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DIRECTORATE OF WEAPONS RESEARCH (DEFENCE)

FC

INVESTIGATIONS OF THE PRINCIPLES OF FRICTIONAL CHARGING

Final Report on work carried out
under EMR Agreement 7/Electrical/333

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CONTENTS

The design of dust generators;

INVESTIGATIONS OF THE PRINCIPLES OF FRICTIONAL CHARGING

FINAL REPORT

HISTORY OF THE CONTRACT

The work described in this report was initiated by Sir George Thomson at the request of Dr. Beeching of the Armament Design Establishment on December 1st, 1947 for the purpose of

(i) Investigating what physical processes are responsible for so-called frictional electrification.

(ii) Advising the Armament Design Establishment on the design of dust generators.

The dust generators were required for non-contact fuses, and the investigation had high priority.

The contract has been renewed on a yearly basis for eight years, during which time fifteen progress reports have been submitted, and a number of papers published with permission of the Ministry, three of these in the Proceedings of the Royal Society.

The contract terminated on November 30th, 1955, and the present report summarises the work done in the eight year period.

PROGRESS REPORTS

The following list indicates the subject matter of the progress reports.

1. Preliminary work on Metal/Metal charging.
2. Correlation of the "Separation Charging" of metals with contact potential.
3. Theory of "Separation Charging".
4. Proposal for using metal dusts in dust generators.
5. Design of an apparatus for the measurement of contact charging with insulators.
6. Preliminary results obtained with the new apparatus.
7. A new method of measuring contact potentials.
8. The existence of two types of insulator.
9. Preliminary work on hydrophilic insulators.
10. Further work on hydrophilic insulators.
11. A new principle for the design of dust generators.
12. Adhesion and charging of quartz surfaces.
13. The charging of recently fused silica.
14. Piezoelectric effect irrelevant.
15. Preliminary rubbing experiments, and the design of dust generators.

/PUBLICATIONS.

PUBLICATIONS.

1. The Volta Effect as a cause of static electrification. Proc. Roy. Soc. A 205, 83 (1951)

2. Interpretation of Experiments on Frictional Electrification. Nature, 167, 400 (1951).

3. A modified ionization method of measuring contact potential. Brit. J. Applied Phys. 4, 111 (1953).

4. Surfaces showing no electrification after light contact with metals. Proc. Roy. Soc. A 218, 111 (1953).

5. Adhesion and charging of quartz surfaces. Proc. Roy. Soc. A 231, 388 (1955).

COURSE PURSUED IN THE INVESTIGATION

It was the unpredictable reversals of the sign of charging, most unsatisfactory in a dust-generator, coupled with the chaotic state of the literature, that provoked the arranging of the contract. A fundamental difference of opinion existed as to whether so called frictional electrification was really dependent on the expenditure of energy in friction, or arose from mere contact, rubbing having the effect of multiplying the points of contact. Little attention had been paid to the possibility that not one, but several processes are involved. There were, furthermore, two other schools of thought: on the one hand that the primary process is chemical, involving the transfer of electrolytic ions in an absorbed water layer, on the other that it is physical, probably involving an electron transfer.

A peculiar observation in the published literature was that metal dusts, blown through metal tubes, had been found very efficacious in a high tension dust generator, whereas it was commonly supposed that two metal surfaces could not charge each other in this way, because of their conductivity. My own guess was that the charging was due to the presence of insulating oxide films, and Sir George Thomson suggested tackling this question first, because there was an anomaly to be cleared up, and because metals were better understood than other solids.

The true explanation proved to be different. A conductor/conductor contact can, under appropriate conditions, give charging comparable with an insulator/conductor contact, because, if approach is made between rounded parts of the surfaces, the capacitance between them tends to infinity as the gap tends to zero, and this capacitor is charged by the contact potential. The process, however, is really quantum-mechanical. It can be calculated theoretically. On doing this, quantitative agreement was obtained between theory and experiment, for the first time in the history of the subject. The effect, however, though it could be separated, in experiments, from others present, was not the only one.

This "Separation Charging" of metals, in accordance with the Volta/Helmholtz hypothesis, is not, in itself, an important phenomenon, but a great deal was learnt from working on it, and made possible the design of new apparatus suitable for the investigation of insulators, and helped the understanding of what was going on in later experiments. At first no sense whatever could be made of the results using insulator/metal and insulator/insulator contacts. It was clear that conditions were much more critical than with metal/metal contacts, and it was a long time before it became apparent just what the important conditions were. No progress at all was made until a few casual observations of contacts not giving any charging were followed up, when it was found

/that

that Teflon gave consistently no charging. This led to the discovery that there are two classes of insulators, those charging freely, and those having an inherent tendency not to charge. The existence of the latter could not have been foreshadowed from any previous work, particularly since amber, from which electricity is named, has the inherent tendency not to charge.' The fact that these insulators are hydrophobic, but those that charge freely hydrophilic, suggested that the charging of the latter was due to electrolytic ions in a water layer. Attempts were made to check this by varying the relative humidity, but without success. Attempts were made to wash off the electrolytic ions, at first with seeming success, but the disappearance of charging after strenuous washing did not always occur, and this capricious behaviour was not resolved for a long time, until it was realised that when a surface is very clean indeed, contamination spreads all over it instantly if any part of it comes into contact with a trace of grease.

Meanwhile, an apparatus for investigating under what conditions hydrophobic insulators would charge when rubbed, was designed, but, as first constructed, was unsatisfactory.

Hydrophilic insulators continued to behave more capriciously, rather than less, and each clue that was followed up led nowhere. It had been noticed that very clean quartz surfaces which tended to stick together also tended to give very large charging, and it was presumed that this charging resulted from the breaking of the adhesion. Almost in despair, and not because it seemed a point of any importance, it was decided to check that this was so. It was not; the charging and the adhesion were independent phenomena. This was so curious as to seem worth publishing, particularly since there was some evidence that the charging might be due to transfer of electrons between surface levels. Sir George Thomson, however, felt that further evidence was required on two points: whether or not the specimens were really free from contamination, and whether or not the effect was associated with the polar properties of quartz crystals.

That the large charging could not have been due merely to inadequate cleaning was confirmed by a rather tricky experiment using recently fused silica. Another experiment was then performed to investigate whether or not the charging was correlated with the piezoelectric effect in quartz. This possibility was excluded, and, during the course of the experiment, it was realised that the charging obtained depended on which crystal faces were being used. This discovery shed light on the capricious results that had been a puzzle for so long: one cannot get consistent results without controlling the crystal face at the point of contact.

Attention was then turned to the rubbing apparatus, which was improved until significant results could be obtained on the charging of polystyrene and other hydrophobic insulators, now measurable because of the much greater sensitivity of the apparatus.

The course pursued in these investigations has been gone into in order to point a moral. The discoveries that have been made, and which will be described shortly, have been almost fortuitous; not a single experiment has been performed (for the first time) without giving an unexpected result. Such clues as were followed up generally proved to be misleading. It was necessary to feel one's way, but to rely on opportunism. Planning further than the next step was impossible; the work could not be tailored to suit the objective. Nevertheless, a great deal has been learnt, and not without relevance to dust-chargers.

/TECHNIQUES.

TECHNIQUES

Before describing the results of the investigations, something needs to be said about the techniques that had to be developed to obtain them. Previous experimenters had worked with areas of surface so large that a great number of points of contact or rubbing contributed to the observed effects, these therefore being statistical in character. Quite crude measuring instruments suffice for such work. By employing more refined instruments, however, measurements can be made on single "points" of contact. This, in addition to making the phenomenon investigated more precise, also permits the concurrent investigation of relevant conditions at the point of contact, such as contact potential, with the certainty that they apply where the charging occurs. Information has been obtained in this way that would certainly have been muddled up in the multiple contact type of experiment.

Single point contact was obtained by using two balls; one sometimes had a flat on it, to identify orientation in the case of quartz, to obtain a better surface in the case of some plastics. The precise topography around the point of contact is significant, particularly with insulators, and it was found necessary to resort to optical polishing. Indeed, the best polishing so far used is probably only just good enough; better polishing would give more reliable results. It may be remarked that the most important result so far obtained, that of the relevance of the crystal face, could not have been obtained without the concurrence of three specialised techniques: that of working piezoelectric quartz, carried out by Brookes Crystals Ltd., that of optical polishing by the Optical Works Ltd., Ealing, and the technique of measurement at a single contact point. The original choice of size of the two balls proved to be a most fortunate one, leading to convenient dimensions for the rest of the apparatus. This was specially important for the avoidance of vibration and general instability when making and breaking contact.

Chemical and physical stability of the specimens used restricted the choice of materials. The metals were sufficiently stable in a laboratory atmosphere for the duration of an experiment, but not longer. Apart from plastics, which are quite stable, insulators of the gem stone type are, sui generi, highly stable, and have the advantage that they can be subjected to stringent chemical cleaning, without spoiling their optical finish. The problem of cleaning the surfaces is probably the most difficult of all in the investigation of frictional electrification. The cleanest surfaces ever made have been prepared by heating to a high temperature in a high vacuum, but this method is of very limited application. It is no use, for example, when the contaminant is more refractory than the substrate, and it spoils optical polish. The problem has, in general, to be tackled by the successive removal of different contaminants, which is not to say that high vacuum technique may not be appropriate in some circumstances. The most thoroughgoing cleaning so far used is that for quartz. The procedure is as follows:-

(i) Dust is first removed. Some of this, probably quartz dust from the optical shop, is very firmly adherent. To remove it without damaging the surface, a cushioned rubbing action is necessary; chamois leather is used. It leaves a surface visibly smeared with the dressing from the leather, and other detritus. This is removed by gently polishing with a well-washed cotton cloth. The surface will now probably be electrified, and some atmospheric dust collect on it. Not being very adherent, this dust can be removed by dusting with a camel-hair brush until none is visible under the microscope. If this is not done, a small hair, for example, left behind, will be oxidised to carbon at a later stage

/in

in the cleaning, leaving a stain.

(ii) Grease is a contaminant much to be feared, and certain to be present since the surfaces will have been handled with the fingers. Forceps must be used from now on. The surface is washed with anhydrous ether to remove the bulk of the grease, absolute alcohol to remove other organic substances, and a mixture of ether, alcohol and concentrated ammonia, which is even more searching. It is then washed in conductivity water to dissolve hydrophilic impurities, and, in case this should uncover further organic contamination, again in absolute alcohol and anhydrous ether.

(iii) At this stage the surface should be freely wettable with water, but such is not always the case, probably because of unreliable ether. The use of freshly distilled ether would probably circumvent this, but, in any case, protein contamination from the atmosphere may still survive. The quartz is therefore treated for 20 minutes with a mixture of equal parts concentrated A.R. nitric and sulphuric acids, warm after mixing. It is then rinsed in several changes of conductivity water.

(iv) Organic contamination cannot survive this treatment but sparingly soluble inorganic contamination may have done so. The quartz is therefore refluxed for a couple of days with conductivity water. It is remarkable how exceptionally wettable quartz treated in this way becomes, and how glistening an appearance the ball acquires, like a diamond, when the illumination comes from well-defined directions. With diffuse illumination, on the other hand, a flat can disappear completely. This was a great nuisance at times.

Special precautions are required, of course, in handling very clean surfaces. Cleaned quartz was used on occasion for this purpose, and it was also found that Perspex, carefully washed in anhydrous ether, is suitable. Considerable thought was given to contamination from atmospheric pollution; it was concluded that trouble from this had just, but only just, been avoided, by making the measurements in an atmosphere of purified argon, and shielding the cleaned surfaces before insertion into the apparatus. Until this was done, violent changes in the charging curves were liable to occur. These disturbances were attributed to the arrival of particulate matter at the contact.

With help from the Armament Design Establishment, an electronic method of measuring the contact potential in the experiments on metals, was set up, involving making the measurement on less than 1 mm^2 effective area. For the testing of this equipment it was found necessary to design a pulse generator giving the same type of pulse as that produced in the apparatus. The pulse rises from zero, slowly at first, then with ever-increasing steepness, until it is suddenly arrested at a value which may be either positive or negative with respect to earth.

In the first apparatus, for experiments on metals, the balls were supported rigidly. It was found, however, that this involved making undesirably large electrostatic corrections to the measurements. For further work, therefore, these, and other, corrections were eliminated. This involved supporting the balls on taut fused silica suspensions, resembling crucible triangles. The small ball required fibres of 1/10 mm diameter, welded at the joints, and lined up with an accuracy of 1/5 mm. Rather curiously, the suspension for the larger ball, with 1/5 mm fibres, and no requirement for great accuracy, proved the more difficult to construct.

/PROCESSES

PROCESSES RESPONSIBLE FOR FRICTIONAL ELECTRIFICATION

A good deal has been learnt about the processes responsible for frictional electrification. In the following account of the conclusions that have been reached no review of the supporting evidence, either from the literature, or from my own work, will be given, since this is available in published papers.

Light contact, in which plastic deformation and sliding are excluded, is capable of generating charge in sufficient quantity for its presence to be obvious in everyday and industrial circumstances, at insulator/insulator, metal/insulator and metal/metal interfaces. There are two, or possibly three, classes of insulator:-

1. Insulators such as silica, glass and magnesium oxide, which are hydrophilic, have an inherent tendency to charge, against metals, and against each other.

II. Insulators such as amber, polystyrene, polythene and Teflon, which are hydrophobic, have an inherent tendency not to charge, against metals, and against each other. The tendency not to charge appears to be dominant, in that there is no charging, for example, with amber/silica.

III. Insulators such as sodium chloride, which can go into electrolytic solution, probably behave differently, but have not been investigated in the present work.

Class II contamination on an insulator of Class I, for example finger grease on magnesium oxide, can eliminate charging, so insulators of Class I show increased charging when cleaned. It is only after very special cleaning that these insulators show the full charging of which they are capable (under laboratory conditions). There is some evidence that insulators of Class II show the less charging the cleaner they are, and would not charge at all if perfectly clean. Such charging as is found is probably due to the presence of contamination of Class I or III. The cleanest insulator of Class I so far used is crystalline quartz, and of Class II polystyrene. The residual charging of the polystyrene was four orders of magnitude smaller than the (very large) charging of the quartz. Class I and Class II insulators, when clean, therefore, run to extremes of large and small charging respectively. Under everyday conditions, hydrophobic contamination on the hydrophilic insulators, and hydrophilic on the hydrophobic, decreases the tendency of the former to charge, and increases the tendency of the latter. Even so, there may be two, and will almost certainly be one, order of magnitude between them. The fact that Class II insulators are poor chargers, by comparison with Class I, is usually obscured by the fact that they are better insulators in a humid atmosphere, and therefore easily retain such charge as they do acquire. A situation in which the two classes of insulator can compete, the one as substrate, the other as contamination, will clearly lead to most irregular charging, due to patchiness, or to penetration of the contamination through violence.

Another factor leading to irregularity in the charging of polycrystalline surfaces is the difference between different crystal faces, which can be as important as the difference between different materials. In the case of quartz an X-cut face is positive with respect to a Z-cut. The effect is not piezo-electric in origin, since it does not reverse when an X-face is used instead of an X+ The sign of charging contradicts Coehn's rule that the surface which becomes positive is the one with the higher dielectric constant. The

/charging

charging appears to be at least an order of magnitude larger than that otherwise obtained so far under any conditions. It was at first thought that the reason for this might be associated with the marked tendency of the very clean surfaces used to adhere to one another, but, in fact, the charging and the adhesion are entirely independent phenomena. This, incidentally, has a relevance to the theory of friction, as well as to the theory of electrification. Not only does the tendency of well cleaned quartz and silica surfaces to adhere to each other seem not to affect the charging, the adhesion itself is not electrical in origin, and it is, furthermore, unlikely that electrostatic forces ever contribute appreciably to the force of friction.

The average charging obtained with a Z-cut face against another Z-cut face was only 1% of that obtained with an X-cut against a Z-cut, but this average was the mean of an irregular charging of random sign which not infrequently amounted to 10% of the X/Z charging. It was still, incidentally, two orders of magnitude above the limit of detection. It is presumed that the irregular charging was the result of wrong crystal facets showing up here and there. Similar charging, about four times smaller, was found with vitreous silica against vitreous silica, and it seems likely that it arose from a similar cause: the presence of incipient crystallization.

It seems likely that the charging of quartz results from a transfer of electrons between surface energy levels, and is similar to the most important process that gives rise to charging at a metal/metal interface. It used commonly to be supposed that frictional charging comparable with that obtainable with insulators does not occur at a metal/metal interface, because, if charges are formed at the beginning, they neutralise themselves by conduction at the last moment of contact when the two metal surfaces are separated. In spite of these theoretical views, the charging of metal powders by blowing them against metal surfaces has, for a long time, been a well-established phenomenon. The charging is not to be explained as being rendered possible by surface films of tarnish which behave sufficiently like insulators to prevent the initial charge from leaking away at the last moment. Such surface films are, indeed present, but they are effectively conductors from this standpoint. An obvious layer of tarnish is nearly always negative with respect to the cleaned metal, though, on occasion, there seems to be little difference between an obvious layer, and an invisible layer, and the tarnished metal has, once, been found positive. But slightly tarnished metals have a surface skin that is a good semiconductor, and charge like conductors. This is possible because the original considerations of Helmholtz, and their subsequent elaboration in the literature, overlooked one fundamental consideration, that the magnitude of the charge to be expected depends in a very critical way on the surface topography around the point of contact. The electrification process is visualised in two stages. In the first, the two surfaces, though in contact, nevertheless have a difference of potential between them - the contact potential - and the two surfaces form a condenser which is charged by this potential. In the second stage, the two surfaces are separated, contact is broken, and the charge that remains is raised to a higher potential because of the decrease of capacitance consequent on the separation of the surfaces. Now, there are two quite different kinds of contact topography, the one typified by a cone resting with its point on a plane, the other typified by a sphere touching a plane. It is easy to verify that, when the two surfaces are separated by an infinitely small amount, the capacitance between these two surfaces is finite in the case of the cone, but

/(logarithmically)

(logarithmically) infinite in the case of the sphere. We note, then, that a classical theory which made no allowance at all for the molecular structure of matter, would predict the generation of an infinite potential in the second case, that is, in a quite realisable experiment. One could, moreover, advance good reasons for supposing that contact topography of the second kind would be sufficiently common to show up frequently. Since it does not, it at once becomes clear that a quantum-mechanical theory is called for.

The quantum-mechanical theory allows for the passage of electrons through a narrow gap of 13 Å width in a typical case, by "tunnel effect", so that the contact potential difference between the metals is maintained in the early stages of the separation, the capacitance magnification of potential following after a fairly sharp cut-off of equalisation current. Formulae for the magnitude of this "separation charging" have been derived, and give good agreement with experiments using two metal spheres brought gently into contact, and then separated with complete absence of rubbing, without there being any adjustable constants to help the agreement. The small systematic difference between theory and experiment can be accounted for by surface irregularities on the experimental spheres.

This electrification of metal/metal surfaces according to a modern interpretation of the Volta-Helmholtz hypothesis, is a manifestation of the contact potential, and, as such, must always be present. Rubbing and impact, however, if they occur, lead to other effects, so uncontrolled contact can give very erratic results.

A contact potential between insulators will arise if there are electron levels at the surfaces with the highest occupied level of the one insulator higher than the lowest unoccupied level of the other, so that electrons stream across on near contact until the double layer so formed compensates the difference of potential between the levels. Assuming no transfer of charge along the insulating surfaces, transfer from the one to the other with spheres just in contact is confined to a region of proximity bounded by the contour for which the distance between the surfaces just permits transfer by "tunnel effect". As the surfaces are separated, this contour contracts, charge outside it can no longer cross the tunnel, but charge inside it will diminish in such a way as to maintain the contact potential between the surfaces. Ultimately the area bounded by the original contour will be charged like a plane parallel condenser, whose separation is equal to the critical gap, with a potential difference equal to the contact potential. This hypothesis accounts correctly for the order of magnitude of the charging of quartz/quartz. It implies enormous surface densities of charge, up to 10^4 e.s.u. cm^2, which would give rise to localised fields approaching 10^7 V/cm. The intense field is limited, however, to a volume of the order of magnitude of 10^{-9} cm^3. The chance of a stray ion from radioactivity or cosmic rays occurring in this volume of gas is negligible; there may, therefore, be nothing to initiate a gas discharge. This seems to be the most likely explanation of the survival of the enormous charges that are found experimentally.

Preliminary experiments with an apparatus for the investigation of rubbing have given results, which, though tentative, are compatible with the assumption that the virtue of rubbing lies in the multiplication of the points of contact. The multiplication is so great that Class II insulators show easily measurable charging. This charging seems not to be due to the expenditure of energy in friction, nor to an effect of pressure such as Richards has postulated, but to the presence of contamination, probably of Class III. The smallest charging so far obtained was with polystyrene, and it

/seems

seems likely that this may be associated with another insulating property for which polystyrene is outstanding - that of charge retention over a period of years, investigated by Mr. Rothwell. If both phenomena are bound up with absence of contamination, it should be possible to select the best polystyrene for charge retention by testing it for absence of charging, and this would take minutes instead of years.

It appears from the foregoing that the Volta-Helmholtz hypothesis is able to explain an important part of the phenomena of frictional charging, perhaps the most important.

THE DESIGN OF DUST GENERATORS

General

Dust generators have hitherto been designed, for both academic and military purposes, on the assumption that the objective should be the maximum interaction of the dispersed cloud and the charging surfaces of the ejector. The difficulty of achieving this is apparent from the observation that the powder left behind after shaking out an ejector can, when ejected, fully charge the generator - most of the powder must normally be wasted.

It therefore appears that a generator should be designed on a different principle: that of a mixed powder. The two components will become oppositely charged in the powder aggregate, retain the charge on dispersal, and must be (partially) separated, and the one retained, before ejecting the other. Two ways of doing this will be discussed later.

It seems likely, that, whatever the design, contact electrification will play the principal part, and impact and rubbing a secondary part, which, however, may cause reversals of sign, and should therefore be minimised. In the existing design of generator, this calls for the minimum particle speeds compatible with the turbulence that is necessary to bring the largest possible number of particles into contact with the surface at which they are charged. In the case of a generator which aims at producing a maximum charge, rather than a maximum current (which is more usual), prolonging the ejection of the dust might, therefore, be advantageous. This would have the additional advantage of minimising the danger of abrasion of the charging surface. Abrasion brought about by particles breaking through the surface "oxide" layer is clearly undesirable, since it can lead to reversed charging.

Since some ionisation within the dust cloud is probably unavoidable, there will be a loss of charge by conduction through the gas from the particles to the inner walls of the charging chamber, unless the particles are removed promptly after charging. This requires a sufficiently high particle velocity, which may militate to some extent against the requirement of preventing rubbing and abrasion. The difficulty can be minimised by arranging that the impact of particles against the charging surface occurs as close to the ejection ports as is compatible with this happening within the field-free space within the generator. It is important, however, that, once the particles have left it, they should remain clear of all surfaces electrically connected to the high potential end of the generator; if they touch, they may carry away charge. Since, moreover, the gas leaving the charging chamber is ionised, it is especially important to design the ports by which it escapes so as to reduce corona discharge to a minimum.

/The

The mixed powder generator

A powder, such as fused silica dust, is not to be regarded as homogeneous from the standpoint of contact charging, and the charging of individual particles against each other in a single powder dust generator is more important than their charging against the ejection ports. Such a generator is therefore designed to work on what is really a secondary effect. It would be better, as already said, to use the main effect by designing differently. If a mixed powder is used, the two components charge each other with opposite sign, so that separating them, retaining the one, and rejecting the other, takes advantage of the main charging effect, and would be correspondingly more efficient. There are two obvious ways of doing this. The first is to have one powder magnetisable, and to separate it from the other in a magnetic field. It should not be difficult to shield the powder from the magnetic field before dispersal, to prevent it from cohering. The second is to rely on a difference of size or density, and centrifuge out the heavier particles in a miniature cyclone separator. A large scale version of the sort of separator required is made by Combustion Equipment, Ltd., for cleaning flue gases.

Short contacts are sometimes more effective at charging, than long contacts. This might make it desirable to keep the powders in separate containers until used, and to mix them after dispersal with two impingeing jets. Less intimate contact would be secured in this way, but the method might be advantageous on balance.

Choice of powder.

The different crystal faces of a Class I insulating powder, such as quartz, charge differently, in the case of quartz to a very marked extent. The different crystal faces may therefore conflict in generating charge, and so lead to inconsistent behaviour.

The inherent tendency of Class II insulating powders not to charge makes them, a priori, unsuitable for use in dust generators. Such charging as they exhibit is probably due to Class III impurity, and is irregular and subject to frequent reversals. On one occasion, however, systematic slight charging was obtained with Nylon/steel, and a Class II powder containing a controlled amount of Class III impurity might be satisfactory, particularly since the inconsistency arising from different crystal faces would be absent.

So far as my own investigations go, the powder of choice is a metal, or two metals for the mixed powder generator. It must not be thought that metals, properly used, would be inferior to insulators in generating capacity. The best size of powder is probably a few μ in diameter. If this size is used, the factor limiting charging at atmospheric pressure in air, may be, not so much the magnitude of separation charging as the capacity of the individual particles to retain charge.

For the ejected powder to be positive, leaving the generator negatively charged, aluminium appears to be the metal of choice. For maximum charging of reliable sign it should be used against tungsten, but if a magnetisable metal is required for, say, the second powder, nickel would be suitable. The nickel should preferably be not clean, but covered with a thin film of oxide.

W. R. HARPER.

Department of Physics,
Royal College of Science,
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