2</sup>Phil. Mag., Vol. 37, p. 94, 1894; Electrician, Vol. 40, p. 87, 1897.

<sup>3</sup>Wied. Ann., Vol. 64, p. 611, 1898.

A disturbance is produced in the coherer of such a nature that each particle is displaced from its old position of equilibrium so that it comes into more intimate contact with its neighbor—it does not return to its former position, after the mechanical vibration, which caused its displacement, has ceased because of adhesion between the particles now in intimate contact.

He proposes to extend this explanation to coherer action in general.

Thus far very few experimental data are at hand to test any of the three theories outlined above. That of Branly can hardly be subjected to a crucial experimental test.

While Auerbach's theory seems probable enough for the rather strong mechanical vibrations he used, it can hardly be assumed that since the effect produced (*viz*: the lowering of the resistance) is the same in the mechanical and electrical case, the cause must be identical.<sup>1</sup>

A number of experimental proofs of Lodge's theory have been reported, notably those of Arons,<sup>2</sup> Tommasina<sup>3</sup> and Sundorph.<sup>4</sup>

The same criticism as the one advanced against Auerbach's theory holds here. It can very well be conceived that if sparks really do pass, a fusion of particles may take place, and the resistance be lowered—but the question still remains, "Is this the action of the coherer made use of in wireless telegraphy?"

If the lowering of the resistance be due to sparking, then we can only expect a very irregular behavior of the coherer. To quote Aschkinass who discusses Arons' and his own results in the following words:

"A lowering of the resistance takes place always when the excitation is weak, while no sparking, fusion or mechanical motion can be observed at the contacts. On the other hand, with stronger excitation, sparks, etc., can be seen, while the resistance is influenced in an irregular manner."<sup>5</sup>

He further states that when sparks of considerable intensity were

<sup>1</sup> See also Drude, *Wied. Ann.*, 65, p. 486, 1898, and Aschkinass, *ibid.*, 66, p. 306.

<sup>2</sup> *Wied. Ann.*, 65, p. 567, 1898.

<sup>3</sup> *C. R.*, 128, p. 1092, 1899; 127, p. 1014, 1898; 129, p. 40, 1899.

<sup>4</sup> *Wied. Ann.*, 68, p. 594, 1899.

<sup>5</sup> Aschkinass, *loc. cit.*, p. 290.

apparent, the resistance was sometimes lowered, sometimes increased, sometimes the changes were not permanent; often sparks could be seen without any change in resistance taking place at all.

From this it would appear that the phenomenon of coherer action can be best studied only when sparking is avoided. This point was thoroughly established by the quantitative experiments made by one of us a year ago<sup>1</sup> in which a remarkable regularity in the behavior of the coherer was observed, undoubtedly due to the fact that the above condition was fulfilled.

In making the experiments here reported, we were careful to avoid all disturbing influences, and here also the results are very concordant.

DESCRIPTION OF APPARATUS.

The lowering of the resistance of the coherer was produced by the closing of a circuit which consisted of a high E. M. F., which could be varied at will, a variable resistance  $R$ , and the coherer, in series.

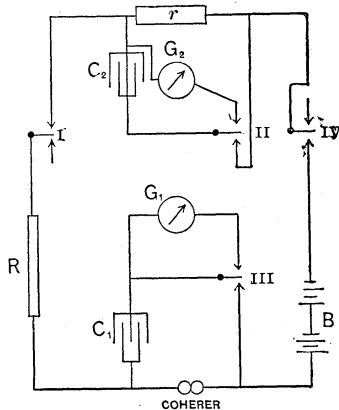


Fig. 1.

The lowering of the resistance of the coherer was produced by the closing of a circuit which consisted of a high E. M. F., which could be varied at will, a variable resistance  $R$ , and the coherer, in series.

The resistance of the coherer was measured by observing simultaneously the current through, and the potential difference at the terminals of, the coherer.

In order to work always under the same conditions, the apparatus was so arranged that the above measurements were taken always after the same very short time interval had elapsed since the circuit was closed.

This could best be accomplished by the use of a pendulum which in short succession actuates four circuit keys.

I., II., III. and IV. are those keys. When the keys are set before the pendulum is released, they make contact on their under sides. The pendulum in swinging from left to right releases them so that they make contact on their upper sides.

<sup>1</sup>Trowbridge, Am. Jour. of Science, Sept., 1899.

As soon as the pendulum in swinging releases key I., the current flows through the coherer and the condensers  $C_1$  and  $C_2$  are charged. Then keys II. and III. are released simultaneously, which discharges the condensers  $C_1$  and  $C_2$  through the galvanometer  $G_1$  and  $G_2$  respectively; key IV. opens the circuit again. In general key I. was kept always in the same position relative to keys II. and III. However this was not necessary, for, as will be seen later, the time element does not enter into the problem. The galvanometers with their condensers, were calibrated beforehand so that the deflection of  $G_1$  enabled us to determine the potential difference at the terminals of the coherer, that of  $G_2$  the current flowing in the coherer circuit.

The coherers investigated by us were all ball coherers. The following form was found very convenient to work with.

The balls  $bb$  were soldered to brass rods, one of which was in turn soldered to a stout metal post firmly embedded in the non-conducting base of the instrument. The other was supported by a brass spring, soldered to a plate which could be clamped to the base in any desired position. Against this spring a screw  $S$  could be pressed, allowing a fine adjustment of the contact.

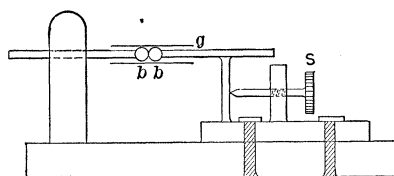


Fig. 2.

In the investigation of a coherer of several contacts a glass tube  $g$  could be slipped over the balls to hold them in position.

In making observations, the method of procedure was the following: The coherer was adjusted by means of the screw so that it had a very high finite resistance. This resistance was roughly measured by means of an auxiliary circuit through the coherer, consisting of a battery of low electromotive force, a resistance and a galvanometer calibrated to indicate the current flowing in the auxiliary circuit.

This method was found to be preferable to one originally adopted by us, which was to set the contact by means of a microscope. By this method it was found difficult to get always an original high finite resistance, as sometimes when under the microscope the balls seemed to be in contact no coherer action took place on closing the

main circuit. By using the method of adjustment with the auxiliary circuit, coherer action always took place on working the pendulum apparatus.

In each series of experiments the applied voltage of the battery  $B$  was kept constant and with a given resistance  $(R + r)$  in series with the coherer the pendulum was released, and the readings of galvanometers I. and II. were noted: the contact was then readjusted to its original high resistance, and the observations repeated from 10 to 15 times.

Next  $(R + r)$  was varied and a similar set of observations taken.

The range of the values of  $(R + r)$  was so chosen that the current through the coherer was varied from 0.002 ampère to 0.7 ampère.

For each coherer, several such series of observations were obtained with different applied voltages at  $B$ .

#### RESULTS.

##### A. *Experiments on coherers of a single contact.*

1. *Steel.*—Balls of three different diameters were used, 4.75 mm., 6.35 mm. and 9.5 mm.

In the following tables  $i$  denotes the current through the coherer observed with the galvanometer  $G_2$ ,  $p$  the potential difference between the terminals of the coherer observed with the galvanometer  $G_1$  and the resistance of the coherer calculated from  $p$  and  $i$ .

TABLE I.

*Steel: Diameter = 4.75 mm. Applied voltage 6.5 volts.*

$i$	$p$	$\rho$	$i$	$p$	$\rho$
0.0027	0.0457	16.59	0.0521	0.234	4.48
0.0054	0.0894	16.62	0.124	0.229	1.84
0.0106	0.174	16.40	0.254	0.237	0.94
0.0273	0.208	7.63	0.492	0.228	0.47

TABLE II.

*Steel: Diameter = 4.75 mm. Applied voltage 14.0 volts.*

$i$	$p$	$\rho$	$i$	$p$	$\rho$
0.0026	0.0218	8.42	0.124	0.224	1.84
0.0064	0.0451	7.10	0.212	0.229	1.08
0.0127	0.0904	7.12	0.309	0.228	0.74
0.0256	0.160	7.07	0.604	0.235	0.39
0.0621	0.211	3.40			

TABLE III.

*Steel : Diameter = 4.75 mm. Applied voltage 60 volts.*

$i$	$\rho$	$\rho$	$i$	$\rho$	$\rho$
0.0051	0.0103	2.01	0.0989	0.141	1.42
0.0124	0.0218	1.77	0.247	0.196	0.78
0.0247	0.0458	1.94	0.494	0.232	0.47
0.0494	0.0832	1.79	0.617	0.226	0.37

TABLE IV.

*Steel : Diameter = 4.75 mm. Applied voltage 220 volts.*

$i$	$\rho$	$\rho$	$i$	$\rho$	$\rho$
0.0056	0.0021	0.38	0.221	0.0873	0.39
0.0223	0.0114	0.51	0.313	0.144	0.45
0.0551	0.0255	0.46	0.438	0.224	0.51
0.0749	0.0374	0.50	0.722	0.218	0.30
0.111	0.0534	0.48			

TABLE V.

*Steel : Diameter = 6.35 mm. Applied voltage = 51 volts.*

$i$	$\rho$	$\rho$	$i$	$\rho$	$\rho$
0.0118	0.024	2.04	0.162	0.186	1.09
0.0236	0.058	2.46	0.219	0.224	1.02
0.0477	0.104	2.20	0.479	0.239	0.50
0.0954	0.160	1.68	0.784	0.240	0.37

TABLE VI.

*Steel : Diameter = 6.35 mm. Applied voltage = 220 volts.*

$i$	$\rho$	$\rho$	$i$	$\rho$	$\rho$
0.0208	0.0134	0.64	0.297	0.121	0.41
0.0512	0.0250	0.49	0.420	0.178	0.42
0.103	0.0450	0.44	0.523	0.190	0.36
0.210	0.0760	0.36	0.696	0.230	0.33

TABLE VII.

*Steel : Diameter = 9.5 mm. Applied voltage = 51.5 volts.*

$i$	$\rho$	$\rho$	$i$	$\rho$	$\rho$
0.0106	0.0260	2.46	0.171	0.213	1.25
0.0257	0.0686	2.66	0.255	0.225	0.88
0.0512	0.0935	1.83	0.510	0.216	0.42
0.0727	0.160	1.72	0.836	0.224	0.27
0.105	0.181	1.68			

2. *Copper.*—Copper plated steel balls, diameter 9.5 mm.

TABLE VIII.

*Copper: Diameter = 9.5 mm. Voltage applied = 50 volts.*

<i>i</i>	<i>p</i>	$\rho$	<i>i</i>	<i>p</i>	$\rho$
0.0101	0.004	0.41	0.512	0.171	0.33
0.051	0.041	0.80	0.819	0.174	0.21
0.102	0.081	0.78	1.252	0.171	0.15
0.256	0.154	0.60			

3. *Lead.*—Diameter 3.0 mm.

TABLE IX.

*Lead: Diameter = 3.0 mm. Applied voltage = 14.2 volts.*

<i>i</i>	<i>p</i>	$\rho$	<i>i</i>	<i>p</i>	$\rho$
0.012	0.020	1.67	0.118	0.120	1.06
0.024	0.040	1.67	0.291	0.121	0.42
0.059	0.081	1.53	0.573	0.123	0.22

TABLE X.

*Lead: Diameter = 3.0 mm. Applied voltage = 39.5 volts.*

<i>i</i>	<i>p</i>	$\rho$	<i>i</i>	<i>p</i>	$\rho$
0.009	0.009	1.00	0.120	0.107	0.90
0.018	0.020	1.11	0.182	0.131	0.72
0.036	0.036	1.00	0.361	0.129	0.36
0.073	0.069	0.94	0.591	0.131	0.22
0.092	0.087	0.94			

TABLE XI.

*Lead: Diameter = 3.0 mm. Applied voltage = 220 volts.*

<i>i</i>	<i>p</i>	$\rho$	<i>i</i>	<i>p</i>	$\rho$
0.021	0.008	0.39	0.433	0.085	0.19
0.051	0.016	0.31	0.512	0.101	0.19
0.102	0.036	0.35	0.683	0.129	0.17
0.209	0.060	0.29	1.024	0.127	0.12

4. *Phosphor Bronze.*—Diameter 3.2 mm.

TABLE XII.

*Phosphor Bronze: Diameter = 3.2 mm. Applied voltage = 220 volts.*

<i>i</i>	<i>p</i>	$\rho$	<i>i</i>	<i>p</i>	$\rho$
0.022	0.024	1.07	0.317	0.182	0.60
0.055	0.032	0.58	0.442	0.189	0.43
0.110	0.072	0.64	0.727	0.197	0.29
0.222	0.112	0.51			

From the foregoing tables it appears that, for increasing  $i$ ,  $p$  approaches asymptotically a finite maximum value. This value is different for different substances but the same for any one substance whatever the applied electromotive force and, at least in the case of steel, it is practically independent of the size of the balls.

We have plotted the results contained in tables I. to IV. in Fig. 3, those of tables V. and VI. in Fig. 4 and those of tables IX. to XI. in Fig. 5.

In these figures the abscissas are the currents and the ordinates the corresponding values of the terminal potential differences at the coherer.

The simplest differential equation which fulfills the condition that  $p$  approaches a finite maximum value  $P$  is  $dp = k(P - p)pi$  where  $k$  is a constant whose dimensions must be an inverse of a current.

This differential equation when integrated gives  $p = P(1 - e^{-ki})$  Eq. 1, and, as will be shown later on, this exponential equation expresses analytically almost all of our results.

It seems perhaps to be more than a mere coincidence that this formula is identical with that which one of us (Guthe, *PHYS. REV.*, Vol. 7, p. 193, 1898) has shown to hold for the polarization of copper in copper sulphate solution.

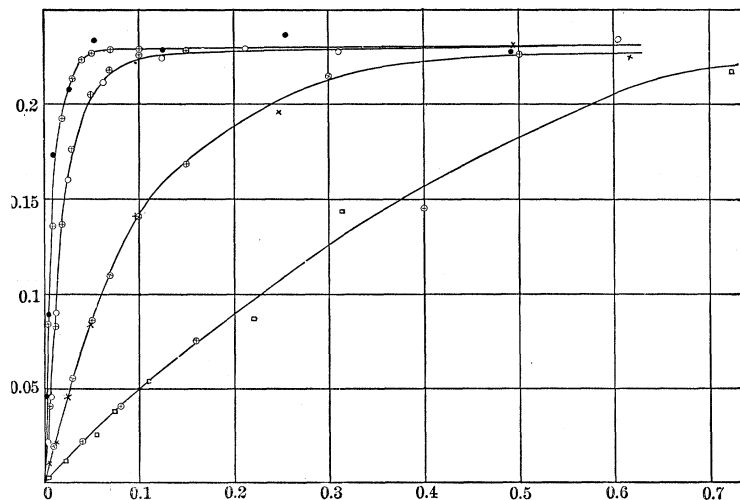


Fig. 3.



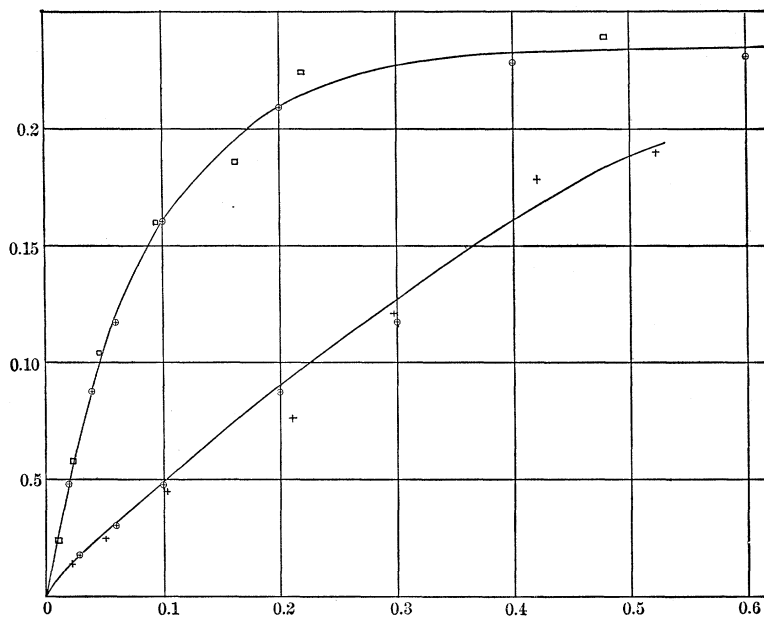


Fig. 4.

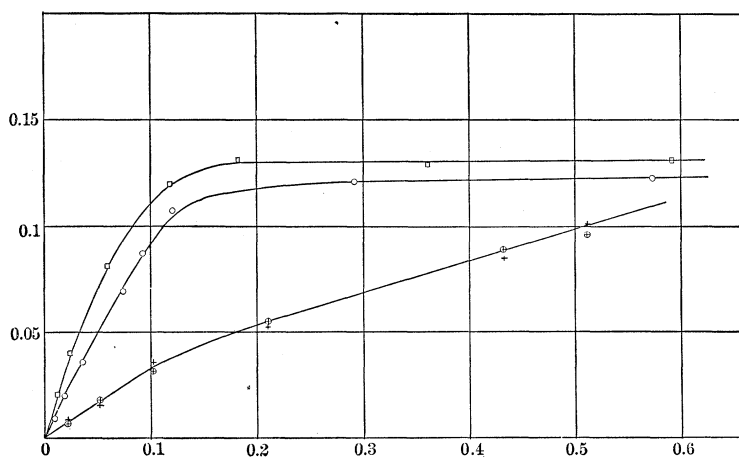


Fig. 5.

May not coherer action be explained in the following way?  
 On the surface of the metals in loose contact we have a con-

densed, badly conducting atmosphere, possibly water vapor. Thus before a current flows the resistance is very high.

For simplicity let us consider two spherical conductors in loose contact with these films between them. As soon as potential difference exists between them the films are squeezed together by electrostatic attraction and over a circular area  $A$  the thickness of the films will be of molecular dimensions.

In Fig. 6, using the same coördinates as in the foregoing figures, the tangent of  $OT$  would represent the resistance of the film  $A$  at the moment the voltage is applied. As the current flows ions from the positive electrode break through the film forming metallic contact and thus reducing the resistance.

After the current stops flowing the balls are in intimate contact and held together by cohesion. Therefore the resistance does not increase again after the current ceases to flow.

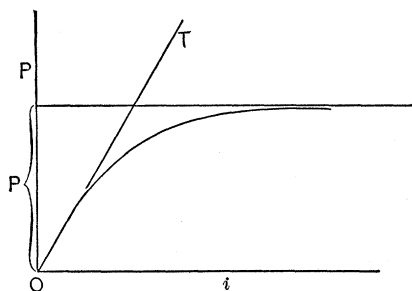


Fig. 6.

That the resistance after lowering is not affected by a current *smaller* than that which produced the lowering was found to be the case by a series of experiments, while if a *larger* current were sent through, the resistance adjusted itself to the value it would have had had we started with a very high original resistance and sent through it this larger current.

In general we found that it makes very little difference what pressure the coherer is under before the current is sent through provided always the pressure is varied within reasonable limits.

As mentioned above the coherer particles under electrostatic pressure are in contact to within molecular distances over a certain area  $A$ . Now we make the supposition that a definite minimum number of ions is needed to carry any given current  $i$ .

Let  $P$  be the difference of potential over a film  $A$  filled with a number of ions just sufficient to carry the current  $i$ . Or in other  $P$  is the potential difference over a molecular layer of ions in which

there flows through each ion the maximum current it can carry. If the current be increased beyond this point one of two things might happen. Either the area  $A$  can be increased by the ions filling out a space exterior to  $A$  and the current be now carried by an area proportional to it or if the area cannot change then heating and perhaps melting might take place.

The area  $A$  defined above we will in future call the *critical area* and we will assume that the first of the above possibilities is what takes place in the coherer as it explains the horizontal part of our curves where  $P = \text{const.}$

Suppose now in the case of a given current  $i$  the area of the film of molecular thickness to be larger than the one which, when filled with ions, would carry this current. A greater than the *critical number* of ions will break through the surface in the first impulsive rush when the voltage is applied. In consequence the difference of potential produced will be less than the critical value  $P$ .

If  $n$  ions would just carry the current  $i$  we would have  $an$  ions in the case of a larger surface where  $a$  is greater than unity and will increase with the size of the contact surface.

For the critical surface the potential difference would be, according to definition,  $P = \frac{r}{n} i$ , for a surface larger than the critical  $P = \frac{r}{an} i$ , i. e.,  $p < P$ .  $r$  would be the ohmic resistance of an ion and  $a$  can be determined from our differential equation.<sup>1</sup>

This would mean that the nearer filled up the area is the less readily the ions will go over and hence the increase of  $p$  with increasing  $i$  will become smaller and smaller until it finally becomes zero when  $P$  is reached.

A rather striking relationship between the critical voltages  $P$  of the substances investigated by us suggests itself.

From the tables above we have  $P$  steel 0.23 volts,  $P$  copper 0.173 volts,  $P$  lead 0.127 volts. Supposing the valency of Fe and

<sup>1</sup> In case of surfaces of very large dimensions as in ordinary metallic contact then  $a$  will approach  $\infty$  and the resistance of the contact which is  $\frac{r}{an}$  would approach zero. Now  $\frac{dp}{di} = \frac{kr}{n} (1 - \frac{1}{a})$  and  $i/n$  is a constant. If  $a$  is so large that  $\frac{1}{a}$  can be neglected we have the case of a continuous conductor and our differential equation reduces to Ohm's law.

Cu to be 2 and of Pb to be 4 then the gramme equivalents are respectively 28, 31.75 and 51.75.

Multiplying  $P/\text{Fe}$  by 28 gives 6.44,  
 $P/\text{Cu}$  by 31.75 gives 5.50,  
 $P/\text{Pb}$  by 51.75 gives 6.57,

or  $P \times \text{gramme equivalent} = \text{const. nearly.}$

When we come to consider the curves for different applied electromotive forces we have to expect different electrostatic attraction between the balls to begin with.

Let us assume Hooke's law to hold for the coherer substance and that no shearing takes place. Let  $S$  be the area on which the pressure  $\pi$  acts, then  $d\pi = a'Sdl$  where  $dl$  is the displacement produced and  $a'$  is a constant. For displacements as small as we must assume them here to be  $dS \sim dl$  from which follows  $d\pi = aSdS$  or the total pressure  $\pi = a/2S^2$ , Eq. 2.

Now to the same order of approximation  $\pi$  varies as the square of the potential gradient; therefore, very nearly,  $S$  varies directly as  $E$ . But the difference of potential necessary to bring the coherer balls into point contact is  $P$  (according to the assumption made above) hence if the applied voltage be called  $ES$  varies as  $(E - P)$ .

As shown in Fig. 6 the tangents of the curves at the origin are a measure of the resistance of the areas  $S$ . Now since for ( $\lim i = 0$ ) all our curves are straight lines the law of resistances must hold for the films at this point and  $\rho$  must be inversely proportional to  $S$ .

If this is true then the general form of our differential equation is  $d\rho = c(P - \rho)/(E - P)di$ , Eq. 3.

The tangent for any curve,  $E = \text{const.}$  for ( $\lim i = 0$ ) is  $CP/(E - P) = kP$ . As mentioned above this is the resistance of the film between the balls when the voltage  $E$  is applied.  $k(E - P)$  should then be constant for one and the same substance. That this is so will be shown in Table XIX. In the tables preceding this one we have compared the numerical values calculated by means of Eq. 1 with the experimentally determined ones from our curves.

The results with phosphor bronze were rather irregular as compared with those for steel and copper.

TABLE XIII.

*Steel: Small Diameter. Applied voltage = 6.5 volts. k = 90. P = 0.23 v.*

$i$	$\beta$ from curve.	$\beta$ calculated.	$i$	$\beta$ from curve.	$\beta$ calculated.
0.005	0.078	0.083	0.04	0.223	0.223
0.01	0.136	0.136	0.05	0.227	0.226
0.02	0.192	0.191	0.07	0.229	0.228
0.03	0.213	0.212	0.10	0.229	0.229

TABLE XIV.

*Steel: Small Diameter. Applied voltage = 14.0 volts. k = 45. P = 0.23 v.*

$i$	$\beta$ from curve.	$\beta$ calculated.	$i$	$\beta$ from curve.	$\beta$ calculated.
0.005	0.040	0.042	0.05	0.205	0.205
0.01	0.080	0.083	0.07	0.218	0.219
0.02	0.137	0.136	0.10	0.223	0.226
0.03	0.170	0.176	0.15	0.228	0.229

TABLE XV.

*Steel: Small Diameter. Applied voltage 60 volts. k = 9.5. P = 0.23 v.*

$i$	$\beta$ from curve.	$\beta$ calculated.	$i$	$\beta$ from curve.	$\beta$ calculated.
0.01	0.020	0.021	0.10	0.141	0.140
0.03	0.056	0.057	0.15	0.169	0.168
0.05	0.086	0.087	0.3	0.214	0.216
0.07	0.110	0.111	0.5	0.227	0.227

TABLE XVI.

*Steel: Small Diameter. Applied voltage 220 volts. k = 2.5. P = 0.23 v.*

$i$	$\beta$ from curve.	$\beta$ calculated.	$i$	$\beta$ from curve.	$\beta$ calculated.
0.04	0.022	0.022	0.4	0.145	0.145
0.08	0.041	0.041	0.8	0.198	0.198
0.16	0.075	0.076			

TABLE XVII.

*Steel: Medium Diameter. Applied voltage = 51 volts. k = 12. P = 0.23 v.*

$i$	$\beta$ from curve.	$\beta$ calculated.	$i$	$\beta$ from curve.	$\beta$ calculated.
0.02	0.048	0.048	0.2	0.210	0.209
0.04	0.087	0.087	0.4	0.232	0.228
0.06	0.120	0.117	0.6	0.235	0.230
0.1	0.160	0.160			

TABLE XVIII.

*Steel: Medium Diameter. Applied voltage = 220 volts.  $k = 2.4$ .  $P = 0.23$  v.*

$i$	$\hat{p}$ from curve.	$\hat{p}$ calculated.	$i$	$\hat{p}$ from curve.	$\hat{p}$ calculated.
0.03	0.018	0.018	0.2	0.090	0.087
0.06	0.030	0.030	0.3	0.125	0.117
0.1	0.048	0.048			

TABLE XIX.

*Summary for Steel Balls.*

(a) Small Diameter.			(b) Medium Diameter.		
$E$	$k$	$k(E-P)$	$E$	$k$	$k(E-P)$
6.5	90	564	51	12	610
14.0	45	619	220	2.4	528
60.0	9.5	568			
220.0	2.5	550			Mean 569
	Mean	575			

TABLE XX.

*Copper: Applied voltage = 50 v.  $k = 6$ .  $P = 0.171$  v.*

$i$	$\hat{p}$ from curve.	$\hat{p}$ calculated.	$i$	$\hat{p}$ from curve.	$\hat{p}$ calculated.
0.03	0.028	0.028	0.2	0.123	0.120
0.06	0.050	0.051	0.3	0.150	0.156
0.1	0.081	0.080	0.6	0.172	0.171

$$k(E - P) = 298.$$

The curves for lead, while they have the same general form as the others, cannot be represented by our equation 1 except in the case where  $E = 220$  volts. Certainly we cannot expect very concordant results with a substance as inelastic as lead. The lead balls on examination after use showed that they had undergone a permanent deformation.

TABLE XXI.

*Lead: Applied voltage = 220 v.  $k = 2.76$ .  $P = 0.127$  v.*

$i$	$\hat{p}$ observed.	$\hat{p}$ calculated.	$i$	$\hat{p}$ observed.	$\hat{p}$ calculated.
0.021	0.0081	0.0071	0.433	0.0848	0.885
0.051	0.0161	0.0168	0.512	0.101	0.961
0.102	0.0363	0.0312	1.024	0.127	0.119
0.208	0.0525	0.553			

$$k(E - P) = 607.$$

In the curves given above the calculated values are plotted with the observed and marked by a  $\oplus$ . In general the agreement seems to be very satisfactory.

We satisfied ourselves that we have here to do not with a time-rate of heaping up of ions until a maximum is reached ( $dp \sim dq$ ) but rather that the potential difference depends, in the main at least, on the current. This we did by changing the position of key I. (see Fig. 1) thus varying the time during which the current flowed within a considerable range without any appreciable effect on the value of  $p$ .

ADDITIONAL RESULTS.

Besides the above observations on coherers of a single contact we made a test of the effects of the number of contacts on the critical voltage  $P$ .

From the foregoing theory we must expect that the formula for a coherer of  $n$  contacts our differential equation must be

$$p = nP(1 - e^{-ki})$$

for if we have  $n$  contacts our differential equation must be

$$dp = k(nP - p)di$$

or we would expect that the potential difference is additive in character.

TABLE XXII.

*Steel; Small Diameter. 5 contacts. Applied voltage = 15.2 v.*

$i$	$p$	$\rho$	$i$	$p$	$\rho$
0.00363	0.228	62.8	0.130	1.258	9.7
0.00744	0.499	60.4	0.630	1.216	1.9
0.0142	0.832	58.6			

TABLE XXIII.

*Steel; Small Diameter. 5 contacts. Applied voltage = 51.75 v.*

$i$	$p$	$\rho$	$i$	$p$	$\rho$
0.0127	0.156	12.3	0.101	0.915	9.1
0.0254	0.339	13.5	0.251	1.210	4.8
0.0508	0.524	10.3	0.499	1.227	2.5

TABLE XXIV.

*Steel: Small Diameter. 5 contacts. Applied voltage = 220 v.*

$i$	$\phi$	$\rho$	$i$	$\phi$	$\rho$
0.00565	0.0166	2.94	0.223	0.478	2.14
0.0223	0.0686	3.08	0.316	0.707	2.23
0.0551	0.145	2.63	0.442	0.998	2.27
0.111	0.305	2.74	0.722	1.112	1.53

TABLE XXV.

*Steel: Small Diameter. 10 contacts. Applied voltage = 220 v.*

$i$	$\phi$	$\rho$	$i$	$\phi$	$\rho$
0.0226	0.143	6.33	0.313	1.684	5.38
0.0551	0.324	5.88	0.438	2.200	5.02
0.110	0.665	6.03	0.727	2.270	3.12
0.221	1.112	5.03			

The above tables are sample ones from the experiments on several contacts. We also investigated lead and phosphor bronze and found them to exhibit the same behavior, *i. e.*,  $\phi_n = n\phi_1$ .

It may be mentioned here that in working with coherers it is advisable to have the coherer substance always in the same condition as regards oxidation. This has been pointed out by other observers. We usually cleaned the balls with the finest grade of emery paper and then let them stand for several hours before using. If used directly after cleaning a high initial resistance could not be obtained when the balls were in contact.

After several days' use a marked oxidation was observed to have set in and the critical voltage was found to have become somewhat higher.

The following example brings out this point. A set of balls freshly set up gave the following critical voltages :

One contact, 0.232 volt.

Two contacts, 0.468 volt.

Four contacts, 0.936 volt.

After a few weeks the values were :

Five contacts, 1.43 volts.

Ten contacts, 2.85 volts.

Twenty contacts, 5.84 volts.



The effect of oxidation may be that the badly conducting oxide particles make our hypothetical film between the balls thicker and hence the resistance of the film greater and the terminal potential differences also greater.

It may be of interest to point out the similarity with the behavior of electrolytic cells. Copper in copper sulphate after the copper is slightly oxidized shows a very much higher value of  $P$  than when the electrodes are clean.<sup>1</sup>

To satisfy ourselves that the coherers used were sensitive to Hertz radiations we set up a Hertz oscillator in the same room with the apparatus described above. The coherer was connected neither to earth nor to a vertical wire.

The resistance of the coherer was measured before and after the lowering due to the radiation by the method employed throughout this investigation, being careful, however, to use a current so small that it alone would produce no further lowering of the resistance of the coherer after radiation.

The Hertz oscillator was placed at distances varying from 2 m. to 7 m. from the coherer. The lower limits of the resistance were wholly independent of the original high resistance and decreased not quite as fast as the square of the distance.

#### CONCLUSION.

From the present investigation and from the work of other observers it seems to be justifiable to attribute the high original resistance of the coherer to the film on the surface of the metallic particles.

Dorn has shown that very little or no coherer action takes place between surfaces of the noble metals when they have been heated in a vacuum so as to expel as far as possible the surface film.<sup>2</sup>

He also found a decided decrease of resistance for other metals.

Aschkinass,<sup>3</sup> on the other hand, tried to remove the surface film from the filing particles in a tube by exhausting and heating but did not observe any change in the behavior of the coherer. He admits himself, however, that this can hardly be considered a decisive test.

<sup>1</sup> See Guthe and Atkins, Proc. A. A. A. S., 1899, p. 109.

<sup>2</sup> Dorn, Wied. Ann., 66.

<sup>3</sup> Loc. cit.

The fact mentioned above that metallic surfaces after thorough cleaning do not show a high contact resistance is also in favor of our supposition and we believe that Auerbach's results can easily be explained by the rubbing away of the films by mechanical action.

The films must form a sort of protecting layer on the metal surface as the following experiment shows :

Two coherers, consisting of one contact each, were put in parallel and the circuit closed through them. The resistance of each was measured before and after lowering and it was found that coherer action took place in one only. After standing a day this one was always oxidized while the other showed a bright surface where the balls had been in contact. The coherer action had apparently destroyed the protecting film of the one in which it took place.

Aschkinass mentions his interesting results with coherers consisting of  $\text{PbO}_2$  or  $\text{CuS}$  particles as a proof against Lodge's theory. They behave in the opposite way from the ordinary coherer.

We would suggest in view of the similarity with polarization that the compounds are in this case broken up into two components, one of which conducts well and the other poorly. No actual metallic contact need then occur and the S or O would play a decided rôle in the increase of the resistance.

It seems that particles of any conducting substance may form a coherer—among others carbon. This suggests an interesting question in connection with the electric arc.

Ayrton and Perry<sup>1</sup> found that the difference of potential between the two carbons of an arc lamp was independent of the current strength provided the distance between them was kept constant, *i. e.*, the *apparent* resistance of the arc was inversely as the current.

Does this correspond to the horizontal line of our curves and does cohesion play any part in the starting of the arc?

We offer the foregoing considerations merely as a tentative explanation of this little-understood phenomenon, being well aware that some of our assumptions are somewhat crude, but hoping nevertheless that they may lead to a fuller understanding of the subject since they seem to furnish a satisfactory hypothesis.

PHYSICAL LABORATORY OF THE UNIVERSITY OF MICHIGAN, June, 1900.

<sup>1</sup> Phil. Mag., May, 1883.