A High Voltage Direct Current Generator

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When powdered materials are blown through metal tubes by means of compressed air considerable quantities of electricity are produced by contact electrification. It was found that 6×10^{-5} coulombs could be produced per gram of diatomaceous earth, a form of silica, blown through a short length of copper tube. A generator of extremely high voltage is proposed, and a small scale model of such a generator is described, by means of which currents of 8×10^{-5} amperes at 260 kilovolts were generated.

THIS work was undertaken to provide numerical data to serve as the basis for the design of a high voltage generator capable of generating a milliampere at voltages above a million.

The Proposed Generator

The discussion to follow will be simplified by a consideration of Fig. 1 which is a diagrammatic representation of the proposed high voltage generator. The small scale model constructed will be described later on.

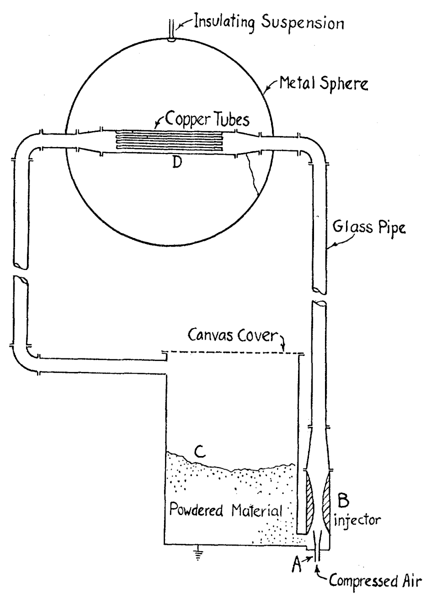

Fig. 1. Proposed high voltage generator.

A blast of compressed air is blown from a nozzle A into a suitably designed injector B. A powdered material C is sucked into the air stream by the action of the injector and carried along through glass or Bakelite pipe. The air laden with the powdered material passes through a number of metal tubes *D* arranged in parallel within a large spherical conductor and electrically connected with it. The particles of powder become electrified by contact with the walls of the metal tubes. The charged particles are carried away from the sphere and returned to an earthed reservoir *C*. The potential of the sphere will rise until limited by corona discharge from its surface.

In order that one milliampere can be drawn from the sphere, enough powder must be blown per second to produce a charge of 10^{-3} coulombs or 3×10^{6} e.s.u. per second. It was the main purpose of this work to find out if such charges can be obtained from reasonably small quantities of powder. From an engineering standpoint quantities up to about 305 grams per second should be feasible since sand blast machines have been constructed capable of blowing this quantity of sand.

Previous Work

It has been known for a long time that considerable charges are developed when particles of solids are blown over the surfaces of metals and other substances. Most of the work recorded in the literature gives no information as to the quantity of electricity produced in this manner by a given amount of material. However, the following brief resumé of the more pertinent articles showed that the charges obtainable were large enough to warrant further work along these lines.

According to Rudge[1] a few centigrams of flour blown into a large room produced a charged dust cloud whose potential as measured by a radium coated collector, or probe, was 200 volts. He pointed out that this and other results of a similar nature obtained by him accounted for potential gradients of 10,000 volts per meter observed during dust storms, and for lightening flashes occurring during the eruption of ashes from volcanoes.

Petri observed that a steel telegraph wire 5 kilometers long became electrically charged during a violent snowstorm. A continuous stream of sparks several millimeters long could be drawn from the wire; and Petri estimated the electrical power generated to be 1.2 horsepower. The effect has been attributed by Ebert and Hoffmann[2] to contact electrification of the snow blown over the wire by the wind.

A similar observation is recorded by Stäger[3] who exposed a wire 9 meters in length to the driving snow during a snowstorm. There was a distinct corona discharge around the wire and a current of 17 to 20 milliamperes could be drawn from it. In this case the power generated was estimated to be 3 watts. Stäger in the same article gave the charge carried away by hoarfrost blown from a surface of ice. Under particularly favorable circumstances it amounted to 1000 e.s.u. per gram of hoarfrost. He also mentions the appearance of a corona discharge 10 cm long during the production of carbon dioxide snow by rapid evaporation of liquid carbon dioxide escaping from a tank.

[1] W. A. Douglas Rudge, Proc. Roy. Soc. London **A90**, 256 (1914).
[2] Ebert and Hoffman, Meteor. Zeits. 317 (1900).
[3] A. Stäger, Ann. d. Physik **77**, 230 (1925).

It is quite likely that the tremendous voltages produced in the Alps, and lately used in attempts to operate large x-ray tubes are generated by the electrification of snow blown over the ice covered peaks.

Theoretical Limitations

In pursuing this work the writer adopted the views of Helmholtz on frictional electricity. According to these, so-called frictional electricity is developed whenever two dissimilar surfaces are brought into contact and then separated. A double layer of charges, whose magnitude is determined by the contact difference of potential between the two surfaces, forms at the surface of contact—one charge residing on one surface and an opposite charge on the other. When the two surfaces are separated the charges of the double layer are torn apart, and a charge remains attached to one surface while the other carries with it a like charge but of opposite sign. A contact of very short duration of two insulators followed by their separation suffices to produce considerable charges, which indicates that the double layer does not penetrate very far into the body of the insulators in contact. The thickness of such double layers has been estimated to be of the order of 10^{-8} to 10^{-7} cm. From this it is evident that in order to produce large charges by contact electrification large surfaces of contact are the main consideration. This immediately suggests that at least one of the two substances brought into contact should be in a finely divided state so as to present a large surface. In this case the charges are produced by blowing the finely divided material over a metal surface; for example, the powder is blown through a metal tube. When the particles strike the metal surface and leave it they acquire a charge which they carry with them as they move along with the air stream. An opposite charge remains on the metal which, if insulated, rises in potential as long as the powdered material is blown over it.

Leaving out of consideration corona discharges from the conductor, the ultimate potential which can be reached depends upon the mobility, k, of the charged particles leaving the conductor and the potential gradient, X, at the point where they leave. The charged particles to escape must be impelled by the air stream with a velocity greater than kX. The electrical image force between the particle and the conductor is considered negligible owing to the smallness of the particles under consideration. It can easily be shown that the above requirement imposes no serious limitation upon the potentials attainable, even though the particles should have to overcome the maximum gradient possible in air, about 30,000 volts per cm.

A charged particle of radius r in air will have a maximum mobility when it is carrying the maximum charge q permitted by the limiting gradient at its surface, that is, $q/r^2=30{,}000$ or $q=100\ r^2$ e.s.u. For particles of radius 10^{-4}, $q=10^{-6}$. Consider 1 cc of material broken into approximately spherical particles 10^{-4} in radius, each charged with the maximum 10^{-6} e.s.u. The total charge carried by all the particles is

$$Q = 10^{-6}/[(4/3)\pi r^3] = -10^6/4.$$

According to this only 12 cc of material would be necessary per second to carry a milliampere. The same calculation for particles of radius 10^{-5} cm gives $10^{-7}/4$ e.s.u. per cc. However, owing to the fact that air in very thin films has a higher breakdown strength, the gradient at the surface can be higher allowing it to carry a larger charge.

It now remains to show that a particle charged to the above calculated maximum can be driven against a gradient of 30,000 volts per cm. This can be done by making use of some data obtained by Deutsch[4] on the motion of charged particles in electric fields in connection with a study of the Cottrell process of precipitating dust from gases.

He found that particles of radius $r=10^{-4}$, after having picked up a charge of 376 electrons $=1.8\times10^{-7}$ e.s.u. in a corona discharge moved with a velocity of 0.56 cm/sec. in a field of 300 volts/cm. Particles of $r=10^{-5}$ cm picked up a charge of 5×10^{-9} and moved with a velocity of 0.42 cm/sec. in the same field. If we assume that the mobility varies linearly with the charge on a particle, we can use these results to determine the velocity of a particle of $r=10^{-4}$ cm and carrying the maximum charge (10^{-6} e.s.u.) in a field of 300 volts /cm. The velocity will be $v=(0.56\times10^{-6})/(1.8\times10^{-7})=3$ cm per sec. For the case of particles of radius 10^{-5} the velocity is less than 0.42 because the calculated maximum charge turns out to be less than that observed by Deutsch. With the above velocity of 3 cm/sec. in a field of 300 volts/cm, a particle of $r=10^{-4}$, carrying a charge of 10^{-6} placed in a field of 30,000 volts/cm would move with a velocity of 300 cm/sec. Now a particle of this size can easily be blown with a velocity ten times as great. Apparently there is no difficulty to be expected in blowing the charged particles away from a highly charged conductor.

Experimental

The following experimental method was used to find the powder most suitable for the purpose in view. Fig. 2 shows the experimental arrangement.

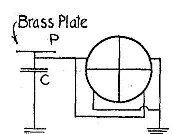

Fig. 2. Experimental arrangement for investigating powers for charges.

An insulated brass plate P was connected to one pair of quadrants of a Dolezalek electrometer and to a condenser c, as shown. One milligram of the powdered material to be investigated was placed on the brass plate, which was earthed and insulated before blowing off the powder with a puff of air. The magnitude of the charge produced was determined from the deflection of the electrometer and the capacity of the system. The powders were prepared by grinding various solids and sifting them through a a 300-mesh sieve. This could not be done very well with metals which were used as obtained in the form of considerably coarser powders. The materials studied were mercuric

[4] Deutsch, Ann. d. Physik **4,** 824 (1930).

sulfide, mercuric iodide, sulfur, rosin, iron powder, antimony powder, clay, and diatomaceous earth, which is a form of silica occurring naturally in a very finely divided form.

The most promising materials were the metal powders and the diatomaceous earth. The metal powders could not be further investigated by the next method to be described because, owing to their great density, they could not readily be blown by the compressed air available. The diatomaceous earth turned out to be ideal for the purpose, not only because it gave such large

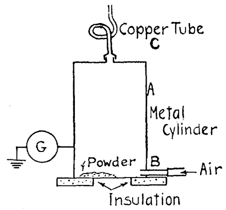

Fig. 3. Experimental arrangement for measuring charge obtainable from diatomaceous earth.

charges, but also because it is very light and easily blown. It consists of particles 10^{-4} cm in diameter and smaller, and it can be obtained commercially at 50 dollars a ton.

The diatomaceous earth was used in larger quantities in such a manner as to permit the charges produced to be measured on a galvanometer. It was placed in a metal cylinder A, Fig. 3, 12 cm diameter and 30 cm high from which it was blown by means of compressed air introduced tangentially at B. The air laden with the powder passed through a piece of copper tubing C having an inside diameter of 0.5 cm and a length of 20 cm. The cylinder, insulated by standing on blocks of paraffin, was connected to ground through a calibrated galvanometer which indicated the current flowing from the cylinder as the powder was being blown out. The measurements were made by placing 5

TABLE I. *Charge obtained from 5 grams of diatomaceous earth blown by air flowing at rate of 1 liter/sec.*

Time in min.	Current in amp.$\times10^8$	Charge in coulombs$\times10^8$	Time in min.	Current in amp.$\times10^8$	Charge in coulombs$\times10^8$
0.5	137.5	4125	8.0	16.5	495
1.0	96.3	2889	8.5	13.8	414
1.5	68.8	2064	9.0	10.5	315
2.0	55.0	1650	9.5	8.3	249
2.5	41.3	1239	10.0	5.5	165
3.0	41.3	1239	10.5	4.7	141
3.5	41.3	1239	11.0	3.9	117
4.0	57.8	1734	11.5	3.0	90
4.5	82.5	2475	12.0	2.8	84
5.0	82.5	2475	12.5	2.2	66
5.5	68.8	2064	13.0	1.9	57
6.0	63.3	1899	13.5	1.9	57
6.5	46.8	1404	14.0	1.4	42
7.0	35.8	1074	14.5	0.8	24
7.5	27.5	825			
			Total	$30,696\times10^{-8}$ coulombs	
			or	6.1×10^{-5} coulombs/gram	

grams of the powder in the cylinder and blowing it out with air flowing at the rate of one liter per second. The current is read on the galvanometer until all the powder is gone. The current is a maximum at the beginning of a run and decreases gradually as the amount of powder blown out per second decreases during the progress of the run. Since the current fluctuated somewhat, an average current was estimated during each half minute interval. These averages are listed in the second column of Table I which gives the result of a typical run. It should be noted that the average current recorded for the first interval is really too low because the initial swinging of the galvanometer prevents the current from being read at all during the first 15 seconds, during which time the current is considerably higher. A small current could still be read after the air had passed for 15 minutes. This is due to the fact that a small amount of the powder clung to the inner surface of the cylinder from which it was gradually dislodged and blown out by the air. The charge obtained per gram of powder is for these reasons somewhat higher than that given at the end of the table. The total charge in coulombs obtained from 5 grams of powder was found by adding together the product of current in amperes and time in seconds for all the half minute intervals. The charge on the powder is negative.

The copper tube *C* in Fig. 3 was at first straight, and it was found that the total charge obtained increased about 25 percent by bending it as shown. This is probably caused by an increased number of particles striking the wall of the tube due to centrifugal force on them. No further charge was obtained by either lengthening or shortening the tube.

The charge given by 5 grams of powder reaches the surprising value of 3.07×10^{-4} coulombs or 6.14×10^{-5} coulombs per gram. According to this value only 16 grams would have to be blown per second to get a current of 1 milliampere. Altogether 20 such runs were made, giving results which deviated at the most 11 percent from those given in Table I. None of the vagaries, such as reversal of sign, usually associated with frictional electricity were ever observed. A few runs made with lower air velocities gave much lower results, ranging from 3.02×10^{-5} coulombs per gram for the lowest air velocity capable of carrying the dust out of the cylinder and up. This is believed to be due to the cohering of the particles of the powder. The individual particles are approximately 10^{-4} cm in diameter and smaller, but they cling together forming larger aggregates which are blown apart by the air stream, the more completely the higher the velocity. It seems likely that larger charges per gram might be obtained by using higher air velocities, but this point could not be proved because the air pressure available was limited to two atmospheres.

The diatomaceous earth used to obtain the above results contained 12 percent of adsorbed water. No difference resulted by using the powder dried at 300°C for 1 hour.

A small scale model of a high voltage generator using diatomaceous earth blown by air was constructed as shown in Fig. 4. In this figure, *A* represents an insulated sphere of spun copper 20 cm in diameter, within which 8 copper tubes *B*, 0.5 cm inside diameter, were mounted. Compressed air introduced at *C* carried along with it diatomaceous earth introduced by a small screw conveyor *D* from a reservoir and blew it through the copper tubes. The charged powder left through a short length of glass tube and escaped into the air.

The potential of the sphere was estimated from the distance between it and a similar grounded sphere placed at such a distance from it that a thin spark jumped the air gap between them. The maximum potential reached

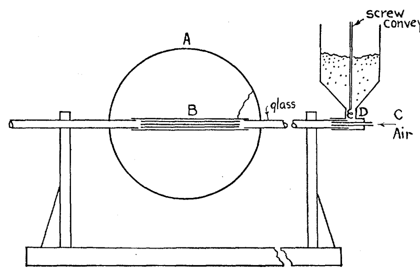

Fig. 4. Experimental high voltage generator.

seemed to be limited by a corona discharge from the sharp edges around the two openings in the sphere. The potential was estimated to be 260 kilovolts. A current of 8×10^{-5} amperes could be drawn from the sphere at this voltage by connecting it to ground through a glass tube filled with water and in series with a microammeter. The amount of powder introduced per second by the screw conveyor was 1.5 grams per sec.

In conclusion the writer wishes to thank Professor Millikan for very kindly placing the facilities of the California Institute of Technology at his disposal.