MEASUREMENTS IN FRICTIONAL ELECTRICITY.

BY N. R. FRENCH.

HISTORICAL.

SINCE all the recent articles bearing upon this subject have appeared in other magazines, a brief outline of the results of the recent researches is given here.

Morris Owen[1] took measurements of the charges produced upon various bodies by known amounts of energy expended in friction and found that with definite amounts of frictional work the charges reached certain fixed maxima, depending upon the kind and size of specimen, but that these same maxima could be reached with a less expenditure of energy by increasing the pressure between the rubbing surfaces. The final maximum charges, however, were independent of the pressure. Owen concluded that Helmholtz's theory that frictional electricity is in the nature of contact electricity, the frictional work being done to bring the surfaces into closer contact, is borne out by his observations, since after several consecutive rubs the maximum charge could be produced by a much smaller amount of work than that required the first time. After several hours' rest the material would return to its original condition in which a much larger amount of energy was required to produce the maximum charge. His theory of this phenomenon was that the surface of the material underwent a slow elastic recovery of its uneven form or that it resulted from the tarnishing of the surface by the atmosphere, thus causing a poor contact during the first rubs. No evidence, however, of the slightest charge was produced by mere contact of the surfaces.

In a recent paper, W. Morris Jones[2] published the results of his work in this field. He found that by increasing the softness of the rubbers the rest between the rubs could be made shorter and still have the specimen return to its original condition. His results give the interesting facts that transparent insulators are positively charged when rubbed with flannel, silk and chamois leather, while negative charges are produced on opaque insulators by rubbing with these same three materials.

[1] Phil. Mag., April, 1909, p. 457.

[2] Phil. Mag., Feb., 1915, p. 261.

He found that in the case of metals, using silk as the rubber, the sign and amount of the charge is not as definite a characteristic of the material as in the case of non-conductors. First, reversal of sign often took place, especially in the case of zinc and iron. The following extract is taken from his paper: "When the metals were all cleaned with very fine emery paper, all the specimens except thallium, lead, and bismuth (which have the highest atomic weights) gave a negative charge at the first rub. Continued rubbing, however, produced a polish on the metals, and then it was found that the negative charges on aluminum, iron, copper, zinc, and antimony became less and less and changed to positive, though the other metals, on continued rubbing, did not show this effect." Later in this paper this statement will receive further treatment. Secondly, low readings were obtained when the surfaces were tarnished with oxide, positive charges being obtained for small amounts of work and negative for large amounts.

Plotting atomic weights against the maximum charges, all the metals being rubbed with the same substance, he obtained a curve which exhibits some evidence of periodicity. No effect upon the production of the charge was obtained by placing the specimen in magnetic and electric fields or by changing the temperature.

Apparatus.

The apparatus for the production of the charge, a sketch of which is shown in Fig. 1, was practically the same as that employed by Owen.

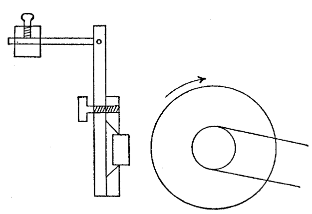

Fig. 1.

A slate wheel, 61 cm. in diameter and 5.1 cm. in thickness, around the rim of which bands of the rubbing material were fastened, was driven by an electric motor through a system of pulleys which made possible several speeds.

The vertical part of the specimen-holder, which possessed an adjustable ebonite vise-like arrangement at the lower end for holding the specimens, consisted of a strip of ebonite 30 cm. long, 5 cm. wide and approximately 0.7 cm. thick; the horizontal part was a steel rod passing through a movable weight. This holder was free to rotate about a horizontal axle which could be moved vertically or in a horizontal plane. The pressure between the specimen and the band on the wheel rim was regulated by means of the movable weight.

After a specimen had been rubbed, the holder was rotated in a horizontal plane till the specimen was above a deep metal can into which it was lowered, a set-screw having previously been tightened to prevent rotation about the axle. This can was contained within a larger one from which it was insulated by shellaced ebonite posts. This outside can was grounded, the inside can being connected to one pair of quadrants of a quadrant electrometer, the other pair of which was also grounded. On account of the small capacity of this system, the inside can was also connected to one side of a condenser of known capacity, the other side being connected to the ground. It was found that the capacity of the condenser could be taken as the capacity of the system with an error of approximately one part in five hundred. The measuring apparatus was kept within a grounded tinfoil covered box which protected it from outside disturbing influences.

The electrometer needle, the deflections of which were read with a telescope and scale, was kept at a constant potential by connection with one side of a set of storage batteries the other side of which was earthed. The electrometer was frequently calibrated by using known potential differences and noting the deflections, which in most cases were proportional to the applied potential differences. After each set of readings throughout all the work tests were made to make certain that the calibrations still applied. By noting the deflection caused by an unknown charge and then referring to the calibration curves, the value of the charge could be easily computed since the capacity of the system was known.

To improve insulation the surface of the slate wheel was coated with shellac and a band of silk placed next to the rim beneath the bands of wool which were used as rubbers. The insulation of this and the specimen-holder was frequently tested.

The specimens consisted of several metals, all 2.5 cm. square and 0.9 cm. in thickness. Great care is needed in preparing the specimen for rubbing because the condition of the surface determines to a large extent the size and in some cases the sign of the charge. It was found, after trying several methods of preparing the surface, that going over it with a fine file just before each set of observations gave the best results and insured all the metals being in the same condition. It is important to always get the metal in the same position with reference to the rubber; if it is not in good even contact a low charge usually results. It was found that a speed of seventeen r.p.m. of the wheel gave the best results, all the work being carried on at this speed. Since the work done was proportional to the time of rubbing, only the time of rubbing was recorded.

The Relationship between the Charge and Work and the Determination of the Maximum Charges for Several Metals and their Alloys.

The following metals were used: aluminum, zinc, an alloy of half aluminum and half zinc, lead, tin, and an alloy of half lead and half tin. In determining the relationship between the charge and the work done, the rubs were taken immediately following each other, *i. e.*, as soon as

Table I.

Specimen.	Maximum Charge in E. S. U.
Lead	65.4
Tin	23.8
Lead and tin alloy	23.0
Aluminum	46.4
Zinc	57.1
Aluminum and zinc alloy	45.6

the measurement of the charge obtained from the first rub was completed, the specimen was discharged as well as the rubber, and at once rubbed again, this time for a longer period. This process of rubbing, measuring the charge, discharging, and then rubbing again for a longer period, was continued till the charge showed no increase. After the maximum charge was obtained, a second set of data, commencing again with a short rub, was immediately taken on the same specimen. In constructing the curves showing this relationship, charges were plotted in terms of the electrometer deflections. The temperature and humidity of the air were kept nearly constant for this part of the work.

Discussion of Results.

These plots showing the relationship of the charge to the work bring out a point mentioned in the paper of Morris Jones and show that his explanation of it (quoted on page 151) is apparently incorrect. The following is taken directly from his paper: "When the metals were all cleaned with fine emery paper, all the specimens except thallium, lead, and bismuth (which have the highest atomic weights) gave a negative charge on the first rub. Continued rubbing, however, produced a polish on the metals, and then it was found that the negative charges on aluminum, iron, copper, zinc and antimony became less and less and changed to positive, though the other metals on continued rubbing did not show this effect."

The following plots show this effect: Curves *1* and *2*, Fig. *2*, Curves *1A*, *1B*, *2A*, and *3A*, Fig. 3. The metals showing this effect are an alloy of lead and tin (although neither lead nor tin alone showed it), aluminum, zinc and an alloy of aluminum and zinc.

On examination of the above extract from the paper of Mr. Jones, one would get the impression that Jones believed the production of the polish to be the cause of the change in sign of the charge after the metal had been rubbed for some time. My results seem to disprove this theory. Curve *2*, Fig. *2*, is constructed from data taken immediately after the taking of data for Curve *1*. Curve *1* shows the change from negative to positive after continued rubbing, the last point in *1* being obtained for a rub of one hour. According to Jones the surface of this metal was polished after being rubbed only 400 seconds, this being the point where reversal takes place. At all times after this, rubbing ought to result in the production of positive charges, which, however, does not

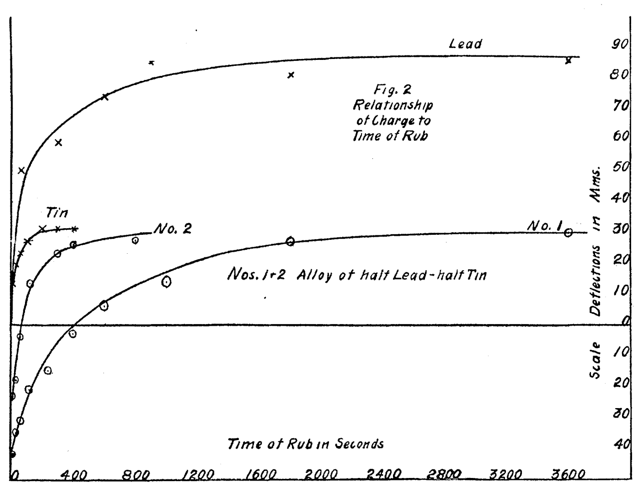

Fig. 2.

take place. Starting once more with short rubs, negative charges are again produced, although as long a time is not now needed to cause the reversal of sign. Nothing, whatsoever, has been done to the specimen between the two series of rubs, the second of which followed immediately after the first. Curve *2B*, Fig. 3, also exhibits this same phenomenon, the "B" Curves being plotted from the data taken immediately after that for the "A" Curves.

It will be noticed from the above plots that the negative charges obtained from the second set of readings are in each case less than those obtained from the first set by the same amount of rubbing.

Rapid oxidation of the specimen between rubs would not account for this reversal as it is found, because the specimens, when oxidized, give positive charges at first and then reverse to negative after enough rubbing to wear away this oxide.[1] This condition is not shown on the plots

[1] Jones, *loc. cit.*

because the surface of each specimen was cleaned with a fine file before each set of observations for the purpose of removing this oxide. Jones stated in his paper that temperature changes had no effect upon the production of the charge so it is probable that this condition was not brought about by an increase in the temperature due to friction.

It may be of interest to note in Table I. that of the alloys used, neither one gave a maximum charge larger than the smaller maximum charge of its two constituents.

An attempt to explain the above results from an entirely new point of view follows:

It is known that, under ordinary circumstances, the surfaces of bodies

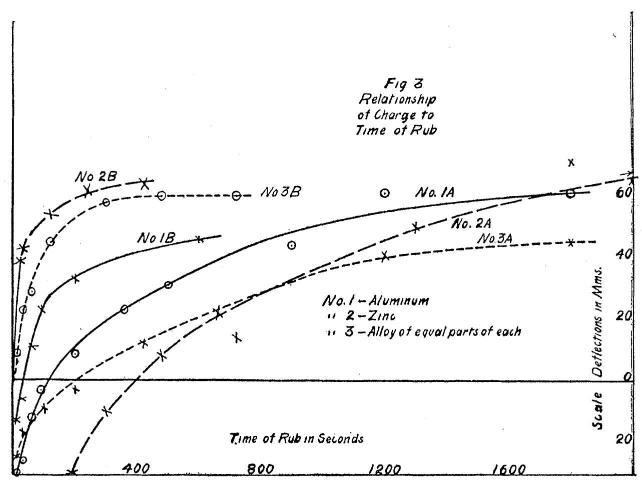

Fig. 3.

are covered with layers of occluded air. This can be shown by what are called "breath figures." Let a glass plate remain in the air for several hours after being cleaned, and then, without scratching the surface, mark upon it with a hard point. If the surface is now breathed upon, the mark is rendered visible. The explanation given for this is as follows: the glass, after being cleaned, has adsorbed air to its surface; the marking removes some of this occluded air, and the breathing distributes vapor unequally over the surface, more being absorbed and condensed where there is still occluded air than in those places where it has been partially or wholly removed. This air is not removed except by hard rubbing or scratching, as can be shown by rubbing this surface after the mark has been made upon it. Breathing upon it again, after this rubbing, will still render this mark visible, showing that the air on the other parts of the surface has not been removed, since it is the contrast between the condensation of vapor on the surface where there is and where there is not condensed air, that renders the mark visible.

Ordinary air contains moisture which would be deposited along with the air upon the surface of the solid, so that all substances probably have layers of air upon their surfaces, this air condensing with it the water vapor which it contains.

Supposing, then, that the surfaces of the metals have these layers of condensed air and water vapor, let the rubber be brought in contact with the surface of one of the specimens and the rubbing commenced. Charges then begin to be developed, not only between the metal and the flannel, but also between this surface layer and the flannel. To explain our results we must now make two assumptions concerning the production of the charge from this layer: (1) The charge which the film yields is negative in sign; (2) the maximum charge given by the film alone is smaller than that given by any of the metals used, meaning by "the charge of the metal," the charge that would be obtained if the film gave no charge.

The following equation, developed by Jones, gives the charge in terms of the work and two constants which have values depending upon the substances used:

$$Q = \frac{a}{b}(I - e^{-bw}), \tag{1}$$

where Q equals charge, w the energy expended in frictional work, a and b being constants which come into the expressions for the rate of liberation of electrons from one surface, and the leakage back to the surface, respectively.

Let Q_1 and Q_2 be the charges produced on the surface layer and metal, respectively; a and b constants for the action between the surface layer and woolen band; c and d constants for the action between the metal and wool; w_1 and w_2 the respective amounts of work done in producing Q_1 and Q_2, where the sum of w_1 and w_2 equals the total amount of energy used in the production of any charge. Then

$$Q_1 = \frac{a}{b}(I - e^{-bw_1})$$

and

$$Q_2 = \frac{c}{d}(I - e^{-dw_2}).$$

The resultant charge is then the difference between Q_1 and Q_2 since, according to Assumption 1, these charges are opposite in sign those metals which show reversal yielding a positive charge finally, or

$$Q = Q_2 - Q_1 = \frac{c}{d}(I - e^{-dw_2}) - \frac{a}{b}(I - e^{-bw_1}). \qquad (2)$$

Although, for any rub, w_2 is probably greater than w_1, it is possible to assign values sufficiently large to b and small to d, if c/d is greater than a/b (Assumption 2), such that $Q_2 - Q_1$ will be negative for short rubs but positive for those of longer duration.

Or d and b may have such values that for a given ratio of w_1 and w_2, $Q_2 - Q_1$ can only have positive values.

The above mathematical reasoning shows how it is possible for reversal of sign to take place on the basis of the adsorption theory. It is evident that if reversal took place for the first set of readings it would also for the second, other conditions being the same. But what will actually happen is complicated by the fact that probably some of the surface film is worn away by the rubbing which, it is evident, would result in a smaller negative charge or even a positive being obtained for the first short rub of the second series of observations.

The Relationship of the Charge to the Humidity.

It was soon found that a much smaller charge was obtained during damp weather than during dry. It was thought, at first, that this was due to a leak from the apparatus, but several tests were tried, when the absolute humidity was high, which seem to disprove the leak explanation. A charged electroscope was slowly moved over the rim of the wheel and the rapidity of the collapse of the gold leaves noted. No appreciable amount was noticed, however, and the electroscope could be left in stationary contact with the rim of the wheel for an hour with no greater leak than would take place from the electroscope alone. The condenser and electrometer would remain charged for several hours in the dampest of weather with only a small loss. After a reading had been taken, removing the holder from the jar and again taking the measurement after an interval was tried. The loss produced in this manner varied but very little in damp and dry weather.

The metals used in this part of the work were aluminum, lead, and tin. The length of the rub was different for each metal, 300 seconds, yielding a maximum charge, being the period for tin, 30 seconds for lead, and 10 for aluminum. To do away with numerical calculation, the values of the charges were not worked out. Instead, the potential of the charge was measured and plotted against the absolute humidity, the shape of the curve being unchanged by this substitution. The plots obtained,

Fig. 4, seem to show that there is some relationship between the charge obtained from specimens of metals and the absolute humidity of the atmosphere.

Discussion of Results.

Using equation 2 we get for the resultant charge in any case,

$$Q = \frac{c}{d}(I - e^{-dw_2}) - \frac{a}{b}(I - e^{-bw_1}),$$

a/b and c/d being the maximum values of the charges obtained from the surface film and metal, respectively. Since, as found by Owen, the charge is directly proportional to the surface area of the specimen, an increase in the absolute humidity will result in an increase in surface area of the surface film, more moisture being deposited, and a corresponding increase in a/b and decrease in c/d. Any positive value of Q will then be decreased by an increase in absolute humidity which is in agreement

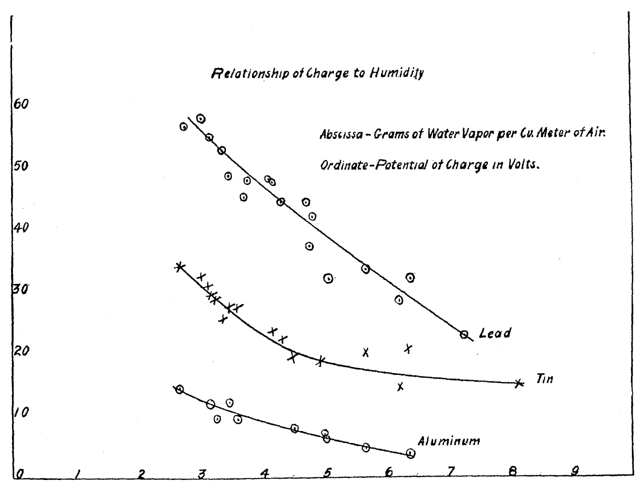

Fig. 4.

with plots for lead and tin in Fig. 4. The data for aluminum was taken before reversal of sign took place—the charges all being negative. According, then, to equation 4 it seems as if, for this particular case, the charges should be increased by an increase in absolute humidity, which is not in accordance with the actuality as shown by the curve for aluminum on Fig. 4. The results are probably complicated, however, by the existence of a changing surface condition upon the flannel rubber, increased moisture being deposited there by the increased humidity, but probably being worn away much more quickly than on the metal. It is to be noticed, however, that the rate of change of charge with respect to absolute humidity for the aluminum is not as great as for the tin and lead, the average rate between the absolute humidities of three and six grams per cu. meter of air being 8.3 volts fall per increase of 1 gram of water vapor per 1 m^3. of air. for lead, 5.0 for tin, and 2.8 for aluminum.

It is barely possible, of course, that this change in the charge was caused by a leak which the writer was not able to detect, although very careful tests were repeatedly made. It seems probable, however, that there should be some change in the charge with a change in the absolute humidity.

Test of Owen's Theories as to what takes place on the Surface of a Specimen between Rubs Several Hours Apart.

After a specimen had been rubbed for a considerable length of time and then discharged, any definite charge can then be obtained with a smaller expenditure of energy than would be required at the first rub. If the specimen be given a rest of several hours, it will then be found that it has returned to its original condition in which a much larger amount of energy is required to produce the same charge. Owen attributed this to either an elastic recovery of the surface of the specimen or to its being tarnished by the atmosphere. The following experiments were tried to test his theories and to determine, if possible, the cause of this phenomenon.

First, the effect of keeping the specimen in a vacuum after being rubbed, was tried. The specimen was first rubbed for quite a long period, the measurement of the time and charge then being taken for several short rubs, after which it was immediately discharged and placed under the bell jar of an air pump and the air removed. After several hours the charge was again obtained.

The effects of keeping the specimen in an atmosphere of water vapor and then in dry air were also tried. One difficulty which prevented more accurate study of these effects lay in the fact that it was necessary to bring the specimen back into the air while the development and measurement of the charge were being taken. Since the results were only qualitative they are left as deflections of the electrometer rather than as charges.

Table II.

Specimen Used: Lead.

Deflections Millimeters.	Remarks.
	All rubs thirty seconds in length.
142	Specimen previously cleaned with fine file.
169	After four hours in a vacuum.
170	After three hours in water vapor.
138	After three hours in moist air.

Discussion of Results.

The data seem to show that the decrease in the charge produced by a definite amount of work on a specimen, which has been allowed to remain in contact with the air after previous rubbing, is caused by an action of the atmosphere upon the surface of the metal and not by an elastic recovery of the surface. In every case tried, and several sets of observations were taken which are not recorded here, the charges obtained by equal amounts of work after the specimen had been given a rest of from three to twelve hours in a vacuum, were as large as those obtained just before the specimen was put away. This seems to show definitely that the phenomenon is not caused by an elastic recovery of the surface but by contact with something in the atmosphere.

Table III.

Specimen Used: Aluminum.

Surface cleaned with fine file before first rub of this set.

No. of observation	1	2	3	4
Length of rub—secs.	30	60	300	600
Deflections—mm.	3	− 27	− 34	− 52

Specimen put in vacuum after last rub above—removed 12 hrs. later.

No. of observation	1	2
Length of rub—secs.	30	300
Deflections—mm.	− 54	− 56

Specimen left in moist air after last rub above—out 8 hrs. later.

No. of observation	1	2	3	4
Length of rub—secs.	30	60	300	600
Deflections—mm.	35	19	− 2	− 10

Table IV.

Specimen Used: Aluminum.

Surface cleaned with fine file before first rub of this set.

No. of observation	1	2	3	4
Length of rub—secs.	300	600	780	
Deflections—mm.	− 22	− 25	− 33	

Specimen put in water vapor after last rub above—out 7 hrs. later.

No. of observation	1	2	3	4	5
Length of rub—secs.	30	60	30	30	30
Deflections—mm.	− 42	− 40	− 30	− 32	− 31

Kept in dry air for ten hours after last rub of above set.

No. of observation	1	2
Length of rub—secs.	30	60
Deflections—mm.	9	6

As shown by Tables II. and III., the charges obtained were larger after the specimen had been given a rest in a vacuum. This seems to be due to the fact that occluded gases and water vapor are given off by the metal when the atmospheric pressure upon it is decreased.

Keeping the specimen in an atmosphere of water vapor only, does not cause a decrease in the charge; in one case, as shown by Table IV., it was increased by this procedure; in another, Table II., it was not changed appreciably.

As can be seen from the last part of Table IV., the charge was decreased and reversed in sign when the specimen was kept in dry air, the change in deflection being 40 mm. Sulphuric acid was used as a drying agent so the air was probably not totally free from moisture. The moist air, however, had over double this effect, the change in deflection being 87 mm., and the time in moist air being eight hours as compared with the ten hours which it remained in the dry air (see Table III.).

These facts seem to indicate that it is a mixture of air and water vapor deposited upon the surface of the specimen which causes this decrease in the charge, for a definite amount of work, after the material has been allowed to rest for some time between rubs. Possibly the formation of oxide upon the surface plays an important part. The dry air alone seemed to produce nowhere near the whole effect and the water vapor practically none at all.

Summary of Results and Conclusions.

1. Jones's theory as to the cause of the reversal in sign of the charge produced on a metal specimen has been proven incorrect.

2. For each of the two alloys examined the maximum charge was not the average of the maximum charges of the constituent metals, being, in fact, no larger than the maximum charge from the constituent giving the smaller charge.

3. A relationship between the charge and the absolute humidity, for a definite amount of frictional work, has apparently been found to exist.

4. The decrease in the charge produced by a definite amount of work on a specimen which has been allowed to remain in contact with the atmosphere after previous rubbing, has been shown to be caused by contact with a mixture of air and water vapor and not by an elastic recovery.

5. To explain the facts, a theory, based upon the adsorption of air to the surface of the metal, has been proposed.

Jones stated that magnetic fields caused no effect upon the production of the charge, but did not mention the kind of metals used for the tests. The writer made a few preliminary observations with paramagnetic substances in a magnetic field and also tried the effect upon the production of the charge of the magnetization of the specimen. Both these tests seemed to influence the results, but nothing definite enough to warrant the drawing of any conclusions, was obtained. The intention is to investigate this question further at some future date using stronger fields.

In conclusion, the writer wishes to express his thanks to Professors J. S. Stevens, L. E. Woodman and R. M. Holmes, of the University of Maine, for valuable advice during the course of the work, and also to Professor K. T. Compton, of Princeton University, for aid in the arrangement of the material for publication.

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