jars, each of capacity C, if q be the whole charge, we get immediately, from (48) of Mathematical Theory (p. 34),

$$Q = \frac{q^2}{2Cn}, \text{ and}$$

$$H = \frac{S}{R+S} \cdot \frac{q^2}{2Cn}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

Hence, if we keep the thermometer and inserted wires the same, the thermometer indications will be proportional to $\frac{q^2}{n}$, or, in words—*the heat evolved in the whole or in any given part of the circuit is proportional to the square of the battery charge directly, and to the number of jars* (i.e., *to the battery surface*) *inversely.*

If the thermometer wire remain the same, while the length section, and material of the inserted wire is varied, then, r being the specific resistance, l the length, and ρ the diameter of that wire, $R = \frac{4rl}{\pi\rho^2}$. Then, according to (3), the heat developed in the thermometer is given by

$$H = \frac{A}{1 + B\frac{rl}{\rho^2}} \quad . \quad . \quad . \quad . \quad . \quad (4),$$

where A and B are constants.

If, again, we use two wires of the same material of lengths l and l' and diameters ρ and ρ', and make two observations with these for inserted and thermometer wires respectively and *vice versa*, then, if H_1 and H_2 be the heat evolved in the two cases,

$$\frac{H_1}{H_2} = \frac{l'\rho^2}{l\rho'^2} \quad . \quad . \quad . \quad . \quad . \quad (5),$$

since R + S is the same in the two cases.

When the discharge is not complete, we have only to substitute for Q in (3) the appropriate expression for the exhaustion of the electric potential energy. Similarly we may find the heating effect caused by the discharge of a battery of jars arranged in series and charged by cascade in Franklin's manner (p. 35). If we discharge through a multiple arc, we may assume that the discharge divides itself between the branches in the ratio of the conductivities, so that the conductivity of the whole arc is the sum of the conductivities of its parallel branches. On these principles it is easy to calculate the heat generated in the whole circuit or in any branch of the arc.

All the cases we have alluded to were treated experimentally by Riess, and satisfactory agreement with formula (2) established in every case.

Comparison of conductivities.

By means of formula (4) he compared the specific conductivities of a variety of metals. A and B were determined, and a standard wire of platinum of given length kept in the thermometer; the wires to be compared with it were inserted in the outside circuit, and the heating in the thermometer observed. From the result the specific conductivity (in terms of platinum) of the wires could be calculated, their dimensions being known. The results agree very well with those got by other means.[1]

Heating by Constant Current.—The heating effect of the current furnished by a voltaic battery was recognized as a distinct and often very remarkable phenomenon for a considerable time before any definite quantitative law was established regarding it. Davy[2] experimented on wires of the same dimensions but of different materials, and found that the metals could be arranged in the following order:—silver, copper, lead, gold, zinc, tin, platinum, palladium, iron,—those standing nearer the beginning of the list being less heated by a given current than those nearer the end.

Joule's law. Metals.

Joule[3] was the first, however, to establish a definite law connecting the amount of heat evolved per second with the current strength and the resistance of the wire. He wound the wire in which the heat generated was to be measured round a glass tube which was immersed in a calorimeter. The resistance of the water is so great that we may assume without sensible error that the whole of the current passes through the wire. The temperature of the water was determined by means of a mercury thermometer immersed in the calorimeter. The amount of heat developed in the wire per second could then be found by the usual calorimetric methods. The strength of the current was measured by means of a galvanometer inserted in the battery circuit along with the wire. By experiments of this kind Joule established that *the amount of heat generated in a given time varies directly as the product of the resistance of the wire into the square of the strength of the current.* So that, if we choose our units properly, we may write

$$H = RI^2t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6),$$

where R is the resistance of the wire, I the strength of the current, and H the quantity of heat generated in time t.

The experiments of Joule were repeated with increased precautions against error by Becquerel,[4] Lenz,[5] and Botto. Becquerel allowed the wire to disengage heat till the calorimeter reached such a temperature that the loss of heat by radiation and convection, &c., was just equal to the gain from the wire, so that the temperature became stationary. The current was then stopped, and the loss of heat per second found by observing the fall of temperature in the calorimeter. Botto used an ice calorimeter. Lenz[6] made a series of very careful experiments with a calorimeter, in which the liquid used was alcohol, which is a much worse conductor than water. He first cooled his apparatus a few degrees below the temperature of the surrounding air, and then allowed the current to generate heat in the wire till the temperature of the whole calorimeter (which was kept uniform by agitation) had risen to an equal number of degrees above the temperature of the air. The current was then stopped, and the time t which it had flowed noted. According to Joule's law, tRI^2 ought to be constant, and it was found to be so very nearly. A very convenient instrument for demonstrating and measuring the heat generated by the electric current in a wire is the galavanothermometer of Poggendorff, which consists simply of an alcohol thermometer with a large bulb, into which is let a spiral of fine wire. The heat generated is deduced from the expansion of the alcohol, which is measured by means of a scale fastened to the stem of the thermometer. The value of the graduations is found by comparison with an ordinary thermometer. The thermoelectrometer of Riess might also be used in a similar way.

Electrolytes.

Heating in Electrolytes.—Joule's law applies also to electrolytes. The phenomenon, however, is not so simple as it generally is in the case of metallic conductors. Disturbances arise, owing to the heat evolved and absorbed in the secondary actions that take place at the electrode; and superadded to this we have in all probability an absorption or evolution of heat corresponding to the Peltier effect between different metals, of which we shall have to speak directly. Joule eliminated these disturbing influences by using a solution of copper sulphate with copper electrodes. In this case copper is dissolved from one electrode and deposited on the other, so that if we except the slight difference in the states of aggregation of the dissolved and deposited copper, the secondary processes are exactly equivalent, and must compensate each other. Joule[7] found that in a certain solution of $CuSO_4$ 5·50 units of heat were generated in a certain time, while in a wire of equal resistance 5·88 units were generated by an equal current in the same time. In a similar manner E. Becquerel[8] found that a current, which would produce a cubic centimeter per minute of explosive gas, generated in certain solutions of $CuSO_4$ and $ZnSO_4$ 0·213 and 0·365 units of heat; while the same current would have generated in wires of equal resistance 0·26 and 0·32 units respectively.

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[1] See Wiedemann's *Galvanismus*, Bd. i. § 194.

[2] *Phil. Trans.*, 1821

[3] *Phil. Mag.*, 1841.

[4] *Ann. de Chim. et de Phys.*, 1843.

[5] *Pogg. Ann.*, lxi., 1844.

[6] Wiedemann's *Galvanismus*, Bd. i. § 670.

[7] *Phil. Mag.*, 1841.

[8] *Ann. de Chim. et de Phys.*, 1843.

Reversible Heating Effects.—Peltier[1] was the first to discover an effect of this nature. He found that, when an electric current passes over a junction of antimony with bismuth, the order of the metals being that in which we have named them, there is an *evolution* of heat at the junction; and, when the current passes in the opposite direction, there is an *absorption* of heat, so that the temperature of the junction falls. Here, therefore, there is an effect which cannot vary as the square of the current strength, but must be some function of the current strength, whose *principal* term at least is some odd power.

The Peltier effect, as it is now called after its discoverer, may be demonstrated by inserting a soldered junction of antimony and bismuth into a Riess's thermoelectrometer. When the current goes $\overrightarrow{BiSb}$, the fluid will rise in the stem, indicating absorption of heat; when it goes $\overrightarrow{SbBi}$, the fluid will fall, indicating evolution of heat. Or we may use Peltier's cross, which consists of two pieces, one of bismuth BB′, and the other of antimony AA′, soldered together in the form of a cross (fig. 28). A and B are connected by a wire through a galvanometer G. A′ and B′ are connected with a battery C through a commutator D, by means of which the current can be sent either from A′ to B′ or from B′ to A′ through the junction. The thermoelectric current indicated by the galvanometer shows that the junction is heated in the first instance and cooled in the second.

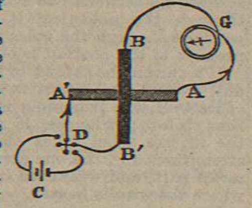

Fig. 28.

By leading the current of a Grove's cell for five minutes through a $\overrightarrow{BiSb}$ junction, Lenz[2] succeeded in freezing a small quantity of water which had been placed in a hole in the junction, and previously reduced to 0° C. The temperature of the ice formed fell to − 4·5° C.

The Peltier effect is different for different pairs of metals. Peltier and Becquerel[3] found that the metals could be arranged in the following order:—

$$\overrightarrow{\text{Bi, Gs,}^{4}\text{ Pt, Pb, Sn, Cu, Au, Zn, Fe, Sb}}.$$

If the current pass across a junction of any two of these metals, cold or heat is generated according as the current passes the metals in the direction of the arrow or in the opposite direction; and the Peltier effect between the metals is greater the farther apart they are in the series. We shall see later on that this is none other than the thermoelectric series.

Von Quintus Icilius[5] showed that *the Peltier effect is directly proportional to the strength of the current.* He passed a voltaic current through a tangent galvanometer (serving to measure it) and a thermopile of 32 BiSb couples. The current was allowed to pass for a fixed time, then the battery was removed and the thermoelectric current of the pile measured by means of a delicate mirror galvanometer. The current of the battery heats the pile in part *uniformly* according to Joule's law: this causes no unequal heating of the junction, and therefore no thermoelectric current; and in part unequally, so that one set of junctions are cooler and the other warmer than the mass of the metal: this causes a thermoelectric current, which, since the temperature differences are small (see below, p. 97), may be taken to be proportional to the temperature difference, that is, to the double of the Peltier effect at each set of junctions.

It is interesting to note the analogy here with the polarization of an electrolytic cell. We turn a battery on to the thermopile, and polarize it, as it were. Then, when we remove the battery and close the pile, we get a return current, which might be called the polarization current of the thermopile.

In general the Peltier effect is, as we have seen, mixed up with Joule's effect, and makes itself felt by producing a disturbance at the junction. Thus Children[6] found that, when a strong current passed through two mercury cups joined by a thin platinum wire, so that the wire became red hot, the temperature of the mercury in the cups next the + pole of the battery rose to 121° F., while in the cup next the − pole the temperature was only 112° F. Frankenheim[7] studied the two effects together. He made a Peltier's cross of the pair of metals to be examined, passed a current I through the cross first in one direction and then in the other, and determined by means of a delicate galvanometer the thermoelectric current generated in each case, which is very nearly proportional to the heat produced. If a and b be the heat from Joule and Peltier effects respectively, and i and i' the observed thermoelectric currents, then $i = C(a+b)$, $i' = C(a-b)$; whence $a = (i+i') \div 2C$, and $b = (i-i') \div 2C$. In this way he found that a was proportional to I^2, and b to I. Thus the whole heat developed may be expressed by $aI^2 \pm bI$. We get in this way a verification of the results both of Joule and of Von Quintus Icilius.

Thomson effect.

Further experiments have been made on this subject by Edlund and Le Roux; and Sir W. Thomson was led by a remarkable train of reasoning to discover another reversible heating effect. We prefer to leave these matters for the present, to return to them when we consider thermoelectric sources of electromotive force.

The Peltier effect between metals and liquids and other reversible effects will also come up again under the Origin of Electromotive Force.

Theory of heating effect.

Theoretical Deduction of the Formulæ.—The above formulæ for the heat developed in wires by statical and dynamical electricity may be deduced from a common formula, which can be deduced from Ohm's law.

Let P, Q be two points of a linear circuit, and let E be the difference between the potentials at P and Q, then, if there be no other electromotive force in the portion PQ, the work done by a unit of + electricity in passing from P to Q is E. Hence, if I be the strength of the current, so that $I\,dt$ units of electricity pass from P to Q in time dt, then the amount dw of work done by the current in time dt is $EI\,dt$. But, by Ohm's law, $E = RI$, hence

$$dw = RI^2dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7).$$

Since the whole of this work is spent in heat, we may for w write H, which denotes the heat[8] generated in PQ. If the current be constant, we get immediately $H = RI^2t$, which is Joule's law (6). If the current be variable, $H = \int RI^2dt$, from which we may very easily deduce the formula for the discharge of a battery of Leyden jars. For, applying Ohm's law to the whole circuit whose resistance is R + S, we have, if U denote the potential of the inside coatings at time t, $I = \frac{U}{R+S}$. Also the capacity of each of the n jars being C, we have for the charge $q' = nCU$, and $I = -\frac{dq'}{dt} = nC\frac{dU}{dt}$. Hence

$$H = R\int I^2dt = -\frac{nCR}{R+S}\int U\frac{dU}{dt}dt = \frac{nCR}{R+S}\,\frac{V^2}{2}$$
$$= \frac{R}{R+S} \cdot \frac{q^2}{2nC} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8),$$

where q and V have the same meanings as in (3). (8) agrees with (3), except that we have reckoned the heat developed in a portion of the circuit whose resistance is R instead of S, as in (3). It appears, therefore, that the theoretical formula (7), when properly interpreted, covers both cases.

If there were a junction of heterogeneous metals in the part PQ of the circuit, at which the potential suddenly fell by an amount Π, then work equal to $\Pi I\,dt$ would be done by the current in passing over the junction, and we should have to write

$$dW = RI^2dt + \Pi I\,dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9).$$

Had there been a *rise* of potential at the junction, we should have written $-\Pi$ instead of $+\Pi$. If all the work done at the junction is transformed into heat, W = H as before, and for a constant current,

$$H = RI^2t + \Pi It \quad . \quad . \quad . \quad . \quad (10).$$

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[1] *Ann. de Chim. et de Phys.*, 1834.

[2] See Wiedemann's *Galvanismus*, Bd. i. § 689.

[3] *Ann. de Chim. et de Phys.*, 1847.

[4] Gs = German Silver.

[5] *Pogg. Ann.*, lxxxix. 1853.

[6] *Phil. Trans.*, 1815.

[7] *Pogg. Ann.*, xvi. 1854.

[8] Measured, of course, in dynamical equivalents.

The first term is Joule's, the second Peltier's effect. Here the coefficient of the Peltier effect appears as an electromotive force. We shall return to this again.

Glowing, melting, &c., of wires.

Glowing, Melting, Volatilization, &c.—If a wire lost none of the heat generated in it, then, for the same current, the rise in its temperature during a given time would vary as its specific resistance directly, and as the product of its specific heat and density into the fourth power of its diameter inversely. Thus, T, r, c, ρ, d denoting these quantities in the order named above, $T \propto \frac{r}{c\rho d^4}$.

If we have a given battery of electromotive force E, and a circuit connected with it of resistance R, and we insert a wire of length l specified in other respects as above, the current will be $\frac{E}{R+S}$, where $S=\frac{4lr}{\pi d^2}$. If the diameter of the wire be given, then $S \propto l$; and $T \propto \frac{S}{(R+S)^2}$, which is a maximum when $R=S$, that is, when the length of the wire is such that its resistance is equal to that of the rest of the circuit.

Owing to our ignorance of the exact law of cooling, and of the manner in which the resistance and specific heat of most metals change at very high temperatures, it is very difficult to predict beforehand to what temperature a given current will raise a given wire. It is, as may be supposed, still more difficult to predict the effect of a given discharge from a Leyden battery. According to Riess, the phenomenon of glow in this case is complicated by concomitant effects of specific nature.[1]

If we assume Newton's law of cooling, *i.e.*, that the heat given out is proportional to the surface of the wire and to the elevation T of its temperature over that of the surrounding medium, then, I denoting the strength of the constant current which heats the wire, we have, when a constant temperature has been attained, $I^2=\text{const.}\times Td^3$, for wires of same length and material but different diameters. If we compare the apparent brightness of the wires, by causing them to illuminate a screen at a constant distance off, and assume that the light given out is proportional to Td, then, if two wires of diameters d_1 and d_2 have the same apparent brightness, $T_1d_1=T_2d_2$, and $I_1^2\div d_1^2=I_2^2\div d_2^2$. In other words, the strength of current requisite to bring a wire of given length and material to a given brightness of glow varies directly as its diameter. A law of this nature is, of course, merely a rough approximation; Müller and Zöllner, however, have made experiments which agree with it within certain limits. The method of Zöllner is interesting (see Wiedemann's *Galvanismus*).

The temperature of a glowing wire is very sensitive to external circumstances, such as air currents, &c. These effects may be very strikingly shown by balancing the wire in a Wheatstone's bridge against a resistance of thick wire, a strong current being sent through the bridge.

The behaviour of the wire in different gases is very remarkable. If a wire which is glowing in air be suddenly immersed in a jar of hydrogen or coal gas, the brightness will be very much reduced, in fact, in most cases the glow will entirely disappear.[2] This is owing to the greater cooling power of hydrogen, of which evidence is furnished by the experiments of Dulong and Petit.[3] The cooling power of different gases was shown by Grove. He arranged a platinum wire in a glass tube, which could be filled with different gases. The current of the same battery was sent through the wire and through a voltameter. When the tube was filled with hydrogen or olefiant gas, the amount of gas evolved in the voltameter per minute was 7·7 and 7·0 cubic inches respectively. The numbers for the other gases experimented on varied from 6·6 to 6·1. They stood in the following order:—CO, CO_2, O, air (2 atmos.), N, air (1 atmos.), air (rarefied), Cl. Experiments of a similar nature were made on liquids. Clausius carried out a calculation of the cooling effect of different gases, and found that the experimental results could be satisfactorily accounted for.[4]

When the strength of the current is sufficiently increased, the wire ultimately fuses, or even volatilizes. The phenomenon is in general complicated. In air, for instance, the wire burns, and the oxidization once started may take a greater share in raising the temperature than the current does, so that the destruction of the wire may take place under certain circumstances with a current, which, under other conditions, would scarcely make it glow. When discharges from a Leyden battery are used it is very difficult, if not altogether impossible, to get melting unaccompanied with mechanical disaggregation of the wire. The reader who wishes for further information concerning these matters, will find the sources sufficiently indicated in Wiedemann, Riess, and Mascart.

Popular experiments.

This department of electricity is very fruitful in popular lecture-room experiments. We shall quote one or two of these, and refer the reader to popular treatises for more of the same kind.

On a sheet of thin card-board is pricked a design, generally what is understood to be a portrait of Franklin, two pieces of tinfoil are pasted on the ends of the card by way of electrodes, and between these a piece of gold leaf is laid. On the other side of the card is placed a piece of white paper or silk. The whole is then tightly screwed up between two boards. When an electric discharge is sent through the gold leaf it volatilizes, sending the disintegrated particles through the holes in the card-board. In this way an impression of the portrait is obtained.

If a current be caused to heat a pretty long thin platinum wire to dull redness, and a portion of the wire be cooled by applying a piece of ice to it, the remainder of the wire will glow much more brightly than before; whereas, if a portion be heated by a spirit-lamp, the reverse effect takes place. The reason is that the current is strengthened in the one case by the decrease of the resistance in the *cooled* part, and weakened in the other by the increase of resistance where the wire is heated.

When two curved metal surfaces rest upon each other, a current passing from the one to the other encounters considerable resistance at the small area of contact. The heat developed in consequence of this causes the parts in the neighbourhood to expand very quickly when the contact is made. This very often gives rise to rapid vibratory movements in the conductors. The Trevelyan rocker[5] can be worked in this way (see art. HEAT), bells rung, &c. The best known experiment of the kind is Gore's railway. This consists of two concentric copper hoops, whose edges are worked very truly into the same plane. A light copper ball is placed on the rails thus formed, a current from two or three Groves is sent from one hoop to the other, and the ball set in motion. If the ball be very true, and the railway be well levelled, the energy supplied by the swelling at the continually changing point of contact is sufficient to keep up the motion, and the ball runs round and round, emitting a crackling sound as it goes.[6]

Electric light.

The Voltaic Arc.—When two electrodes of volatile or readily disintegrable material forming the poles of a powerful battery (say 30 or 40 Grove's cells) are brought into contact and then separated, the current continues to pass across the interval, provided it is not too great. The conducting medium appears to be a continuous supply of heated matter, suspended in glowing gas or vapour. This phenomenon seems to be more akin to the subject we are now discussing than to the disruptive discharge of which we shall speak by-and-by. The light thus generated with a large battery, especially when electrodes of graphitic carbon are used, is brilliant in the extreme. It was thus that Davy first obtained the phenomenon.[7] With a battery of 2000 cells he obtained a luminous arc 4 inches in length, and when the carbons were placed in an exhausted receiver the arc could be lengthened to 7 inches.

The fact that the electrodes must be brought in contact in order to start the light is quite in accordance with what we know of the extremely small striking distance of even very powerful batteries. When the contact is made, the place where the electrodes touch, owing to its small section, is intensely heated; the matter begins to volatilize, and then the current is kept up by the quickly increasing cloud of metallic vapour and disintegrated matter. With a battery of 60 Grove's cells the arc once started has a certain persistence, for we may break the current for $\frac{1}{20}$th of a second or so, and the light will start again when the current is turned on afresh. We may start the light without bringing the electrodes into contact by causing a spark from a Leyden jar or an inductorium to pass across the interval.

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[1] *Reibungselectricität*, Bd. ii. §§ 557 *sqq.*

[2] Grove, *Phil. Mag.*, 1845, or Wied. *Galv.*, Bd. i. 679.

[3] Poggendorff, *Pogg. Ann.*, lxxi., 1847.

[4] Wied. *Galv.* (*l. c.*), or *Pogg. Ann.*, lxxxvii., 1852.

[5] Wied. *Galv.*, Bd. i. § 726.

[6] This motion has been attributed to electromagnetic action. Such an explanation is quite inadmissible.

[7] *Phil. Trans.*, 1821. According to Quetelet, Curtet observed the light between carbon points in 1802. Wied. *Galv.*, Bd. i. § 783.

If an image of the voltaic arc be thrown on a screen by means of a lens, its constitution can be examined very readily. Four distinct parts at once strike us;—first, the dazzling white positive carbon, which assumes a crater-like shape after the current has passed for some time; second, the more pointed and if anything less brilliantly-white negative carbon, which is in general strewed with little beads of melted or at least softened carbon; third, the central core or streak of glowing matter, which has a white appearance, though it is considerably less brilliant than the carbon; fourth, the globe-shaped aureole which surrounds the whole, whose brilliancy is greatly inferior to that of the other parts, and whose colour depends on the surrounding gas. If the electrodes be horizontal, the arc is in general curved upward by ascending air currents, its form is also affected in general by the earth's magnetic action.

The hollowing out of the positive electrode is obviously due to a transfer of matter in the direction of the current. It is very easy to prove by a variety of conclusive experiments that there is such a transfer, mainly in the direction of the current, but also in part in the opposite direction. If we take a platinum point for positive, and a platinum plate for negative electrode, the matter carried to the plate forms a series of rings on it like the colour rings of Nobili. If, on the other hand, the platinum plate forms the positive electrode, a series of slight excavations are formed where the matter has been torn away. There can be no doubt that the disintegration of the electrodes plays a very important part in the formation of the arc, for if we saturate the carbons with volatile matters, the brilliancy of the arc, the ease with which it forms, and its maximum length for given battery power are greatly increased. It is probably owing, in part at least, to the tearing away of matter at the positive electrode that the temperature there is in general highest. This effect is very marked in some cases. If we take a platinum point and a plate of the same metal for electrodes, the point glows through a considerable length when it is positive, but only at the end when it is negative. Again, when the light is generated between two platinum wires held crosswise at a small distance apart, the glowing portion is much longer on the positive electrode than on the negative.

The electric light is the only artificial light whose brilliancy can compare with the sun. Measured by its actinic properties simply, it is not so very far behind the great luminary; its spectrum is longer towards the violet, and it has accordingly great advantages when it is required to produce fluorescence (see art. LIGHT). Its great chemical power is also shown by the readiness with which it induces the combination of hydrogen and chlorine; by means of it underground buildings, such as the catacombs, have been successfully photographed. Its illuminating powers have for a considerable time been employed in lighthouses, the current for its maintenance being furnished by powerful electromagnetic machinery, and it is now proposed to employ the Gramme machine and the electric lamp to light streets and public buildings, manufactories, &c. It was used for war purposes during the last siege of Paris, and in the Russo-Turkish war on the Danube; and further applications to torpedo warfare have been contemplated.

In most of these applications of the electric light it is important that the arc should be of constant length, and maintain a fixed position. Owing to the unequal consumption of the carbons, special appliances are required to secure the fulfilment of these conditions. The best known and perhaps the most efficient of the older electric lamps is that devised by Foucault. It consists of a piece of clockwork, which moves the carbons towards each other with relative speed nearly equal to that at which they are consumed. The machinery is controlled by a detent worked by an electromagnet, which is excited by the current which feeds the arc. When the carbons are too far apart the electromagnet is weakened and releases the detent. The machinery then moves the carbons until the current is strong enough to enable the electromagnet to apply the detent again. This apparatus works well enough for lecture-room and other purposes, but has not given perfect satisfaction in industrial applications. Accordingly many devices have been proposed, more especially of late years, to supersede it. One of the simplest and it would appear most effective of these is the electric candle of Jablochkoff. This consists simply of two carbons, separated from each other by a plate of kaolin. The arc passes between the carbons, and plays over the kaolin, which gradually melts away like the wick of a candle, and by its incandescence greatly helps the brightness of the light.[1]

The heating powers of the electric arc are no less remarkable; platinum and iridium melt in it like lead, and volatilize. In this way the spectra of the glowing vapour of these metals can be projected on a screen. Almost nothing seems to resist the elevated temperature of the arc. Despretz generated it in vacuo by means of 500 to 600 cells of Bunsen, and observed pieces of carbon volatilize like a piece of heated iodine, while the carbon vapour condensed on the walls of the receiver in the form of a crystalline powder. Flint melted to a glassy mass, and boron behaved similarly, while cylinders of retort carbon softened and bent into an S-form.

The voltaic arc behaves in many respects like an ordinary electric current. It is affected by the magnet, for instance, as an ordinary current would be. Owing, however, to the variety of transformations of energy taking place, it is difficult to estimate accurately the resistance and electromotive force of the arc. Edlund made experiments which seemed to show that a certain minimum electromotive force in every case was necessary for the maintenance of a continuous arc, yet the arc does not appear to consist of a series of disruptive discharges, for its image in a rotating mirror is a uniform band. It would seem, therefore, as if polarization in some form or other were present. Edlund, in fact, found that when a galvanometer was substituted for the battery by which the arc was formed a considerable current was obtained, which might have an origin similar to that of electrolytic polarization, or be a thermoelectric effect.[2] For further details on these and other matters connected with the electric light, we refer the reader to the admirable account of Wiedemann, *Galvanismus*, Bd. i. § 701 *sqq.*), from which most of the above is taken.

Disruptive Discharge, Light Effects, &c.

Phenomena of disruptive discharge.

A definite meaning has already been attached to the term disruptive discharge; the object of the present section is to consider this phenomenon a little more closely in several particular cases. The disruptive discharge proper is in general accompanied by sound, heat, light, and mechanical effects, very often by all four. The attendant luminous phenomena have absorbed by far the greatest share of the attention of experimenters, partly, no doubt, on account of their great variety and wonderful beauty. It would be a hopeless task to endeavour, within the limits set us here, to give even a meagre summary, not to speak of a critical account, of all the experiments and observations that have been made on this subject. The scientific investigator will find sufficient guide for his reading in the three standard treatises of Riess, Wiedemann, and Mascart. Riess is particularly interesting in his account of the older

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[1] See *Nature*, Sept. 1877.

[2] Wiedemann explains Edlund's results by means of an "Uebergangswiderstand." It is difficult to understand how in this way a return current could arise.

experiments; Wiedemann, on the other hand, gives elaborate accounts of the more modern results of De la Rive, Plücker, Hittorf, and others.

When induction is exerted across a dielectric, we may consider the action at any point of it in one or other of two ways. We may regard the resultant electromotive force arising from the action at a distance of all the free electricity in the field as tending to separate the two electricities in the molecules of the dielectric. In this view, we might measure the dielectric strength of the medium by the value of the electromotive force, when the electricity is on the point of passing from one molecule to the next. We might, on the other hand, consider, with Faraday and Maxwell, that the dielectric is the seat of a peculiar kind of stress, consisting of a tension p along the lines of force, and an equal pressure perpendicular to them, p being equal to $\frac{K}{8\pi}R^2$ (Maxwell, vol. i. § 104). We shall adopt the latter alternative, and when we speak of tension henceforward it means $\frac{K}{8\pi}R^2$. In this view the dielectric strength may be defined as that tension under which the dielectric just begins to give way. The reader who prefers the other way of looking at the matter will find no difficulty in translating any statement from the one language into the other.

We have started by considering any point of the dielectric, and it is obvious that the dielectric (supposed homogeneous) will first give way at that point which first reaches the limiting tension ϖ; just as an elastic solid begins to give way where the stress first reaches the breaking limit. It may be proved, however, that R^2 cannot have a maximum value at any point where there is no free electricity, which shows us at once that the point at which the limiting tension is first reached must always be on *some* electrified surface, in general therefore on the surface of one of the conductors of the system.[1] Disruptive discharge, thus begun at the surface of a conductor, spreads out into the dielectric. Its farther course is influenced by a variety of circumstances very hard to define in the great majority of cases.

An attempt will be made by-and-by to give an idea of the varieties of luminous discharge that arise in this way; meantime we concentrate our attention on a feature common to all disruptive discharges, viz., the definite limiting tension at which under given circumstances they begin.

Dielectric strength.

Striking distance.

Dielectric Strength of Gases.—The earlier measurements bearing on this subject were conducted under circumstances which render a comparison of the results with the theory, as at present developed, very difficult. Harris found that the striking distance between two balls connected with the armatures of a condenser was directly proportional to the charge of the condenser as measured by a Lane's jar. Riess used a Leyden battery, and varied the number of jars and the charge of the battery. The balls of his spark micrometer were of diameters 5·7 and 4·4 lines respectively, while the distance between them varied from 0·5 to 2·5 lines. Under these circumstances, he found the striking distance to be proportional to the charge of the battery directly, and to the number of jars inversely. The results of Harris and Riess might be summed up in the statement that the striking distance between two balls connected with the armatures of a condenser varies as the electromotive force or difference of potential between the armatures. This result is purely empirical, and must not be extended beyond the experimental limits within which it was found. Even Riess's experiments themselves show that the striking distance increases more rapidlv than the difference of the potentials.

The experiments of Knochenhauer[2] led to a similar result. Gaugain[3] made experiments of the same kind through a wider range of striking distances, and found, in conformity with the result of Riess, that, with balls of 10 or 15 mm. diameter, the striking distance is proportional to the potential difference between the balls when the distance between them lies between 2 and 5 millimetres. Beyond these limits the ratio of potential difference to striking distance falls off; whereas, for smaller distances, it increases very rapidly. He also found that the deviation from the law of Harris and Riess is more marked when unequal spheres (3 mm. and 10 mm.) are used, and still more when a ball (3 mm. diam. used as + electrode) and a disc (35 mm. diam.) were used as electrodes. Experiments leading to similar conclusions are cited by Mascart,[4] who finds that, for spheres of diameter 3 to 5 centimetres, the striking distance for given potential difference is sensibly the same; whereas for plates, both the striking distance and the law of the whole phenomenon is different. The same experimenter examined the striking distances between two equal balls (3 cm. diam.) from 1 mm. up to 150 mm. Taking the potential difference for one millimetre as unity, he found for 10, 20, 40, 80, 150 mm. the potential differences 8·3, 11·8, 15·9, 20·5, 23·3. The deviation from proportionality is obvious; the potential differences in fact tend to become constant. Wiedemann and Rühlmann, in their experiments on the passage of electricity through gases (see below, p. 61), made some experiments on the influence of the form and distance of the electrodes. They used two brass balls of 13·8 and 2·65 mm. diameter respectively, and sent between them the discharges of a Holtz machine. The distance (δ) between the nearest points varied from 3 to 22·3 mm. They found that the quantity of electricity (y) required to produce discharge, could be represented by the formulæ $y = A - \frac{B}{\delta}$ and $y = C + D\delta^2$, according as the larger sphere formed the positive or negative electrode. The constants A, B, C, D depend on the pressure, which varied in these experiments between 25 and 60 mm. of mercury.

Sir Wm. Thomson's experiments.

In most of the experiments that have just been described the effect of the form of the electrodes and the surrounding conductors could not be estimated theoretically. Experiments in which the theoretical conditions are simple have been made by Sir Wm. Thomson.[5] The spark was taken between two parallel plates of considerable area; one of these was plane, and the other very slightly curved, to cause the spark to pass always at a definite place. The electrical distribution on the opposing surfaces can be found (see above, Math. Theory of Electrical Equilibrium), as if the plates were plane and of infinite extent. This distance between the plates was measured by a micrometer, the contact reading being determined by observing when the electricity ceased to pass between the plates in the form of a spark. The potentials were measured in absolute electrostatic (C.G.S.) units, by means of Thomson's absolute electrometer (see art. ELECTROMETER). The limiting tension or dielectric strength is given in each case in grammes per centimetre, the formula for calculating it being

$$p = \frac{V^2}{8\pi \times 981{\cdot}4d^2},$$

in which V represents the potential difference or electromotive force between the plates, and d the distance in centimetres. If we take the older view of Poisson's time that the action of the electricity on the surface of a conductor is simply a fluid pressure, then p represents that pressure.

If we could consider the air between the plates as a homogeneous dielectric, then, for air at a given pressure (and temperature?) and given state of dryness, p, which measures its dielectric strength, would have a constant value, independent of the distance between the plates, and V would be proportional to d. A glance at Sir Wm. Thomson's[6] tables shows that this is not the case. For a distance of ·00254 cm., $p = 11{\cdot}290$, whereas for a distance ·1524, $p = {\cdot}535$. It appears, therefore, that the dielectric strength of a thin stratum of air is much greater than that of a thick one. It is very difficult to understand why this should be so. "Is it possible that the air very near to the surface of dense bodies is condensed, so as to become a better insulator; or does the potential of an electrified conductor differ from that of the air in contact with it, by a quantity having a maximum value just before discharge, so that the observed difference of potential of the conductors is in every case greater than the difference of potentials on the two sides of the stratum of airby a constant quantity equivalent to the addition of about ·005 of an inch to the thickness of the stratum?"[1] It is remarkable that the limiting tension should be so small, somewhere about half a gramme per sq. cm., as compared with the atmospheric pressure, which is about 1032 gm. per sq. cm.

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[1] The dielectric is supposed to be homogeneous. Prof. Maxwell has pointed out that exceptions might occur in the case of a weak dielectric interposed between two strong ones, *e.g.*, a current of hot air passing through cold.

[2] Mascart, t. i. § 463, or *Pogg. Ann.*, lviii.

[3] Mascart (*l.c.*).

[4] t. i. § 478.

[5] *Proc. R.S.*, 1860, or *Reprint*, p. 247

[6] *Reprint*, pp. 252, 258.

A series of absolute measurements of the potential required to produce a spark between equal spheres at different distances has been made by Mascart. The method employed was very ingenious.[2]

Effect of Pressure, Temperature, &c., on the Dielectric Strength of Gases.—The dielectric strength of a given gas depends on its pressure, or at all events on its density. Harris, who experimented on this subject, inclosed two balls in a receiver which could be exhausted to any required degree, and connected them with the armatures of a battery of jars. He found that the charge which had to be given to the battery in order to produce a spark between the balls was proportional to the density of the air in the receiver, while it seemed to be independent of its temperature. This amounts to asserting that the difference of potentials required to produce a spark between the balls is proportional to the density of the gas and independent of its temperature. Since we keep the distance between the balls the same throughout, this statement is equivalent to saying that the dielectric strength of a gas varies directly as its density, and does not depend on the temperature. Masson, using the method which Faraday had employed in comparing the dielectric strength of gases (*vide infra*) arrived at the same conclusion as Harris. Knochenhauer, however, experimenting with pressures ranging from 3 to 27·4 inches of mercury, found that for a given interval the difference of potentials required to produce disruptive discharge was proportional to the pressure increased by a small constant quantity.

Faraday, in the 12th and 13th series of his *Experimental Researches*, examines this subject; and the reader who desires to have a clear idea of what the issues involved really are will do well to begin by carefully studying Faraday's results, and still more his views on this matter. Faraday directs his attention to the specific behaviour of different gases.

The gas to be examined was introduced into a receiver in which were arranged two balls s and l, of diameters 0·93 in. and 2·02 in. respectively, at a constant distance 0·62 in. apart. Two balls, S and L, of diameters 0·96 in. and 1·95 in., were placed on suitable insulating supports outside the receiver. S and s were connected with an electric machine, and l and L to earth. The distance u between S and L could be varied at will; if it was greater than a certain value β, the sparks always passed between s and l in the receiver; if it was less than a certain value α, they always passed between S and L in the outer air. It might have been expected that α and β would be equal, or at least very nearly so, *i.e.* that there would be one definite value of u, for which the spark would hesitate between the alternative intervals. This is not so, however. Nor again is the value of u the same when s and l are negative as when they are positive. The following table will illustrate these points, as well as the relations of the different gases:—

Gas.	s and l positive.			s and l negative.		
	α	β	Mean.	α	β	Mean.
Air	0·60	0·79	0·69	0·59	0·68	0·63
Oxygen	0·41	0·60	0·50	0·50	0·52	0·51
Nitrogen	0·55	0·68	0·61	0·59	0·70	0·64
Hydrogen	0·30	0·44	0·37	0·25	0·30	0·27
Carbonic acid	0·56	0·72	0·64	0·58	0·60	0·59
Olefiant gas	0·64	0·86	0·75	0·69	0·77	0·73
Coal gas	0·37	0·61	0·49	0·47	0·58	0·52
Hydrochloric acid.	0·89	1·32	1·10	0·67	0·75	0·72

It will be seen that the different gases present considerable variety, and cannot be classified in any way so as to connect the dielectric strength with any other physical property. The numbers given cannot be regarded as *measuring* the dielectric strength, owing to the disturbing influences which cause the inequality of α and β. This inequality is not by any means small; *e.g.*, for air the uncertainty amounts to about 32 per cent. These experiments show very clearly that the sign of electrification of the surface at which the discharge begins has a great effect on the limiting tension. The discharge passes much more readily from a small ball to a large one when the former is negative than when it is positive. Faraday made a variety of experiments to elucidate this point, and he was driven to the conclusion "that, when two equal small conducting surfaces equally placed in air are electrified, the one positively the other negatively, that which is negative can discharge to the air at a tension a little lower than that required for the positive surface, and that, when discharge does take place, much more passes at each time from the positive than from the negative surface."

Positive and negative limiting tension.

The inequality of α and β may be due to various causes, among which may be mentioned the charging of the glass of the receiver, dust, &c., in the air, heating of the air, and the presence of finely divided metal dispersed by preceding sparks. The last of these causes would account to a considerable extent for the fact that the sparks show a tendency to persist in a path once opened, and that the interval $\beta - \alpha$ is less for the negative spark, which starts at a smaller limiting tension, and may therefore be supposed to produce less mechanical effect.

Wiedemann and Rühlmann.

Wiedemann and Rühlmann have recently taken up this subject in a research which has already been alluded to.[3]

The gas and the spark terminals were inclosed in a cylindrical metal receiver with rounded ends. A small window allowed the light from the spark to fall on a rotating mirror fixed on the axis of a Holtz machine, which furnished the electricity. The images of the successive sparks were observed by means of a heliometer. One-half of the divided object-glass was moved until one of the images of one discharge coincided with one of the images of the next; then a similar coincidence was brought about by displacing the half-lens in the opposite direction. The difference (y) of the two readings on the micrometer of the heliometer measures the rotation of the disc of the Holtz machine between the two sparks. Preliminary experiments showed that the amount of electricity furnished by the machine while the disc moves through a given angle is independent of the angular velocity of the disc. It varies from day to day, however, according to the quantity of moisture in the air and the arrangement of the machine; but, on the principle just laid down, correction can easily be made by taking the reading each day of a galvanometer through which the current of the machine is sent. It follows, therefore, that y is proportional to the quantity of electricity which passes at each discharge through the gas, and by means of a galvanometer observations on different days can be compared.

It was found that at the lowest pressures worked with (·5 to ·25 mm. of mercury) the discharge of the Holtz machine was still discontinuous; and that in all the experiments the tension at the electrodes was such that the discharge was independent of the nature of the metal,—in

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[1] Maxwell, *Electricity and Magnetism*, vol. i. § 57.

[2] *Électricité*, t. i. § 481

[3] *Abh. d. k. Sächs. Gesellsch.*, 1871, or Wiedemann, *Galv.* ii. 2, § 933, &c.