that they have been formed by the upheaval of shoals, deposited where currents met. These phænomena, it is very probable, are connected in their origin with the same causes which have produced the remarkable bar of sandstone off Pernambuco. The town of Pernambuco stands on a low narrow islet and on a long spit of sand, in front of a very low shore, which is bounded in the distance by a semicircle of hills. By digging at low water near the town the sand is found consolidated into a sandstone, similar to that of the breakwater, but containing many more shells. If, then, the interior of a long sandy beach in one part, and in another the nucleus of a bar or spit extending in front of a bay became consolidated, a small change, probably of level, but perhaps simply in the direction of the currents, might give rise, by washing away the loose sand, to a structure like that in front of the town of Pernambuco, and along the coast southward of it; but without the protection afforded by the successive growth of organic beings, its duration would be short, if indeed it were not destroyed before being completely exhibited.

XXXVIII. *On the Heat evolved by Metallic Conductors of Electricity, and in the Cells of a Battery during Electrolysis.* *By* James Prescott Joule, *Esq.**

1. THERE are few facts in science more interesting than those which establish a connexion between heat and electricity. Their value, indeed, cannot be estimated rightly, until we obtain a complete knowledge of the grand agents upon which they shed so much light. I have hoped, therefore, that the results of my careful investigation on the heat produced by voltaic action, are of sufficient interest to justify me in laying them before the Royal Society.

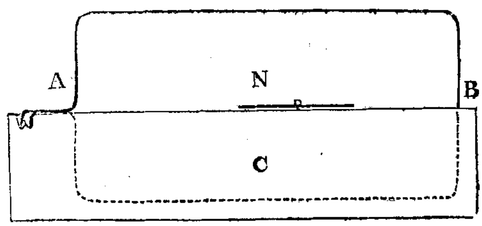
Chap. I.—*Heat evolved by Metallic Conductors.*

2. It is well known that the facility with which a metallic wire is heated by the voltaic current is in inverse proportion to its conducting power, and it is generally believed that this proportion is exact; nevertheless I wished to ascertain the fact for my own satisfaction, and especially as it was of the utmost importance to know whether resistance to conduction is the *sole* cause of the heating effects. The detail, therefore, of some experiments confirmatory of the law, in addition to those already recorded in the pages of science, will not, I hope, be deemed superfluous.

* Communicated by the Author.

3. It was absolutely essential to work with a *galvanometer*, the indications of which could be depended upon, as marking definite quantities of electricity. I bent a rod of copper into

Fig. 1.



the shape of a rectangle (A B, fig. 1.), twelve inches long, and six inches broad. This I secured in a vertical position by means of the block of wood C; N is the magnetic needle, $3\frac{3}{4}$ inches long, pointed at its extremities, and suspended upon a fine steel pivot over a graduated card placed a little before the centre of the instrument.

4. On account of the large relative size of the rectangular conductor of my galvanometer, the tangents of the deviations of the needle are very nearly proportional to the quantities of current electricity. The small correction which it is necessary to apply to the tangents, I obtained by means of the rigorous experimental process which I have some time ago described in the 'Annals of Electricity*'.

5. I have expressed my quantities of electricity on the basis of Faraday's great discovery of definite electrolysis, and I venture to suggest, that that quantity of current electricity which is able to electrolyze an atomic element expressed in grains in one hour of time, be called a *degree*. Now by a number of experiments I found that the needle of my galvanometer deviated $33^{\circ}\cdot5$ of the graduated card, when a current was passing in sufficient quantity to decompose nine grains of water per hour; that deviation, therefore, indicates one *degree of current electricity* on the scale that I propose to be adopted. We shall see in the sequel some of the practical advantages which I have had by using this measure.

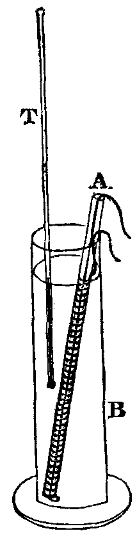
6. The thermometer which I used had its scale graduated on the glass stem. The divisions were wide, and accurate. In taking temperatures with it, I stir the liquid gently with a feather; and then, suspending the thermometer by the top of its stem, so as to cause it to assume a vertical position, I bring my eye to a level with the top of the mercury. In this

* Vol. iv. pp. 131–132, and 476.

way a little practice has enabled me to estimate temperatures to the tenth part of Fahrenheit's degree with certainty.

7. In order to ascertain the heating power of a given metallic wire, it was passed through a thin glass tube, and then closely coiled upon it. The extremities of the coil thus formed were then drawn asunder, so as to leave a small space between each convolution, and if this could not be well done, a piece of cotton thread was interposed. The apparatus thus prepared, when placed in a glass jar containing a given quantity of water, was ready for experiment. Fig. 2 will explain the dispositions: A is the coil of wire; B the glass jar partly filled with water; T represents the thermometer. When the voltaic electricity is transmitted through the wire, no appreciable quantity passes from it to take the shorter course through the water. No trace of such a current could be detected, either by the evolution of hydrogen, or the oxidation of metal.

Fig. 2.



8. Previous to each of the experiments, the necessary precaution was taken of bringing the water in the glass jar, and the air of the room to the same temperature. When this is accurately done, the results of the experiments bear the same proportions to one another as if no extraneous cooling agents, such as radiation, were present; for their effects in a given time are proportional to the difference of the temperatures of the cooling and cooled bodies; and hence, although towards the conclusion of some experiments this cooling effect is very considerable, the *absolute quantities* alone of heat are affected, not the *proportions* that are generated in the same time. [See the table of heats produced during half an hour and one hour, p. 264.]

9. Exp. 1.—I took two copper wires, each two yards long, one of them $\frac{1}{28}$th of an inch, the other $\frac{1}{30}$th of an inch thick, and arranged them in coils in the manner that I have described (7.). These were immersed in two glass jars, each of which contained nine ounces avoirdupois of water. A current of the mean quantity 1°·1 Q*, was then passed consecutively through both coils, and at the close of one hour I observed that the water in which the thin wire was immersed had gained 3°·4, whilst the thick wire had produced only 1°·3.

* I place Q at the end of my *degrees*, to distinguish them from those of the graduated card.

10. Now by direct experiment, I found that three feet of the thin wire could conduct exactly as well as eight feet of the thick wire; and hence it is evident that the resistances of two yards of each were in the ratio of 3·4 to 1·27, which approximates very closely to the ratio of the heating effects exhibited by the experiment.

11. Exp. 2.—I now substituted a piece of iron wire $\frac{1}{27}$th of an inch thick, and two yards long, for the thick copper wire used in Exp. 1, and placed each coil in half a pound of water. A current of 1°·25 Q was passed through both during one hour, when the augmentation of temperature caused by the iron was 6°, whilst that produced by the copper wire was 5°·5. In this case the resistances of the iron and copper wires were found to be in the ratio of 6 to 5·51.

12. Exp. 3.—A coil of copper wire was then compared with one of mercury, which was accomplished by inclosing the latter in a bent glass tube. In this way I had immersed, each in half a pound of water, 11¼ feet of copper wire $\frac{1}{50}$th of an inch thick, and 22¾ inches of mercury 0·065 of an inch in diameter. At the close of one hour, during which the same current of electricity was passed through both, the former had caused a rise of temperature of 4°·4, the latter of 2°·9. The resistances were found by a careful experiment to be in the ratio of 4·4 to 3.

13. Other trials were made with results of precisely the same character; they all conspire to confirm the fact, that *when a given quantity of voltaic electricity is passed through a metallic conductor for a given length of time, the quantity of heat evolved by it is always proportional to the resistance* which it presents, whatever may be the length, thickness, shape, or kind of that metallic conductor.*

14. On considering the above law, I thought that the effect produced by the increase of the intensity of the electric current would be as the square of that element, for it is evident that in that case the resistance would be augmented in a double ratio, arising from the increase of the *quantity* of electricity passed in a given time, and also from the increase of the *velocity* of the same. We shall immediately see that this view is actually sustained by experiment.

15. I took the coil of copper wire used in Exp. 3, and have found the different quantities of heat gained by half a pound of water in which it was immersed, by the passage of electri-

* Mr. Harris, and others, have proved this law very satisfactorily, using common electricity.

cities of different degrees of tension. My results are arranged in the following table:—

Mean Deviations of the Needle of the Galvanometer.	Quantities of Current Electricity expressed in Degrees (5.)	Quantities of Heat produced in half an hour by the Intensities in Column 2.	Ratio of the Squares of the Intensities in Column 2.	Quantities of Heat produced in one hour by the Intensities in Column 2.	Ratio of the Squares of the Intensities in Column 2.
16°	0°·43 Q	......°	......	1°·2	1
31½	0·92 Q	3	2·9	4·7	4·55
55	2·35 Q	19·4	18·8		
57⅔	2·61 Q	23	23·2		
58½	2·73 Q	25	25·4	39·6	40·

16. The differences between the numbers in columns three and five, and those in columns four and six, are very inconsiderable, taking into account the nature of the experiments, and are principally owing to the difficulty which exists in keeping the air of the room in the same state of quiet, of hygrometry, &c. during the different days on which the experiments were made. They are much less when a larger quantity of water is used, so as to reduce the cooling effects (28.).

17. We see, therefore, that *when a current of voltaic electricity is propagated along a metallic conductor, the heat evolved in a given time is proportional to the resistance of the conductor multiplied by the square* * *of the electric intensity.*

18. The above law is of great importance. It teaches us the right use of those instruments which are intended to measure electric currents by the quantities of heat which they evolve. If such instruments be employed (though in their present state they are far inferior in point of accuracy to many other forms of the galvanometer), it is obvious that the *square roots* of their indications are alone proportional to the intensities which they are intended to measure.

19. By another important application of the law, we are now enabled to compare the frictional † and voltaic electri-

* The experiments of De la Rive show that the calorific effect of the voltaic current increases in a much greater proportion than the simple ratio of the intensities.—*Ann. de Chimie*, 1836, part i. p. 193. See also Peltier's results, *Ann. de Chimie*, 1836, part ii. p. 249.

† The experiments of Brooke, Cuthbertson and others, prove that the quantity of wire melted by common electricity is as the square of the battery's charge. Harris, however, arrived at the conclusion, that the heating power of electricity is *simply* as the charge, Phil. Trans., 1834,

cities, in such a manner as to determine their elements by the quantity of heat which they evolve in passing along a given conductor; for if a certain quantity of voltaic electricity produce a certain degree of heat by passing along a given conductor, and if the same quantity of heat be generated by the discharge of a certain electrical battery along the same conductor, the product of the quantity and velocity of transfer of the *voltaic* electricity will be equal to the product of the quantity and velocity of the *frictional* electricity, or Q V $= q$ V, whence $\frac{Q}{q} = \frac{v}{V}$.

Chap. II.—*Heat evolved during Electrolysis.*

20. Under the above head, I shall now examine the heat produced in the cells of the battery, and when electrolytes are experiencing the action of the voltaic current. It has been my desire to render these experiments strictly comparable, both with themselves and with those of other philosophers. I have therefore taken care to apply the corrections which either specific heat, or other disturbing causes might require, and have by these means been able to express, in every case, the *total* amount of evolved heat.

21. The first of these corrections, which I call Cor. A, arises from the difference between the mean temperature of the liquid used in an experiment, and that of the surrounding atmosphere. Its amount is determined by ascertaining the rapidity with which the temperature of the liquid is reduced at the end of each experiment.

22. The second correction (Cor. B) is for the specific heat of the liquids, and the vessels which contain them; and when the necessary data could not be found in the tables of specific heat, I have supplied them from my own experiments. The *vessels* were white earthenware jars, 4½ inches deep, and 4¼ inches in diameter: their caloric was one-twelfth of that contained by two pounds of water, *to which capacity I have reduced all my subsequent results.*

23. As resistance to conduction is the sole cause of the heat produced in the connecting wire of the voltaic battery, it was natural to expect that it would act an important part in this second class of phænomena also. It was important, therefore, to begin by determining the amount of heat evolved by that quantity of conducting metal which I found it convenient to adopt as a *standard of resistance.*

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p. 225. Of course the remark in the text is made on the presumption, that when the proper limitations are observed, the calorific effect of electricity is as the square of the charge of any given battery.

24. Ten feet of copper wire, 0·024 of an inch thick, were formed into a coil in the manner described in (7.); its resistance to conduction was called *unity*. Three experiments were made in order to ascertain its heating power.

25. 1st. A jar was filled with two pounds of water, and a current which produced a mean deviation of the needle of the galvanometer (3.) equal to $57\frac{1}{4}°$ = 2°·54 Q of current electricity, was urged through the coil for twenty-seven minutes, by means of a zinc-iron* battery of ten pairs. The heat thus acquired by the water, after Cor. A, and that part of Cor. B which relates to the caloric of the jar, had been applied, was 6°·22.

26. 2nd. The battery was now charged with a weaker solution of sulphuric acid. In this case it passed the mean current 2°·085 Q during forty-five minutes. The heat thus produced, when corrected, was 7°·04.

27. 3rd, A battery of five pairs (three of which had platinized silver; one silver, and one copper, for their negative plates,) passed the mean current 1°·88 Q during one hour, in which time 7°·47 were generated.

28. When the first two experiments are reduced, in order to compare them with the third, we have, in accordance with the principles laid down in (17.), $\frac{(1{\cdot}88)^2}{(2{\cdot}54)^2} \times \frac{60'}{27'} \times 6°{\cdot}22 = 7°{\cdot}57$, and $\frac{(1{\cdot}88)^2}{(2{\cdot}085)^2} \times \frac{60'}{45'} \times 7°{\cdot}04 = 7°{\cdot}63$. Thus we have $\frac{7°{\cdot}57 + 7°{\cdot}63 + 7°{\cdot}47}{3} = 7°{\cdot}56$, the mean and total quantity of heat produced per hour by the passage of 1°·88 Q of current electricity, against the *unit* of resistance.

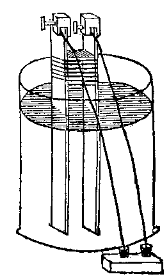
29. Before I proceed to give an account of some experiments on heat evolved in the cells of voltaic pairs, it is important to observe that every kind of action not essentially electrolytic must be eliminated. For instance, the dissolution of metallic oxides in acid menstrua, which has been proved by Dr. Faraday to be no cause of the current, is the occasion of a very considerable quantity of heat, which, if not accounted for in the experiments, would altogether disturb the results. I have taken the oxide of zinc, prepared either by igniting the nitrate, or by burning the metal, and have repeatedly dissolved it in sulphuric acid of various specific gravities; and on taking the mean of many experiments, none of which dif-

* Whenever an iron battery was used, it was of course placed at a distance from the galvanometer sufficiently great to render its action on the needle altogether inappreciable.

fered materially from the rest, I have found that the total corrected heat produced by the dissolution of 100 grains of the oxide of zinc in sulphuric acid, is able to raise two pounds of water 3°·44.

30. Exp. 1.—I constructed a single voltaic pair, consisting of thin plates of amalgamated zinc and platinized silver (Mr. Smee's arrangement): the plates were two inches broad, and were kept one inch asunder by means of a piece of wood, to the opposite sides of which they were bound with string: to the top of each plate, a thick copper wire formed a good metallic connexion, by means of a brass clamp. The voltaic pair, thus prepared, was immersed in two pounds of sulphuric acid, sp. gr. 1137, contained by one of the earthenware jars (22.). The arrangement is represented by fig. 3.

Fig. 3.



31. When the circuit was completed so as to present to the current the total metallic resistance 0·06, the galvanometer stood at $49\frac{1}{2}° = 1°{\cdot}84$ Q; and at $17\frac{1}{2}° = 0°{\cdot}453$ Q, when the total metallic resistance was increased to 1·16 by the addition to the circuit of ten feet of thin copper wire. Hence, according to the principles laid down by Ohm, $\frac{1{\cdot}84}{r+1{\cdot}16} = \frac{0{\cdot}453}{r+0{\cdot}06}$; from which r, the resistance of the voltaic pair, = 0·299. Immediately after this trial, the temperature of the liquid being exactly 49°, and that of the air 50°·2, the circuit was completed for one hour, during which the needle first advanced a little from 50°, and then declined to 46°, the average* deviation was 48° 44′ = 1°·8 Q. The temperature of the liquid was then 53°·7, indicating a rise of 4°·7. Another trial now ave $\frac{1{\cdot}59}{r'+1{\cdot}16} = \frac{0{\cdot}382}{r'+0{\cdot}06}$; whence r', the resistance of the pair at the close of the experiment, = 0·288: the mean resistance of the pair was therefore 0·293.

32. Now in order to obtain the total amount of heat evolved by the pair, reduced to the capacity of two pounds of water, we have 4°·7 + 0°·4 (on account of Cor. A (21.)) and − 0°·5 (on account of Cor. B (22.)) = 4°·6. The correction due to the dissolution of oxide of zinc is found by multiplying its

* During each experiment the deflections of the needle were noted at intervals of five minutes, or less. From thence I deduce my averages.

quantity by $\frac{3^{\circ}\cdot 44}{100}$ (see (29.)); the quantity of the oxide being obtained by multiplying the equivalent of oxide of zinc by the mean quantity of current electricity. We have then

$$4\;0\cdot 3 \times 1\cdot 8 \times \frac{3^{\circ}\cdot 44}{100} = 2^{\circ}\cdot 5:$$ this, when subtracted from $4^{\circ}\cdot 6$, leaves $2^{\circ}\cdot 1$, the *correct voltaic heat.*

33. Assuming in this case, as well as in that of a metallic conductor, that the heat evolved is proportional to the resistance multiplied by the square of the electric intensity, we have, from the data in (28.) and (31.), $\frac{(1\cdot 8)^2}{(1\cdot 88)^2} \times 0\cdot 293 \times 7^{\circ}\cdot 56 = 2^{\circ}\cdot 03$, which is very near $2^{\circ}\cdot 1$, the heat deduced from experiment.

34. Exp. 2.—I now constructed another pair, consisting of plates precisely similar to those used in Exp. 1, but half an inch only asunder: it was also immersed in two pounds of sulphuric acid, sp. gr. 1137. The circuit was closed for one hour, during which the needle of the galvanometer advanced gradually from $47\frac{1}{2}^{\circ}$ to $50\frac{1}{3}^{\circ}$, the mean deviation being $49^{\circ}\ 35' = 1^{\circ}\cdot 84$ Q. The liquid had then gained $4^{\circ}\cdot 8$: this, $+0^{\circ}\cdot 1$ (for Cor. A) and $-0^{\circ}\cdot 5$ (for Cor. B), $= 4^{\circ}\cdot 4$. The heat due to the dissolution of oxide of zinc is in this case

$$4\;0\cdot 3 \times 1\cdot 84 \times \frac{3^{\circ}\cdot 44}{100} = 2^{\circ}\cdot 55,$$ which, when subtracted from $4^{\circ}\cdot 4$, leaves the correct voltaic heat $1^{\circ}\cdot 85$.

35. The resistance of the pair was ascertained in this, as in every other instance, at the beginning and at the end of the experiment. The equations thus obtained were $\frac{1\cdot 714}{r+1\cdot 16} = \frac{0\cdot 432}{r+0\cdot 06}$, and $\frac{1\cdot 91}{r'+1\cdot 16} = \frac{0\cdot 446}{r'+0\cdot 06}$; whence $r = 0\cdot 311$, and $r' = 0\cdot 275$: the mean resistance was therefore $0\cdot 293$. Now, calculating as before (33.), on the basis of the heat produced by the passage of electricity against the standard of resistance, we have $\frac{(1\cdot 84)^2}{(1\cdot 88)^2} \times 0\cdot 293 \times 7^{\circ}\cdot 56 = 2^{\circ}\cdot 12$.

36. Exp. 3.—I formed another pair on Mr. Smee's plan; it was similar to the last, with the exception that the plates were only one inch broad. When the circuit was closed, a current of the mean intensity $1^{\circ}\cdot 46$ Q passed through the apparatus during one half hour. The heat thereby produced,

when corrected, and reduced on account of the dissolution of oxide of zinc, was 0°·84.

37. In this instance the mean resistance was 0·32 ; whence, by a calculation precisely similar to those given under Exps. 1 and 2, we have the theoretical amount of heat = 0°·74.

38. The three instances above given, are specimens taken from a number of experiments with the platinized silver pairs. The mean of the eight unexceptionable experiments which I have made with them, gives 2°·08 of actual, and 2°·13 of theoretical heat, and not one of the individual experiments presented a greater difference between real and calculated heat, than Exp. 2.

39. Exp. 4.—A plate of copper, four inches broad, was bent about a plate of amalgamated zinc three inches and a half broad, so as to form a pair of Wollaston's double battery. It was placed in a jar containing two pounds of dilute sulphuric acid. In this instance, the total voltaic heat that was generated was 1°·2, the calculated result being 1°·0 only. Repeated experiments with the copper pairs gave similar results, the real heat being invariably somewhat superior to that which the doctrine of resistances would demand. The cause of this I have found in a slight local action, which it is almost impossible to avoid in the common copper battery.

40. Exp. 5.—I now constructed a single pair on Mr. Grove's plan. The platinum, two inches broad, was immersed in an ounce and a half of strong nitric acid contained by a 4-inch pipe-clay cell; the amalgamated zinc plate, also two inches broad, was immersed (at the distance of an inch and a half from the platinum) in thirty ounces of sulphuric acid, sp. gr. 1156. The whole was contained by one of the jars (22.).

41. A trial, made first as usual, in order to ascertain the resistance of the pair, gave $\frac{4{\cdot}4}{r+2{\cdot}26} = \frac{0{\cdot}816}{r+0{\cdot}06}$, whence $r = 0{\cdot}441$. As soon as the slight heat acquired during the above trial was equably diffused through the apparatus, the thermometer placed in the dilute sulphuric acid stood at 51°·95, the temperature of the air being 52°·4. The circuit was then immediately closed for ten minutes, during which time the needle of the galvanometer advanced steadily from 68° 40′ to 71° 20′; the mean deviation being 70° 9′ = 4°·77 Q. As soon as the heat thus generated was equably diffused*,

* By gently stirring the dilute sulphuric acid with a feather, so as to bring every part in successive contact with the porous cell during two minutes.

the thermometer immersed in the dilute sulphuric acid stood at $56^{\circ}\cdot 7$, indicating a rise of $4^{\circ}\cdot 75$. Another trial now gave $\frac{5\cdot 14}{r'+2\cdot 26} = \frac{0\cdot 91}{r'+0\cdot 06}$, whence $r' = 0\cdot 413$. The mean resistance of the pair was therefore $0\cdot 427$.

42. $4^{\circ}\cdot 75 + 0^{\circ}\cdot 1$ (for Cor. A), and $- 0^{\circ}\cdot 4$ (for Cor. B, which in this case includes the capacity for heat of the porous cell) $= 4^{\circ}\cdot 45$. The heat generated by the dissolution of oxide of zinc was in this case $40\cdot 3 \times 4\cdot 77 \times \frac{3^{\circ}\cdot 44}{100} \times \frac{10}{60'}$ $= 1^{\circ}\cdot 1$, which, subtracted from $4^{\circ}\cdot 45$, leaves the correct voltaic heat $3^{\circ}\cdot 35$.

43. The *theoretical* result is $\frac{(4\cdot 77)^2}{(1\cdot 88)^2} \times 0\cdot 427 \times 7^{\circ}\cdot 56 \times \frac{10'}{60'}$ $= 3^{\circ}\cdot 46$.

44. Exp. 6 was made with a pair in every respect similar to the last: the circuit, however, was completed by means of a thin copper wire, in order to reduce the intensity of the current. At the end of one hour, during which the needle of the galvanometer advanced gradually from 41° to 42°, the correct voltaic heat that was generated was $1^{\circ}\cdot 7$. The *theoretical* result was $1^{\circ}\cdot 82$.

45. I was desirous of knowing how far the same principles would apply to the heat generated in Prof. Daniell's constant battery. But in this battery considerable *cold* is produced, in consequence of the separation of oxide of copper from the sulphuric acid to which it is combined. This is altogether a secondary effect, and should be eliminated as decidedly as the *heat* produced by the dissolution of oxide of zinc. I have not yet been able to obtain accurate data for the correction thus needed, and shall therefore content myself with remarking, that my results with Mr. Daniell's arrangements are, as far as they go, quite consistent with the theory of resistances.

46. Experiments, such as I have related, were varied in many ways; and sometimes a number of pairs were arranged so as to form a battery. Still the results were similar, and established the fact, that *the heat which is generated in a given time in any pair, by true voltaic action, is proportional to the resistance to conduction of that pair, multiplied by the square of the intensity of the current.*

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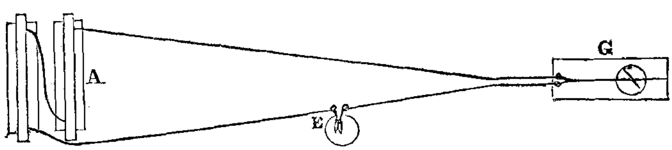
47. I now made some experiments on the heat consequent to the passage of voltaic electricity through electrolytes.

48. Exp. 7.—Two pieces of platinum foil, each of which was an inch long, and a quarter of an inch broad, were her-

metically sealed into the ends of two pieces of glass tubing: within these tubes, pieces of copper wire were metallically connected with the platinum; these, when the apparatus was in action, terminated in mercury cups. The tubes thus prepared were bound together by thread, so as to keep the pieces of platinum foil at the constant distance of half an inch asunder. This apparatus was immersed in two pounds of dilute sulphuric acid, sp. gr. 1154, contained in one of the jars (22.).

49. A battery of twenty-four inch, double iron-zinc plates, was then placed, with its divided troughs (which were charged with a pretty strong solution of sulphuric acid), at a distance from the galvanometer sufficiently great to obviate any disturbing effect on the needle. To the electrodes of this battery thick copper wires were secured, so that by means of one of them connexion could be made to the galvanometer, and by means of the other, to the decomposing cell. In fig. 4, A

Fig. 4.



represents the battery, G the galvanometer, and E the decomposing apparatus (48.).

50. In order to ascertain the resistances of the battery or of the cell, I provided several coils* of silked copper wire, the resistances of which had been determined by careful experiments. When these were traversed by the current, they were placed in such a position as to prevent any action on the needle, and at the same time they were kept under water, in order to prevent them from becoming hot, which would have had the effect of increasing their resistances.

51. When everything was duly prepared, the battery was placed in its troughs, and the current from it was urged through the galvanometer and each of three of the coils, which were placed in succession at E (the decomposing apparatus having been removed). The resistances of these coils were 4·4, 5·5, and 7·7, and the currents which they allowed to pass were $1^{\circ}{\cdot}88$ Q, $1^{\circ}{\cdot}65$ Q, and $1^{\circ}{\cdot}29$ Q.

52. The decomposing apparatus was now replaced, and the proper connexions being made, electrolytic decomposition

* Two of these coils had been previously employed (31. 41.), &c. in ascertaining the resistances of the voltaic pairs: the resistance 0·06 was that of the galvanometer and connecting wires.

was allowed to proceed during twenty minutes, in which time the needle of the galvanometer gradually declined from 55° to 48½°, the mean current being 1°·9 Q. The temperature of the liquid had now advanced from 46°·6 to 53°·95, indicating an increase of 7°·35. The temperature of the surrounding atmosphere was 46°·4.

53. The decomposing cell was now removed again, and the several coils, of which the resistances were, as before, 4·4, 5·5, and 7·7, were successively put in its place. The battery now urged through them, 1°·73 Q, 1°·48 Q, and 1°·22 Q.

54. In this case 7°·35 + 0°·55 (for Cor. A) and − 0°·64 (for Cor. B) = 7°·26, the heat which was generated in the decomposing jar.

55. The mean intensity of the current when passing through the coil of which the resistance was 4·4, was $\frac{1°\cdot 88 + 1°\cdot 73}{2}$ = 1°·805 Q, but 1°·9 Q when it passed through the decomposing cell. Hence $(4\cdot 4 + 3\cdot 15^*)\frac{1\cdot 805}{1\cdot 9} = 7\cdot 17$, this, −3·15*, leaves 4·02, the amount of *obstruction* presented by the decomposing cell.

56. Now we must remember, that when the electric current was passing through the coils, it was urged by the whole intensity of the battery; but that in the case of the decomposing cell, a part of the intensity of the zinc-iron battery, equal (as I have found by experiment) to 3⅓ pairs, or to one sixth part of the whole, is occupied solely in overcoming the *resistance to electrolyzation* † of water in the decomposing cell. In order therefore to deduce the true *resistance to conduction*, we must subtract $\frac{4\cdot 02 + 3\cdot 15}{6}$ from the *obstruction* 4·02; and thus we have 2·83, the true *resistance to conduction* of the decomposing cell.

57. The latter part of this process is difficult to express clearly, I have therefore drawn a figure to illustrate it. Suppose that in fig. 5, 6 represents the intensity of the battery; the line R 3·15, the resistance of the battery and the connecting wires; and the remainder of the line A B, or 4·02 W,

* From (51. 53.) we have the equations $\frac{1\cdot 88}{R+7\cdot 7} = \frac{1\cdot 29}{R+4\cdot 4}$ and $\frac{1\cdot 73}{R'+7\cdot 7} = \frac{1\cdot 22}{R'+4\cdot 4}$, whence R = 2·81 and R′ = 3·49 : the mean resistance of the battery and connecting wires was therefore 3·15.

† Faraday's Experimental Researches, (1007).

the resistance of wire. I have shown, (55.) that the cur-

Fig. 6.

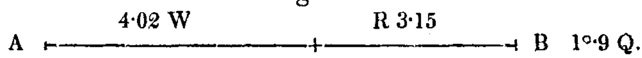


Fig. 5.

rent 1°·9 Q would pass against the resistance A B. But we know that 1°·9 Q was also passed when the cell and the battery formed the sole opposition (52.), and that on account of the resistance to electrolyzation, the virtual battery intensity was then one-sixth less, and hence that only five-sixths of the resistance represented by A B could have been opposed in this case, in order to the passage of the same current. Draw, therefore, another line, C D, one-sixth less than A B, and it will represent this resistance; from which, on subtracting R 3·15, we have *r* 2·83, the true resistance to conduction of the decomposing apparatus.

58. From (28.), and the data above given, we have $\frac{(1{\cdot}9)^2}{(1{\cdot}88)^2} \times 2{\cdot}83 \times 7^\circ{\cdot}56 \times \frac{20'}{60'} = 7^\circ{\cdot}29$, the *theoretical* result.

59. I made three other experiments with the same electrodes, and with the same battery. The results of these with those of the experiment just given at length, are as follows:—

	Experimental.		Theoretical.	
Exp. 7.	7°·26	....	7°·29	
Exp. 8.	8·12	....	8·32	
Exp. 9.	10·2	....	10·2	
Exp. 10.	9·64	....	9·75	(Refitted battery.)
Mean	8·8	....	8·89	

60. Exp. 11.—The mean current 0°·846 Q from a battery of ten zinc-iron pairs, was, by means of the same electrodes, sent through two pounds of dilute sulphuric acid for half an hour, during which the correct heat that was generated was 3°·09.

61. In order to find the true resistance to conduction of the decomposing cell, it was necessary to remember that in this instance one-third of the intensity of the ten pairs was expended in overcoming the resistance to electrolyzation of the water. With this exception the calculations were made precisely as before, and gave 3·76, the resistance of the cell; whence we have the theoretical heat 2°·88.

62. I now dismissed the narrow electrodes, and substituted for them two pieces of platinum foil, dipping to the bottom of the liquid; they were one inch apart, and each presented to the dilute sulphuric acid a surface of seven square inches. In this case I used twenty pairs of zinc-iron plates arranged in a series of ten.

63. The mean of six experiments with this apparatus gave $4^{\circ}\cdot42$ of real, and $4^{\circ}\cdot13$ of theoretical heat. I have no doubt that the difference is principally occasioned by the formation of the deutoxide of hydrogen, which is known to occur to a considerable extent when oxygen is evolved from an extended surface. Of this we have another instance in the following experiment.

64. Exp. 12.—Using the same electrodes, and a battery of ten zinc-iron pairs, I now passed a current of the mean intensity $1^{\circ}\cdot08$ Q through two pounds of dilute nitric acid, sp. gr. 1047, for half an hour. The heat that was thus generated, when properly corrected, was 3°.

65. This experiment was, as the others, conducted in the manner described at length under Exp. 7. Water chiefly* was decomposed; and I ascertained, experimentally, that about $\frac{1}{3\cdot5}$ of the intensity of the battery was expended in overcoming resistance to electrolysis. Thus I had $3\cdot52 - \frac{3\cdot52 + 1\cdot68}{3\cdot5} = 2\cdot03$, the resistance to conduction; and hence $\frac{(1\cdot08)^2}{(1\cdot88)^2} \times 2\cdot03 \times 7^{\circ}\cdot56 \times \frac{30'}{60'} = 2^{\circ}\cdot53$, the theoretical heat.

66. Exp. 13.—Two plates of copper, each of which was two inches broad, were secured at the distance of one inch apart, and immersed in two pounds of a saturated solution of sulphate of copper. Through this apparatus, a battery of ten zinc-iron pairs passed the mean current 1° Q during half an hour. The heat thus produced, when properly corrected, was $5^{\circ}\cdot8$.

67. In this case there was no *resistance to electrolysis*, and the action may be regarded simply as a transfer of copper from the positive to the negative electrode. All the *obstruction*, therefore, that was presented to the current, was *resistance to conduction*. Its mean was 5·5, whence we have $\frac{1}{(1\cdot88)^2} \times 5\cdot5 \times 7^{\circ}\cdot56 \times \frac{30'}{60'} = 5^{\circ}\cdot88$, the theoretical heat.

* See Faraday on the Electrolysis of Nitric Acid, 'Experimental Researches,' (752.).

68. We have thus arrived at the general conclusion, that *the heat which is evolved by the proper action of any voltaic current is proportional to the square of the intensity of that current, multiplied by the resistance to conduction which it experiences.* From this law the following conclusions are directly deduced:—

69. 1st. That *if the electrodes of a galvanic pair of given intensity be connected by any simply conducting body, the total voltaic heat generated by the entire circuit (provided always that no local action occurs in the pair) will, whatever may be the resistance to conduction, be proportional to the number of atoms (whether of water or of zinc) concerned in generating the current.* For if the resistance to conduction be diminished, the quantity of current will be increased in the same ratio, and hence, according to the law (68.), the quantity of heat which would thus be generated in a given time will be also proportionally increased; whilst of course the number of atoms which would be electrolyzed in the pair will be increased in the same proportion.

70. 2nd. That *the total voltaic heat which is produced by any pair, is directly proportional to its intensity, and the number of atoms which are electrolyzed in it.* For the quantity of current is proportional to the intensity of the pair, and consequently the quantity of heat evolved in a given time is proportional to the square of the intensity of the pair, but the number of atoms electrolyzed is proportional, in the same time, to the simple ratio only of the current, or of the intensity of the pair.

71. And 3rd. That *when any voltaic arrangement, whether simple or compound, passes a current of electricity through any substance, whether an electrolyte or not, the total voltaic heat which is generated in any time, is proportional to the number of atoms which are electrolyzed in each cell of the circuit, multiplied by the virtual* intensity of the battery.*

72. Berzelius thinks that the light and heat produced by combustion are occasioned by the discharge of electricity between the combustible and the oxygen with which it is in the act of combination; and I am of opinion that the heat arising from this, and some other chemical processes, is the consequence of resistance to electric conduction. My experiments on the heat produced by the combustion of zinc turnings in oxygen, (which, when sufficiently complete, I shall make public) strongly confirm this view; and the quantity of heat which Crawford produced by exploding a mixture of hydrogen and

* If a decomposing cell be in the circuit, the *virtual* intensity of the battery is reduced in proportion to its resistance to electrolyzation.

oxygen may be considered almost decisive of the question. In his unexceptionable experiments, one grain of hydrogen produced heat sufficient to raise one pound of water 9°·6. Now we know from Exp. 5, that the heat generated in one of Mr. Grove's pairs by the electrolysis of $\frac{4 \cdot 77 \times 32 \cdot 3}{6} = 25 \cdot 7$ grains of zinc, is theoretically 3°·46; and the heat which must in the same time have been generated by the *metallic* part of the circuit, which presented the resistance 0·06, is $\frac{0 \cdot 06}{0 \cdot 427} \times 3^{\circ} \cdot 46 = 0^{\circ} \cdot 48$: the total voltaic heat was therefore 3°·94. Hence the total heat which would have been evolved by the electrolysis of an equivalent, or 32·3 grains of zinc, is $\frac{32 \cdot 3}{25 \cdot 7} \times 3^{\circ} \cdot 94 = 4^{\circ} \cdot 95$; which, when reduced to the capacity of one pound of water, is 9°·9. But from the table of the intensities of voltaic arrangements (74.), the intensity of Mr. Grove's pair, compared with the affinity of hydrogen for oxygen, is $\frac{1}{0 \cdot 93}$; whence, from (70.), we have $9^{\circ} \cdot 9 \times 0 \cdot 93 = 9^{\circ} \cdot 2$, the heat which should be generated by the combustion of one grain of hydrogen, according to the doctrine of resistances: the result of Crawford is only 0°·4 more.

73. I am aware that there are some anomalous conditions of the current which seem to militate against the general law (68.), particularly when in the hands of Peltier it actually produces *cold**. I have little doubt, however, that the explanations of these will be ultimately found in actions of a secondary character.

Note on Voltaic Batteries.

74. In the foregoing investigation I have had occasion to work very extensively with different voltaic arrangements, and have repeatedly ascertained their relative intensities by the mathematical theory of Ohm. It will not, therefore, I hope, be deemed out of place to subjoin a table, in which the intensities of the batteries which are most generally used, are inversely as the number of pairs which would be just requisite in order to overcome the resistance of water to electrolyzation.

* If antimony and bismuth be soldered together, cold will be produced at the point of junction by the passage of the current from the bismuth to the antimony. Peltier, *Annales de Chimie*, vol. lvi. p. 371. In his paper, however, a misprint has inverted the direction of the current.

Mr. Grove's.	Platinum Nitric acid	Amalgam. zinc Dilute sulp. acid	$\frac{1}{0·93}$	Constant Intensities.
Prof. Daniell's.	Copper Sulphate of oxide of copper	Amalgam. zinc Dilute sulphuric acid	$\frac{1}{1·54}$	
Mr. Sturgeon's.	Iron. Amalgamated zinc Dilute sulphuric acid		$\frac{1}{3·33}$	
Mr. Smee's.	Platinized silver. Amalg. zinc Dilute sulphuric acid		$\frac{1}{3·58}$	
	Copper. Amalgamated zinc Dilute sulphuric acid		$\frac{1}{5·40}$	

75. Without entering particularly into the respective merits of these arrangements, I may observe that each of the first four may be used advantageously, according to the circumstances in which the experimenter is placed, or the particular experiments which he wishes to execute. The zinc-iron battery is somewhat inconvenient on account of local action on the iron; but then it presents great mechanical facilities in its construction. Mr. Smee's and Mr. Grove's are also very good arrangements; but the battery of Daniell is the best instrument for general use, and is, moreover, unquestionably the most œconomical.

Broom Hill, Pendlebury near Manchester,
March 25, 1841.

P.S. In the above table of galvanic intensities, that of zinc-iron immersed in dilute sulphuric acid is somewhat overstated. Recent experiments convince me that when the iron is in its best condition it possesses the same powers as the platinized silver. I attributed the iron battery to Mr. Sturgeon, who constructed one of these excellent instruments early in 1839*. It consisted of twelve cast-iron tubes, furnished with strips of amalgamated zinc. But I find that the experiments of this gentleman were not published as early as those of Mr. Roberts. Prof. Daniell (Phil. Trans. 1836, p. 114) observed that iron is sometimes more efficient than platinum in voltaic association with amalgamated zinc.

August 11, 1841. J. P. J.

[* A paper by Dr. A. Fyfe, on the employment of iron in the construction of voltaic batteries, appeared in Phil. Mag. for August 1837: S. 3, vol. xi. p. 145.—Edit.]