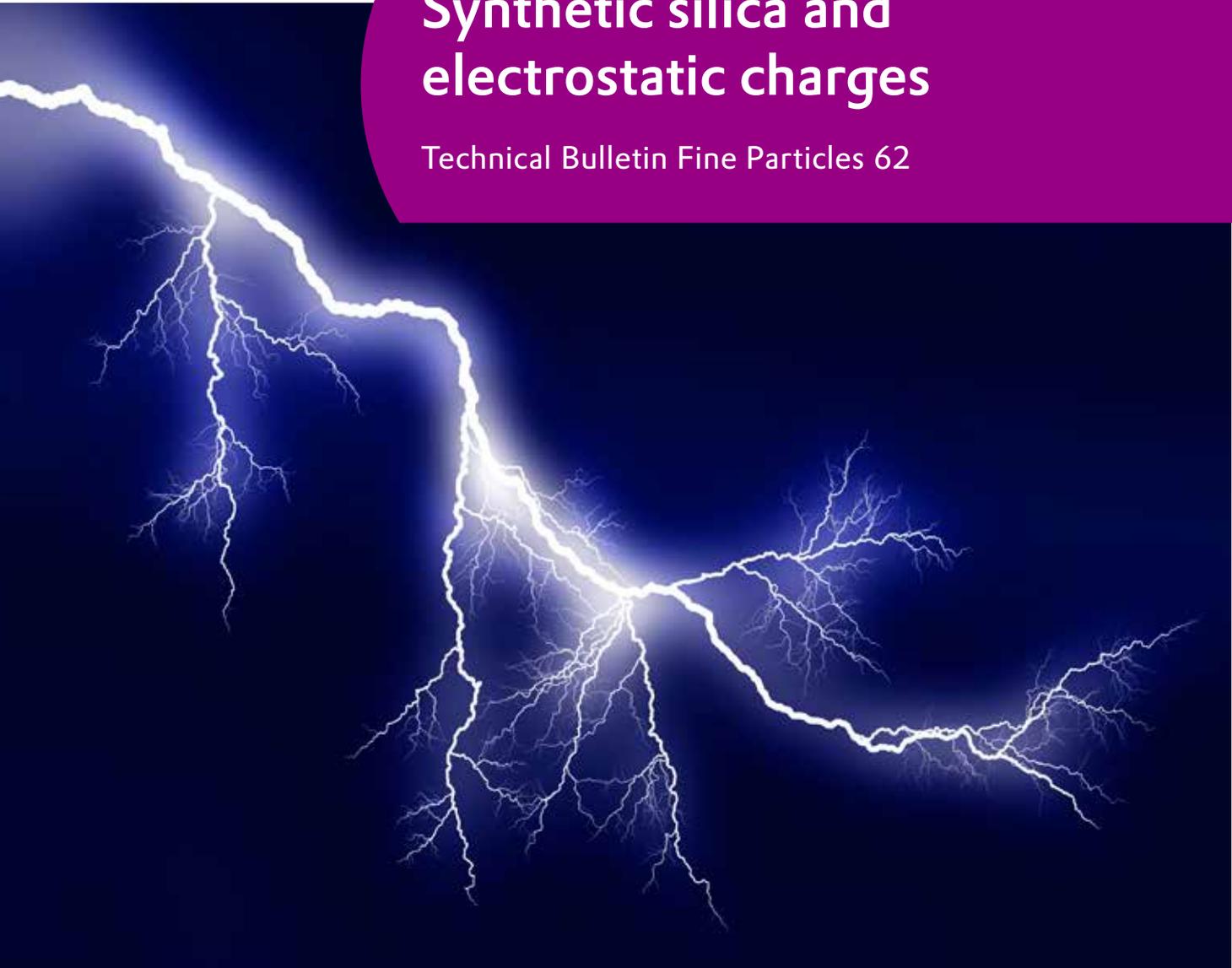


Synthetic silica and electrostatic charges

Technical Bulletin Fine Particles 62



Foreword

This publication deals with static electricity in general, and enables the reader to correctly assess the dangers caused by static electricity when handling AEROSIL® fumed silica and Performance Silica from Evonik Industries (tradenames SIPERNAT® and ULTRASIL®), and to take appropriate measures where necessary.

Practical applications to prevent or reduce electrostatic charging through the use of AEROSIL® and performance silica are also addressed.

Finding an answer to the question of electrostatic charging ought not to be too difficult in a world where electrostatic effects are nowadays encountered on an almost daily basis. However, an understanding of the phenomenon of static electricity is more difficult.

The largely undesirable consequences of static electricity are the gas discharges, commonly known as sparks. This area, too, will be looked at in depth, since it is here that the hazards lie, especially in the possible ignition of vapors of flammable liquids.

Since AEROSIL® is a material which, firstly, has a higher propensity toward electrostatic charging and, secondly, is used in flammable liquids (in paint making, for example), there is good reason to return to the topic of electrostatics.

A brochure of this scope can only explain the causes, point out interrelations, and suggest remedial measures. When drawing up a safety concept, experts should be consulted, and the authors are ready to give some advice as well.

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1 Introduction

Since the beginning of time there have been three great inventions: fire, the wheel and "...".

It started with amber (Greek "elektron"). Around the year 500 B. C., Plato reports that amber, after being rubbed, exerts magical forces of attraction for tiny particles such as small seed grains, for example.

But, with the fragmentation of cultures, this observation was forgotten for almost 2000 years. William Gilbert (1544–1603), a physician to Elizabeth I of England, noticed while experimenting with magnets that there was a force of attraction other than the magnetic force – namely that of the rubbed amber. He found clear distinguishing features between the two effects and named that associated with amber as "electric". However, what Gilbert found was not the electricity with which we are nowadays familiar – that started only in 1866 with the discovery of the electrodynamic principle by Werner von Siemens. It is impossible to picture our modern everyday life without that dynamic electricity. Gilbert's electricity, on the other hand, had a more static character; it found its outlet first of all in entertaining and educational playthings in the baroque era. Only with the massive development in the chemical industry following World War I was static electricity recognized as a source of danger, since its spark discharges were able to ignite flammable gas mixtures. Thus 1941 saw the appearance of the first guidelines of the German "Berufsgenossenschaft" association. Amounting to eight pages, they could be bought for the sum of 10 pfennigs.

So then: static electricity, the subject of many an amusing physics lesson – what has become of it today? Now and again an electric shock is felt when stepping out of a car, clothing clings to the body on a dry winter's day, and hair stands upright when being combed. But did anyone ever hear about static electricity being of any use? Indeed it is.

Who would imagine that the car door which occasionally gives us an electric shock has been painted electrostatically? However, that is not the reason for the shock – that will be explained later. And the entire realm of office copier technology (photocopiers) is based on an electrostatic principle. Likewise the laser printer – the list goes on. Speed and miniaturization, such as micromotors (with a diameter of less than 1 mm), will be the future focus of electrostatics. Soon, then, it will be impossible to imagine a life without static electricity as well.

It is a shame really that this brochure has to deal with the less praiseworthy aspects of electrostatics: the hazards brought about by electrostatic charges in areas where, for example, flammable solvents are used. Particular attention will be paid to handling AEROSIL®, performance silica (ULTRASIL®, SIPERNAT®), and matting (flatting) agents (ACEMATT®).

It is easy to disregard the dangers which may under certain circumstances arise from these fine powders, given that these substances themselves are not combustible at all. However, they acquire a high electrostatic charge, in which case they pose a hazard in areas which are at risk from explosion as a result of other combustible materials.

The line of the Evonik matting agents (ACEMATT®), owing to their electrostatic properties, should be treated in the same way as performance silica. An exception here is ACEMATT® TS 100, a fumed silica which in terms of its electrostatic properties is comparable with AEROSIL®.

To avoid dangers caused by static electricity when handling highly disperse silica, it is necessary to get acquainted with the general demands of electrostatic explosion protection, introduced in Chapter 7.

On the other hand, static electricity is often, incorrectly, blamed as the cause of accidents involving fire and explosion when no other plausible explanation can be found. The real cause may be other ignition sources, such as electrical or mechanical sparks.

2 Origin of static electricity

To comprehend static electricity it is necessary to look into its basic nature. First, one has to form a picture of an atom being the smallest unit, not to be split any further by chemical means. In the course of this century, experiments have led to different models of the atom being created. The physical properties of the atom can be illustrated with the help of these models.

According to Bohr's model of the atom, the atom consists of a central nucleus around which electrons orbit in so-called quantum paths. The nucleus consists of positively charged protons and electrically neutral neutrons. Normally, atoms are electrically neutral because, for each positively charged proton in the nucleus, an electron carrying negative charge orbits the nucleus so that the overall charge of the atom is zero. In contrast to the positively charged protons, electrons are mobile and can transfer charge readily from one type of atom to another. So a surplus of charge can only be developed by the increase or decrease of negative charge carriers (electrons).

A surplus of electrons results in a region of negative polarity. A deficiency of electrons signifies a region of positive polarity. A balance of these charges can be achieved by connecting the poles to an electric conductor, through which the electrons may flow from the negatively charged object to the positively charged one. The term "electricity" stands for all manifestations of charges, settled or in motion, and the resulting electric or magnetic fields.

In deciding how to approach the subject of electrostatic charge formation, we consider the analogy of someone going on holiday in a strange land. The person would need to take with him a suitable map: in the case of a hiker, a map on which the contours and footpaths were shown in detail, and for a motorist, one on which the roads were given prominence. In a way, a map can be regarded as a model of the area to be explored. An analogy in electrostatics could be the exploration of the formation of static electricity. Some explorers might be interested in the fundamental quantum mechanics of charge transfer as described in the electron energy band model, while others would prefer a phenomenological approach. For the practical cases which are dealt with in this brochure, the latter is considered to be most useful – according to a Latin epigram:

Simplex sigillum veri

(Simplicity is the hallmark of truth.)

A simple experiment is meant to visualize the origin of static electricity: two disks of different materials (e.g. plastic and metal) are placed on one another and separated again. Afterwards, when measuring the charge on both parts, it is found to be of opposite polarity. The explanation follows.

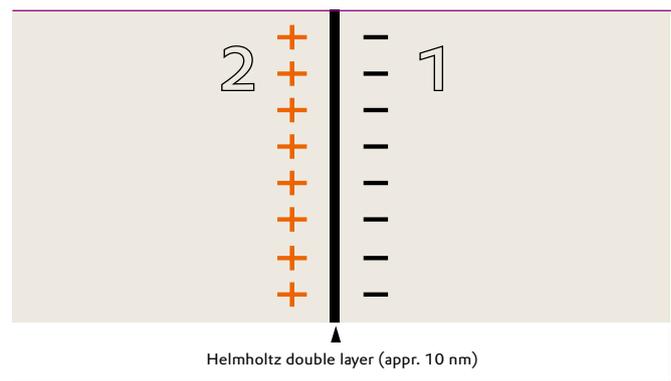
2.1 Double layer charge

When two different materials are brought into close contact with each other, i.e. with a distance between them of the order of a few nanometers, a transfer of electrons takes place across the interface, the number of which is dependent on the difference in the work functions of the two materials (work function: energy required to remove an electron from the surface of a material to infinity). In terms of this simple representation, electrons from the material with the lower work function (DONOR) migrate to the material with the higher work function (ACCEPTOR), thereby producing a layer of negative charge on one surface and positive on the other.

An equilibrium state is reached when the potential difference corresponding to the two work functions equals the potential difference between the two layers of charge of opposite polarity. A double layer of charge is produced at the interface, as postulated by Helmholtz (1879).

In the example (Figure 1) the work function of material 2 is lower than that of material 1. Consequently, electrons move from 2 across the interface to 1, causing 1 to become charged negatively and leaving 2 in a positively charged state. The potential difference caused by this polarization of charge at the interface is usually of the order of millivolts and, because of the extremely small gap between the surfaces, the capacitance of the system is high.

Figure 1 Donor material 2 has a lower work function than acceptor material 1



Contact charging itself depends only on surface contact between materials irrespective of whether or not the surfaces are stationary or moving relative to one another. The term frictional electrification has been in use for many years, described and discussed thoroughly innumerable times. However, it is now known that friction itself has no bearing on the electrification process. Basically, all it does is cause an increase in the contact between the surfaces.

Following their contact electrification (Figure 2) the surfaces are moved apart so that the distance between them increases by several orders of magnitude (about 6 to 8). This is accompanied by a reduction of the capacitance of the system and corresponding increases in the potential difference between the surfaces, and in the energy of the charge in the system. In the electrical double layer, values in the order of millivolts may be noticed, but when separating the surfaces, an increase up to the order of kilovolts can be measured. At the same time the electrical energy of the system increases correspondingly.

Figure 2 Materials 1 and 2 moving apart. Charge is neutralized at the last points of contact

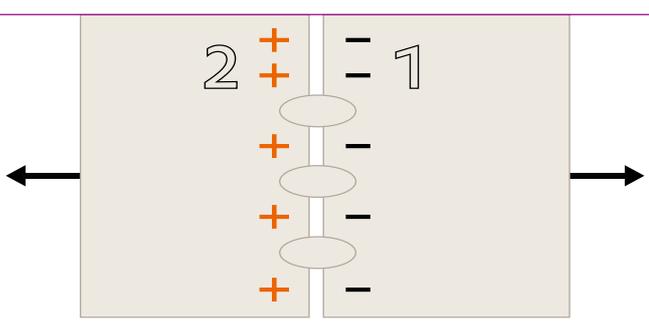
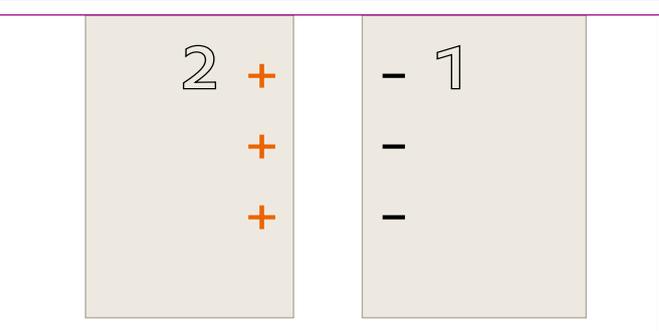


Figure 3 Residual charge on materials 1 and 2 after their separation



In separating two charged surfaces the Coulomb forces of attraction between the opposite layers of charge at the interface have to be overcome by expending mechanical energy on the system. Electrostatic charge is a kind of electrical energy, ultimately the equivalent of the mechanical energy used for separating both surfaces.

Out of that follows the important knowledge that electrostatic charge takes effect outside the double layer only when mechanical energy is supplied to it. When looking into the phenomena of electrostatic charge, it becomes obvious that during electron transfer the pattern of charge distribution is imprinted. The combination of this charge with the prevailing capacitance leads to the corresponding voltage.

2.2 Effects on the remaining charge

While the surfaces move apart, a high potential between the materials is reached. In practice the total charge transferred during contact is reduced when the surfaces are separated. This reduction is a result of two factors, namely surface resistivity and gas discharge.

Surface resistivity: During the separation of two surfaces the charge on each of them has a tendency to flow across the surfaces to the last points of contact as indicated in **Figure 2**, where the charges are neutralized. The speed with which this occurs follows the equation

$$\tau = R \cdot C$$

(see also section 8.8)

In this equation,

τ = time constant of discharge in seconds

R = resistance in Ω

C = capacitance in Farads

If the capacitance in this equation is replaced by the quotient Q/U (Q = charge in ampere seconds and U = voltage in volts), the charge reflux during separation of the materials is defined as

$$Q = \tau \cdot U/R$$

It may be deduced from this that, with high speed of separation of the surfaces (short time for discharge) and/or high surface resistances, the neutralization of charge by conduction will be restricted and a larger amount of the original charge will remain on the surfaces. On the other hand, with low speeds of separation (long times for discharge) and/or low surface resistances, the charges on the surfaces will be readily neutralized, thereby leaving little charge behind (**Figure 3**).

It also follows that the charging of the surfaces can occur even if only one of the materials being separated is of high resistance. When separating an insulating material from metal, consequently, it leads to equally high charges on both surfaces but with different signs.

Gas discharges: As the surfaces in contact are separated, the electrical field strength in the gap may reach the breakdown value for air, resulting in gas discharges (see also section 8.4). The ions which are produced are attracted to opposite charges on the surfaces which they neutralize. This effect occurs, for example, when adhesive tape is pulled off a roll. Gas discharges can be accompanied by audible "crackling" and, in the dark, by a visible glow.

To sum up, one can say that electrostatic charge is always generated when surfaces are being separated, no matter if there are solid or liquid interfaces involved. It manifests itself only when at least one of the partners is a poor conductor (insulating material) and when the separating process is faster than the neutralization caused by the reflux of charge carriers.

The previous explanation of the charging process needs to be amplified by the following remarks: Analysis of contacting surfaces shows after separation that broken bonds of the other material partner remain. When surface particles are breaking off, the crack plane is mostly found near small (nanometer) defects where trapped electrons preferentially remain, so further charge transfer will take place there. Ions, dragged along during the separating process, will also cause charge transfer. Now it may become comprehensible why electrostatic charge will arise even when materials of the same kind are being separated, e.g. during size reduction.

2.3 Charging of flowing liquids

Double layers of charge are formed, as with solids, at liquid/liquid and liquid/solid interfaces. However, in contrast with the charging of solids, that for liquids also requires the additional presence of ions to transfer charge. Ions of one polarity are being adsorbed in the interface, attracting ions of the other polarity. So, near the interface a diffuse layer is formed and is swept along with the flowing liquid according to its flow profile.

In this way charge separation occurs, provided that the electrical resistivity of the liquid is high enough to prevent charge reflux. The interrelation between volume resistivity and separating speed is obvious. In general, the means of preventing or reducing the charging of liquids are the same as those recommended for solids.

2.4 Charging of flowing gases

As has already been discussed, contact electrification can occur at solid/solid, liquid/liquid and liquid/solid interfaces. In the case of gases there is no static electrification at their boundaries. This means that gases flowing in pipes will not themselves give rise to static charges. However, any liquid or solid particles (aerosols or dust) entrained in the gas stream may readily produce charges. It is remarkable that even very small amounts of aerosols can give rise to high electrostatic charges (e.g. rust particles in pipes for compressed air).

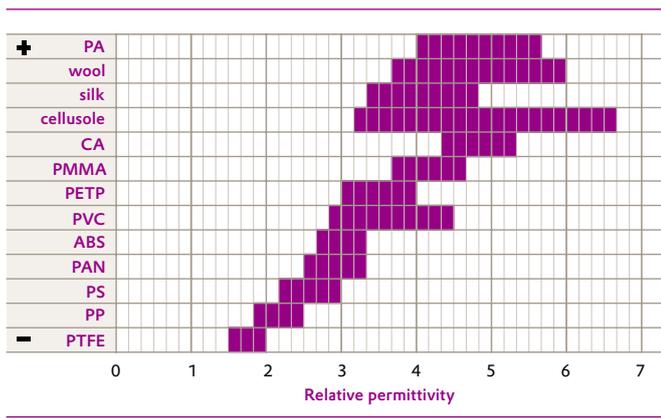
Deliberate electrostatic charging of gases, such as to remove disturbing static electricity, may be achieved by ionizers (corona discharge; section 5.2.1).

3 Reducing the tendency of charging

3.1 Decrease of the interfacial area of contact

From the discussion above it is clear that electrostatic charging is essentially a surface phenomenon, caused in its first step by intimate contact (distance about 10 nm in Figure 1). It therefore seems reasonable to expect that the formation of charge may be reduced by decreasing the area of contact between the materials to be separated. For example, plastic films may be highly charged when running across metal shafts in rewinding machines. The effect of moderately roughening the surfaces of these shafts by matt finishing them is known to significantly reduce static charging, without any change to the plastic film itself.

Figure 4 Triboelectric series



This also can be achieved by structuring surfaces of plastic films to prevent close contact of surfaces, e.g. by using performance silica or AEROSIL® as spacers. Thus the clinging together of materials caused by electrostatic charging can be avoided. Antiblocking agents also belong to this field (Technical Information, Evonik TI 1206).

3.2 Relative permittivity/Triboelectric series

As has already been noted, the separation of electrostatic charges depends, primarily, on the difference in the work functions of the materials involved. The higher the difference, the larger the charge separated and vice versa. On this basis it should be expected that in order to reduce static charging, materials should be selected which differ as little as possible in their work functions. Related results were found by Coehn in 1898, who formulated a rule stating that materials of high relative permittivity (dielectric constant) become positively charged when separated from materials of low permittivity. A corresponding triboelectric series is shown in Figure 4, which lists the range of permittivity values for several plastics and natural materials.

According to such triboelectric series, it is to be expected that materials standing far apart will give rise to high separating charges, whereas materials standing close together will cause only small charges (e.g. wool/PAN → high charges, wool/silk → small charges).

Unfortunately, this method does not always lead to the expected result, because the electron work function also depends on the surface state of the materials involved (which may be changed by temperature, humidity, dirtiness, etc). One practical application of AEROSIL® here is in producing powder coatings.

3.3 Reducing surface resistivity

The electrostatic charge caused by separating processes at an insulating material will be balanced more or less quickly, according to the electrical surface resistivity of the materials involved. Moreover, at most times connections to ground exist, which, according to the dissipating properties of the material, will partially drain off the charge. Resistance on the material (surface resistivity σ), as well as resistance in the material (volume resistivity ρ), are critical in this process. Test measures to determine values of resistance are laid down in DIN-IEC 93 (VDE 0303 part 30).

As surfaces of insulators remaining in free atmosphere always have to be regarded as being unclean in the physics sense (don't forget the accumulation of water molecules from the surrounding air), the resistance at the surface of the material is always lower than on the inside of the material. As the surface resistance is influenced by the relative air humidity of the ambient atmosphere, it follows that all tests to determine electrical properties have to be carried out under standard test conditions.

3.3.1 Measuring resistivity on AEROSIL® and performance silica

While international standards for measuring the resistance of solid (compact) materials are available (IEC 93), there are not even any national standards at hand for determining the resistance of bulk powders (e.g. AEROSIL® and performance silica). From a safety aspect there are statements concerning the electrical resistance of bulk powders in different guidelines and standards, but there are no binding instructions for test procedures.

Meanwhile, there is a tacit agreement to use a multipurpose electrode, generally employed for testing textiles (DIN 54 345 part 1), when measuring electrical resistance of bulk powders. In its original or a modified form it is suitable for resistance measurements of bulk powders, because with this electrode not only surface and volume resistivity of textiles can be determined but also the resistance of fibers and rovings. Between the latter and powders an analogy is to be seen, and so there is a chance to use this electrode for testing bulk powders as well. **Figure 5** shows such a measuring device.

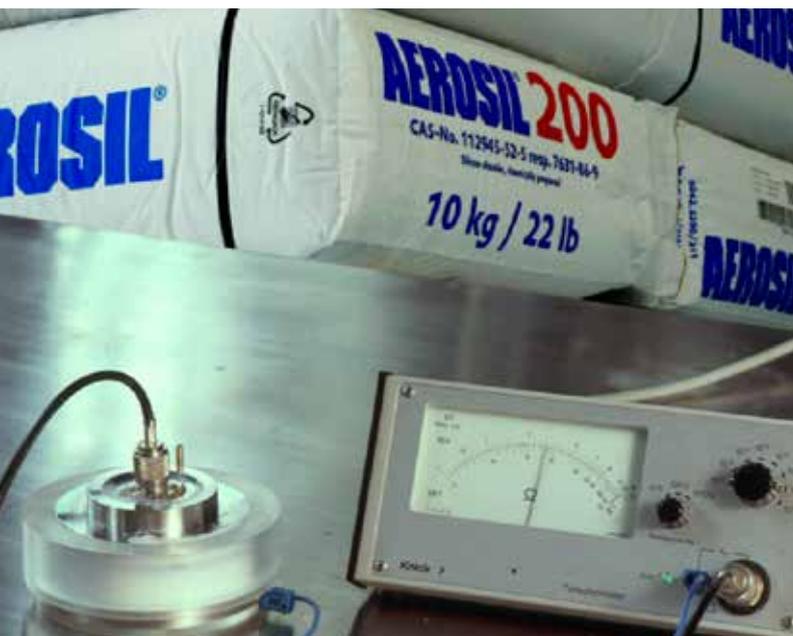


Figure 5 Measuring resistivity on AEROSIL® and performance silica

The measured resistance values always have to be converted into the volume unit, cubic meters. Therefore the resistivities of bulk powders that have been determined in this way depend only on the powder density, which is caused by the contact pressure of the electrodes and is not related to the electrode configuration.

To assess the electrostatic properties, resistivity measurements are being performed in the high ohm range, at values above 1 MΩ. Here only the orders of magnitude are decisive, in contrast to high precision measurements with deviations in the percent range. That is why the measuring principle is not the accurate Wheatstone bridge circuit, but the “voltage/ current” method. A constant direct voltage, adjustable between 100 and 500 or, respectively, 1000 volts, generated in the measuring device, is applied to the measuring electrode and the current flowing through the specimen is determined. According to Ohm’s law, from the voltage and the measured current, the resistance can be calculated. As this procedure runs automatically within the measuring device, the values of resistance will be indicated directly. Taking into account that customary picoamperemeters may determine currents down to 1 picoampere satisfactorily, it follows that potentials of 1000 volts lead to an upper limit of resistance measurements of 1 PΩ. Higher values can be achieved only in costly special measuring devices. It has to be observed that in these ranges of resistance, the electrical conductivity of the ambient atmosphere has an interfering effect.

4 Electrostatic induction

Frequently, undetected electrostatic induction causes electrostatic charging. Therefore it will be discussed here, although it is not easy to comprehend.

4.1 Phenomenon

An electric field has the ability to cause the movement of charges in nearby conducting bodies (Coulomb forces). The process, which is called electrostatic induction, causes a separation of charge within a conductor, which initially was not charged when placed into an electric field.

The induction effect is illustrated in **Figures 6–10** and shows the course of induction at a conductive object, insulated to ground by its supporting plastic rod.

Figure 6 No significant charge on the object

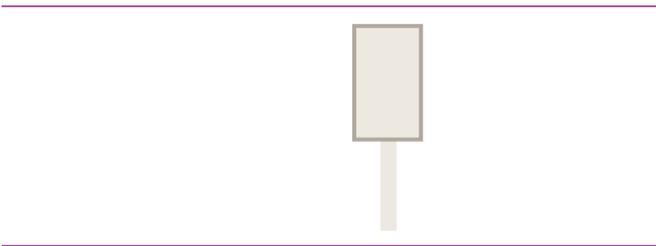


Figure 7 A negatively charged plastic part is moved towards the object. Positive charge will be held captive, negative charge will be moved to the far side of the object and can be measured there

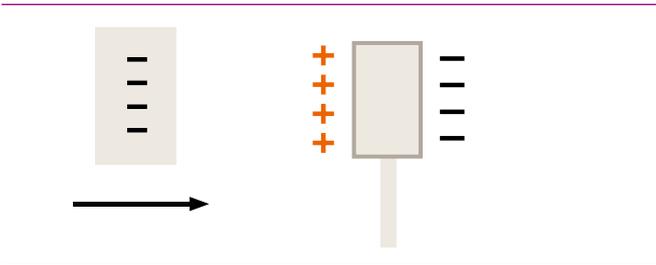


Figure 8 By grounding the object, the free negative charge is dissipated

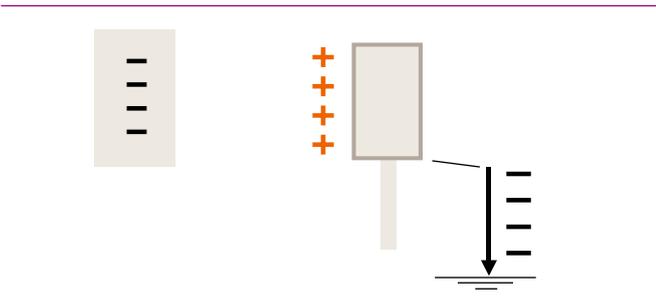


Figure 9 On removing the negatively charged plastic part the positive charge on the object is redistributed over its surface where it remains

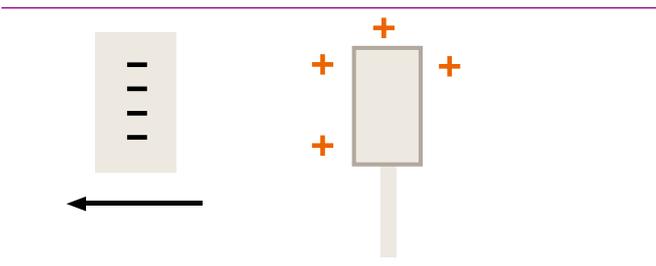
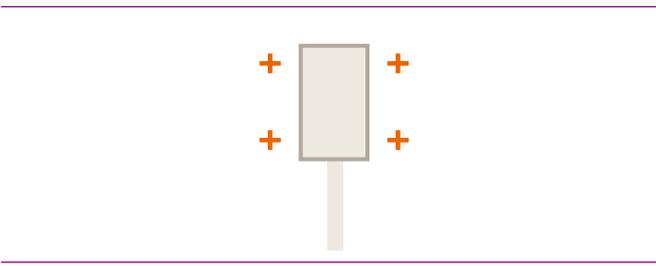


Figure 10 At the end of the induction process a measurable positive charge remains all over the object

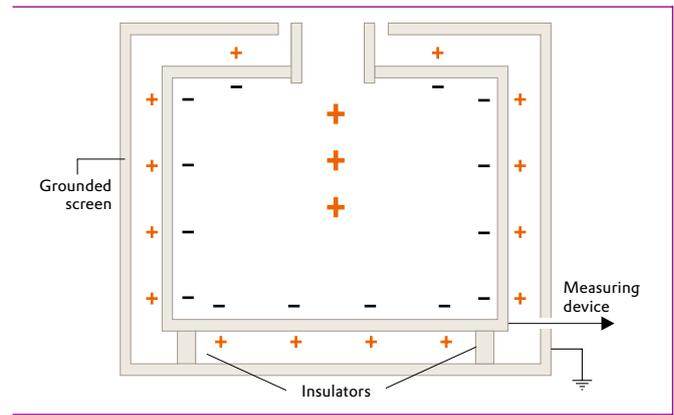


For the induction process, it does not matter whether the source of charge is switched on and off again, or if a charged subject is moving toward the conductive object and back again. Decisive for charge creation at the object is only that while the electric field is effective, charge dissipation has to take place (dissipation of free charge).

4.2 Determining charge by induction

A direct measurement of electrostatic charge, e.g. by contact with a voltage meter, is only possible if the object is sufficiently conductive. In general, preferably non-conductive materials become charged. As no charge transfer is possible with them, measuring of charge by means of contact does not work. This is why at charged non-conductors the effect of induction is used for charge transfer from the object to the measuring device, as pictured by way of example in Figure 11.

Figure 11 Measuring equipment for charge determination



Three insulating particles, positively charged, drop through the upper aperture into a metal measuring chamber (Faraday cup), where instantly the corresponding opposite induction charge is held on the inner side. Thus the same quantity of positive induction charge will be set free at the outside of the measuring chamber. Via a connected Coulomb meter it is easily possible to determine the charge of the particles.

5 Electrostatic gas discharges

The electrostatic discharge phenomena, such as sparks, which can be noticed as an audible crackle and a bluish glow, are correctly indicated in terms of physics as gas discharges. This is a generic term for all effects arising by a flow of electric current through gases: Radiation (light and UV emission, high frequency sweep radiation), noise (crackle, hiss, thunder), and chemical reaction (generation of ozone and nitrogen oxides).

In general, gases consist of neutral molecules and do not possess free charge carriers to conduct an electrical current. To reach conductivity in gases, charge carriers like free electrons and ions must be formed. These charge carriers can be developed from the outside by cosmic or nuclear radiation (dependent gas discharges) or by ionizing energy directly withdrawn from the gas discharge circuit itself (independent gas discharge). The force of electrical fields causes dependent gas discharges to alter into independent gas discharges above a critical field strength, i. e. breakdown voltage (see section 8.4). The reason is an avalanche of charge carriers caused by impact ionization of single charged particles.

In general, gas discharges are divided into two groups:

- one electrode discharges: corona, brush, propagating brush discharges;
- two electrode discharges: spark discharges

It is inevitable that there will always be free electrons (negative charges) in the atmosphere produced, for example, by cosmic rays. In an electric field these electrons are caused to drift in a direction opposite to that of the field. Their speed depends on the field strength and is limited by the frequency of their elastic collisions with the molecules of gas in the air. As the field strength is increased, the electrons gain speed until a critical value is reached when the collisions become inelastic. At this stage the gas molecules suffering collisions with the electrons release other electrons, and themselves become positively charged ions. This effect, known as ionization, leads to an avalanche of charge carriers (electrons and positive ions) which move with or against the field, depending on their polarity. This movement of charge constitutes an electric current of a magnitude dependent on the number of charges and the speed with which they move. This process is termed gas discharge. In a homogeneous electric field, gas discharges extend along the entire length of the field and are initiated when the field strength reaches that height required to cause an electrical breakdown of the ambient gas, which is usually air. Under atmospheric conditions this is reached in a uniform electric field of about 3 MV/m.

Manifestations of gas discharges:

- A** Luminous appearance
(light emission of electrically stimulated gas atoms)
- B** Radio-frequency transmission (kHz to MHz)
- C** Noise (hissing, crackling)

A and **C** may be perceived directly, but only at short distances if they are weak. Radio-frequency signals (**B**) may be detected over longer distances by simple AM-radio receiving sets.

Noise and radio-frequency signals of gas discharges are caused by the so-called pinch effect (see also 5.1).

5.1 Spark discharges

A spark always takes place between two electrodes when the field strength between them reaches the breakdown value, e.g. 3 MV/m for air.

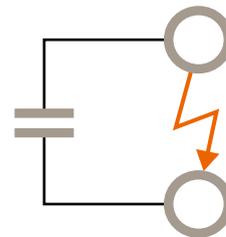
The field strength between the electrodes follows the equation:

$$E = U/d$$

(**U** = voltage, **d** = distance between electrodes, in m) (see also section 8.4)

It is characteristic of a spark discharge that the discharge channel, consisting of ionized gas molecules (gas ions), extends the entire distance between the electrodes. In the beginning, the gas ions represent a diffuse ionic current, which is circumvented by a magnetic field. If the latter is strong enough the gaseous ions are compressed to a thin channel (pinch effect) of high temperature plasma, while at the same time emitting a sharp crack.

Figure 12 Spark discharging of a capacitor



In general all gas discharges in which the pinch effect occurs are so hot (plasma) that they may ignite any fuel, providing there is sufficient energy. When the charge is neutralized the electric and magnetic fields collapse. This instantaneous change in the magnitudes of the fields is accompanied by a release of energy in the form of electromagnetic waves, which are radiated as radio-frequency signals and are detectable by means of an AM-radio receiver (see above). For the case of a spark discharge from a charged capacitor (**Figure 12**), the energy W released is calculated using the equation:

$$W = 0.5 \cdot C \cdot U^2 \text{ or}$$

$$W = 0.5 \cdot Q \cdot U$$

(see also section 8.8)

Spark discharges, for instance, may occur between an insulated metal drum which has become charged during filling, and a nearby grounded part of the structure. In electrostatic terms the drum behaves like a charged capacitor.

As the human body is electrically conducting, it also acts as a capacitor when insulated from earth and is capable of delivering spark discharges. For example, a person being charged by walking on a carpet and then touching a grounded part, e.g. a door knob, may cause a spark. The perception threshold of these sparks begins at about 2 kV (see also section 7.4).

5.2 One electrode gas discharges

When approaching a highly charged insulating material with a grounded electrode, the electrical field will be distorted in such a way that a higher field strength is produced there than at the surface of the insulator.

In an inhomogeneous field, gas discharge occurs first at the strongest part of the field, where it is sufficient to cause an avalanche effect. As field strength is synonymous with the field concentration, high field strengths occur most readily at the surfaces of conductors of small radii when placed in the electric field. If its strength reaches the breakdown voltage of air (3 MV/m) for example, corona discharges or brush discharges may be initiated. The region of the breakdown is close to the electrode and does not extend toward the insulator because of a rapid decrease in field strength in that direction.

The field strength at an electrode approximately follows the equation:

$$E = U/r$$

(r = radius of electrode curvature)

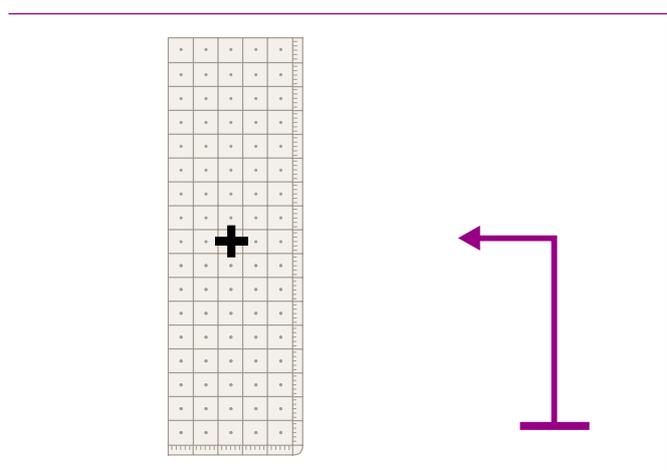
The energy released in single one electrode gas discharges, in contrast to that of spark discharges, cannot be calculated.

5.2.1 Corona discharges

This kind of discharge is visible only to eyes adapted to the dark and appears as a faint blue-violet glow. This weak and almost continuous one electrode gas discharge appears at needlepoint electrodes (radius of curvature < 0.1 mm) when placed in an electrical field of a few kV/m strength (Figure 13).

As no pinch effect is caused, no ignition danger is posed and therefore no radio-frequency signal will be emitted. So corona discharges are simple and effective means without ignition potential for eliminating interfering static electricity, e. g. for draining off charge from plastic sheeting.

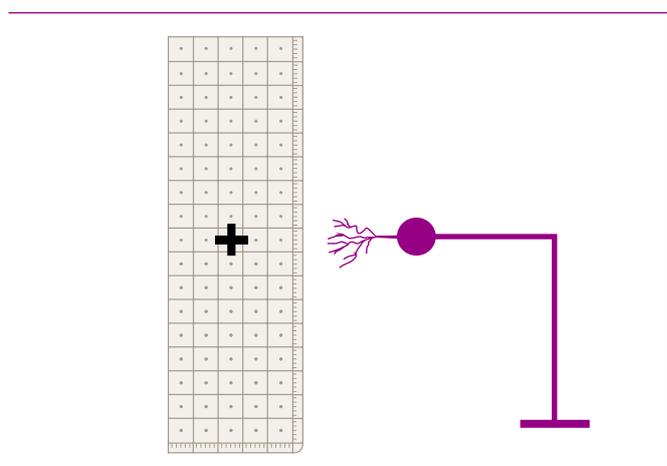
Figure 13 Corona discharge



5.2.2 Brush discharges

In principle, these are generated like corona discharges but originate from electrodes with a much higher radius of curvature (> 1 mm) and so they need a much higher field strength to trigger them (Figure 14).

Figure 14 Brush discharge



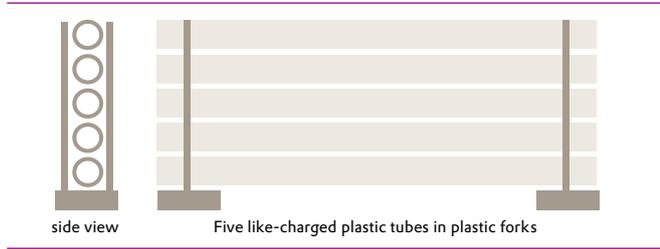
This brush-like discharge can be seen in the region of the electrode which is closest to the charged object.

It appears as a short spark-like channel which starts at the electrode and fans out into faintly luminous filaments before disappearing in the gap between the electrode and the charged object. This brush discharge also manifests itself in an audible crack and a short pulse of current, caused by the pinch effect at its short spark-like channel. Therefore it shows an ignition potential as attributed to small spark discharges. Brush discharges may ignite flammable gas and vapor/air mixtures, whereas an ignition of combustible dust/air mixtures is not yet proven.

5.2.3 Super brush discharges

Much stronger brush discharges may be generated when the charge density is increased at a charged insulating surface.

Figure 15 Development of super brush discharges



An insight into these rare discharges is given in **Figure 15**. Five plastic tubes of the same material are electrostatically charged by rubbing them with a cat's fur.

When placed on top of each other, between insulating forks, the electrostatic force arising from the charge causes them to repel one another. These forces act against gravity, causing the tubes to hang suspended above one another.

Considering the Coulomb energy and the charge on any system, the following can be deduced:

- Overcoming Coulomb forces of attraction between opposite charges produces higher potentials (see 2.1).
- Overcoming Coulomb forces of repulsion between like charges produces higher charge densities.

As each of the above processes causes an increase in the electrical energy, the energy transferred in any resulting gas discharge is also increased. This becomes evident when a grounded metal electrode is brought up to one side of the charged tubes. A more energetic brush discharge than is ordinarily the case is caused, in which brush-like luminous channels are produced which sometimes reach the surfaces of the tubes.

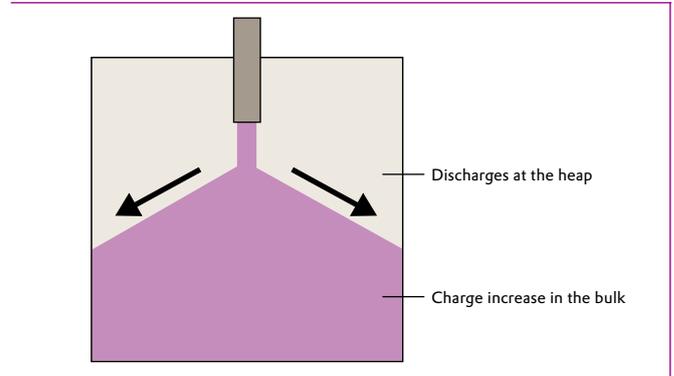
Accordingly the ignition potential of a super brush discharge has to be classified as being higher than that of a brush discharge.

5.2.4 Cone or bulking discharges

In general, pneumatic conveying of highly insulating granules causes higher amounts of static electricity. When feeding charged particles into a silo, there is an accumulation of charge at the heap. The field from this charge exerts repulsive forces on the similarly charged particles which are falling onto the heap. As the gravitational forces on the particles act against the repulsive forces there is an increase in the charge density of the bulk material at the heap (see 5.2.3). If charged particles continue to fall onto the heap after the field strength in that

region has reached the breakdown value for air, gas discharges will always occur in a direction toward the conducting wall of the silo (**Figure 16**).

Figure 16 Course of cone (bulking) discharges



As parts of the discharge channels are strongly luminous it follows that the pinch effect, which has already been discussed, is taking place. These so-called cone discharges occur not only at the surface of the heap but also within the bulk and can be detected as radio-frequency signals, as can brush discharges. A photograph of cone discharges taken with a camera mounted on top of a silo, as the latter was being filled with plastic granules, is shown in **Figure 17**.



Figure 17 Photo of a cone discharge inside a silo: top view of bed of material, with central filling port

From this explanation it is obvious that the mechanism of cone discharges is in some way similar to that of super brush discharges. With decreasing particle size, the mass charge ratio changes in such a way that the influence of gravity diminishes in view of Coulomb forces of repulsion. More and more small particles will be pushed away toward the wall of the silo and will also form a suspended cloud of charged dust. That means lower charge density in the powder heap. It is suggested by theoretical and experimental evidence that cone discharges should not be expected for very fine powders.

However, ignition danger always prevails when charged granules are being fed into a silo containing an ex-plosible atmosphere (e. g., that caused by evaporating residual monomers).

5.3 Propagating brush discharges (Lichtenberg discharges)

Compared with the types of gas discharges already described, propagating brush discharges are the most powerful kind of electrostatic discharges, with the sole exception of lightning.

5.3.1 Propagating brush discharges on shielded systems

Under normal atmospheric conditions, the maximum theoretical field strength at the surface of an insulating material is not more than 3 MV/m, corresponding to a charge density of about 26 $\mu\text{C}/\text{m}^2$. Any further charge will be sprayed off (see 8.1.1).

If the insulating material is in the form of a thin foil and is placed onto a grounded conducting plate, opposite charges will be bound there by induction.

The reason for this is that, as the electric field from the surface charge is directed mainly toward the plate, through the dielectric, the charge density is now limited only by the breakdown strength of the dielectric, which, typically, is 100 to 1000 times higher than that of air. Such high charge densities can only be generated by spraying charge from a corona discharge onto the surface, and by certain industrial operations, e.g. the pneumatic transport of powders through insulating tubes. Upon the latter a multitude of charged particles will impinge so that high charge densities will follow the single separating processes. Obviously charge densities of that amount cannot be produced by simply rubbing and separating surfaces.

Should the field in the dielectric, from the charge of its surface, reach the breakdown value of the dielectric, a spontaneous discharge occurs resulting in a puncture of the foil (Figure 18).

Figure 18 Principle of propagating brush discharges



Starting from the puncture, a very high electric field is created parallel to the foil's surface, which initiates a series of strong surface discharges, thereby releasing most of the surface charge. The discharges themselves exhibit spark-like channels (Figure 19), and will equalize the charge at the surface with the induction charge accumulated at the reverse side of the foil.

Propagating brush discharges may extend up to about one meter, and, since they may produce energies of up to 10 J, a possibility of severe physiological shocks to personnel must be taken into consideration.

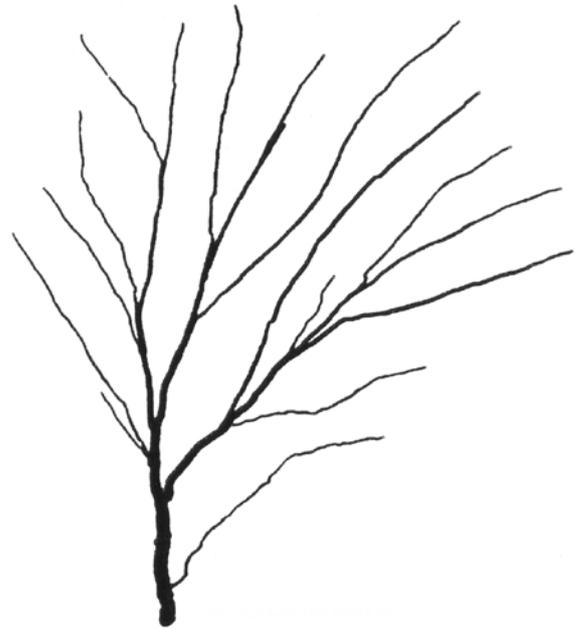
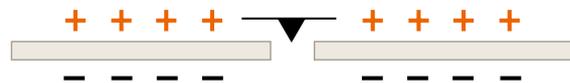


Figure 19 Photo of a propagating brush discharge

5.3.2 Propagating brush discharges on unshielded systems

Propagating brush discharges can also occur on the surfaces of free-standing insulating materials, e.g. plastic bags and plastic tubes, when bipolar charges of sufficient density are produced on their surface (Figure 20). As with shielded systems, such discharges are only possible subject to the conditions mentioned above. This type of discharge may sometimes be observed with FIBCs made of insulating materials, e.g. polypropylene, on filling them with highly charged materials. When such a bag is left standing for some time, charges of opposite polarity to that on the contents of the bag are attracted to the outside surface. As the field from this charge is directed into the bag, charge densities sufficient to induce a propagating brush discharge may accumulate on the surface of the bag.

Figure 20 Propagating brush discharge on an bipolar layer



In assessing the occurrence of propagating brush discharges on insulating layers of shielded as well as of unshielded systems, experimental evidence has shown that such discharges will not occur when the thickness of the insulator is more than 10 mm or when the breakdown potential of the insulating material is less than 4 kV.

6 Static electrification and safety measures when handling AEROSIL® and performance silica

As explained in Chapter 2, the amount of electrostatic charge is mainly determined by the chance of charge equalization during the separating process; i. e., surface resistance and separating speed are decisive factors.

Therefore, low resistances of the materials will lead to low electrostatic charges. In corresponding technical guidelines (see Chapter 9), thresholds for the electrical resistance of isolating materials are listed. How is electrostatic charging of bulk materials to be evaluated and controlled?

6.1 Electrostatic properties of finely divided silica

In general, fine powders can be charged significantly when their resistivity ρ exceeds the value of $10 \text{ G}\Omega\text{m}$. Most synthetic polymers, if not treated antistatically, as well as highly disperse silica (AEROSIL®) belong to that group. However, the performance silica in general shows resistances below this threshold value.

The high variation in the tendency of both types of silica to become electrostatically charged is related to the difference in their manufacturing process. Performance silica results from the conversion of water glass with sulfuric acid. AEROSIL® is produced by a high-temperature hydrolysis process from silicon tetrachloride in an oxyhydrogen flame.

According to their origin, performance silica in comparison with AEROSIL® show a higher moisture content. This may be indicated by the desiccation loss factor which is listed in Table 1; section 6.3. The smaller particle size of AEROSIL®, which results in a larger surface of the product and therewith a higher tendency of charge, is also related to its manufacturing process.

6.2 Charging effects on highly disperse silica

Two typical procedures may be used to explain how charging takes place:

- pneumatic conveying through a pipe
- filling a container

6.2.1 Electrostatic charging of highly disperse silica AEROSIL® and performance silica during pneumatic conveying

When streaming through a pipe, particles touching the wall will be charged by separating processes (section 2). The charge of a product will become more significant the higher the resistivity, the specific surface and the velocity. It is apparent that the threshold of resistance alone (section 6.1) is only partially reliable. Furthermore, the electrical quality of the pipe material is of great influence as well. Pipes made of electrically insulating or chargeable materials may be charged whether or not

the conveying material is conductive. This is why no insulating materials must be used for pneumatic conveying systems. To avoid interfering and incendiary propagating brush discharges (see section 5.3) no electrically insulating lining should be used in otherwise conductive pipe systems.

The counter-charge of the charge dragged along with the material conveyed remains on the electrically conductive pipes and fittings. This charge is easily eliminated by permanent grounding. If not, it has to be taken into consideration that now and again spark discharges (s. a. part 5.1) and unpleasant electric shocks to personnel will occur.



Figure 21 Part of pipe insulated from conveying system

Figure 21 shows a steel pipe in which a part of 300 mm length is electrically insulated to both sides by means of non-conductive hose couplings. With the aid of a surge pump, AEROSIL® was transported through the pipe system. After only 5 seconds of conveying, the electrical potential at the insulated pipe amounted to 15 kV, indicated by a connected static voltmeter, and spark discharges of 5 mm in length took place when approaching a grounded electrode.

6.2.2 Electrostatic charge when feeding AEROSIL® and performance silica

When feeding electrostatically charged AEROSIL® or performance silica into a vessel, charge accumulation will occur.

A spontaneous charge transfer caused by induction takes place toward the wall (see section 4.2) if the vessel is electrically conductive (metal drum). As with the conductive pipe system, a permanent grounding of the conductive vessel is necessary to prevent spark discharges. When the vessel is left ungrounded, high electrical potentials may arise there. Because of its larger capacity in comparison with the pipe already mentioned above, the possible spark discharges are of higher energy.



Figure 22 Filling an insulated metal drum

To demonstrate the charge built up at a metal drum, the latter was put on an insulating plastic panel (**Figure 22**) and filled with AEROSIL® via an insulating hose of the conveying system. Thus any charge dissipation was prevented. In the left hand side of the picture, toward the front, there is a static voltmeter (measuring range 1 kV) with integrated storage capacitors for stepwise connection. This facilitated direct analysis of the charge at the drum, transferred from the product by induction.

When feeding bulk material into an electrically nonconducting vessel (plastic drum), the situation is of much higher complexity. First, the electrical field caused by the charge directly reaches through the insulating material. The charge itself may induce ionization in the empty part of the drum (air) as well. In the end, both occurrences result in static electrification being perceptible outside of the insulating vessel; there is “crackling” when approaching with a conductive part, e. g. a hand. The corona and brush discharges (sections 5.2.1 to 5.2.3) generated thereby are capable of acquiring similar charges of opposite polarity, thus forming a charge double layer at sections of the outer wall. When the charge density inside the vessel is sufficient to cause an electrical breakdown this can lead to a propagating brush discharge puncturing the wall (section 5.3.2).

When filling very large containers (silos a few meters in diameter) with highly charged bulk material, cone discharges may result (see 5.2.4). They mainly have to be expected when coarse material is fed into electrically conductive silos.

Table 1 Measurement results (climate: 22 °C, 46% r. h.)*

Product	resistance Ωm	charge μAs/kg	pipe potential kV	desiccating loss weight percentage**
AEROSIL® 200	>100 T	10	37	1.1
AEROSIL® 300	20 T	10	21	2.4
AEROSIL® R 202	>100 T	3	20	0.2
AEROSIL® R 972	>100 T	1	15	0.3
SIPERNAT® 320 DS	1 G	0.3	1.2	5.8
SIPERNAT® 22	2 M	0.1	35	5.5
SIPERNAT® D 17	8 T	0.4	18	3.2
ULTRASIL® VN 3	4 M	0.3	25	5.7

* single measurements ** measured after pneumatic conveying

6.3 Electrostatic measurements on AEROSIL® and performance silica

Highly disperse silicas of synthetic origin from Evonik may be subdivided according to their manner of production:

- high-temperature hydrolysis process (AEROSIL®)
- conversion of water glass with sulfuric acid (ULTRASIL®, SIPERNAT®)

Now the aim is to find out if these different kinds of silica also exhibit different electrostatic properties.

Therefore, the following electrostatic measurements were carried out:

- 1 Determination of resistivity
- 2 Determination of specific static electrification
- 3 Potential measurements at a part of the conveying system

Measurement of resistivity (Ωm) has already been discussed in section 3.3.1.

To determine static electrification the equipment already described in 6.2.2 was used. Deriving from that, the specific electrification ($\mu\text{As/kg}$) could be calculated after the amount of product deposited in the drum was weighed.

It was also important to find out to what extent a part of the conveying system, insulated to ground, could be electrostatically charged by silica passing through. For this, potential measurements (kV) were carried out at an insulated section of pipe as **Figure 21** shows. As these measurements suffered strong fluctuations up to the reversal of polarity, only the maximum (absolute) values were noted.

In view of the potential measurements there are two more basic statements as follows:

- The measuring devices read the potentials referring to ground.
- The insulating conditions were so excellent that no significant charge dissipation took place during the measuring process.

With the exception of SIPERNAT® D 17 the measuring values show an approximate correlation between resistance and electrostatic charging of several highly disperse silica. However, even products with a low tendency to become charged (SIPERNAT® 22 and ULTRASIL® VN 3) led to high potentials at the insulated section of pipe (**Figure 21**). The reason may be found in the high speed of product flux, which permits separating charges to take place even with resistances in the range of $\text{M}\Omega$ (short dissipation times, section 2.2).

The desiccation loss expressed in weight percentage as shown in **Table 1** characterizes the humidity of the product. When comparing the resistance values shown in **Figure 23** with the desiccation loss of all products tested, the following was found:

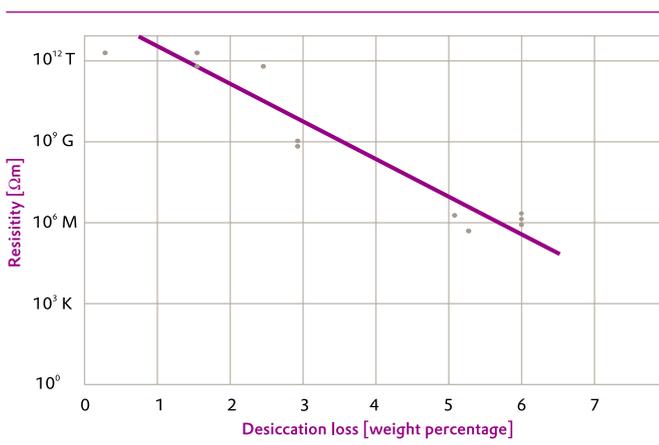
The measured results approximately resemble a straight line, showing the resistance of a material to be lower the higher its humidity.

Table 2 Measurement results (climate: 21 °C, 45% r. h.)*

Product	resistance Ωm	charge against paper $\mu\text{As/kg}$	charge against PE $\mu\text{As/kg}$	desiccating loss weight percentage
AEROSIL® 200	> 100 T	6	4	1.70
AEROSIL® 300	20 T	10	4	1.73
AEROSIL® R 202	> 100 T	1	2	0.16
AEROSIL® R 972	> 100 T	0.08	0.04	0.12
SIPERNAT® 320 DS	1 G	10	5	3.18
SIPERNAT® 22	2 M	0.3	2	6.02
SIPERNAT® D 17	8 T	0.08	0.9	2.88
ULTRASIL® VN 3	4 M	0.2	1	6.01
ACEMATT® TS 100	1 G	20	5	2.84
ACEMATT® OK 412	400 M	2	6	5.03
ACEMATT® OK 520	10 M	< 0.01	5	6.06
ACEMATT® OK 607	60 M	0.02	8	5.31

* measured after filling tests

Figure 23 Resistivity depending on desiccation loss



6.4 The influence of packing on the level of charge of AEROSIL® and performance silica

When handling bulk material in explosion-endangered areas, it has to be considered that electrostatic ignition dangers may be caused by the bulk material as well as by the packing. If packing made of electrostatically nonconductive material is used, e.g. bags of polyethylene or polypropylene, it always has to be taken into account that dangerous static electrification may arise. However, under normal air humidity, packing made of paper shows dissipating properties. Only in very dry climate conditions may paper become dangerously charged. This also applies to paper bags with an intermediate layer of plastic material, e.g. polyethylene. Linings which may be electrostatically charged are not dangerous as long as they are fixed at least at a few points to the paper bag, so preventing them from slipping out during the emptying process.

Apart from that, packing has an influence on the amount of charge on the bulk material emptied out of them. This correlation was examined and the results are shown in **Table 2**. In principle, the measurements were carried out in the same way as shown in **Figure 22**. However, instead of feeding the product pneumatically it ran along a chute by gravity, simulating the emptying process of a bag. The chute was lined with a kind of paper also used in paper bags and with an untreated polyethylene film as well. The results of these charge measurements were also converted into specific electrification values ($\mu\text{As}/\text{kg}$), permitting a direct comparison with the values gained during pneumatic conveying as listed in **Table 1**.

Here again, the measured values show an approximate correlation between resistance and electrostatic charging of several highly disperse silica. The charging of product with a resistivity of $10 \text{ M}\Omega\text{m}$ or less, in general, is very low when generated against paper. But, when slipping along polyethylene, these low resistivity products become charged as highly as silica of high resistivity. This can be explained by the principle of charge separation (Chapter 2): all that matters is that one of the materials involved in separating process shows a high electrical resistance, as is always the case with untreated polyethylene.

7 Dangers caused by static electricity

From the present-day standpoint, dangers caused by static electrification may be divided into 3 different groups:

- Ignition danger to flammable mixtures
- Danger of shock to living individuals
- Damaging of electronic equipment

The degree of risk (i. e. the likelihood) of fire or explosion due to electrostatic charging depends not only on the probability that the charging will lead to an incendiary spark, but also on the probability that there will be an explosive atmosphere. To assess ignition dangers for combustible mixtures, the explosion endangered areas are subdivided into Zones, according to the probability of a hazardous explosive atmosphere occurring (see DIN EN 1127-1 Explosive atmospheres—explosion prevention and protection—part 1: basic concepts and methodology).

Classification

Zone 0: Area in which a flammable vapor or gas atmosphere is continuously present, or is present for long periods.

Zone 1: Area in which a flammable vapor or gas atmosphere is likely to occur during normal operation.

Zone 2: Area in which a flammable vapor or gas atmosphere is unlikely to occur during normal operation but, if it does occur, will exist only for a short period.

Zone 20: Area in which a hazardous explosive atmosphere formed by a dust cloud in air is present continuously, or for a long period, or frequently, and where dust layers of unknown or excessive thickness may be formed.

Note: Areas where piles of dust are present but where dust clouds are not present continuously, or for a long period, or frequently are not included in this Zone.

Zone 21: Area in which a hazardous explosive atmosphere formed by a dust cloud in air is likely to occur during normal operation, and in which layers of combustible dust will usually be present.

Zone 22: Area in which a hazardous explosive atmosphere formed by a dust cloud in air is unlikely to occur in normal operation but, if it does occur, will exist only for a short period, or in which accumulations of layers of combustible dust are present.

Note: *The definitions of the Zones are at present under discussion in Europe. Users of this brochure are recommended to consult the latest editions of EN 60079-10 and EN 61241-3 for the outcome of this discussion.*

Precautions considered necessary to avoid electrostatic charging where there is often an explosive atmosphere are not always necessary, where such an atmosphere occurs infrequently. Furthermore, the flammability of materials, expressed in their minimum ignition energy (MIE), has to be observed. With the exception of acetylene, carbon disulfide and hydrogen (group IIC), which are extremely sensitive, flammable gases and vapors with a minimum ignition energy of about 0.2 to 1 mJ belong to group II A and II B (EN 50014). As both can be ignited by all kinds of electrostatic gas discharges (exception: corona discharge), extensive safety measures have to be taken.

A subdivision in view of flammability is quite common with combustible dusts as well, although relevant regulations are still lacking. Only a few dusts are very sensitive and show an MIE below 10 mJ, whereas most dusts are above that value (cf. **Table 4**).

Related to the subdivision into Zones and the flammability of the combustible materials mentioned there, restrictions have been established on area or width values of non-conductive solid materials, listed in CENELEC/R044-001 (see Bibliography).

In **Zone 1**, e.g. in the surrounding area of vessels containing flammable liquids with an MIE between 0.2 and 1 mJ, non-conductive materials are permitted if they have a surface area of below 100 cm² or a diameter less than 3 cm. A maximum of 400 cm² are permitted if the chargeable surfaces are surrounded by a conductive and grounded frame.

In particular, these demands apply to all packaging made of chargeable materials, from the shrink films around a pile of bags on a pallet, and the bags themselves, on up to drums and buckets. It also applies to pipes and hoses made of plastic, e.g. in exhaust systems. If larger installations which cannot be made of conductive material, for example protective shieldings of

transparent plastic, are absolutely necessary, their protective function is to be evaluated as higher than the dangers caused by static electricity. It has to be ensured by preventive measures that these parts will not be dangerously electrostatically charged. This may be achieved by warning signs instructing personnel to use only water-wetted cloths for cleaning, for example.

All electrically conductive parts as well as the human body have to be grounded reliably in the event of becoming electrostatically charged (e.g. by contact or induction). An important requirement for that is a permanently conducting floor. Personnel (not necessarily visitors) are obliged to wear conductive footwear and, if appropriate, conductive gloves as well. All vehicles used in explosion endangered areas must be equipped with conductive tires or rollers, as appropriate. In spite of the fact that modern clothing can really become electrostatically charged it is not, in general, an ignition risk provided that the wearer is earthed by means of suitable footwear and flooring. However, in explosion endangered areas it is not permitted to remove clothing or to change it.

In Zone 2 safety measures against electrostatic charging are only compulsory if frequent incendiary discharges occur during normal operation (e.g. conveyor belts consisting of non-conductive materials).

In the dust Zones 20, 21 and 22 there are, in general, no restrictions on the use of non-conductive materials unless there is a possibility of incendiary discharges (**Table 4** is to be noted).

7.1 Ignition dangers in explosion endangered areas

Although Evonik silica (AEROSIL®, performance silica) is not in question because they represent non-combustible materials, the following has to be considered: problems start when these silica has to be inserted into substances to improve their quality. In the case of paints containing flammable solvents of low flash point, vapors will be produced, forming an explosive atmosphere. When handling silica there, gas discharges may arise that are capable of igniting these atmospheres (see part 5).

The same applies to operations in which silica is processed together with combustible dusts. But as the energy required to ignite dust atmospheres is higher here, the dangers of ignition are minor.

In Table 3, influencing factors in connection with gas discharges (Chapter 5) are listed to indicate the likelihood of ignition dangers under existing conditions.

Table 3 Influencing factors on the ignition capacity of gas discharges

Type of gas discharge	Influencing factor on ignition capacity
Corona/Brush	electrode radius, polarity of the charged area
Cone	charge density in bulk volume
Propagating brush	charge density on surface, thickness of layer
Spark	amount of energy stored in the capacitor

As discussed above, for the ignition of combustible atmospheres the energies needed differ considerably. With the exception of the calculable spark discharges (section 5.1) statements of ignition potentials for the other types of gas discharges are based merely on experience.

The statements of Table 4 indicating ignition potentials of different types of gas discharges for combustible gases, vapors and dusts find general acceptance at present.

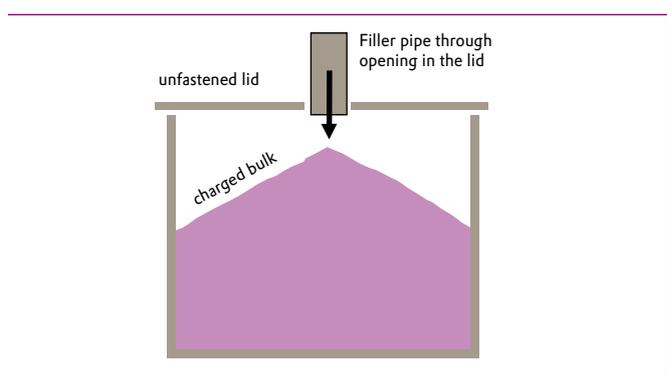
Table 4 Incendiary behaviour of different fuels by gas discharges

Type of gas discharge	Gases and vapors MIE: 0.2 1.0 mJ	Sensitive dusts MIE: 1 10 mJ	Dusts MIE: >10mJ
Corona	no	no	no
Brush	possible	not proven	no
Super brush	possible	suspected	suspected
Cone	possible	suspected	suspected
Propagating brush	yes	yes	yes
Spark	(Incendivity can be calculated, see part 5.1)		

When investigating a large number of fires and explosions initiated by static electricity, it became evident that in most of the events, spark discharges were the ignition sources. The other types of electrostatic gas discharges, such as brush, cone or propagating brush discharges, were the ignition source only in a very small though not negligible number of cases. An example of an ignition caused by a spark discharge is shown in Figure 24.

The electrostatically charged bulk material streaming through the filler pipe is settling in the silo, thereby causing the electric field from the product to be drawn more and more towards the unfastened lid, charging it by induction.

Figure 24 Feeding bulk material into a small silo



As the lid was insulated, because of product lying at the silo's rim, spark discharges may have occurred toward grounded conductive parts, e.g. the filler pipe or the silo itself. As it is certain that an ignitable dust/air mixture was present in both places, these spark discharges were liable to be the cause of ignition.

The consequence for practice is that the prevention of spark discharges requires particular attention. It is fortunate that spark discharges, in most cases, can be avoided in a way easily comprehended:

GROUNDING of every CONDUCTIVE PART that may be CHARGED.

This statement includes three important terms which will be explained briefly

- Grounding is to be understood here only in terms of electrostatics. It means reliably draining off hazardous static electricity. Therefore the resistance to ground must be lower than 100 MΩ for all conductive parts such as drums, containers, filter supports and human bodies. Only for very large conductive vessels (e.g. tank cars) a grounding resistance of less than 1 MΩ is required.
- Conductive Parts: here, conductive is meant in terms of electrostatics again, i.e. the resistivity must not exceed 10 kΩm. This applies not only to all metals but also to conductive plastics, humid wood and, last but not least, the human body.
- Charged might be every part in the plant in general. It is impossible to evaluate the state of charging without an exact knowledge of the operation process.

With every use of high resistivity non-conducting material, there is an inherent danger of ignition due to electrostatic charging. These chargeable materials can bring about brush discharges and also, indirectly, cause spark discharges by means of induction to adjacent conductive materials which are not grounded.

This explanation shows that the electrostatic definitions of grounding and conductance differ significantly from those used in electrical engineering. In electrostatics, relatively high values of resistance (magnitude of $M\Omega$) still comply with them. This fact often leads to misunderstandings; conductive parts remain undetected and sufficient grounding is not accepted.

Though the ignition source “spark discharge” will be eliminated by grounding every conductive part that can be charged, there may remain ignition dangers caused by brush, cone or propagating brush discharges.



Figure 25 Ground connection on pipe system

Figure 25 shows an example of grounding. As already mentioned in 6.2.1, high electrostatic charges can be generated when conveying AEROSIL® through metal pipes. The resulting spark discharges can reliably be avoided when all conductive parts of the system are permanently grounded.

Although static charges are almost everywhere, they are, for the most part, benign in terms of the danger and nuisance they can give rise to, because of their small quantity. It is when charges of different polarities become separated and then accumulate in more substantial quantities that problems can arise. Charge separation can occur in a number of ways but the most frequent means are by the contact and separation of materials and by electrostatic induction. **Figure 27** shows a schematic diagram of the development of different types of incendiary gas discharges arising from accumulated static charges.

7.2 Nuisance discharges

The accumulation of static charge on the human body can lead to uncomfortable shocks when a grounded or large conductor is touched. Most people these days are familiar with these shocks.

Electrostatic discharges are considered to be a direct hazard to health if the discharge energy exceeds 350 mJ. It follows that brush discharges or spark discharges from small insulated metal objects (hand tools, cans, funnels) do not cause electric shocks which are directly harmful. But spark discharges from large objects and propagating brush discharges can be harmful since the energies from both these types of discharge can exceed 1 J.

However, discharge energies as low as a few mJ can be an indirect hazard to health, owing to involuntary movement. Such shocks can cause injury due to contact with moving machinery or to falls. Even minor shocks are undesirable since they can cause unnecessary anxiety and lead to loss of concentration.

7.3 Interfering discharges

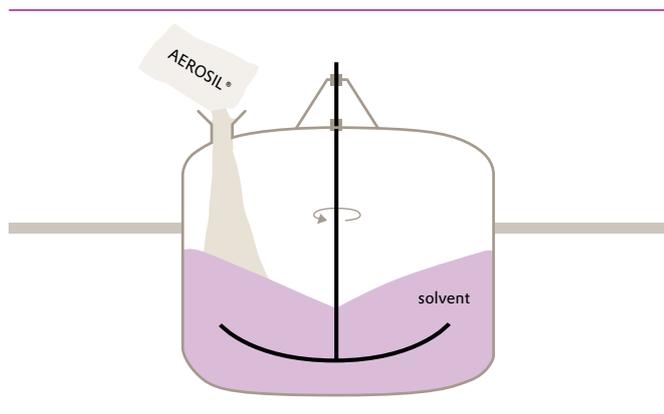
Electronic systems can suffer interference inter alia by gas discharges of static electricity. In electronic components this can lead to premature damage, with the consequence of reduced lifetime or total destruction. At times, damage to the software (program disruptions) may also result. As silica tends to induce high electrostatic charges causing equivalent gas discharges, electronic equipment used in this area should always be shielded and grounded. Notebooks, for example, may be interrupted in operation when used by an electrostatically charged person or in the vicinity of a highly charged object.

7.4 Static electricity on persons when handling AEROSIL® and performance silica

In electrostatic aspects the human body is electrically conducting. If insulated to ground by means of non-conducting footwear it resembles a capacitance to the environment of 100 to 200 pF and may become charged. On cold winter days in heated rooms, everyone is aware of this annoying phenomenon when getting up from a chair and then touching a grounded part, e.g. a door knob. The threshold of perception of these sparks depends on the physiological characteristics of the individual and begins at about 2 kV. The maximum voltage on insulated persons was found to be about 15 kV when removing an outer garment, e.g. a pullover. The energy of resulting sparks amounts to 0.4 mJ when they are just perceptible and will rise up to 20 mJ at the maximum voltage mentioned above. Considering that the minimum ignition energy (MIE) of various combustible vapor/air mixtures is only 0.2 to 0.3 mJ, precautions against incendiary sparks may be necessary even before they become perceptible.

Up to now, experience has shown that there is hardly any danger of ignition of dust/air mixtures by static electricity discharges from persons because the minimum ignition energy for most combustible dusts is much higher than that for gases and vapors. As long as no extremely incendiary dusts are present, it is not necessary to dissipate charge from persons from a plant safety standpoint. Despite this, shocks to the body caused by static electricity are, generally, regarded as being no more than a nuisance. Nevertheless, measures for charge dissipation are recommended when human beings are often aggravated by such shocks.

Figure 26 Feeding AEROSIL® into an agitated vessel

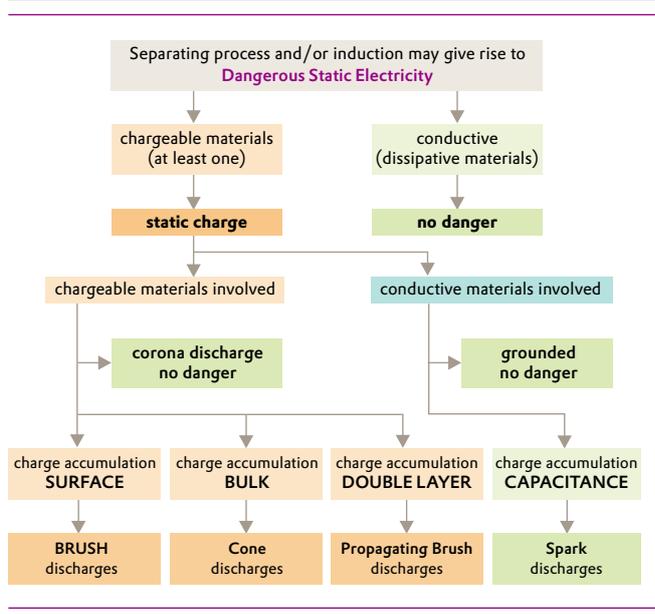


For the application of AEROSIL®, Figure 26 shows a typical procedure: an agitated vessel is partly filled with an intermediate paint solution forming an explosive atmosphere inside the vessel and around the manhole. AEROSIL® is fed in manually out of a bag via a metal funnel. AEROSIL® becomes charged when flowing out of the bag leaving behind charge of opposite polarity on the bag and the operative.

In principle the electric field arising from the product fed in may cause brush discharges in the vessel. Therefore it should be poured slowly to keep the charge density low. The same applies to charged bulk material being conveyed by a conductive and grounded feeding pipe into the vessel and set free there. The field strength arising from the charged product may cause incendiary brush discharges at conductive parts in an exposed position (e.g. a filling level probe). Experience shows that conveying with diaphragm pumps may also give rise to brush discharges and thus to ignition danger for flammable gas or vapor atmospheres. When filling larger amounts of product by means of gravity this danger also has to be taken into consideration.

In all these cases, inerting the vessel is a recommended safety measure. The required limiting oxygen concentrations are, for example, about 10% by volume for hydrocarbon gases.

Figure 27 Scheme for systematic hazard assessment



Outside the agitator vessel, measures for preventing electrostatic ignition dangers are also compulsory if explosive atmosphere is present (Zone 1): The funnel may become charged by the passing silica and has to be grounded permanently. A countercharge remaining on the bag will be transferred to the operative by contact or induction, electrostatically charging the person, unless the charge is being dissipated via conductive shoes and a grounded stand.

It is not realistic to assume that all conceivable possibilities for electrostatic charging of persons could be prevented. To ensure sufficiently fast charge dissipation from persons, which means a time less than 0.1 s, is the best way to resolve this problem. That demands a maximum value for the resistance to ground via socks, shoes and floor of 100 MΩ ensuring safe dissipation of static electricity in all situations. In terms of electrical engineering this resistance value represents an excellent electrical insulation. Nevertheless, it is absolutely sufficient for a safe charge dissipation from persons. It will be achieved by using correspondingly conductive materials for soles and flooring. Concerning the socks there are no further demands because, as experience shows, sufficient conductivity is already achieved when wearing them for a few minutes.

Charge dissipation in this way cannot be achieved when sitting at work. Grounding the wrist (bracelet with a cable) will fit the bill. To avoid danger of death from the mains in case of a fault, it is mandatory to provide this "bracelet grounding" with a protective resistor of 1 MΩ.

7.5 Electrostatic properties of floors

One of the most important measures to dissipate electrostatic charges is conductive flooring. In terms of their dissipating properties the following definitions are given according to IEC 1340-4-1 (VDE 0303 part 83):

- Electrostatically conductive floor (ECF): resistance to ground $< 1 \text{ M}\Omega$.
- Dissipative floor (DIF): resistance to ground between $1 \text{ M}\Omega$ and $1 \text{ G}\Omega$.
- Astatic floor (ASF): a person walking on this floor must not be electrostatically charged higher than 2 kV.

The relevant testing procedures are also given in this standard. The dissipative qualities of the floor always depend on the conductivity of the floor covering and the flooring plaster. The influence of the latter decreases with the increase of the flooring area because, on the one hand, a large area reduces the total resistance to ground of a conductive floor covering; on the other hand, the capacitance of this covering to ground increases accordingly. Both effects counteract a possible rise of potential. Therefore, additional grounding measures like incorporated grounded metal strips are not necessary in areas $> 10 \text{ m}^2$. In order to keep the abovementioned properties effective, floors should not be covered by rubber mats or plastic sheets etc. and care should be taken to prevent the build-up of contaminants such as resin or other non-conductive substances.

Floor coverings of concrete, as well as of artificial stone made of cement mortar, are permanently electrostatically dissipative. The reason is that hardened concrete and mortar continue to hold sufficient latent water, so-called crystalline water, causing conductivity which enables dissipation of electrostatic charges.

Floor coverings of ceramics, e. g. fired tiles, are in general considered not dissipative since ceramics are known for their excellent insulation properties. Ceramic floors could only be made capable of dissipating charge by additional moistening, e. g. by frequent wet cleaning. Correspondingly, when measuring the resistance to ground it has to be taken into account that any moistening of the probe area for better contacting would distort the results. Recently, "semi-conducting" tiles have become available, which show dissipative properties regardless of their moisture content.

Floor coverings of synthetic resin in general are not capable of dissipating electrostatic charges. However, when producing the flooring material it is relatively easy to work in fine granular conductive substances (e. g. graphite, carbon black etc.) thus rendering it sufficiently conductive.

At thin insulating layers of resin on a conductive base the principle of "high voltage perforation" has given satisfactory results for charge dissipation.

7.6 Static eliminators

If the interfering effects of an electrostatic charge are limited only to a few areas in the manufacturing process, it may sometimes be appropriate not to take general measures to avoid these charges, but only to eliminate them where they cause interference. Since, by definition, insulating material is unable to conduct electricity, no charge dissipation is to be expected from an electrical contact to ground. Only one possibility remains: making the surrounding air sufficiently conductive by means of ionization. The neutralizers used for that may be subdivided into

- active neutralizers: electrical neutralizers with high voltage connection
- passive neutralizers: inductive neutralizers with connection to ground

7.6.1 Electrical neutralizers with high voltage connection

The most appropriate way of ionizing the air is an electrical neutralizer that is a line-powered high voltage device. It consists of needle points mounted on a rod and coupled either by capacitance or resistance to an AC high voltage power supply (ca. 5 to 8 kV). When switching on the AC supply the air molecules around the points become positively and negatively charged alternately in phase with the power supply, so enabling the neutralization of either positively or negatively charged insulators.

Because there is a high rate of recombination of the positive and negative gas ions their lifetimes are only a few milliseconds. To avoid losing the discharging effect by this means the points need to be located at a distance of not more than about 100 mm from the charged surface. As negative coronas begin at a little lower potential on the points than do positive ones, a surplus of negative charge has to be expected when using AC powered neutralizers. However, high voltage neutralizers also show disadvantages which must be considered: they produce ozone, which needs to be controlled by venting, and if there is a malfunction they may cause incendiary spark discharges to explosive atmospheres.

7.6.2 Inductive neutralizers with connection to ground

The advantage of these neutralizers in comparison with the high voltage neutralizers is that they do not represent an ignition source for explosive atmospheres. Their efficiency is based on the fact that the electrical field strength will increase on a grounded needlepoint (see 5.2). Electrostatically charged insulating parts bring about an electric field, which by itself causes the release of ions of opposite polarity when approaching grounded needlepoints. In this way charge compensation will be achieved, just as with high voltage neutralizers. Still, there is a disadvantage: their efficiency begins only above an initiation field strength of about 300 kV/m. This means that they can reduce the unwanted charge only from a high to a low level without eliminating it altogether. If this is all that is required then passive neutralizers are the best choice for the job.

Passive neutralizers should take priority over active ones because they are much less expensive and do not need any electrical installation except grounding. Their advantages are: no electrical shock will occur to personnel when touching them, no ignition danger will arise as already mentioned, operation is almost maintenance free, and—with some skill—they can easily be constructed by the user.

7.7 Interferences caused by electrostatic forces

Electrostatic charge manifests itself in a field of force which is not perceivable immediately through our senses. This electrical field is a phenomenon analogous to the gravitation field.

Charges with similar polarities repel each other, charges with opposite polarities mutually attract each other. In general, forces lead to motions, as far as the relevant parts are moveable. Considering gas discharges (see Chapter 5) the charge-carrying electrodes are fixed and the gas molecules are moveable. Impact ionization is the result. In case of electrostatic interferences, electrical forces will work preferably on charged parts which are moveable. The following examples will illustrate this interrelation:

- Plastic sheeting will cling to the storage roll when being separated (attraction caused by opposite charge polarities).
- Sheeting sections will mutually repel themselves when being stacked up after the printing process (repulsion of similar charge polarities).
- Plastic parts, charged e. g. by injection molding, will attract airborne dust particles, and become soiled.
- Small particles of bulk materials being transferred will cling to the walls of the apparatus and pipes.

In general, it may be said that the resulting forces, originating from interferences due to electrostatic charges, will become effective where the charged object is released from the compulsory guideway of a processing machine.

All these forces obey Coulomb's law, the essential statement of which is that the magnitude of the force between two electrical charges depends on the magnitudes of the charges themselves and on their spatial separation. The magnitude of the force is given by the inverse square law.

Here is a chance to diminish disturbing clinging effects caused by static electrification: it will be achieved by depositing extremely small particles in the range of micrometers or, respectively, nanometers (e. g. AEROSIL® or performance silica) to the surfaces of the charged materials. In this way the distances between charged surfaces will be enlarged, thus reducing the Coulomb forces of attraction. Thus agglomerations can be avoided between the particles of bulk materials, resulting in better flow properties and making grinding, pulverizing and sieving easier.

This effect of "range spacing" also causes a decrease in the interfacial area of contact (section 3.1), significantly reducing static charging of materials. This process, based only on mechanical effects, is also termed "astatic" and differs from the so-called "antistatic agents" which preferably work by chemical effects causing an increase of conductance at the surfaces of materials.

8 Basic concepts and units

8.1 Charge

Symbol Q

Units: ampere second (As) = coulomb (C)

Comment:

- Charges may have a positive or a negative sign.
- Charges give rise to electric fields.
- Charges exert forces on one another in accordance with Coulomb's law. The force is proportional to the inverse of the square of the distance between the charges and to the product of the charges.
- Charges can neither be created nor destroyed in a self-contained system (Law of the conservation of energy).
- The smallest charge e is that on the electron where $e = 1.6 \cdot 10^{-19} \text{ C}$.

Practical examples:

- A person of capacitance 200 pF and a potential of 10 kV carries a charge of 2 μC .
- The charge on pneumatically conveyed fine dusts can reach 1 mC/kg.
- A 100 watt light bulb at 230 V passes a charge of about 0.4 C every second.

8.1.1 Surface charge density

Symbol σ

Units: C/m²

Comment:

- There is a limit to the density of charge on a solid surface. Under normal atmospheric conditions the maximum charge density is 26 $\mu\text{C}/\text{m}^2$.

8.1.2 Volume charge density

Symbol ρ

Units: C/m³

8.2 Potential

Symbol Φ

Units: volt (V) = joule/coulomb

Comment:

- The potential at a point in space is defined as the work required to bring a unit charge from infinity or ground up to the point.

8.3 Voltage

Symbol U

Units: volt = v

Comment:

- The potential difference between any two electrically conducting points in space is the voltage U . As long as the voltage specified is for one point in space, either ground or infinity are taken as being at zero potential.

Practical examples:

- The contact potentials between different materials are of the order of mV.
- When taking off a pullover the potential on a person insulated from ground may reach 15 kV.
- A Van de Graaf generator produces potentials of about 100 kV relative to ground.

8.4 Field strength

Symbol E

Units: V/m

Comment:

- An electric field is produced by electric charges.
- The direction of the fields is out of a positive charge and into a negative charge.
- As electric fields can be superimposed according to the principle of superposition, they must be added vectorially. Any inhomogeneities in a material cause changes in the field strength.
- Field strengths of 3 MV/m, under normal atmospheric conditions, give rise to spontaneous gas discharges.

8.5 Current intensity (current)

Symbol I

Units: ampere = A

Comment:

- Current intensity is the amount of charge flowing through a cross section of material per unit time.
- The direction of the current is the same as that of the moving positive charges.

Practical examples:

- A Van de Graaf generator produces a current of about 20 μA .
- Charging currents produced by manual procedures in industry are usually less than 1 μA .
- Currents of up to 50 μA may be reached during the pneumatic conveying of materials.

8.6 Resistance

Symbol R

Units: volt/ampere = ohm [Ω]

Comment:

- For many materials, e. g. metals, the resistance is independent of the applied voltage, i. e. they obey Ohm's law. However, the resistances of poor conductors and of non-conductors can be strongly dependent on the applied voltage.
- When measuring resistance the appropriate standard test method should be used.

8.6.1 Volume resistivity

Symbol ρ

Units: Ωm

Comment:

The volume resistivity of a material is calculated by multiplying the measured resistance by the ratio of the area of the electrodes to the distance between them.

8.6.2 Surface resistivity

Symbol σ

Units: Ω

Comment:

The surface resistivity of a material is calculated by multiplying the measured resistance by the ratio of the length of the electrodes to the distance between them. It is equivalent to the resistance between opposite edges of a square of the material and is independent of the size of the square.

8.7 Permittivity (free space)

Symbol ϵ_0

Numerical value and units:
 $8.85 \text{ pF/m} = 8.85 \text{ pAs/V/m}$

Comment:

The permittivity of free space ϵ_0 is related to the permittivity ϵ of a dielectric and its relative permittivity ϵ_r (dielectric constant) by the following equation:

$$\epsilon = \epsilon_0 \cdot \epsilon_r$$

8.8 Capacitance

Symbol C

Units: coulomb/volt = farad (F)

Comment:

- Any two electrical conductors which are isolated from each other form a capacitor. Its capacitance C is given by the ratio of the charge Q on either conductor and the potential difference U between the conductors.
- Capacitance is a measure of the ability of a capacitor to store charges, as expressed in the equation $Q = CU$. For a parallel plate capacitor the capacitance depends on the area A of the plates and the distance d between them. If there is a dielectric (polarizable) material between the plates of the capacitor, the capacitance increases proportionally with the relative permittivity of the dielectric.
- The rate of charging or charge dissipation of a capacitor C through a resistor R is exponential with time. The product $RC = \tau$ is called the relaxation time or the time constant of the circuit, i. e. the time taken for the capacitor to charge up to 0.63 U or for it to discharge down to 0.37 U.
- The electrical energy W of the charge stored on a capacitor is determined by the equation $W = 0.5 CU^2$ watt-second (joule).

Practical examples:

- Person wearing insulated shoes 100 - 200 pF
- Metal drum placed on an insulating support 200 - 400 pF
- Metal flange on plastic or glass tubes 10 - 30 pF
- Vehicle with insulating tires 500 - 1000 pF

8.9 Decimal Notation (DIN 1301)

Notation	Sign	Factor	Notation	Sign	Factor
femto	f	10^{-15}	kilo	k	10^3
pico	p	10^{-12}	mega	M	10^6
nano	n	10^{-9}	giga	G	10^9
micro	μ	10^{-6}	tera	T	10^{12}
milli	m	10^{-3}	peta	P	10^{15}
I	-	10^0			

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