ON THE NATURAL CHARGES OF METALS[1]

IN 1789 Bennett discovered that when two similar, insulated brass plates are placed very close together and parallel to each other and are simultaneously touched with pieces of different metal held in the hands they become charged relative to each other, and oppositely charged relative to the earth. Bennett gave the results of touching his plates with six different pairs of metals, and thus laid the foundation for what later came to be called the Volta contact series of metals. Bennett concluded as the result of his experiments that different substances have "a greater or less affinity with the electrical fluid," and he published a series of "Experiments on the Adhesive Electricity of Metals and Other Conducting Substances."

Bennett also tried the effect of touching one brass plate with a single metal while the other plate was parallel and very close to it but was joined to earth, and he found that his brass plate would take a positive charge when touched with lead ore, gold, silver, copper, brass, regulus of antimony, bismuth, tutenag, mercury and various kinds of wood and stone; but that it would take a negative charge from zinc and tin.

Six years later (in 1795) Cavallo published the results of a series of experiments on contact electrification. Cavallo placed a tin plate upon insulating supports and dropped a piece of metal upon it from the hand or from tongs or a spoon. He then tilted the tin plate and allowed the metal to slide off it, after which it was picked up and dropped onto the plate again. By sufficient repetition of this process, the plate became so highly electrified that the nature of its charge could be determined. Cavallo tried the effect of dropping his pieces of metal from a spoon or tongs of another metal, and made a large number of experiments upon the effect of heating or cooling the pieces of metal before they were dropped upon the tin plate. At the end of his experiments, he said, among his other conclusions:

> I am inclined to suspect that different bodies have different capacities for holding the electric fluid, as they have for holding the elementary heat.

In the meantime, Volta had discovered the existence of an electric current in a circuit made of two metals and a moist conductor. He first thought the source of the current to be in the surfaces of contact of the metals with the moist conductor, but later concluded that the current was not only originated, but was sustained, by the mutual contact of two metals of a different kind. In support of this conclusion, he published a series of experiments on contact electrification which were a virtual repetition of Bennett's experiments which had been published eight years before, but for which Volta gave Bennett no credit.

Meanwhile, in 1792, Fabroni had published his celebrated paper entitled "Upon the Chemical Working of the Different Metals upon Each Other at Ordinary Air Temperatures, and Upon the Explanation of Certain Galvanic Phenomena." In this paper Fabroni showed that the surface cohesion of different metals is changed merely by their mutual contact, so that metals which before contact were not attacked by the oxygen of the air or of water are readily oxidized when in contact with another less oxidizable metal. When Volta's discovery of the current was announced, Fabroni naturally concluded that the chemical action which took place at the surface of contact of at least one of the metals and the moistened membrane was the cause of the electrical current.

As a result of the controversy which followed regarding the source of the electromotive force in the voltaic current, a similar controversy arose over an entirely different question, viz., as to whether the transference of electricity from one metal to another as observed by Bennett and Cavallo was a primary phenomenon of metallic contact, or whether it was due to a preceding action of oxygen or some other element upon one or both of the metals. Ostwald, speaking of the theory of direct electrification by contact says:

[1] Read before a joint meeting of Section B of the American Association for the Advancement of Science and the American Physical Society, at Berkeley, California, August 5, 1915.

We stand at a point where the most prolific error of electrochemistry begins, the combating of which has from that time on occupied almost the greater part of the scientific work in this field.

This opinion has undoubtedly been shared by most chemists and by many physicists from that day to this.

It seems strange that those champions of the theory of the chemical origin of the contact charge who look upon Fabroni as the founder of their theory have overlooked the fact that what Fabroni especially undertook to show in his paper was that the mere contact of two metals weakens the cohesion between the molecules of at least one of them, and that this change was precedent to the chemical action which he regarded as the cause of the electrical current. Since we now know that cohesion is an attraction between the electropositive and electronegative ions of the metal, or more definitely, between the positive sub-atoms and the electrons within the metal, if we accept the foundation hypothesis of Fabroni we must conclude that the mere contact of two different metals produces a change in the electrical forces between their surface atoms before any chemical action is set up.

That this opinion was shared by Berthollet may be gathered from a translation in *Nicholson's Journal*[2] of a part of Berthollet's "Essai de Statique Chimique."

After a discussion of a number of experiments performed by Charles and Gay Lussac for the purpose of deciding whether the dissipation of a fine wire by the electric discharge of a Leyden jar was due to the heating effect of the spark or to some other cause, and their conclusion that the wire was not vaporized by heat, Berthollet concludes that the dispersion of the metallic particles precedes their oxidation, and says:

Electricity favors this oxidation, inasmuch as it diminishes the force of cohesion; it is thus that an alkali renders the action of sulphur on oxygen much more powerful, by destroying the force of cohesion opposed to it, and that a metal dissolved in an amalgam is oxidized more easily than when it is in the solid state.

[2] Vol. 8, p. 80.

All the chemical effects produced in substances submitted to the action of electricity seem capable of being deduced from these considerations, and of being explained by the diminution of the force of cohesion, which is the obstacle to the combinations which their molecules tend to form.

The fundamental question at issue in the century-long battle which has been fought over contact electrification has been: Are the charges which are found upon two plates of different metals when they have been placed in contact and then separated due to some chemical action which has taken place at the time of contact, or were the two metals before they were brought into contact already electrically different with respect to each other? Or, since metals are said to be unelectrified when they have been put into good metallic contact with the earth while at a distance from other bodies, may two metals which are unelectrified with reference to the earth still be in different electrical states relative to each other?

Many physicists have maintained that two metals which have been discharged to the earth or to the inside of a hollow conductor are in absolutely the same electrical state, *i. e.*, that they are in a condition of absolute electrical neutrality. Others have believed that the change in the electrical state of both metals when they are brought into contact with each other proves that they were not in an electrically neutral condition before contact.

Among those who believe that before contact the metals are in an electrically neutral condition it is commonly held that the electrical displacement which occurs when two metals are brought into contact is due to the greater affinity of oxygen for one of the metals than for the other. Those who hold this view seem to overlook the fact that affinity for oxygen must be, itself, an electrical attraction. If zinc has an affinity for oxygen, it is because the zinc is either electropositive or electronegative to oxygen. If zinc has a greater affinity for oxygen than copper has, the zinc must be more electropositive or electronegative to oxygen than is copper, and in consequence it must be electropositive or electronegative to copper. This being the case, and both being conductors, they should when brought near together each induce a free charge upon the other.

This phenomenon was actually observed by Exner, who describes an experiment for showing it in *Repertorium der Physik*, XVII., 444 (1881). In this experiment a zinc plate was placed in a horizontal position, and after being discharged to earth was insulated. A similar copper plate could be lowered parallel to the zinc plate and very near it. This copper plate was earthed, then insulated and brought very near to the zinc plate and connected to an electrometer. This caused an electrometer deflection of + 9 scale divisions, due to the free charge induced upon the copper plate by the zinc. The copper plate and electrometer while still connected were earthed, and the electrometer deflection returned to zero. They were then again insulated, and while still connected, the copper plate was raised from the zinc plate. The electrometer then showed a deflection of — 9 scale divisions, due to the bound charge which had been induced upon the copper plate. After the copper plate was removed the zinc plate was tested and showed no free charge, it having been insulated throughout the experiment.

This seems to show conclusively that a zinc plate which has been discharged to earth and insulated is capable of inducing a free positive charge upon an insulated copper plate which is brought near it.

Exner also showed that when a platinum plate and a zinc plate, after having been discharged to earth and then insulated, are brought very near together each induces a free charge upon the other which may be shared with an electrometer. If the electrometer be connected first with the platinum plate it will show a positive charge. If the electrometer and plate be discharged to earth and again insulated and the electrometer connected to the zinc plate, it will show a negative charge. After this has been discharged to earth and the plate and electrometer again insulated the platinum will show another positive charge. In this way Exner was able to take twenty successive charges, alternately positive and negative, from his plates before their induced free charges were entirely discharged. This corresponds exactly to discharging the conductors of an insulated Leyden jar alternately.

The free charges induced by the approach of different metals to each other are discussed by Majorana in *Phil. Mag.*, XLVIII., p. 241, where they are called approach charges. Majorana also showed the attraction of one metal upon another at very small distances.

It is difficult to see how these induced charges can be accounted for by any chemical explanation. Neither can they be accounted for on the assumption of a double electric layer of any kind on the surface of the metal, since the distance between the positive and negative surfaces in such a layer would necessarily be so small that their differential effect would vanish at very small distances, and the induced charges may easily be observed when two plates of different metal are more than a centimeter apart. They may even be shown at much greater distances by using a hollow conductor of one metal and introducing the other metal into it. In this way an induced charge may be taken from the outer surface of the hollow conductor without bringing the two metal surfaces near together. In this case all talk of a double electrical layer is excluded, as is also any chemical action taking place within the hollow conductor after the inner metal is introduced.

This induced charge upon the outer hollow conductor may be shown even while the inner metal is in contact with the earth or with the inside of an earthed hollow conductor. A simple method of doing this is as follows:

A Dolazalek quadrant electrometer, *E*, in the diagram, is enclosed in a cage of fine wire mesh which is earthed through a wire soldered to the water system of the laboratory. The outer case of the electrometer and one pair of quadrants are connected to this cage. The other pair of quadrants is connected to a hollow metal cylinder, which may conveniently be about 15 centimeters long and 2 cm. in internal diameter. This cylinder, *C*, in the diagram, is supported horizontally upon hard rubber blocks inside the cage.

A round metal rod or tube, *R*, in the diagram, about one centimeter in diameter, is mounted in earthed metal guides which are concentric with the hollow cylinder, *C*. One of these guides passes through the wall of the wire cage, and is in metallic contact with it. A hole is cut in the cage opposite the other end of the hollow cylinder, so that the rod can be pushed concentrically through the hollow cylinder without touching its walls. The rod is thus always in contact with the cage which forms the earthed hollow conductor, and the part of it within the hollow cylinder is also within this earthed hollow conductor and in metallic contact with its walls.

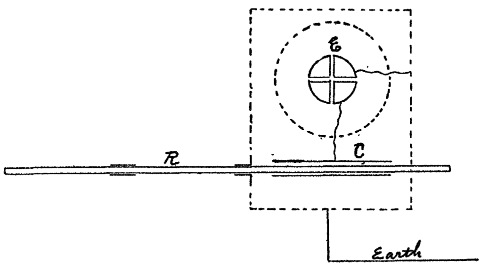

Fig. 1.

Before beginning an experiment, the needle of the electrometer, which was suspended by a quartz fiber, was charged from 200 dry cells and then insulated. The hollow cylinder, *C*, was then put in contact with the outer cage so that the free charge induced upon it by the electrometer needle might be taken off. When, now, the earthed rod was pushed through the cylinder, a charge was induced upon the cylinder which varied with the metal of the rod. Thus when a compound rod consisting of rods of the same diameter of zinc and copper put together, end to end, was pushed through the cylinder, the electrometer needle was differently deflected according as the zinc or copper part of the rod was in the cylinder. Thus in one experiment the copper part of the rod was pushed through the cylinder *C*, which was then discharged to the cage and again insulated. The zinc part of the rod was then pushed into *C*, and the electrometer showed a deflection of 12.5 scale divisions. This was repeated regularly many times. When the whole rod was withdrawn from the cylinder and an insulated copper rod of the same diameter was substituted for it and was alternately connected to the zinc and the carbon of a single dry cell, the electrometer gave a difference of scale reading of 35 scale divisions. Since the electromotive force of the dry cell used was about 1.25 volt, the difference of deflection for the zinc and copper ends of the rod indicated a difference of electric state of about .4 volt, the zinc being electropositive to the copper. This difference remained unchanged when the rod was in contact with the outer cage on both sides of the cylinder *C*.

By substituting an induction cylinder only 2.5 cm. long for *C*, it was found that the zinc was most electropositive next to the copper, and that its electropositive charge decreased gradually with the distance from this junction.

It has been known since the experiments of Cavallo that the contact charges of two metals depend upon their temperature. Since the contact charges which have been observed from Bennett's time on are apparently the bound charges induced by the two metals upon each other when close together, it was to be expected that the charges which metals hold while in contact with the earth or with the inside of a hollow conductor should vary with the temperature of the metal. By heating one section of a rod of a single metal and cooling another section, this expectation was verified. Thus, in the case of iron, steel, copper, brass and tin, the warmer part of the rod was electronegative to the colder part; in aluminium the warmer part became markedly electropositive, while in zinc the change was very slight.

Since the Thomson effect in iron indicates a change in the direction of the electromotive force at the junction of a hot and a cold part at about 150 degrees, an attempt was made to heat one end of a steel tube and keep the other end cold and measure the change of induced charge with a change in temperature. It was found that the tube used became more electronegative as its temperature increased up to 150 degrees, or more. From 150 to 200 degrees the electric charge of the metal changed very little, but beyond 200 degrees the tube became more electropositive with an increase in temperature. It was impossible to measure the induction of the tube much beyond 200 degrees, since at higher temperatures the hot tube ionized the air and allowed the induced charge of the cylinder to discharge to the tube.

It is interesting in this connection to note that the internal cohesion of iron and steel seems to change with a change in the fixed electric charge of the metal. In a paper on "Contact Electromotive Force and Cohesion" written several years ago it was shown that when the metals are arranged in their proper order in the contact electromotive series they are arranged in the inverse order of their cohesion, so that the more electronegative a metal is in the contact series the greater is its cohesion. Since in the case of the steel tube used in the experiment described above the metal became more electronegative up to a temperature of about 150 degrees, it would seem to be a legitimate deduction that the tensile strength of the tube should increase up to this temperature and then begin to decrease with a rise of temperature.

In a series of experiments made by C. Bach and described in *Zeitsch. d. Deutsch. Ingénieure,* 1904, p. 1300, the tensile strength of iron was actually found to be much greater at 200 degrees than at 20 degrees. From 200 to 300 degrees it decreases, but it is still greater at 300 degrees than at 20 degrees. At 400 degrees it is only a little less than at 20 degrees.

In the *Valve World* of January, 1913, is an article by I. M. Bregowski and L. W. Spring on "The Effect of High Temperatures on the Physical Properties of Some Metals and Alloys." In this article it is shown that samples of cast iron, both soft and hard, have a greater tensile strength at 300° F. than at 70° F., and that at 750° F. the tensile strength is still within one per cent. of as great as it is at 70° F. In the case of a sample of Crane Ferrosteel the tensile strength is greater at 750° F. than at 70° F.

In a dissertation by A. Lantz, entitled "Einwirkung der Temperatur auf die Biegfähigkeit von Flusseisen und Kupferdraehten," Berlin, 1914, the author finds that what he calls the *Biegfähigkeit* of iron, *i. e.,* its malleability or toughness as measured by the number of times it can be bent short forward and backward at a given point before breaking, increases with the temperature to about 220 degrees and then decreases. In some cases the wire would stand twice as many short bendings at 220 degrees as at room temperature, while at 350 degrees it would stand only one fifth as many as at room temperature. The toughness of copper measured in this way continued to increase to 320 degrees, which was the highest temperature of the experiment.

The above mentioned experiments all seem to indicate that the cohesion of iron increases with its increase of temperature so long as the iron continues to become more electronegative, and that the cohesion begins to decrease at about the temperature at which the iron begins to lose its negative charge.

This is what we should expect if cohesion is an attraction between positive and negative charges. An increase of cohesion would then mean a greater attraction of the positive subatoms of the metal for movable electrons and a consequent increase of the negative charge of the metal. So far as we know, such a change in the attraction of the positive sub-atoms for electrons can be brought about only by a change in the specific inductive capacity of the metal.

It would seem that all known phenomena of contact electrification may best be explained on the hypothesis that different metals when in electrical contact with the earth or with the inside of a hollow conductor, although by definition at zero potential, still actually retain characteristic charges which are capable of inducing a charge upon a different metal when brought near it. It is these characteristic charges which I have ventured to call the natural charges of the metals.

When two metals are brought near together while in electrical contact with the earth, their natural charges are increased or diminished by the bound charges due to their mutual induction. If insulated while in this position and then separated, the whole or a portion of their bound charges become free charges. If while separated they are electrically connected with the earth, such a transference of electricity will take place between each of them and the earth as will restore their original fixed charges.

Since a metal within a hollow conductor of another metal is wholly within the field of induction of the outer metal, the fixed charge which the inner metal will take when in contact with the outer will be determined to the greatest possible extent by the bound charge induced by the outer metal. Accordingly, this will, in general, be different from the fixed charge which the inner metal will take in the earth's field alone. It follows from this that when two metals inside a hollow conductor are brought into contact with each other and with the outer hollow conductor, the bound charges which they acquire are partly due to their mutual induction and partly to the induction of the outer hollow conductor. If they are flat plates and are placed parallel and very close together when touched to the outer conductor, their bound charges may be quite largely due to their mutual induction; if they are spheres with their surfaces touching while they are put into contact with the outer conductor, their bound charges will be determined principally by the induction of the outer conductor.

Thus, a zinc ball about 5 centimeters in diameter was insulated by a silk thread and was lowered into a metal beaker of 750 c.c. capacity until it touched the bottom. It then held the fixed charge due to the induction of the surrounding beaker. When it was lifted out of the beaker, this charge became free, and could be shared with an electrometer. The tilted gold leaf electrometer of C. T. R. Wilson was used on account of its small capacity.

The difference in the gold leaf deflection due to twenty successive charges from the inside of the bottom of a copper beaker and to the same number of charges from the inside bottom of an exactly similar aluminium beaker was 20.8 scale divisions, when the sensitivity of the instrument was 14 scale divisions for an ordinary dry cell.

A disc of tinfoil a little larger than the bottom of the beaker was then pressed down into each beaker until it rested on the bottom and was turned up about a centimeter around the inside of the beaker. The zinc ball was then charged as before by contact with the tinfoil instead of the metal of the beaker. As a mean of twenty such readings for each beaker made exactly as before the electrometer deflection amounted to 20 scale divisions for the difference of charge taken from the tin foil inside the two beakers. This showed that the fixed charges induced upon the zinc ball were due almost wholly to the outside beakers instead of the inside tinfoil.

The beakers were then inverted and the tinfoil discs were placed on the outside of their bottoms and the zinc ball charged by contact with the tinfoil as before. Here, where inductive influence of the beakers was almost wholly removed, the difference of the charges taken from the tinfoil discs averaged only 1.2 scale divisions, which was not greater than the probable error of the experiment.

A third series of readings was then made with the beakers loosely wrapped on the outside with tinfoil which was turned in for a centimeter or so around the top. The zinc ball was lowered into the beakers and charged by contact with the bottom, as in the first series of experiments, both with the tinfoil around the beakers and with it removed. In this series, the difference in deflection due to the two beakers without the tinfoil was 23.4 scale divisions, while with the beakers wrapped in tinfoil it was only 7.5 scale divisions. In this case, since the bound charges induced by the tinfoil wrapping upon the two beakers were different from their normal fixed charges, the charges which they, in turn, induced upon the zinc ball were also different from the charges which they induced with the tinfoil wrapping removed.

Summary

I have tried to show in the preceding paper that metals, and probably all other bodies, when in electrical contact with the earth still retain characteristic charges which are capable of inducing electric separations in other bodies brought near them.

That when two metals are brought near together, their induced free charges will escape to the earth or to any other conductor with which they may be in metallic contact.

Their bound charges remain in or on the metal. If after their free charges have escaped the metals be insulated and then separated, the bound charges become free, and are the so-called contact charges of Bennett and Cavallo.

The magnitude of the natural charge of a metal seems to be determined by its internal cohesion, and hence presumably by its specific inductive capacity. Whatever changes the specific inductive capacity of the metal, or even of its surface, will accordingly produce a change in the fixed charge of the metal.

This point of view consists merely in introducing the earth into the contact series. It seems certain that the same metal will hold different charges when in contact with different parts of the earth, as it will when in contact with the interiors of different hollow conductors.

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THE FIRE AND THE MUSEUM AT OTTAWA

THE Museum of the Geological Survey, Ottawa, Canada, is to Canada practically what the National Museum is to the United States and the British Museum to the United Kingdom. This museum has been greatly affected by the fire which, beginning about 9 P.M., Thursday, February 3, 1916, destroyed the Dominion Parliament building and caused the loss of several lives. Before 2 A.M., February 4, while the flames were still spreading, a member of the cabinet was considering the use of the large auditorium in the Victoria Memorial Museum building as possibly a suitable place for the meetings of the House of Commons, and members of the Geological Survey were holding themselves in readiness to clear any of the other space necessary. It will be remembered that this museum building was the home of the Geological Survey of Canada and the temporary quarters of the National Gallery of Canada. It was open to the public from nine till five daily except Sundays, Christmas day and Good Friday, and from two till five on Sundays during the winter.

On the ground floor were the central hall, usually with special and timely exhibits, the main floor of the auditorium, the west hall with tentative mineralogical exhibits, the west wing for geology, but containing boxed specimens and camp equipment, the east hall with invertebrate paleontological exhibits, and the east wing with tentative exhibits of vertebrate paleontology.

On the first floor were the tower hall with some ethnological specimens, the lecture hall gallery, the west hall—three fourths devoted to tentative archeological exhibits and one fourth occupied by entomological exhibits—the west wing with permanent archeological and ethnological exhibits, and the east hall with zoological exhibits. On this same floor the east wing was occupied by Canadian pictures, and Greek, Roman and Italian renaissance sculpture, of the National Gallery. On the second floor were most of the offices and the library of the Geological Survey, and in the northeastern room of the east hall an office of the National Gallery. On the same floor the east wing was occupied by Medieval and French renaissance sculpture, Royal Canadian Academy Diploma Pictures and colored prints of the world's most famous pictures, of the National Gallery. On the third or top floor were offices, the much used though small and tentative museum lecture hall, the gallery of the library, the drafting room, study and storage rooms. On this floor the east wing was occupied by the oil and water colors, prints, etchings, drawings and bronzes of the National Gallery. In the basement were work shops, laboratories, distribution offices, photographic department, and half a hall devoted to a workshop of the National Gallery.

The Geological Survey, it may be seen, oc-