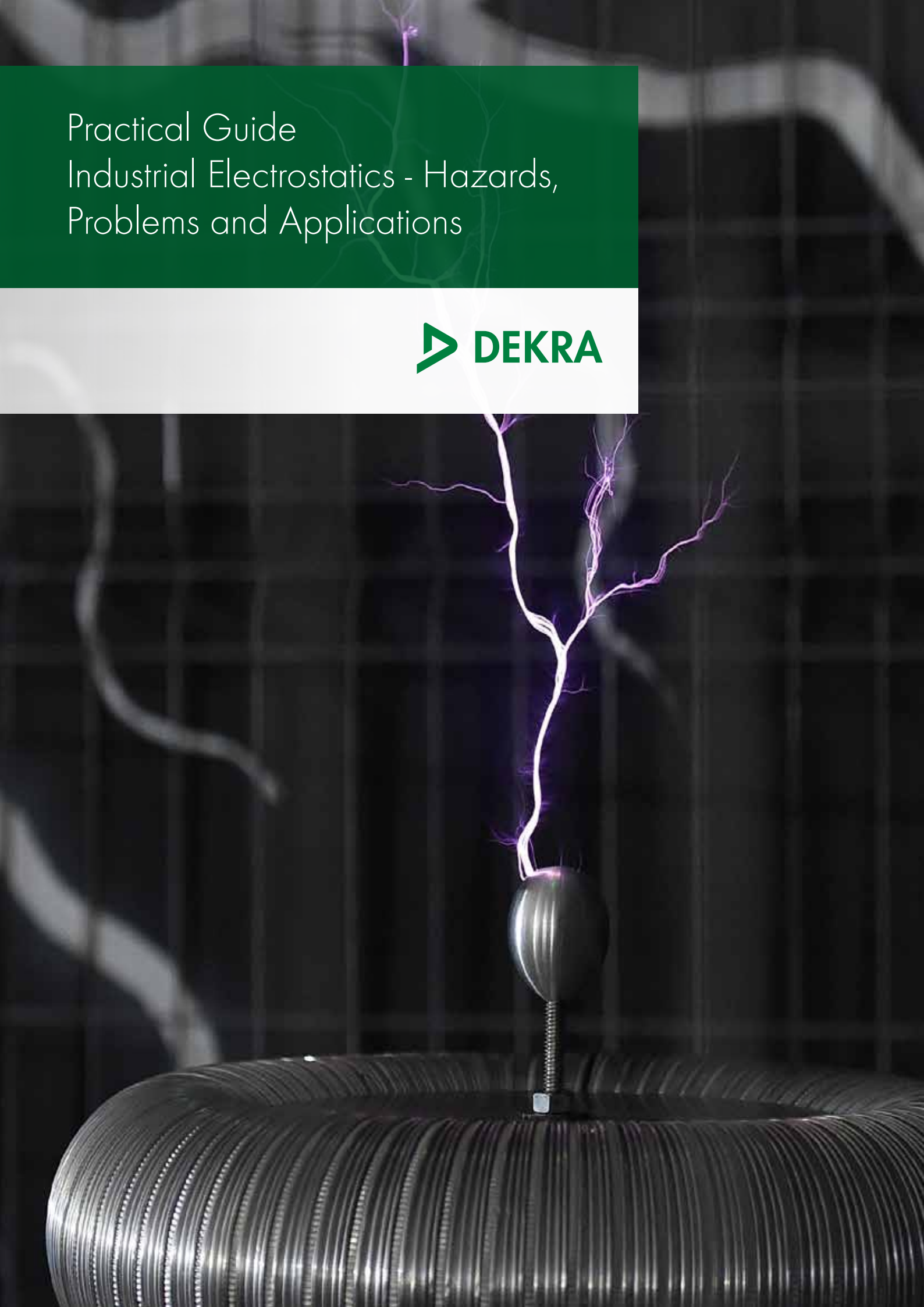
Practical Guide
Industrial Electrostatics - Hazards, Problems and Applications

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About the Author

Ian Pavey M.Phil, BSc (hons), M.Inst.P, C.Phys, A.M.I.Chem.E, graduated from Bath University with a BSc in Chemical Engineering. After acquiring practical experience of electrostatic hazards while working as a process development engineer, he gained an M.Phil. in Applied Electrostatics at the University of Southampton. Thereafter he specialised in electrostatic applications, problems and hazards. Ian worked for ICI for 11 years on projects involving electrostatic applications research and development. Now Ian is Principal Electrostatics Specialist at DEKRA Process Safety (formerly Chilworth Technology).

Whilst at DEKRA Insight, Ian has been responsible for a variety of problem solving and research projects where electrostatics is involved. These have included powder and liquid handling problems and applications. Ian has led multinational research projects under EC Framework programmes, including one investigating powder handling and processing problems caused by static electricity in industrial processes, and one aimed at developing new tests for anti-static footwear. In addition Ian has more than 20 years' experience of fire and explosion hazard assessment, investigation and training.

During his career spanning more than 30 years Ian has published numerous articles covering subjects from new electrostatic applications to powder handling problems to fundamental research leading to new understanding of hazardous situations. In addition, he is a named inventor on a number of patents in areas from electrostatic sprays for agricultural purposes to electrostatic fibre production for liquid crystal displays.
Ian is a member of: the Institute of Physics' Electrostatics Group (and a committee member); the Institution of Chemical Engineers' Safety and Loss Prevention Group; British Standards GEL 101 committee (the UK shadow for the International Electrotechnical Commission's Technical Committee on electrostatics); the Electrostatics Society of America and; the Electrostatic Discharge Association.

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1. Introduction

1.1 Everyday experience of static electricity

Electrostatic effects were originally observed by the Greeks more than 2500 years ago when it was discovered that amber which had been rubbed with a silk cloth would attract small particles. Indeed, no other form of electricity was studied until 1800 and the introduction of Volta's wet cell. The wet cell provided the first means of producing high electrical currents with only low voltages, and it was this combination which ultimately led to the full range of electrical equipment that is now considered essential to the modern way of life throughout the world.

There is no doubt that with the growth of electromagnetics, in which the effect of electric current is predominant, interest in electrostatics waned somewhat. However, as work in electromagnetics and electronics eventually led to repeatable and reliable sources of high voltage, interest in electrostatics enjoyed a revival. So it was that details of the first significant application of electrostatics were published in 1906 when the electrostatic precipitator was patented by Cottrell. Electrostatic precipitators continue to be used today to reduce particulates in industrial exhaust gases, and in the intervening period many other applications have also been found. However, it is probably fair to say that for the most part the contribution of static electricity to the operation of these often widely used applications is largely hidden from the general public.

One electrostatic phenomenon that has never left people's minds is lightning. Also, as insulating materials have been more commonly used in domestic and industrial products, people have become familiar with the small shocks that for most are the only direct experience of static electricity. These shocks, like those sometimes received when getting out of a car and shutting the door, or when pushing a supermarket trolley, might be considered annoying and sometimes even unpleasant. However, few would go so far as to suggest they are dangerous, and few are aware of the cost to industry in both human and financial terms of such seemingly benign phenomena.

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1.2 Why static is so important

The reason that electrostatic phenomena are so important to industry can be set under three headings: hazards, problems and applications. This Guide will address each of these in turn.

As will be seen, there is no doubt that, one way or another, static electricity has an often critical role to play across the whole breadth of industry and beyond.

1.2.1 Hazards

The greatest and most common hazard resulting from static electricity arises because the small sparks that are simply annoying in our everyday world can easily ignite many flammable materials that are found in industry. Indeed, even sparks that are far too small to be felt by people can readily ignite many of the most common industrial substances. Hence static in many industrial environments can and does lead to fires and explosions causing injury and even death to people, destruction of plant, and loss of business. Clearly reducing the risk of such incidents occurring makes good business sense. However, when people are in danger of being hurt there is also a moral and ethical obligation to ensure so far as is possible that such risks are kept to an acceptably low level.

Of course, where there is such a real risk, legislation aimed at controlling it usually follows. In Europe this is embodied in the European Community's ATEX Directive 1999/92/EC, which is also adopted into the local legislation of all EC countries. This addresses the protection of personnel potentially at risk from explosive atmospheres, by requiring that companies handling or processing flammable materials must undertake a risk assessment. This identifies methods of controlling the risk to an acceptable level.

This legislation even describes the prioritised approach that must be taken:

i). Minimise the risk of a hazardous flammable mixture arising.
ii). If the overall risk to personnel cannot be adequately controlled by the above, avoid ignition sources, including those arising from static electricity.
iii). If the overall risk to personnel cannot be adequately reduced by i) and ii), protective measures must be in place such that when an explosion occurs personnel will not be harmed.

It is interesting to note that although there are many potential sources of ignition that must all be controlled in Item ii), such is the importance attached to the ignition hazard of static electricity that it is the only source of ignition explicitly mentioned in the European Directive and the national legislation deriving from it.

This same general approach can also be seen in many other parts of the world, and it would be true to say there is now no industrialised country where the ignition hazard arising from unwanted static electricity can be legitimately disregarded.

1.2.2 Problems



Although static electricity clearly presents a very real hazard as a result of its ability to ignite flammable mixtures, it can also lead to a number of other problems where there is no risk to life or property but there are still very real business issues.

Product damage as a result of static electricity can range from the complete destruction of integrated circuits, to poor surface finishes as a result of dust attraction.

Even if there is no product loss or reduction of quality, static causing powders to not flow properly, or to stick where they should not, are just two problems which can lead to significant loss of productivity.

Hence, static can lead to reduced profits, and sometimes in ways which are so subtle that they are not even recognised until somebody experienced in static electricity points it out.

1.2.3 Applications

Aside from the electrostatic precipitator mentioned earlier, practical applications of static electricity include photocopiers, laser printers, ink jet printers, surface coating technology, microphones, filtration and many others. Clearly, some of these applications are so widely used that without them life in the office, in industry and at home would be very different for many. What is more, many applications are continually under development with a certainty that there will be more to come.

2. Basic Principles

2.1 What is static electricity?

Charge is intrinsic to all materials, in that atoms comprise both positively charged protons and negatively charged electrons. When the positive charges exactly balance the negative charges, the material is said to be uncharged or neutral and, at least at a macroscopic level, it exhibits no effect due to charge. If, for whatever reason, the material acquires an excess of negatively charged electrons, it is said to be negatively charged. Conversely, if it loses some electrons it is said to be positively charged. Whether an object is positively or negatively charged, is referred to as its polarity.

Most electrical equipment that we come across, from cookers to computers, and from torches to televisions, whether they are powered by mains electricity, batteries, or other sources, work because of the effects that arise from moving charge from one place to another through a variety of different materials. That is, their operation depends on electric current – the movement of charge. On the other hand, the effects of static electricity are primarily those due to stationery charges – hence the term "static". That is not to say that there is no movement of charge in static electricity; simply that charge movement is not the cause of the main effects.

2.2 How is static charge generated?

If electrostatic hazards are to be assessed and controlled, or if the effects of static charge are to be harnessed, it is important to understand how it is generated. Indeed, a major part of the assessment of static hazards is reviewing what charging mechanisms may actually be occurring, which presupposes at least a basic understanding of the mechanisms. In common industrial situations there are four basic ways by which static charge may be acquired. Each is dealt with in this section.

2.2.1 Tribocharging

Tribocharging (rubbing) is perhaps the most common way in which charge is acquired accidentally, and the one that most people are aware of. Whenever two dissimilar materials contact one another, electrons will have a greater affinity for one material than the other, and some will move across the interface. If both materials are good conductors, when they are separated, the exchanged charge will flow back by conduction through the last point of contact, and there will be no evidence of the exchange of charge that took place.

If one or both of the materials are insulating the exchanged charge will not be able to flow back by conduction and one material will become positively charged and the other negatively charged. In this context, what is meant by the term "insulating" depends on how quickly the two materials are separated. If a moderately conducting material is separated from a good conductor slowly, the charge will have plenty of time to flow back, the separated materials will carry no charge and both materials will be deemed good conductors in this situation. However, if the same moderately conducting material is separated very quickly from the same good conductor there may be insufficient time for the charge to flow back. In this case the materials will carry away charge and one will be deemed to be an insulator in the new situation.

Which direction electrons move across an interface depends on the relative surface energies of the two materials, which means that a significant factor is their molecular structures. In general, therefore, it would be expected that if the same two materials were brought into contact with one another in any number of experiments in any number of locations, it would always be the same material that became positively charged. On this basis, lists of materials have prepared by various workers in which each material in the list charges positively with respect to the one below it. A list such as this is termed a "triboelectric series", and one is shown in Table 1, below.

Not only does reference to a series such as that given in Table 1 indicate the polarity of charging but, in a qualitative sense, it also indicates magnitude, since the further apart two materials are in the list the greater will be the amount of charge exchanged. However, triboelectric series must be used with caution, since it is the precise nature of the two contacting surfaces that matters. That means that nominally identical materials whose surfaces have been produced by different mechanisms (such as moulding or machining) may behave differently. Temperature differences can also lead to different behaviour. In some instances these effects have led to different orders of materials in triboelectric series produced by different workers. However, it also means that charge can be exchanged by nominally identical materials.

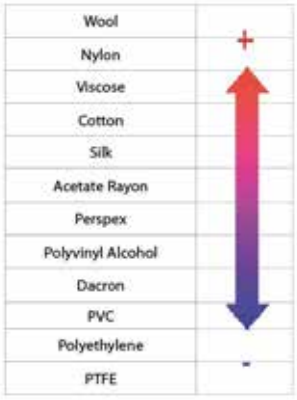


Table 1: Triboelectric Series

Impurities or other trace components are particularly important. It can be shown that a moderately charged polymer may actually only have one too many, or one too few, electrons for one in 109 (one in a billion) molecules. That means very low levels of impurity can have a very significant effect on tribocharging.

Finally, exchange of charge only occurs at a point of contact. At a microscopic level most surfaces that appear flat will only be in contact at a relatively few points. Thus, repeated contact, or sliding contact, significantly increases the opportunity for charge to be exchanged. Furthermore, the higher the velocity and pressure of the contact – the more violent or energetic the process – the higher will be the charge acquired, since this will lead to attrition or deformation of surfaces and hence more intimate contact. Just some of the processes that lead to tribocharging in industrial situations are: movement of powders and granules (by whatever means); conveyor belts, and; web handling. Clearly many other operations are also capable of generating charge in this way, and the higher the velocity, or the more violent the contact, the more charge is likely to be generated.

2.2.2 Streaming Currents

Insulating liquids flowing in pipes can become charged. The charge that a flowing liquid carries through a pipe is referred to as "streaming current". The larger the area of contact, and the higher the velocity, the higher will be the streaming current. If the liquid flows though fittings and filters the streaming current may increase very significantly as the effective contact area and velocity both increase.

Charging may occur at any liquid interface. Stirring or pumping a suspension or emulsion in which the continuous phase is an insulating liquid is a particularly effective way of generating charge, as one phase moves against the other. The basic way in which charge is exchanged at a liquid interface is much the same as for tribocharging of a solid, although the detailed mechanism for retaining the charge is somewhat different. When a liquid is in contact with a solid, such as a pipe wall, charge separation will occur such that one polarity is tightly bound to the interface, leaving the opposite charge distributed through a layer of liquid some distance away from the interface.

When the liquid is pumped through the pipe, the diffuse layer of charge will be carried along with the liquid, leaving behind the bound interfacial charge. The result is a tendency for flowing liquids to carry charge with the flow, such that the liquid emerging from the end of the pipe will be charged.

If the liquid is conducting, separation of the two charges will be mitigated by conduction back through the liquid, and no charging will be observed. However, charging of liquids can be a very significant effect for insulating liquids, and the charge carried along with the liquid flow is the "streaming current".

From the above description it can be seen that the larger the pipe diameter (or the greater the surface area of contact), and the higher the liquid velocity, the greater will be the streaming current. This can be seen in the equation for streaming current in a long pipe, given in BS5958:

$$I_{\infty} = K v^2 d^2 \qquad (1)$$

In Equation 1, I ∞ refers to the streaming current in microAmps (following transport in a long pipe), K is a constant and equal to 4 μA.s2.m^{-4}, v is the liquid velocity in metres per second and d the pipe diameter in metres.

A rearranged version of Equation 1 also appears in CLC/TR 50404:20032, and is shown here as Equation 2:

$$\rho_{\infty} = 5v \qquad (2)$$

In Equation 2 ρ ∞ is the charge density in the liquid after passage through a long pipe in μC.m-3 and v is the liquid velocity in metres per second. Both BS5958 and CLC/TR 50404:20032 define a long pipe as one in which:

$$L \geq 3v\tau \qquad (3)$$

in which L is the pipe length in metres, v the liquid velocity in metres per second, and τ the liquids charge relaxation time in seconds. In this case, charge relaxation time can be calculated as follows:

$$\tau = \frac{\varepsilon_r \varepsilon_0}{\gamma} \qquad (4)$$

where εr is the relative permittivity of the liquid (dimensionless), γ the liquid conductivity (Siemens per metre), ε0 and is the Electric Constant. The Electric Constant is one of the fundamental physical constants with units of Farads per metre (F.m-1). Its value is approximately 8.85 x 10^{-12} F.m^{-1}.

In fact, charge separation occurs at all liquid interfaces: liquid-solid, liquid-liquid and liquid-gas. It can therefore be appreciated that charging is particularly effective when any interface involves high surface areas. This includes a liquid being pumped through a filter, but even stirring a liquid containing a dispersed second phase (solid, liquid or gas) can generate a great deal of charge if it is not a good conductor.

2.2.3 Induction Charging

Objects can become charged simply by being in close proximity to another object that is already charged, by a process known as induction charging. For induction charging to occur, the materials involved must have finite conductivity although they certainly do not have to be good conductors in the normal sense. Consider the diagram in Figure 1 (a) over. An object is in the electric field developed between the positive and negative electrodes. Because the object has at least some degree of conductivity, charges within the object have been separated as a result of interaction with the field. However, at this point no net charge has been lost or gained by the object and if it were to be

removed from the electric field there would be no lasting evidence of what had happened.

However, if the object touches one electrode (and it does not matter which one), as in Figure 1 (b), because both the electrode and the object are sufficiently conducting, the charge separated to that side (negative, in the illustration) is conducted away through the electrode. Now when the object leaves the electrode system it carries away the residual charge – positive in the illustration of Figure 1(c). This whole process is known as induction charging.

Having discussed the basic concept of induction charging it is useful to consider some specific situations. The object became charged because of the initial charge separation induced by the electric field. There would be an electric field between the electrodes even if one of them was actually at earth potential and the other at a high voltage. It would still not matter which electrode the object touched – it could actually become charged

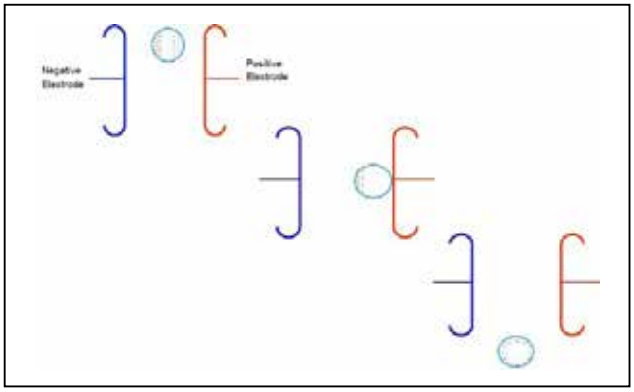


Figure 1: Induction Charging

by touching the earthed electrode.

An example of where this can happen in practice would be if a person walked past a highly charged plastic sheet. The conducting object is the person, the field is between the plastic sheet and the floor, and the person is in contact with the floor. The result will be the person acquiring charge of opposite polarity to that on the sheet.

A little thought will also show that an uncharged conductor acquiring charge by contact with a charged conductor, although sometimes referred to as charge sharing, or contact charging, is actually just a special case of induction charging. Qualitatively it can readily be appreciated that the magnitude of charge acquired in induction charging depends on the field strength, the conductivity of both objects that contact one another and the duration of contact.

2.2.4 Corona Charging

Corona is a type of electrostatic discharge, and as such the mechanism is described in detail in the section dealing with discharges. For the purposes of this section it is sufficient to note that corona occurs from sharp points in electric fields, which results in a stream of positive or negative ions moving away from the point. Any object, conducting or insulating, which intercepts this ion stream will capture ions. If the object is an earthed conductor the acquired charge will be very quickly lost, but otherwise the object will be left with a net positive or negative charge, depending on the polarity of the corona. Alternatively, if the sharp point is in a high electric field and is part of an electrically isolated conducting object, the entire object can be left with a net charge due to the loss of charge.

Although not the most common means of acquiring charge accidentally, when it is realised that the necessary sharp points can simply be corners, or even hairs or fibres, it is clear that inadvertent charge acquisition by this process is quite feasible.

2.3 Effects of static electricity and some important parameters

Just as a magnet is attracted towards the opposite pole of another magnet, opposite polarity charges (positive and negative) are attracted towards one another. Similarly, just as a magnetic north pole will repel another north pole, and a south pole repel a south pole, so a negative charge will repel another negative charge, and a positive charge repel another positive.

It is this attractive or repulsive force that causes most of the nuisance effects of static electricity such as powders sticking where they should not and not going where they should, or plastic films being difficult to handle because they are strongly attracted towards surfaces. The force of attraction or repulsion between two charges is given by the equation

$$F = \frac{q\,q'}{4\pi\varepsilon_0 d^2} \qquad (5)$$

where F is the force in Newtons (N), q and q' the magnitude of the two charges, ε0 the Electric Constant ($F.m^{-1}$) and d the distance between the two charges (m).

This leads very nicely to an initial discussion of some of the important variables in static electricity and which appear in Equation 5. Others will be covered as they arise.

2.3.1 Charge

The fundamental sub-atomic charged entity is the electron, which carries one fundamental negative charge. As already explained, negatively charged materials include atoms or molecules that have an excess of electrons, while positively charged materials have too few. The unit of charge, the Coulomb, can be related directly to an actual number of electrons. One Coulomb is approximately equal to 6.24×10^{18} electrons.

ε0 is the Electric Constant (sometimes referred to as the permittivity of free space). It is one of the fundamental physical constants and has units of Farads per metre ($F.m^{-1}$). Its value is approximately 8.85 x 10-12 $F.m^{-1}$. d is the distance between the two charges in metres (m). Since it appears on the right hand side of the equation as an inverse square term, it is clear that the force between two charges (attraction or repulsion) increases very steeply as they get closer together. It is for this reason that charged fine powders or thin films stick so well.

2.3.2 Electric Field

When forces act over a distance it is often convenient to define a "field" – in this case an electric field. Equation 5 can then be rewritten as:

$$F = q\,E \qquad (6)$$

where E is the electric field due to the charge q'. The units of electric field are Volts per metre ($V.m^{-1}$). By comparing Equations 5 and 6 it is clear that the electric fie ld due to the charge q' is given by:

$$E = \frac{q'}{4\pi\varepsilon_0 d^2} \qquad (7)$$

2.3.3 Potential

When two like charges are pushed together against the force of repulsion, or if two opposite charges are pulled apart against the force of attraction, it is clear that energy is being put into the system. If released, the opposite charges will accelerate towards each other and the like charges away from each other: clearly recoverable potential energy was put into the system. It is useful to express this potential energy as a specific quantity: Joules per Coulomb ($J.C^{-1}$).

However, in electrical terminology, this specific potential energy is given its own variable name: the Volt. Strictly the Volt is a measure of a difference in potential energy as charge is moved from one place to another, though it is often treated as an absolute value by setting earth potential as zero. In the light of this description, Electric Field may now be seen as equivalent to potential gradient which would lead to the same qualitative conclusion as given in Equation 6: the higher the electric field the greater the accelerating force on any charge residing within it.

2.3.4 Capacitance

Capacitance is, in effect, a measure of the ability of an object to hold charge. Although the concept of capacitance has not arisen from the foregoing equation and discussion, as it defines the relationship between charge and potential it is appropriate to introduce it here.

It has already been shown that as like charges are forced together the electrical potential increases. However, the electrical potential (potential energy per unit charge) will also depend on exactly where these charges are forced together relative to any other charges, or even relative to the defined zero potential energy associated with a conducting object connected to earth.

The effect of capacitance can be presented as an equation:

$$V = \frac{Q}{C} \qquad (8)$$

where V is the electrical potential obtained (in Volts) when an object of capacitance C (in Farads) contains a total charge, Q (in Coulombs). If the relationship given in Equation 8 is difficult to grasp, an analogy may be helpful. If gas is forced into a container, potential energy may have to be put into the system such that the gas acquires a particular pressure. If the same amount of gas is forced into a smaller container, more energy per unit mass of gas

will have to be applied and the resulting pressure will be higher. Similarly, Equation 8 shows that if the same amount of charge is "forced into" items of increasingly small capacitance, the resulting voltage will be increasingly high. For a conductor on which the location of charges relative to another location can be well defined the capacitance can easily be calculated. Such a conductor would be a flat plate parallel to a second flat plate, as illustrated in Figure 2.

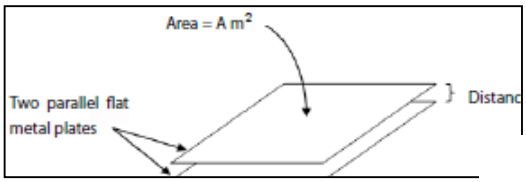


Figure 2: Simple Flat Plate Capacitor

The capacitance of this arrangement (in Farads) is given by:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \qquad (9)$$

where A is the area of the facing surfaces (m2), d the distance between the two plates (m), ε0 the Electric Constant (8.85 x 10^{-12} $F.m^{-1}$), and εγ is the relative permittivity (also known as the dielectric constant) of the material filling the gap between the two plates. Relative permittivity is dimensionless and very close to 1 for air. It effectively indicates the ability of the material to maintain an electric field and might be seen as a measure of polarisability of the molecules. From this, it is clear that the capacitance of a conductor depends on both its physical size and its location. Hence, for most real objects capacitance will be very difficult to calculate and will vary depending on exactly where they are relative to other objects.

However, capacitance can be measured and some typical values for real objects are given in published standards and guidelines, such as CLC/TR 50404:2003. Some of these are shown in Table 2:

Object	Capacitance (pF)
Small metal items (e.g. scoop, hose nozzle, etc)	10-20
Small containers (e.g. buckets, 50 litre drum)	10-100
Medium containers (e.g. 250 litre to 500 litre drums)	50-300
Major plant items (e.g. reaction vessels)	100-1000
Human body	100-300

Table 2: Typical Capacitance Values

2.4 Charge Dissipation

If parts of an object are at different potentials (voltages) charge will always try to move from the high potential to the low potential, only stopping when there is no potential difference across the object. How quickly this happens will depend on how difficult it is for charges to move through the object or across its surface. The property of the object which quantifies this difficulty is its resistance, and the mathematical relationship which defines what has just been explained in words can be seen in Equation 10:

$$\frac{dq}{dt} = \frac{V}{R} \qquad (10)$$

where dq/dt is the rate of charge transfer with respect to time, V is the potential difference across the object (V) and R its resistance in Ohms (often represented as Ω). The rate of charge transfer is referred to as electrical current, so Equation 10 can be rewritten as:

$$i = \frac{V}{R} \qquad (11)$$

where i is electrical current in Amps. This, of course, is the familiar expression known as Ohm's Law. Sometimes the property of an object which controls movement of charge is referred to not from the seemingly "negative" viewpoint of "resistance" but by reference to conductance – the ability to carry or transfer electric charge. Conductance is the reciprocal of resistance, so Equation 11 can be rewritten as:

$$i = VG \qquad (12)$$

where G is the object's conductance in Siemens. Older texts sometimes give the units of conductance as the mho (Ohm written backwards), though the correct SI unit is the numerically identical Siemen. The resistance or conductance of objects leads to specific properties of the materials from which they are made, and this is the subject of the next subsections.

2.4.1 Volume Resistivity

For an object of simple geometry such as a cuboid, in which the cross section for conduction is constant between two electrodes in contact with opposite parallel faces, the resistance is given by:

$$R = \rho_v \frac{d}{A} \qquad (13)$$

in which R is the resistance in Ohms (Ω)), d is the distance between the two electrodes in metres, and A the cross sectional area for conduction in square metres. The constant of proportionality, ρv is the volume resistivity of the material from which the object is made in Ohm-metres (Ω.m). Volume resistivity is therefore a fundamental, geometry-independent property, of a material, indicating its ability to transfer charge through itself. Volume resistivity is commonly used for solids and also powders. In the latter case, the bulked powder is treated as a solid in its own right, so the volume resistivity of a powder

may not be the same as the volume resistivity of the solid from which the powder was made.

For reasons which will be discussed shortly, volume resistivity of a powder is often particularly affected by relative humidity. Hence, it is especially important to measure the resistivity of a powder at known and controlled humidities after first conditioning at the desired humidity.

2.4.2 Conductivity

The conductance of the same object as discussed above can be written as:

$$G = \sigma \frac{A}{d} \qquad (14)$$

in which G is the conductance in Siemens (S), and d and A are as previously defined. Now, the constant of proportionality, σ is the conductivity in Siemens per metre (S.m-1) of the material from which the object is made. Conductivity is therefore a fundamental, geometry-independent property of a material, indicating its ability to transfer charge through itself, and every bit as valid as volume resistivity, as described above. However, in practical electrostatics, for reason only of convention, the term "conductivity" is almost exclusively used for liquids.

2.4.3 Surface Resistivity

For materials in which the volume resistivity is very high, conduction will often take place preferentially across the surface. This is because the surface may have acquired contaminants, which at its simplest could be extremely small quantities of water adsorbed from the atmosphere. Nevertheless, for this reason it is often useful to also refer to surface resistivity.

For a simple geometry the resistance across the surface of a material between two parallel linear electrodes in contact with it is given by:

$$R = \rho_s \frac{d}{w} \qquad (15)$$

in which R is the resistance in Ohms, d the distance between the two electrodes in metres and w the width for conduction, also in metres. Now the constant of proportionality, ρs is the surface resistivity. The unit of surface resistivity is the Ohm, though it is often given as Ohms per square (Ω/□) to avoid confusing this specific property of a material with the geometry-dependent resistance of an object. From the brief discussion above, it will be clear that surface resistivity will often be significantly affected by relative humidity, and must therefore be measured at known and controlled humidities after first conditioning at the desired humidity.

A little thought will make it clear that for a powder made from a highly insulating material, the path for conduction through the bulked powder is probably going to be across its constituent particles' surfaces rather than through them. It is for this reason that it was earlier stated that powder resistivity should be determined under controlled humidity conditions, even though powders are bulked and treated as though they are solids when determining volume resistivity.

It sometimes comes as a surprise to learn that the amount of water adsorbed on a surface to significantly affect resistivity of highly insulating materials is very small. Indeed, it is likely to be less than a molecular monolayer,

2.4.4 Charge Decay Time

When people believe they have a problem with static, they do not necessarily want to know about resistivity. What they will generally be interested in is how quickly charge will be lost from something. Charge decay time provides a direct and useful indicator of this. In that sense, and at an intuitive level, charge decay time should be at the top of the Charge Dissipation section. However, to understand charge decay at a technical level requires an understanding of the concepts of capacitance, relative permittivity, resistance and resistivity; hence placing it at this point in the Guide.

Consider a simple two-plate capacitor in which the gap between the plates is filled with a material whose volume resistivity is ρv and relative permittivity, εγ as shown in Figure 3.

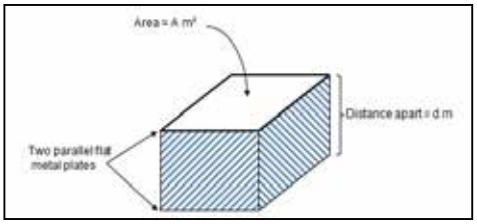


Figure 3: Parallel Plates

Equation 9 tells us the capacitance, C, between the two plates is given by:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \qquad (9)$$

and Equation 12 shows the resistance between the plates is given by:

$$R = \rho_v \qquad (12)$$

Furthermore, as electrical components the two plates can be represented as a capacitor and resistor in Figure 4.

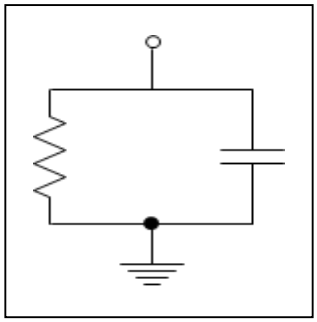


Figure 4: Electronic Component Representation of Figure 3

For the circuit shown in Figure 4, it is well known that if the capacitance is initially charged to a voltage V0 and then allowed to decay through resistance, the capacitance voltage, V, at any time, t, is given by:

$$V = V_0 e^{-\frac{t}{\tau}} \qquad (13)$$

That is, the decay is exponential with a time constant τ (when time τ has elapsed the voltage will be 1/e, or about 0.37, of its initial value). Furthermore, it can be shown that:

$$\tau = RC \qquad (14)$$

And by substituting Equations 9 and 12 into Equation 14 we can see:

$$\tau = RC = \rho_v \frac{d}{A} \times \varepsilon_0 \varepsilon_r \frac{A}{d} = \rho_v \varepsilon_0 \varepsilon_r \qquad (15)$$

In other words, for a material in which the volume resistivity is unchanging (sometimes referred to as ohmic) when in contact with an earthed conductor charge will decay from it exponentially with a time constant which is equal to the product of the volume resistivity, the relative permittivity and the Electric Constant. While this model shows why a charge decay curve is generally of exponential appearance, the reality is that for some materials, especially those which are relatively insulating, the volume resistivity is not constant but increases as the potential difference across the material decreases. This results in a decay curve which is not truly exponential, but which slows more than would be expected for a true exponential as the decay proceeds. This of course significantly complicates the model relating charge decay time to resistivity, such that it may be quite impossible to predict how quickly charge will decay from a material based only on a resistivity determined at a single potential difference. Hence the value of experimentally determined charge decay times.

2.5 Discharges

Sometimes, the electric field between two objects will be so high that charge will effectively jump a gap in what is commonly referred to as a spark. More generally, this phenomenon is known as an electrostatic (or electrical) discharge.

A number of different types of electrical discharge have been identified. Which type occurs depends on the nature of the materials and objects involved. Each type dissipates its own characteristic range of energies and will be discussed in detail below. However, the fundamental mechanism by which they all occur is the same, and will therefore be described first.

Suppose two oppositely charged objects are located a short distance apart in air, such that an electric field is established between them. The air between the objects will always include a few free electrons, and the effect of the field on these will be to accelerate them towards the more positive end of the field and away from the more negative end. Sooner or later a field-accelerated electron will hit a gas molecule with an energy that depends on the accelerating force and the time since it last hit something.

When an electron hits a molecule one of three things can happen. One option is that the electron may simply be absorbed and effectively lost as a negative ion is formed. Alternatively the electron may bounce off and begin to accelerate again, with no real change to the original situation. However, if the electron hits the molecule with sufficient energy, not only will it bounce off, but it will also knock another electron off. Now there are two electrons to accelerate where previously there was one. Both of these will be accelerated and each knock another electron off, and so on.

Overall, the process will have led to an avalanche of free electrons, with an equal number of positive ions – the molecules from which the electrons were removed. Now the large number of free electrons between the two objects means that the region is conducting, allowing charge to transfer between them until the field collapses and the effect ceases.

Accompanying the ionisation and the charge transfer there is a localised transient increase in temperature within the charge transfer channel, accompanied by the emission of visible light. The local pressure excursion as a result of the temperature rise leads to the audible crack accompanying the visible blue (in air) flash, which together we recognise as a "spark". As indicated earlier, whether or not an electron acquires sufficient energy to initiate an electrical discharge depends on the accelerating force it is subjected to, and the time since it last hit something. The accelerating force is obviously directly related to the magnitude of the electric field which means, for example, that as the potential difference between two electrodes is gradually increased, initially nothing appears to happen until, at a potential

difference that is characteristic of the electrode system, a discharge occurs. Under normal atmospheric conditions this typically occurs at a potential gradient (field strength) of 3 x 10^6 $V.m^{-1}$. This is often referred to as "breakdown strength".

The other factor affecting the energy acquired by an accelerating electron is the time since it last hit something. This depends on the molecular density of the gas, or its pressure (for a given temperature). Consequently, at reduced pressure an electron will acquire greater energy for a given potential gradient before it hits a gas molecule, so that gas ionisation will occur at a lower potential gradient than for higher pressures. In other words, the breakdown strength of air (and other gases) decreases as the pressure decreases. This trend continues until a particular pressure is reached, below which there are simply too few gas molecules around and the breakdown strength increases again. This explains Paschen's Law, which is shown graphically in Figure 5, below.

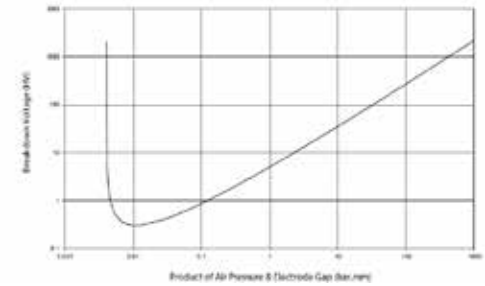


Figure 5: Paschen Curve for Air

Now we can discuss the different types of discharge which have been identified.

2.5.1 Spark Discharges

Spark discharges occur between two conducting objects. Consider a spark discharge between a charged conductor and another conductor connected to earth. As fast as charge leaves the charged object at the point of discharge, it is replenished by conduction from all other parts of the object. Thus the discharge continues until virtually all the charge has been transferred. On the other side of the spark gap, the received charge is rapidly conducted away from the spark, again ensuring that it can continue until all the charge has been transferred.

From the above description it can be seen that unless there is a continuous or repeating charging mechanism, one spark is all that occurs between two conductors.

The energy dissipated in a spark from a conductor is well defined and related to its capacitance and the initial voltage before the discharge started – both variables than can be readily measured or estimated.

The relevant equation is:

$$E = \frac{1}{2} C V^2 \qquad (16)$$

where E is the energy dissipated in Joules (J), C the object's capacitance in Farads (F), and V the initial voltage in Volts (V).

2.5.2 Brush Discharges

Brush discharges occur when an insulator is involved. Think about a charged insulator approached by an earthed conductor. A discharge is initiated in exactly the same way as before, only this time charge cannot migrate to the point of discharge through the insulating object. Consequently only a very small part of the total charge is transferred from the immediate vicinity of the point of initiation before the loss of charge, and the resulting drop in local field, quenches the discharge.

However in practice this process generally occurs from several points on the surface in the general area of the first discharge, either together, one after the other in quick succession, or both. The overall appearance is therefore of several faint discharge channels in parallel near to the insulator, joining together into a single channel closer to the conductor. The resulting brush-like (as in "witch's broom" or besom) appearance is the reason for the name of this form of discharge.

Similar effects result from a charged conductor discharging to an uncharged insulator, or discharges between two insulators. In all cases, the reason is that charge cannot migrate through the insulator away from the discharge region. Because each brush discharge channel transfers charge from an extremely localised area of the insulating surface, repeated brush discharges can be drawn without charging the surface again, since each time charge is transferred from a slightly different location.

Experiments with flammable gases of known ignition energy indicate that brush discharges dissipate a maximum energy that is equivalent to about 3 mJ - 4mJ, numbers which are often quoted. However, failure to ignite even very low ignition energy powders (<<3mJ) with a brush discharge indicates the cited energy should be deemed an equivalent energy in the presence of flammable gas atmospheres rather than an absolute energy.



Figure 6: Propagating Brush Discharge

2.5.3 Propagating and Transitional Brush Discharges

A propagating brush discharge can occur from highly charged, thin insulating films, and mostly when they are in close contact with a (normally earthed) conductor. A thin insulating film in close contact with a conductor is like a capacitor and this arrangement means that an unusually large amount of charge can be accumulated on the outside surface of the insulator.

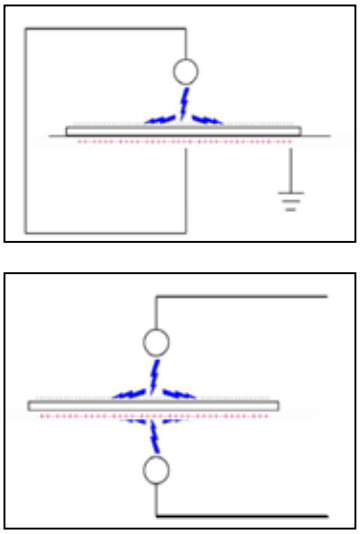
When a discharge is initiated from this arrangement, a number of almost lightning-like discharge channels propagate across the surface of the insulator, broadly radiating towards the point of initiation. However, because there is such a high level of stored charge the total charge transferred can be very high, as can the energy dissipated, as is obvious from the very loud crack heard when this type of discharge occurs. Even so, since the discharge has come from an insulator not all the charge is transferred, and more than one propagating brush discharge can be drawn without re-charging.

The energy dissipated in a propagating brush discharge can exceed 1J (1000mJ), and a photograph of one can be seen in Figure 6.

In order to achieve the charge density necessary to produce a propagating brush discharge there has to be a sufficiently high charging mechanism to produce the necessary charge density of $2.5 \times 10^{-4} C.m^{-1}$ or more. This also requires that in normal atmospheric conditions the surface must have a sufficiently high capacitance which can only be achieved if the layer of insulator is 8 mm thick or less. Furthermore, to achieve the required charge density it also requires that the insulating layer is capable of withstanding a potential difference across its thickness of 4 kV or more.

Transitional brush discharges require the same type of structure as for a propagating brush discharge, but occur at lower charge densities and dissipate lower energies – though still higher than a brush discharge. Undoubtedly there is more to be learned about the nature and energy of both transitional and propagating brush discharges. However, for the time being it is sufficient to note that through one mechanism or the other, discharges from thin insulators can be of a higher energy than brush discharges and can reach very high energies.

So far we have talked of propagating brush discharges occurring across a thin insulator on an earthed conductive backing. Although this is perhaps the most common structure, the effect can also be achieved if the thin film has high charge densities but of opposite polarities on both sides of the film. This is what actually happens when the film is in close contact with an earthed conducting substrate, as charge is induced in the conductor and resides on that side of the film. However, as shown in Figure 7 below, the same thing can happen if both sides of the film are charged with opposite polarity charge.



a) Charged Insulating Sheet and Earthed Backing

b) Opposite charge on Each Side

Figure 7: Two Charging Arrangements for Propagating Brush Discharges

2.5.4 Lightning

We are all familiar with lightning. Although capable of producing discharges that dissipate very high energies indeed, protection against true lightning as a result of meteorological conditions is beyond the scope of this document.

Concerns have been raised that a similar phenomenon could occur on a smaller scale with charged powder particles or spray droplets suspended in the space inside vessels. However, experiments have been unable to detect lightning-type discharges in these situations, leading to the conclusion that this type of discharge is unlikely to occur inside vessels of practical volumes and certainly not inside vessels of less than 60m3 in volume, or less than 3m in diameter.

2.5.5 Cone Discharges

When a charged insulating powder particle falls towards a heap of similar particles the force of repulsion may exceed the force of gravity and the particle will be unable to land. In this case it will run across the heap either widening it, or, if the heap is bounded by a container, sticking to the container wall.

If the charge is not so high as to prevent landing, the effect is for the force of gravity to compress the charges as the powder forms a heap. This compression against the repulsive forces of like charges increases the potential energy in the heap, which manifests itself as an increasing electric field across the surface.

If the field becomes high enough an electrical breakdown will occur. In this case, the breakdown tends to propagate across the surface of the heap in the form of a number of radial discharge channels as powder is added to the heap. Since such heaps tend to be conical in shape, the discharges are known as cone discharges. There is some debate about the energy dissipated in cone discharges. In the US NFPA 77:2007 states that cone discharges (or bulking brush discharges) dissipate energies of between 10 mJ and 25 mJ. In Europe CENELEC's CLC/TR 50404:2003 presents an empirical equation for the maximum energy dissipated in a cone discharge, as given below.

$$E = 5.22 \times D^{3.36} \times d^{1.46} \qquad (17)$$

where E is the maximum energy dissipated in milliJoules (mJ), D the diameter of the vessel in metres (m) and d the diameter of the powder particles or granules in millimetres (mm). Based on the experiments that led to Equation 17, it is said to be valid for particles up to 3 mm in diameter and vessels to 3 m in diameter.

Evaluating E for these conditions gives a maximum dissipated energy in excess of 1 J. Clearly there is enormous disparity between the two documents in this respect, and it is expected that this will be addressed in part by a revision to the recommended use of the equation when the CENELEC document is replaced by IEC 60079-32.

2.5.6 Corona

Corona occurs at a sharp point in an electric field. The sharp point has the effect of intensifying the electric field in its immediate vicinity. The intense field near the sharp point can mean that the "avalanche" of free electrons occurs here (see the text at the beginning of this section on discharges) but does not extend to regions further away from the point.

If the point electrode is negative with respect to its surroundings the extra electrons produced will be repelled. As they move outside the avalanche region they will simply be absorbed by gas molecules and then continue to be repelled, now as negative ions. The positive ions left behind when electrons were knocked off gas molecules within the avalanche region will be attracted towards the electrode. Conversely, if the point is positive, the effect is that a stream of positive ions are repelled from it.

Thus, corona discharge may be viewed as a source of positive or negative ions which can be considered as a means of transferring charge between the sharp electrode and its surroundings. If the transferred charge arrives at an uncharged surface, corona can be considered to be a means of charging. If the transferred charge is of the opposite polarity to charge already there, corona can be considered to be a means of neutralising charge. Either way, corona discharge is a process that dissipates only low energy. In air a visible blue glow, or haze, in the vicinity of the point, and an audible hiss, are often apparent. For further information on corona see also Section 4.1.2: "Static Elimination".

3. Electrostatic Hazards

3.1 Shocks

When an electrostatic discharge is to a person it may be experienced as a "shock": something with which most people will be familiar. For low energies this may be experienced as something similar to a pin-prick on the skin. This might be as a result of the momentary and very localised temperature rise associated with the discharge, or it might be as a result of the physical damage to the outer, relatively insulating, skin layer which is penetrated by the discharge in order to reach the more conducting lower layer, or a combination of the two effects. Either way, the limit of perception is about 1 mJ, and discharge energies less than this will not be felt even in relaxed, domestic or office environments. Brush discharges being inherently relatively low energy discharges (see the section on Discharges) will always be in this regime: barely perceptible.

However, as spark discharge energies increases the above effects simply become more significant; probably up to a spark energy in the region of 50 mJ. This is a little higher than the worst shock that might ever be encountered simply by getting out of a car and touching it, or by walking across a carpet and touching a door handle or lift button. That is momentarily uncomfortable, unpleasant especially because of the unexpected nature of it, but otherwise harmless in its own right. Nevertheless, the surprise of receiving such a shock can lead to a reaction out of proportion to the harm it actually causes and, in industrial situations especially, this can lead to what might be termed a secondary hazard. For example, if somebody receives such a shock while on a ladder the almost involuntary reaction could lead to a fall. Similarly, if working close to moving machinery, or even other workers, the reaction could lead to an accident.

Because at this level the discomfort is primarily as a result of the high energy density at the skin, the effect can be reduced by controlling the energy density in space or time. For example, if a metal object is grasped firmly in the hand and the discharge drawn to the metal instead of the skin, the effect will be much reduced since although there will still be a localised spark between the two conducting items, the charge transfer to the skin will be spread across a much larger area. Alternatively, if the skin contact is with a semiconducting part (e.g. getting out of the car and first touching the window glass rather than a metal part of the door), the charge transfer will occur much more slowly (the spark itself may be all but supressed). Although the same energy will be dissipated overall, the fact that it takes much longer will mean it is much less keenly felt, if at all.

As the spark energy increases still further and reaches perhaps 100 mJ, the above skin effects still occur (even more strongly) but now the transient current is sufficient to start to produce some muscle contraction. Hence, at this level the shock is becoming very uncomfortable. Even though there is still unlikely to be any lasting effect, the involuntary reaction to it is likely to also become stronger, thereby increasing the potential for secondary hazard. Fortunately, spark discharges of this energy are relatively rare as it is higher than can result only from a person being charged, and would need a charged isolated conducting object so large that it becomes increasingly difficult for it to be even inadvertently isolated.

Propagating brush discharge can also dissipate energies of 100 mJ and more; even up to more than 1 J. At this latter level the muscle contraction due to the transient current is likely to be so strong that its effect, which may even include temporary paralysis, may last for some time after the event. This is why propagating brush discharges are said to be the one type of discharge that can cause direct injury to personnel. Indeed, in principle at least, if such a shock were received in a way that resulted in the transient current affecting the heart, it is conceivable that such discharges could be life threatening.

As we saw in the section on Discharges, propagating brush discharges are most likely to arise from thin insulating materials in close contact with an earthed conductor. However, they can also occur when thin insulators become charged on opposite sides with opposite polarity charges. Hence, there is the potential for propagating brush discharges wherever thin insulators are used and where they are, or have been, exposed to a high charging regime. This would include sheet made from polythene, PVC or a wide range of other plastics.

3.2 Fire and Explosion Hazards

Although most electrostatic discharges provide little direct hazard to personnel (with the one exception of Propagating Brush Discharges, as noted in Section 3.1), the main hazard associated with static electricity is the ability of electrostatic discharges to ignite flammable materials.

Of all the types of electrostatic discharge, only one cannot ignite the vapours of the many flammable solvents that are daily handled in industry: corona discharge. Even then, uncertainty about the safety of corona in the presence of unusually sensitive gases, such as hydrogen and carbon disulphide, means it is best to assume ignition of these gases is possible.

That means that if any flammable materials are present, static electricity can never simply be dismissed. It is always important that the risks be properly assessed and a full justification given for the protective measures that are put in place, and more importantly, for omitting those protective measures that are not employed. Given the importance of this aspect of how to undertake an assessment of the hazard in different situations, and how to decide on the necessary protective measures, this is the subject of the rest of this section.

3.2.1 Electrostatic Hazard Assessment

This section provides a systematic approach to assessing the electrostatic hazard in respect of fire and explosions, by answering the questions in the flowchart in Figure 8.

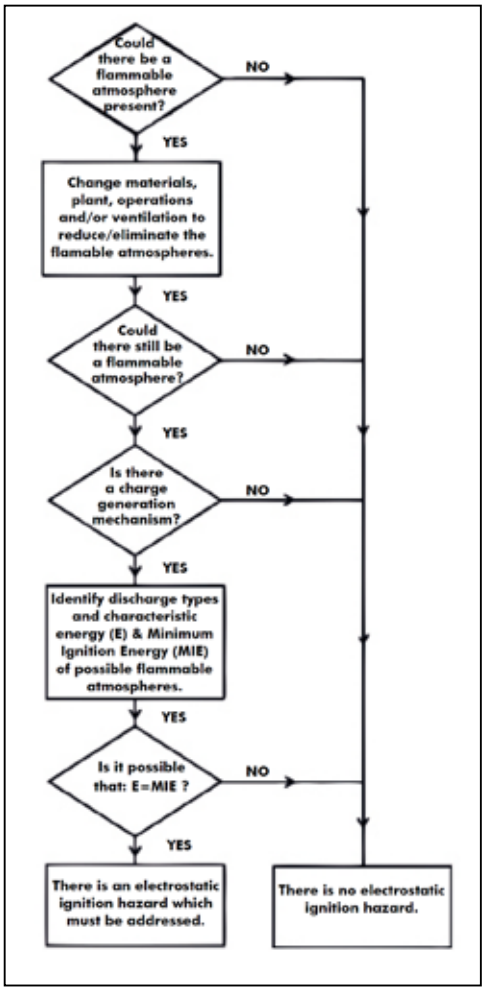


Figure 8: Flow Chart for Deciding if there is an Electrostatic Ignition Hazard

Then, if the final outcome from the flow chart is that there is an electrostatic ignition hazard requiring appropriate control of static electricity, this will be addressed by trying to change the answer to one of the electrostatic questions from "yes" to "no". This is the subject of Section 3.2.2.

If no effective control measures can be put in place it will be necessary to return to the question about flammable atmospheres and try harder to eliminate those. For example, this might be by employing inerting techniques (e.g. nitrogen blanketing). If, even after revisiting the flammable atmospheres questions there is still a residual, uncontrolled electrostatic fire and explosion hazard, the only option will be to install mitigation measures, whereby protection is provided against the worst happening. This will ensure that, even in the event of an ignition, personnel (first) and plant (second) are protected against the effects of that ignition. Of course, electrostatic discharges are one of a range of ignition sources which must be assessed and, if necessary, controlled as part of an overall fire and explosion risk assessment. However, the others are beyond the scope of this document and will not be discussed further here.

A. IS THERE A FLAMMABLE ATMOSPHERE PRESENT?

In order to establish if there is a flammable atmosphere present, certain material characteristics are required. The following sections identifies these characteristics, for gases/vapours, mists, powders and hybrids.

a) Basics

For an explosion to exist, three items must be present simultaneously: fuel, oxidant (usually air), and an ignition source. This is usually displayed as the "Fire Triangle" (Figure 9), the points of which represent the three elements essential for an ignition. If any one of these elements is missing or removed there is no ignition hazard.



Figure 9: The Fire Triangle

Removal of the fuel or the oxidant prevents the occurrence of a flammable atmosphere, whilst removal of the energy source prevents ignition even if a flammable atmosphere exists.

However, it is often not possible to be sure of removing all possible ignition sources with sufficient reliability when it is certain that the other two elements (fuel and oxidant) are present. Hence, avoidance of ignition sources is often used in conjunction with other factors, such as being able to demonstrate that the flammable mixture will at worst only be present intermittently, or that the flammable mixture is difficult to ignite.

The fuel can be a gas such as hydrogen or methane, the vapour from a volatile liquid such as acetone, toluene or methanol, or a fine dust. Sugar, starch, flour and cocoa are common powders that can form dust clouds which are capable of exploding.
The ignition of a flammable mixture of gas, vapour or dust in air in a closed space produces pressure, which, if it is high enough, can lead to rupture of the vessel or container. The addition of at least some degree of confinement, especially when combined with good mixing of the fuel and oxidant for a faster reaction,

leads to an explosion. This is illustrated in the explosion pentagon of Figure 10.



Figure 10: Explosion Pentagon

Explosions are characterised by a rapid and significant pressure rise, and the greater the rate pressure rise the more violent the explosion. In general terms the maximum pressure produced in an explosion will be up to about eight times the initial pressure. An ignition starting at normal atmospheric pressure (1 bara) would be expected to give a maximum explosion pressure of up to 8 bara (7 barg), although some materials can produce pressures up to 10 times the initial pressure, or more. The flammability of materials and mixtures is discussed below with particular reference to the parameters relevant to industrial electrostatic hazards.

b) Flammability

For many common vapours and gases it will be immediately obvious if, at least under some circumstances, they are flammable. However, for others, and for many powders, it will be less obvious and an initial laboratory test may be required even to determine if the material is flammable at all.

Whether or not dust dispersions are flammable is determined using two tests for each of two ignition source types:

- The vertical tube (A-B rig), and
- The Godbert - Greenwald (GG) furnace.

In the Vertical Tube test a dust cloud is formed at ambient temperature in the presence of a standard source of ignition by dispersing material by an air jet. If ignition occurs, and the flame moves away from the ignition source, the material is classified as Group A (flammable). If ignition does not occur the material is classified as Group B and is not considered flammable at ambient temperatures (i.e. up to 110 °C), although some can still be ignited by very powerful ignition sources.

If a dust is handled at elevated temperatures it may be flammable, even if it was classified as Group B in the vertical tube test. Dusts that are handled at elevated temperatures are tested in the GG Furnace. If spontaneous ignition occurs at furnace temperatures in excess of 800°C the material is regarded as flammable. If ignition does not occur the material is considered not to be capable of forming flammable dust clouds under general plant conditions. The ignitability of dust clouds is affected by the particle size of the dust. Where the particles exceed diameters of about 500 µm, flammable dust clouds generally will not be formed. Maximum ignitability occurs with particle sizes of 75 µm and smaller and material of this fineness should always be used for tests.

c) Limits of flammability for gases and vapours

Mixtures of flammable gases or vapours in an oxidant, which for the purposes of the discussion will be assumed to be air, are only ignitable over a restricted range of concentrations, the limits of which are termed the lower and upper explosive limits.

The lower explosive limit (LEL) is the minimum concentration of gas or vapour for which flame propagation can occur once ignition has been effected, and the upper explosive limit (UEL) is the maximum concentration that will permit flame propagation following ignition. Concentrations below the LEL are often referred to as too lean, while concentrations above the UEL may be described as too rich. However, mixtures which are over-rich can easily be diluted with air in some situations, moving them into the flammable region.

Care must be taken to ensure published data is relevant to the conditions being assessed. For example, measured limits of flammability are influenced by the test conditions, notably the vessel dimensions, and the direction of flame propagation. Upward propagation in a vertical tube of at least 50 mm diameter gives the most appropriate conditions for the majority of mixtures at normal temperature and pressure. Most data in the literature are reported for these conditions. Also, limits of flammability are affected by temperature and pressure; both causing a widening of the flammability limits as they increase, so deviations from normal atmospheric conditions must be accounted for.

d) Limits of Flammability for Powders

In the same way as gases and vapours, dusts (the terms “dust” and “powders” are used interchangeably here) in the form of a cloud are only ignitable over a range of concentrations.

In principle, the concepts of LEL and UEL are applicable to dust clouds, but only the LEL is of practical use. This is because of the inherent difficulty of achieving a homogeneous dust cloud at high concentration, which would inevitably result in some parts of a dispersion being within the flammable range even if others were above a nominal UEL. For this reason, a UEL for dusts is never routinely determined or referred to. For dusts the LEL is more commonly called the Minimum Explosible Concentration (MEC).

The MEC for most dusts is in the range 20-60 g.m-3, although some materials have values much higher than this, reaching 250 - 300 g.m-3. The presence of flammable gas or vapour in the dust air mixture (referred to as a "hybrid" mixture) will reduce the value of the MEC. Indeed, hybrid mixtures of flammable dusts and flammable gases or vapours may be flammable even if the individual mixture components are below their LEL / MEC. Temperature and pressure also influence the limits of flammability for dusts in a similar way to those for gases and vapours. However, it is of little practical significance as the UEL is not used, and the small change in the concentration at the MEC usually will have little effect on the hazards.

d) Flash Point

It is sometimes convenient to know the conditions under which flammable mixtures of gas or vapour in air will naturally be formed, and the parameter most used in this context is the flash point. Flash point is the temperature to which a liquid must be heated before it will produce a mixture of vapour in air that will ignite momentarily. At the flash point continuous combustion does not occur; this takes place at a higher temperature known as the fire point.

The concept of flash point applies to all liquids including liquefied gases. In practice, because the temperatures are so low, flash point is not usually relevant or quoted for permanent gases such as methane and hydrogen, which are considered to be capable of forming flammable mixtures at any temperature. Flash point results are affected by a number of factors including: equipment design, size of sample, ignition source, ambient pressure, operator bias, etc., although some have been minimised by national standards for flash point determination.

Corrections still have to be made for variations due to changes in ambient pressure. Flashpoints are normally corrected to standard barometric pressure (760 mm Hg); the correction being to add, or subtract, 0.03 °C to the measured value for each millimetre of mercury below or above 760 mm, respectively.

Flash point can be measured in closed equipment (closed cup), or in open equipment (open cup). The most extensively used pieces of apparatus for the test are the Abel Closed Cup, Pensky Martens Closed Cup, the TAG Closed and Open Cups, and the Cleveland Open Cup. Closed cup flash points are normally several degrees lower than open cup values because they are determined on saturated vapour/air mixtures extending throughout the test volume, whereas in the open cup test free access to open air means there will be a concentration gradient with distance from the liquid surface. Some typical values can be seen in Table 3, below:

Material	Flash point (°C)	
	Closed cup	Open cup
Acetic acid	40	43
Acetone	-17	-9
n-butanol	29	44
Methanol	10	16
Toluene	4	7

Table 3: Flash Point Data

Flash point can be regarded as a lower temperature limit of flammability, and, similarly, an upper temperature limit can be defined. In this way the temperature range over which a closed vessel can contain a flammable atmosphere in the presence of excess liquid can be obtained.

It should be noted here that the finely divided form of liquid sprays and foams means that they can be flammable even when the temperature is well below the liquid flashpoint. Also, as previously discussed, hybrid mixtures can be flammable even when the flammable gas or vapour concentration is below its LEL. In the present context this means a flammable hybrid of powder and vapour can be formed even when the temperature is below the flashpoint of the liquid from which the vapour derives. Flashpoints are not relevant or meaningful for powders.

e) Vapour Density

Vapour density is not a flammability characteristic of gas or vapour, but it is an important factor in hazardous area classification. Vapour density (strictly, relative vapour density) is the ratio of the weight of a given volume of a gas or vapour to the weight of an equal volume of air at the same temperature and pressure. In hazardous area classification it is important to know how a gas or vapour is likely to move when it is released. This is of great assistance in deciding the shapes and extents of zones, and determining if, and where, layering may occur. Gases and vapours with vapour densities around 1 will diffuse in the air being carried largely by convection currents etc. Materials with values significantly higher than 1 will tend to settle and layer, and will not mix readily with the air. If the gas or vapour has a vapour density significantly less than 1, it will rise and mixing with the air may be similarly slow as it accumulates at high points. Hydrocarbon solvents such as toluene and xylene have vapour densities of about 4, whilst for hydrogen the value is 0.1 and for methane 0.6.

B. IGNITION SENSITIVITY?

If there is or could be a flammable atmosphere present the next question to ask is: How sensitive to ignition is the flammable atmosphere? Of course for a full fire and explosion risk assessment sensitivity to all ignition sources will be required, including high temperatures of the flammable atmosphere itself or of surfaces it may contact. However, for the purposes of this document only those ignition sensitivity tests relevant to electrostatic hazard assessment will be discussed. Details of other ignition sensitivity tests can be found elsewhere.

a) Gas groups

Gases and vapours are placed into groups according to the results of standard ignition sensitivity trials compared with results for selected standard materials. These groups are referred to as Gas Groups. Group I refers to methane found underground, while Group II refers to any gas or vapour which might be present other than in a mining (underground) situation. Group II gases are further sub-divided as described below.

The ignitability of flammable mixtures varies between materials, and the energy needed to ignite mixtures of a given gas or vapour depends on the concentration. For the purposes of gas group determination, ignition sensitivity is measured for optimum mixtures (i.e. the most sensitive) as this represents a "worst case" situation. The ignitability of gases and vapours is determined by breaking a standard electrical circuit carrying a known current. The resulting spark is produced in the flammable mixture under test and the minimum current producing a spark which ignites the mixture is referred to as the Minimum Igniting Current (MIC).

The Maximum Experimental Safe Gap (MESG) is another test used to aid the grouping of gases and vapours. This determines the maximum gap between two standard 25 mm flange surfaces which will prevent an ignition of the test flammable mixture propagating through the flange surfaces to ignite the test flammable mixture on the other side of the flange assembly.

By comparing the MIC test results with those of known materials, and if necessary also comparing the MESG test results with those of known materials, all vapours and gases can be assigned to Gas Groups IIA, IIB or IIC, which represent increasing sensitivity to ignition. Examples of Group IIA, IIB and IIC gases would be propane, ethylene and hydrogen, respectively. Gas groups are used to specify electrical equipment, but they are also used to assess the electrostatic hazard associated with objects made from insulating materials.

b) Minimum Ignition Energy

Minimum Ignition Energy (MIE) is determined by producing sparks of known energy in a flammable atmosphere. For powders this clearly means simultaneously dispersing the powder. The smallest spark energy that will ignite any mixture of fuel with air is defined as the Minimum Ignition Energy for that material. Clearly this will require testing a range of fuel/air concentrations until the lowest ignition energy for all possible mixtures of the fuel under test with air has been obtained.

The MIE is reduced significantly at elevated temperatures. Also, the presence of flammable gases or vapour in a flammable dust cloud will usually lead to a lower MIE than for the powder alone. The spark generating circuit can be a simple discharge of a capacitor into a low inductance spark gap and circuit, which is referred to as a capacitive discharge. However, for some issues the MIE is determined using a discharge from a capacitor into a circuit which includes a defined inductor: referred to as MIE with inductance.

For electrostatic hazard assessments it is important to use the purely capacitive discharge measurement for two reasons. First, it is extremely unlikely that anything other than a capacitive discharge would occur outside of a test laboratory. Secondly, the MIE with inductance will invariably give a lower MIE value, which means if the MIE with inductance is used for electrostatic hazard assessments, the precautions that will appear to be necessary may be unrealistically severe. In some cases this may simply mean a modest increase in cost associated with the measures that appear to be necessary. However, in other cases using the wrong MIE could even wrongly indicate that adequate ignition protection cannot be provided at all, leading to an apparent need for very expensive protection measures or even a complete re-think of the process.

Table 4 gives some typical MIE values for some common materials. When looking at Table 4 it is worth bearing in mind that the discharge energy when a person gets a shock when touching a car could be around 30 mJ.

Fuel under Test	Minimum Ignition Energy (mJ)	
	In Air	In Oxygen
PVC	1500	
Wheat flour	40	
Sugar	30	
Aluminium	10	
Sulphur	<1	
Acetone	1.15	
Ethane	0.24	0.0019
Methane	0.21	0.0027
Methanol	0.14	
Hydrogen	0.016	0.0012
Carbon disulphide	0.009	

Table 4: Typical Gas, Vapour and Dust Minimum Ignition Energy Values (for illustrative purposes only)

C. IS THERE A CHARGE GENERATING MECHANISM?

Any actual or possible charge generating mechanisms must be identified and noted. The fundamental concepts involved with charge generation were discussed in Section 2.2, but here we consider practical situations in which these effects may be occurring.

a) Tribocharging

In commercial and industrial situations, including process plant, there is the possibility of charge generation taking place whenever there is relative movement between one material and another.

Charging tends to be particularly high when there is a large interfacial charging area, when relative velocities are high or when the energy input to a process is high. With non-conducting liquids, an immiscible dispersed phase (e.g. water in toluene) or the use of fine filters can lead to very high streaming currents. Clearly the range of possibilities is very high so, to help get started, some typical charge generating situations are listed:

Charge Generation in Liquid Handling:

- Flow (especially two-phase: liquid/liquid, liquid/solid, liquid/gas) through pipes and fittings, and especially through fine filters.
- Pouring from containers (e.g. buckets), particularly with low conductivity liquids.
- Stirring or agitating two-phase liquids (particularly water in hydrocarbons) or solid/liquid mixtures.
- The flow of two-phase gas/liquid mixtures (e.g. wet steam, condensate in gas).
- Atomisation of liquids (especially conducting liquids e.g. water washing, spray painting).
- Splash filling of liquids into vessels.
- Gravity settling of liquids, solids or gases from liquid suspensions.

Charge Generation in Powder Handling :

- Size reduction (e.g. milling, grinding, micronising)
- Some drying processes (e.g. fluid bed drying, 'flash' drying, spray drying)
- Pneumatic Transfer
- Sieving
- Emptying and filling powder from / to bags or drums

To illustrate the effect of relative velocity and energy put into processes, Table 5 shows some typical ranges of charge: mass ratios for powders subjected to different types of process operation (from CLC/TR 50404).

Operation	Charge: Mass Ratios (mC/kg)
Sieving	10^{-3} to 10^{-5}
Pouring	10^{-1} to 10^{-3}
Scroll feed transfer	1 to 10^{-2}
Grinding	1 to 10^{-1}
Micronising	10^{2} to 10^{-1}
Pneutmatic conveying	10^{3} to 10^{-1}

Table 5: Typical Powder Charge to Mass Ratios from Different Process Operations

Charge Generation – Additional Possibilities:

- Rubbing or cleaning insulating surfaces.
- Walking on insulating floors or wearing footwear with insulating soles.
- Removing clothing – especially man-made materials.
- Conveyor belts passing over rollers.
- Plastic or paper webs passing over rollers – especially at high speed.
- Unwrapping plastic film
- Pulling plastic liners out of drums

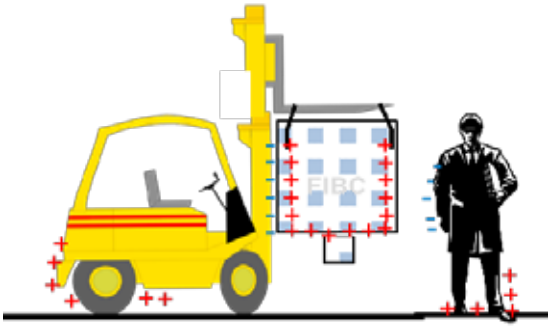


Figure 11: Practical Industrial Scenario for Induction Charging

b) Induction and Contact Charging

There is no doubt that tribocharging (including streaming currents) is the basic mechanism of inadvertent charge generation, and ultimately all other mechanisms must derive from that. However, once charged objects are present other mechanisms can also occur.

Induction charging was discussed in Section 2.2.3, and reference to that section will provide a reminder that induction charging occurs on items of finite conductivity when they are exposed to an electric field and contact a conducting field boundary. Figure 11 shows exactly this structure but now in a more practical embodiment than Figure 1, which appeared in the earlier discussion.

However, if the earth connection is poor, charge transfer will depend on the magnitude of the FIBC charge, the actual resistance to earth and the duration of exposure to the field. Similarly, once the FIBC is left behind the net negative charge acquired will be carried away and will only be lost relatively slowly. If during this time another conductor is encountered, a spark could occur between it and the charged man or forklift. Contact charging is actually a special case of induction charging when it occurs by a charged conductor coming into contact with another conductor. As the two conductors approach one another there may be a spark if the potential differences are high enough, but in any case charge will transfer from one to another until both are at the same electrical potential.

c) Corona Charging

Inadvertent corona is perhaps the least likely to occur in a practical industrial environment. As for induction or contact charging, corona charging will only occur if something is already charged. Transfer of charge can then occur if there is a field-intensifying sharp point on or near the charged object. However, as this could simply be a corner, fibres, hairs, or even machining burrs it becomes clear that although this mechanism might be the least likely to occur inadvertently it is by no means impossible and must always be considered as a possibility if charged items or materials are expected to be present.

D. WHAT TYPE OF ELECTROSTATIC DISCHARGES CAN OCCUR?

Having identified possible charging mechanisms in the previous section it will be clear what type of materials, if any, might become charged: isolated conductors, isolated semiconductors (dissipative materials), or insulators, all of which could be solids (including films and powders) or liquids. As discussed in Section 2.5 the discharge types which must be considered possible from each of the different types of charged material are indicated in Table 6:

Material Form	Material Type	Possible Discharge Type
Solid (> 8mm thick)	Conducting	Spark
	Semiconducting	Spark
	Insulating	Brush
Solid sheet (< 8mm thick)	Conducting	Spark
	Semiconducting	Spark
	Insulating	Brush, Propagating Brush
Solid film	Conducting	Spark
	Semiconducting	Spark
	Insulating	Brush, Propagating Brush
Powder	Conducting	Spark
	Semiconducting	Spark
	Insulating	Brush, Cone
Liquid	High conductivity	Spark
	Medium conductivity	Spark
	Low conductivity	Brush

Table 6: Discharge Types from Different Materials

For completeness it should be noted that although in Table 6 "Semiconducting" materials (sometimes referred to as "static dissipative" or, for liquids, as "medium conductivity") are all shown capable of producing spark discharges, this may not always be the case. In reality, such materials can sometimes be too insulating to produce spark discharges and may also be too conducting to produce brush discharges. However, it is safest to assume spark discharges are possible and any deviation from this assumption is probably best adopted with specialist help.

Of course, just because charged material is present, it doesn't necessarily follow that an electrostatic discharge will occur. Indeed, for a discharge to occur another object has to be close

enough for the electric field somewhere in the area to exceed the breakdown strength of air at 3 x 106 V.m-1 (see also Section 2.5). However, the difficulty of foreseeing all possible reasons why this might occur means that for most practical purposes it must be assumed that if charge can be generated and can accumulate on one or more of the material types in Table 6, sooner or later there will be an electrostatic discharge. Only in the most exceptional circumstances and with expert help should it ever be considered justifiable to cite the complete absence of electrostatic discharges, despite the expected presence of charged materials, as a basis of safe operation.

E. COULD THE DISCHARGE IN D IGNITE THE FLAMMABLE ATMOSPHERE IN A?

Each of the discharge types identified in Question D dissipate a characteristic energy which can be compared with the MIE of the flammable atmosphere, which was obtained when answering Question B of this hazard assessment process. These were discussed in some detail in Section 2.5, but are briefly covered again here.

a) Spark Discharges

The energy dissipated by a spark discharge is given by Equation 16 (see also Section 2.5.1)

$$E = \frac{1}{2}CV^2 \qquad (16)$$

where E is the energy dissipated in Joules (J), C the object's capacitance in Farads (F), and V the initial voltage in Volts (V). If the voltage to which an object might be charged is unknown, it is probably appropriate to use 15 kV (1.5×10^4 V) to evaluate Equation 16.

The capacitance of an object is highly dependent on its position, so ideally it must be measured in situ, or as a second best measured in a mock-up designed to represent the normal situation. If that is too difficult the values in Table 2 (Section 2.3.4) can be used to provide an estimate. Table 7, below, shows the items of Table 2 now with discharge energy evaluated based on the given capacitance and potential of 15 kV.

Object	Capacitance (pf)	Spark
Small metal items (e.g. scoop, hose nozzle, etc)	10 – 20	1 – 2
Small containers (e.g. buckets, 50 litre drum)	10 - 100	1 - 10
Medium containers (e.g. 250 to 500 litre drums)	50 - 300	5 - 30
Major plant items (e.g. reaction vessels)	100 - 1000	10 - 100
Human body	100 - 300	10 – 30

Table 7: Typical and Spark Energy Values

If estimated spark discharge energies are close to or exceed the MIE of flammable atmospheres which may be present, it must be concluded that there is an electrostatic hazard and appropriate control measures must be employed, as discussed in Section 3.2.2. Indeed, as spark discharges are so easily avoided, it is recommended that employing control measures should be considered whenever flammable atmospheres and isolated conductors are present, irrespective of estimated discharge energies.

b) Brush Discharges

Brush discharges are capable of discharge energies equivalent to about 4 mJ in terms of incendivity of flammable gases and vapours. Hence, if flammable gases and vapours with MIEs of 4 mJ or less are or could be present, and if it has been shown that brush discharges are possible, it must be concluded that there is an electrostatic hazard, and appropriate control measures must be employed.

Despite many trials, it has not been shown to be possible to ignite any flammable dust atmospheres with brush discharges. Nevertheless, it would be considered prudent to assume that the most sensitive powders might be. Hence, it is recommended that if flammable powders with MIEs of 1 mJ or less might be present, control measures to avoid incendive brush discharges should be taken in the same way as for Group IIA gases and vapours.

c) Propagating Brush Discharges

Propagating brush discharges (and to a lesser extent enhanced brush discharges) can be high energy discharges capable of igniting all types of flammable atmosphere (gas, vapour or powder).

Hence, if propagating brush discharges are deemed possible and any flammable atmosphere could be present it must be concluded that an electrostatic hazard is present and appropriate control measures put in place.

d) Lightning

Lightning is really only included here for completeness as it is one of the discharge types referred to elsewhere. However, it was not one of the discharge types which might have been identified in Question D since lightning-like discharges will not occur in normal process plant. Indeed the only place lightning will ever be encountered is outdoors and associated with meteorological conditions.

Lightning is capable of igniting all types of flammable atmosphere and cannot be controlled. Hence, if there is an electrical storm in the area, any outdoor activity involving significant flammable atmospheres must be considered hazardous. However, the only practical measures that can be taken are avoiding the flammable atmosphere by ceasing the activity while the storm is in the area. Where flammable vapours and gases are vented outdoors from inside plant, such that the presence or otherwise of an outdoor flammable atmosphere, albeit limited in extent, can neither be controlled or timed, flame arrestors must be employed such that in the event of an external ignition due to lightning (or other causes), the ignition will not propagate to the inside of the plant or tank.e) Cone Discharge For conducting vessels or containers where cone discharge has been identified as a possible discharge type, it will be necessary to estimate the discharge energy using Equation 17.

$$E = 5.22 \times D^{3.36} \times d^{1.46} \qquad (17)$$

where E is the maximum energy dissipated in milliJoules (mJ), D the diameter of the vessel in metres (m) and d the diameter of the powder particles or granules in millimetres (mm). If the container is insulating and cone discharges have been identified as a possibility, the modified equation given below must be used:

$$E = 5.22 \times (2D)^{3.36} \times d^{1.46} \qquad (18)$$

The above equation is taken from the CENELEC document CLC/TR 50404:2003, "Electrostatics – Code of practice for the avoidance of electrostatic hazards". At the time of writing this document will shortly be superseded by a new IEC document: IEC 60079-32. This is expected to include further comment on, and possibly adjustment to, Equations 17 and 18. If anything this will reduce the predicted cone discharge energy, so continued use of the above equations could be seen as erring on the side of safety, though it is recommended that any such revisions be used as soon as they become available.

In any case, if the predicted cone discharge energy is close to or exceeds the MIE of flammable atmospheres that are or may be present it must be concluded that there is an electrostatic hazard and appropriate control measures must be put in place.

e) Corona

Corona is a low energy discharge. As such it is not deemed an ignition risk for any but the most sensitive gases. Hence, if flammable atmospheres as a result of the presence of Group IIC gases are or may be present even corona must be considered to represent an electrostatic hazard and control measures must be in place. However, two other points should be borne in mind with corona.

First corona may lead to charging of other objects, which depending on the situation and the material types could lead to other types of electrostatic discharge. Also, if corona is supressed (e.g. by the sharp point becoming rounded or covered), or if something comes sufficiently close to the corona source to enter the ionisation region, the corona could change to another discharge type (e.g. spark discharge). Hence, although corona is in itself usually a benign form of electrostatic discharge, unless it is being deliberately utilised (see Section 4.1.3) it is recommended that control measures are put in place to prevent it occurring.

3.2.2 Control of Electrostatic Hazards

If the Electrostatic Hazard Assessment of the previous section (Section 3.2.1) indicates an electrostatic hazard is or could be present, one or more of the control measures indicated in this section must be employed. If, for whatever reason this proves to be impossible, one option will be to modify the process or operation in some way to change the likelihood of a flammable atmosphere being present. Alternatively, it will have to be accepted that sooner or later an ignition will occur, and appropriate protection measures must be employed to ensure personnel are not harmed and ideally also that the plant remains usable.

Although some clues as to how the probability of a flammable atmosphere being present might be gleaned from Section 3.2.1, sub-section A, control of flammable atmospheres and explosion protection are both outside the intended scope of this document. To better consider these aspects reference to other Chilworth Technology document(s) is recommended.

In principle it might be possible to prevent or limit charge generation, and this is a contributory well-defined approach for liquids where published and expert guidance may include limiting pumping or agitator speeds (see below). Also, in relatively few cases electrostatic hazards can be controlled by neutralising the charge generated. This approach is discussed in Section 4 on Electrostatic Problems, though it is strongly recommended that it should only be attempted as a means of controlling fire and explosion hazards with expert help. However, for the most part protection is best achieved by preventing charge accumulation such that discharges cannot occur, or by limiting the discharge energy. It is helpful to discuss the recommended measures for this approach under headings of discharge types:

a) Spark Discharges

As already discussed, spark discharges only occur between conductors which are not electrically connected. Hence, protection against all spark discharges can be provided by ensuring all semiconducting or conducting items are electrically connected to earth. However, the question then arises: just how good does the connection to earth need to be?

The first approach to considering this is based on the following:

- One implication of Paschen's Law (see Section 2.5) is that an electrostatic discharge in air at normal atmospheric pressure and temperature is impossible with potential differences below about 300 V. Hence, a rounded maximum permissible voltage for avoidance of electrostatic hazards might be taken as 100 V (under normal atmospheric conditions).
- Most natural charge generation processes to not exceed a charge transfer rate (expressed as electric current) of 1 μA. It is therefore considered inconceivable that a natural charging current should ever reach 100 μA.

We can then use Ohm's Law to calculate the maximum permissible resistance to earth to ensure that the above voltage limit is never exceeded even if the given, inconceivably high charging current must be conducted to earth:

$$R = \frac{V}{I} = \frac{100}{100 \times 10^{-6}} = 10^{6}\ Ohms \qquad (19)$$

where R (Ohms) is the calculated maximum resistance to earth, V is maximum permissible voltage (Volts) and I the maximum expected current (Amps). The conclusion from this is that here are no foreseeable circumstances where a resistance to earth as high as 1 MOhm would not be acceptable, and this is therefore taken as the maximum permissible resistance to earth for any conductive items which are part of an active process operation. However, it is important that any connections to earth are robust to avoid failure by physical damage and for a direct connection to earth made by a robust cable, it is hard to see why the resistance would even exceed 10 Ohms.

Hence, for most practical purposes, it is recommended that the resistance to earth of conductive plant items which are actively part of a process operation should not exceed 10 Ohms. This connection might be made by fixed wiring or for moveable items (e.g. product collection bins) by flying earth leads. Flying earth leads should be robust, ideally permanently connected at one end, and with a clip which is strong enough to make a good connection, including breaking through any surface coatings to contact the conducting substrate, where necessary.

Where conducting items are present where a flammable atmosphere could be but are not actually part of an active process operation (e.g. bins simply stored in or moved through an area, or personnel), it would be difficult to imagine a charging current even as high as 1 μA. Now, Equation 19 becomes:

$$R = \frac{V}{I} = \frac{100}{1 \times 10^{-6}} = 10^{8}\ Ohms \qquad (20)$$

So for these items (conductors not part of the process) and for semiconducting material, it is clear that a resistance to earth of 10^8 Ohms (100 MOhms) is acceptable. This not only allows the inherent resistance of semiconductors to be acceptably earthed themselves, but also permits good conductors in a non-process situation to be earthed via the floor. Hence, for portable conductive equipment and personnel, contact with an earthed, suitably conductive floor via suitably conductive wheels, skids or footwear as appropriate is acceptable. From the resistance requirements in Equation 20 it is clear that the resistance to earth from anywhere on the surface of floors installed for this purpose must not exceed 10^8 Ohms. Similarly, the resistance between the floor and the conductive item itself (the skid, wheel or footwear sole resistance) must also not exceed 10^8 Ohms. In the case of footwear, in most situations it is also recommended that the sole resistance should not be less than 10^5 Ohms, which helps to provide some protection again electric shock injury from mains supplies even if the floor resistance to earth is very low (e.g. an earthed metal platform).

Although of necessity only limited examples are given, the above guidance applies to all conducting and semiconducting materials, whether part of the plant, portable or moveable items not directly involved in the process, and even to process materials themselves, such as liquids, powders or films, etc. Process liquids, for example, should be earthed by contact with earthed conductive parts of the plant. If the plant is such that the liquid would not normally be in contact with conducting parts (e.g. a glass lined vessel) special measures must be employed (e.g an earthed tantalum plug through the liner at the bottom of the vessel, or an earthed bare metal dip pipe extending to as close to the bottom of the vessel as possible).

As indicated at the beginning of this section on control of hazards, liquid processing is one of those rare situations where specific measures aimed at limiting charge generation are also recommended. For low conductivity liquids, or single phase medium conductivity liquids it is recommended that transfer velocities are limited to a maximum of 7 $m.s^{-1}$. Also, for low and medium conductivity liquids where there is a second dispersed phase present (liquid or solid), transfer velocities should be limited to 1 $m.s^{-1}$.

Item	Earthing Requirement
Conducing plant – part of active process (fixed or portable)	≤10^6 Ohms Ideally <10 Ohms
Conducting items - not part of active process	≤10^8 Ohms
Semi-conductive items	≤10^8 Ohms
Personnel	≤10^8 Ohms
Floor surface	≤10^8 Ohms
Conducting process materials (solids, films, powders, liquids)	≤10^6 Ohms
Semi-conductive process materials (solids, films, powders, liquids)	≤10^8 Ohms

Table 8: Summary of Earthing Requirements for Avoiding Spark Discharges

It should be noted here that every item down to the last bolt does not need a separate earthing cable. Reliance can be placed on earthing via conductive plant items, provided the above requirements are demonstrably complied with by measurement. For example, a stainless steel pipe section bolted to a similar earthed pipe by a flange fitting should itself be earthed via the flange bolts and the first pipe. Provided compliance with the above requirements are confirmed by measurement no further earthing measures will be required. Also, the very smallest items (perhaps single, small bolts) will not need earthing at all if their capacitance has been shown to be <3 pF and no high charging mechanism is present. If only Group IIA or Group IIB gases or vapours are likely to be present, or powders with MIEs greater than 10 mJ, then this capacitance can be increased to 10 pF. For any situations that have not been covered in the risk assessment section or in the recommended control measures, expert advice should be sought.

b) Brush Discharges

Brush discharges occur from insulating materials and the only way of avoiding them altogether is to avoid the insulating materials. However, for Group IIA and Group IIB flammable atmospheres thin materials (<2 mm thick) in close contact with an earthed conducting substrate (including clothing on personnel) will not produce incendive brush discharges, although it must be confirmed that the much more energetic propagating brush discharges are not then possible. If it is not possible to avoid the insulating material its size can be limited to ensure brush discharges which might be produced are not incendive to the flammable atmosphere which may be present. Tables 9 and 10 below, taken from CLC/TR 50404 indicate maximum acceptable sizes:

Hazardous Area Zone	Maximum Projected Area (cm^2)		
	Group IIA	Group IIB	Group IIC
0	50	25	4
1	100	100	20
2	No limit*	No limit*	No limit*

Table 9: Area Restrictions for Insulating Materials

Hazardous Area Zone	Maximum width (cm)		
	Group IIA	Group IIB	Group IIC
0	0.3	0.3	0.1
1	3.0	3.0	2.0
2	No limit*	No limit*	No limit*

Table 10: Width Restrictions for Long, Narrow Insulating Materials (e.g. pipes, cable sheaths, etc)

If insulating materials cannot be avoided and the given size restrictions are not possible, special "charge transfer" tests can be carried out to determine the magnitude of discharges from actual items made from insulating materials after deliberate and severe charging. This test may still show the use of the item to be acceptable. Taking all of these together the following recommendations are offered for avoiding incendive brush discharges:

- Avoid insulating materials. Wherever possible replace them with conductive or semi-conductive materials, earthed as appropriate and as discussed above.
- Thin insulators in close contact with an earthed conductor (including clothing on personnel) will not normally produce brush discharges capable of igniting Group IIA or Group IIB gases or vapours.
- Limit the sizes of insulating materials permitted in areas where flammable atmospheres are or could be present to those given on Tables 9 and 10.
- Special charge transfer tests may show the item made from an insulating material to be acceptable despite non-compliance with the foregoing requirements.

Even if compliance with the above is not possible, it may still be possible to justify using an insulating material or object in an area where a flammable atmosphere is or could be. However, the complexity and room for error is such that it is recommended this should only be done with expert help.

c) Propagating Brush Discharges

The best way of avoiding propagating brush discharges is to avoid the structure capable of generating them: the thin insulating layer either in contact with an earthed conductive substrate or the thin insulating sheet or film which might acquire opposite polarity charge on opposite sides.

If that cannot be done, the next option is to ensure that the thin insulator cannot support a propagating brush discharge. There are two requirements if an insulator is to be capable of producing a propagating brush discharge in air:

1. i) It must be less than 8mm thick, and
2. ii) Its breakdown strength must be >4 kV.

If either of these can be shown by measurement to not be true, that is sufficient to state that a propagating brush discharge is not possible. Propagating brush discharges also need a strong charging regime, so the absence of a strong charge generating mechanism can sometimes be used to justify a stance that propagating brush discharges will not happen. However, it is recommended that expert help be sought in reaching this conclusion.

d) Cone Discharges

As cone discharges arise from the electrical properties of the process material (the powder or granule) it may not be possible to prevent them completely. In principle the cone discharge energy might be altered, but based on Equations 17 and 18, it is clear that the main way of controlling it is by changing the diameter of the vessel. Again, this may not always be practical. It may be possible to reduce the effective size of the vessel by the use of inserts, but this is complex and with no properly developed procedures. Hence if cone discharges have been shown to be a potential ignition hazard it is recommended either that expert help be sought to consider addressing the cone discharge issue itself, or consideration be given to inerting the vessel at risk.

e) Corona

Corona is not in itself an ignition hazard, with the possible exception of Group IIC gases. As previously discussed, there is a risk of corona charging other items or its deteriorating into a spark or brush discharge. However, if all of the foregoing guidance has been complied with there will be no isolated conductors capable of acquiring charge by corona, any remaining insulating surfaces will have been limited in size such that brush discharges will not be hazardous, and it will have been confirmed that thin insulators cannot support propagating brush discharges. Hence, although corona may be undesirable, it is also unlikely as a direct or indirect ignition hazard if all the other discharge types have been addressed as recommended. If there are any residual concerns in this respect it is recommended that expert advice be sought.

4. Electrostatic Problems

"Electrostatic Problems" refers to those issues which do not result in a hazard to personnel or property, but which nevertheless do lead to an identifiable problem.

In fact most if not all problems can be can be covered by two basic electrostatic phenomena:

- Electrostatic discharges (shocks to personnel, discharges to equipment, etc.)
- Forces of attraction and repulsion (e.g. materials sticking where they should not and not going where they should).

However, once you start to think of the implications of these in different situations, it quickly becomes apparent that there are a huge range of possible problems, since each operation, process and industry sector will have its own specific variation of what, on the face of it, can be identified as one of only two fundamental issues.

For that reason, it is felt helpful to present a few examples of problems to assist readers to get into the frame of mind to identify, analyse and, ultimately address their own. To this end problems have been grouped into four types: Discharges, Materials Handling, Packaging and Product Quality. Each of these will be discussed in different subsections with single or composite examples drawn from our own experience. However, in order to facilitate a full discussion for each example it is helpful to briefly discuss solutions to electrostatic problems.

4.1 Solutions to Electrostatic Problems

4.1.1 Introduction

For many electrostatic problems, once they have been identified, they can be addressed using exactly the same principles as for dealing with hazards. These are mainly based on reducing charge generation or, more commonly, preventing charge accumulating. The principles which can be employed can be found in Section 3.2.2 "Control of electrostatic hazards". For the most part, if the measures taken would avoid all ignition sources they will also avoid problems.

4.1.2 Special Measures for Electronics

For most common use of commercially available microcircuits in standard packaging, the above principle applies. However, different techniques are often employed. For example, because personnel are usually working in more or less one place, and often at a bench, earthing of personnel is commonly achieved using a wrist strap connected to earth via a suitably sized resistor (to limit the shock hazard from mains powered items). Having said that, a significant exception to this general rule is where microcircuits are unprotected or inadequately protected. Paschen's law (see Section 2.5: "Discharges") means that discharges in air at normal atmospheric pressure will not occur at potential differences less than about 300 V.

Hence, provided nothing exceeds that voltage there will be no ignition sources due to electrostatic discharge. However, direct contact between charged items and unprotected or inadequately protected microcircuits can lead to damage at much lower voltages. Hence, in some situations, particularly in manufacture of electronic microcircuits, even more rigorous controls will be required than for fire and explosion hazards. For that reason it is simply recommended here that expert help should be sought for these situations.

4.1.3 Static Elimination

In some situations it is appropriate to accept that charge generation will occur, and then address the problem by combining the charge produced with an equal and opposite charge to leave the item neutral. This is a technique most commonly used for addressing problems, but is occasionally used for controlling hazards, too. It is also a technique which is almost exclusively used for control of problems associated with insulators, since for conductors earthing is normally so easy and totally effective. Nevertheless, the principle can be applied to conductors, and if they are of necessity isolated from earth this may sometimes be an approach to consider.

a) Principles and Basic Types of Static Eliminator

Figure 12 diagrammatically shows corona discharge as previously described in Section 2.5.6

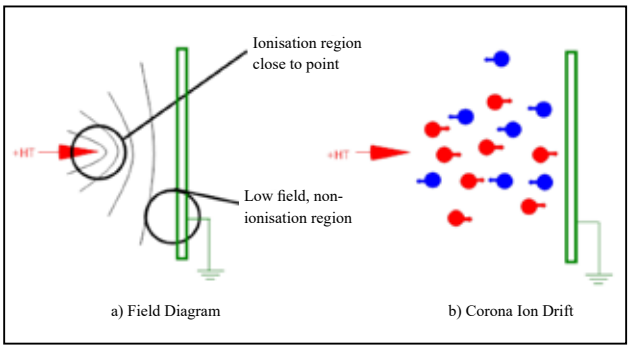


Figure 12: Corona Discharge from a High Voltage Electrode

As previously discussed, ions are generated in the high field region close to a sharp point, but not in the lower field region further way from the point. Nevertheless, ions generated at the electrode drift away from or towards it (depending on the polarity), with those drifting away passing through the low field region until they are captured by something – in the diagram the earthed surface (see Figure 10). If we look at Figure 11, we can see that although the pointed electrode is now earthed, and the plane surface is at high voltage, in terms of electric field the situation is exactly the same as it is in Figure 10.

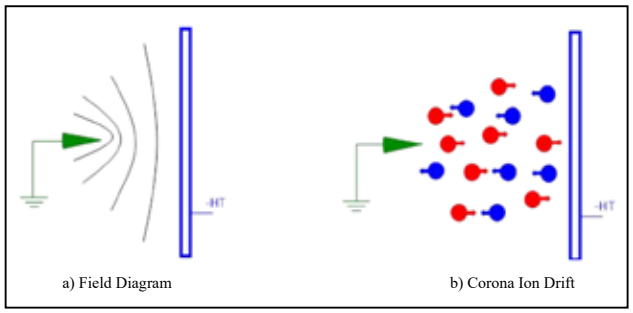


Figure 13: Corona Discharge from an Earthed Electrode

As before, the high field in the immediate vicinity of the earthed electrode leads to ionisation, and positive ions drifting away from the electrode, through the non-ionisation region, to be captured by, in this case, the negatively charged surface. Clearly, the capture of positive ions will tend to neutralise the charge which caused ionisation in the first place.

Hence, this general type of structure, comprising an earthed sharp point, can be used to neutralise charge on nearby objects, irrespective of the polarity. The sharp point is referred to as a passive static eliminator, with practical embodiments being in the form of tinsel, carbon fibre brushes, pins or thin cut wire, two of which can be seen in Figure 14.

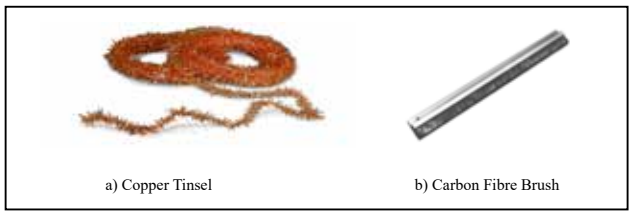


Figure 14: Two Examples of Passive Static Eliminators

Although low cost and often very effective, passive static eliminators have one drawback: they will always leave a residual charge. This is because it is the charge to be neutralised which drives the corona ionisation, and this simply becomes ineffective once the surface potential drops below a threshold value.

This can be addressed by applying a high voltage to sharp points such that ions are always generated irrespective of the residual voltage on the charged item (more like the diagram in Figure 12). However, the risk then is that the object being treated continues to receive corona ions even after it has been neutralised. In other words, it becomes charged with the opposite polarity from the one it started with, which can lead to just as big a problem as the one that was to be solved. Hence, when a DC voltage is applied to corona electrodes for the purpose of static elimination there must be a means in place to prevent opposite charging. For example, one approach may be to include a residual voltage sensor with the system to control the static eliminator.

Another approach is to apply a high A.C. voltage to the sharp point. This is shown diagrammatically in Figure 15.

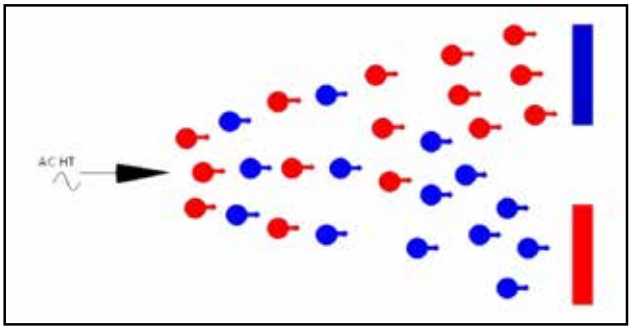


Figure 15: Diagram Showing Action of an AC Static Eliminator

Here the AC high voltage sequentially generates positive and negative ions, which are attracted towards items of opposite charge. Hence, an AC static eliminator will neutralise charge on any items, whichever the polarity of charge.

Furthermore, provided the design has taken account of the normal imbalance in ion production for symmetrical AC about earth potential, once the item is neutralised it will attract equal numbers of positive and negative ions, thereby maintaining neutrality.

A typical AC static eliminator can be seen in Figure 16. In this case it is an all stainless steel and PTFE construction designed for pharmaceutical applications. The sharp points are visible along the front of the bar and the design is such that opposite polarity ion generation is equal, to ensure true neutrality is achieved. An air connection is available to aid ion transport.



Figure 16: Chilworth Technology AC Static Eliminator Bar

A wide range of static elimination equipment is available based on the above basic approaches.

b) Air Assistance

In addition to the basic static eliminators discussed above, some types use a stream of air to enhance the range. Without air assistance static eliminators are probably most effective over a distance of perhaps 25 mm to 50 mm. With air, effectiveness can be increased to perhaps 100 mm – 200 mm with local jets, or to 2 m or more with broad flow, fan assistance.

c) Static Eliminator Installation

It is also important to locate static eliminators correctly.

As indicated, static eliminators work by generating ions which are attracted towards the charge item. The higher the voltage on the charged item, the more effective it will be at attracting ions. However, for a given charge, the higher the effective capacitance the lower the voltage (see also Section 2.3.4 – "Capcitance"). Hence, static eliminators will be most effective if placed in a location where the charged surface is as far away from earth as possible. Examples of good and bad locations for static eliminators are shown in Figure 17.

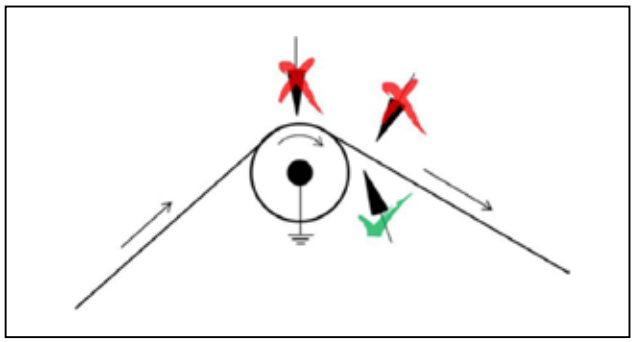


Figure 17: Examples of Good and Bad Static Eliminator Placement

This diagrammatically shows a highly insulating plastic web passing over an earthed conducting roller. Three possible locations of static eliminator are indicated by the large arrows.

Thinking first about the static eliminator above the roller, there are two problems with this location. The first is that the charged plastic film is in close contact with the roller and will therefore be only at low potential. As a consequence the driving force attracting ions to the film will be low, minimising the effectiveness of ion transfer and hence neutralisation.

Now think about the static eliminator a little downstream of the roller and above the film. Here the film has moved away from the roller so the charge generated at the roller will be seen at high potential. Hence, the driving force for ion transfer will be high, and ion transfer from the static eliminator to the film effective. However, charge was generated by contact between the roller and the film, and will therefore reside on the underside of the film.

On the other hand, ions from the static eliminator will be captured on the top side of the film. In fact the film will for the most part appear uncharged, although the reality will be a high charge of one polarity on one side of the film and a high charge of the opposite polarity on the other side. This, it will be recalled, is exactly the charge structure that can lead to highly energetic propagating brush discharges (see Section 2.5.3). Charges may stay separated in this way for days or even weeks for very insulating films. Also, when the film is wound on to a wind-up reel the potential difference across each layer and each turn will be additive, which can (and often does) lead to substantial discharges across the sides of the wound film.

The third location is on the underside of the film just downstream of the roller. Here, not only has the charge left the immediate vicinity of the roller, thus promoting effective ion transfer, but it is also the charged side of the film being treated. Hence, although this will often be the least convenient location in terms of the physical installation, it is likely to be the most effective in terms of ensuring the film shows minimal problems due to charge as it moves downstream.

d) Where to use Static Eliminators

Static eliminators are often routinely employed where problems (as opposed to hazards) due to static electricity have been experienced or are expected. Where the issue is one of electrostatic hazards, special core is required, which means their use in this type of application is much less common. First, of course, by installing an active static eliminator a high voltage source is being deliberately placed in an area, which by definition could be hazardous in the presence of an ignition source.

However, the total energy required for effective static elimination is usually very low, and many modern static eliminators are now certified for use in hazardous areas arising from the possible presence of Group IIA or Group IIB materials. Hence, by appropriately specifying the equipment, this should not be problem.

Perhaps the bigger problem is that for the most part static eliminators work invisibly. That is, there is usually no obvious way of knowing how well they are doing their job, if at all! And if safety is reliant on the continuing effectiveness of one or more static eliminators there is a clear fail to danger situation: static elimination could be lost without ever knowing it until an electrostatic discharge causes an ignition!

It is this uncertainty, and the special precautions that are required to avoid it, which means static eliminators are rarely used for controlling electrostatic hazards, and usually only when there is no other effective means. Even then, their use will usually be in combination with other measures as the ultimate basis of safety (e.g. explosion protection) or to guarantee effectiveness of the static eliminator.

4.2 Examples of Electrostatic Problems

In the next sub-sections examples of some different types of electrostatic problem are briefly presented. However, it must be appreciated that neither the listed types of problem, nor the examples under each type, can be considered in the least extensive or complete. They are simply presented as examples, for interest or perhaps as an aid to thinking in the right way to identify electrostatic problems. In fact, so many problems can be caused by static electricity across such a broad range of industries and situations, that if you are encountering a problem and don't know what's causing it, or even if you think you know what's causing it but your solution is not working, it may be worth asking the question: could it be caused by static?

4.2.1 Discharges

a) Shocks from a Production Line

The production line in question delivered metallic items to a manual packing facility via a conveyor belt. At the end of the conveyor belt a man was required to pick up the items and place them in a box. The problem was that every time the man at the end of the line touched one of the items he was to pick up, he got a shock! After a while this can become very tiresome and stressful, so something had to be done.

By the time we visited the site it had already been established that the conveyor belt was highly insulating and charged. Also, a static eliminator had been placed over the conveyor – but had been found to be totally ineffective. When something you think is going to work doesn't, it is often best to go back to first principles and properly analyse what is going on. This was our first approach, the outcome of which can be seen with the help of the diagram in Figure 18.

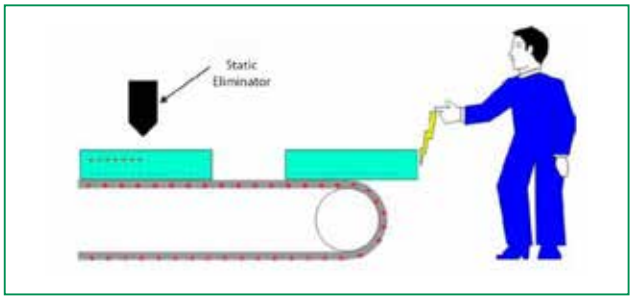


Figure 18: Sketch of Shock Problem After Static Eliminator Installed

The conveyor was indeed insulating and highly charged – illustrated as positively charged in Figure 16. Placing the conducting objects on the conveyor meant that charge was separated within the objects by induction, though at that point there had been no net transfer of charge.

The static eliminator neutralised the positive charge residing close to the surface of the metal, leaving only the negative charge closely coupled to the positive charge on the belt. However, it is interesting to note that only with the introduction of the static eliminator did the metal items acquire a net charge!

Now it is clear, that whether the metal items are treated with a neutraliser or not, the man at the end is still going to get a shock!

Two approaches could be used to avoid the problem. The first would be to replace the belt with an earthed conductive or static dissipative belt. The second would be to ensure the metal item is earthed by direct contact even as it leaves the belt. In the diagram an earthed chain or conductive brush might be appropriate, though the precise approach would depend on the exact nature of the metal item and the manual transfer.

b) Damage to Electronic Communications Device

A hand-held electronic communications unit had been sold worldwide but was exhibiting failures in the Middle East. The failure mode involved the display becoming gradually dimmer before failing altogether. It was speculated that the problem was static electricity in the particularly low humidity environment of the Middle East, but failure to prove the hypothesis led to DEKRA being asked to investigate.

The display drivers of the failed units were found to have all failed in a particular way, and it was speculated that cleaning the display with a cloth or by rubbing on clothing could have led to electrostatic discharges in that area, leading to the failure.

Trials in which unit displays were deliberately subjected to electrostatic discharges from a Human Body Model (HBM) discharge simulator circuit resulted in failures similar to those observed in the field. Subsequent electron microscopic examination of the driver chips also revealed observable damage at the same locations for both field and lab-induced failures.

Trials were then undertaken with a ring electrode connected to the unit's ground plane and located around the display, as a discharge sink. This was found to prevent damage from the HBM discharges, even when voltages of more than 20 kV were used, and was presented as a practical solution to the problem. Figure 19 shows diagrammatically the unit, the trials approach and the proposed solution.

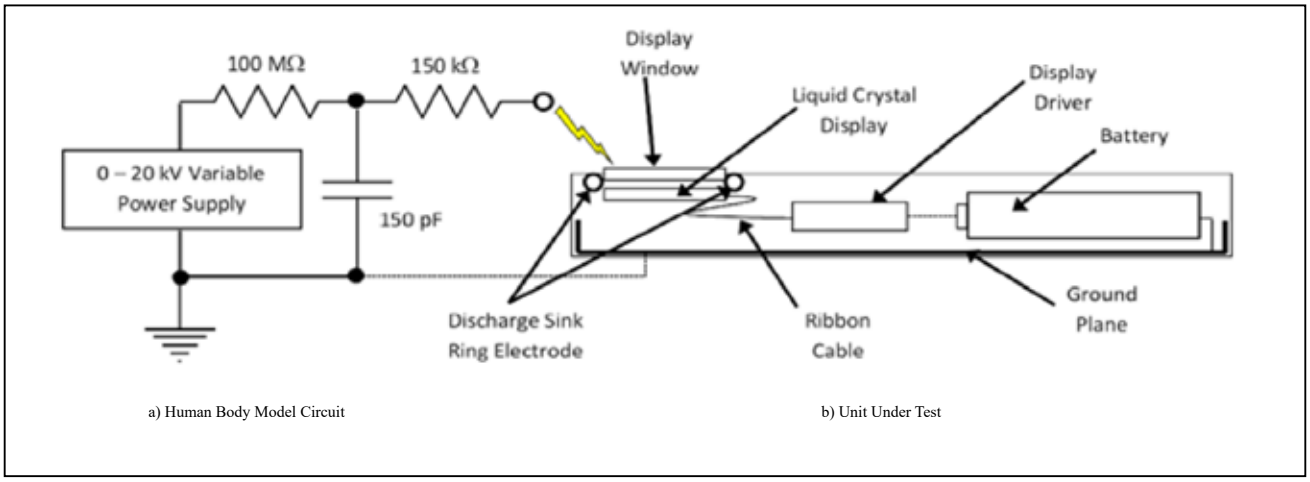


Figure 19: Diagrammatic Representation of Trials Approach and Solution

4.2.2 Materials Handling and Processing

a) Sieving

Electrostatic charge generated on powders can lead to sieve blinding. The charged powder adheres to the mesh, gradually building up until the holes in the mesh are covered and particles cannot get through. One client suffered such problems on "upgrading" their process. The polymer powder was initially separated from water in a centrifuge and then size graded by passing through a sieve, before final drying of the product in a fluid bed dryer. This process worked well.

However, the "upgraded" process fully dried the powder by centrifuging and passing through a fluid bed dryer before size grading in the sieve. Sieving rate for the upgraded process was very poor. The problem was identified as static-related as a result of the very dry environment downstream of the fluid bed dryer and the high levels of charge generated as a result, leading to blinding of the sieve. The solution implemented in the light of the above analysis was to increase the post-drying humidity by adding steam between the fluid bed dryer and the sieve!

b) Powder Flow

A client was micronising a pharmaceutical powder in a jet mill, collecting the product in a hopper beneath the jet mill. The plant was fully closed since the basis of safety for the process, which involved a flammable powder, was explosion containment. Once enough powder had been collected, the micronising process was stopped and the powder dropped out of the hopper via a bottom valve. Unfortunately, after micronising the powder was so highly charged that it adhered to the inside of the hopper and was

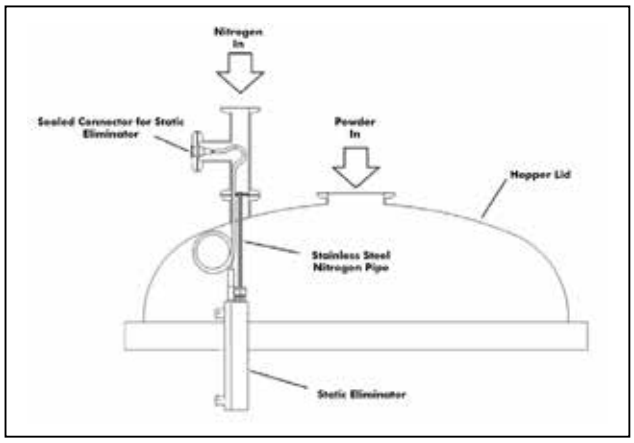


Figure 20: Static Eliminator Installed Beneath Hopper Lid

extremely difficult to get out. This was not only frustrating for operators but also a rate limiting step, keeping overall productivity down. DEKRA undertook trials with a static eliminator fitted inside the hopper, such that it treated powder dropping from the microniser. Figure 20 shows how the static eliminator was installed beneath the hopper lid. With the static eliminator switched off, but nitrogen passing through it to keep the static eliminator clean, the powder was just as difficult as always to get out of the hopper. However, when the static eliminator was switched on during micronising, the p owder readily fl owed out of the hopper when required. Indeed, the powder was so free-flowing in the bin into which it had been dropped that it had the appearance of being aerated. However, when the bulk density was measured it was found to be higher for the free flowing powder treated with the static eliminator, suggesting that, if anything, this was less aerated than the problem powder!

4.2.3 Packaging

a) Sack Filler Productivity

A client was filling a powder product into a sack. The sack was sealed by the weight of the product pressing on the closure from inside, so although the sack was filled by weight, it was designed to just take the correct volume. A reduced volume and the closure seal would be ineffective.

Unfortunately, it was often found that the automatic sack filler attempted to overfill the sack, resulting in the powder backing up in the machine and the machine stalling. This meant spending considerable time stripping the machine down, clearing it out and restarting. The overall result was a considerable loss of productivity from the sack filler.

It was known that the powder was susceptible to electrostatic charging, especially under particularly dry conditions. A hypothesis was therefore proposed that unusually high rates of charging could lead to a reduced bulk density due to mutual repulsion of particles. In the extreme, the bulk density could then be so low that the desired weight would no longer fit in the sack.

Laboratory trials were carried out in which the powder was charged by corona in a free falling stream. It was then caught and allowed to settle naturally (without shaking or tamping) and the total charge, volume and weight measured. The bulk density was then plotted against charge to mass ratio, Figure 21.

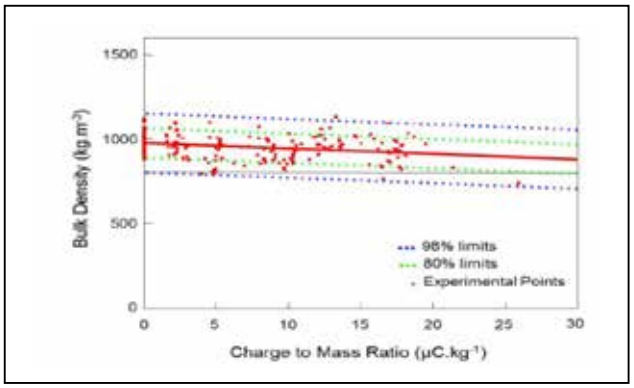


Figure 21: Corona Discharge from a High Voltage Electrode

As might be expected in a graph of this type, there is quite a lot of scatter in the data points, although there is a clear trend of reducing bulk density with increasing charge to mass ratio. In addition to the data points and trend line, limit lines are also shown on the graph. The 80% limit lines (green dashed lines) contain 80% of the data points. In other words, 10% of all the data points appear above the upper 80% line and 10% below the lower 80% line. Similarly, 1% of all data appear above the upper blue 98% line and 1% below the lower 98% line.

Let's imagine the sack is designed such that when the powder is uncharged, random variation in the bulk density means that for one in a hundred sack fills the desired weight will not fit in the bag. From the graph, this position is represented by the point where the lower 98% limit line crosses the y-axis. Now suppose the powder becomes highly charged: say, 30 $\mu C.kg^{-1}$. Drawing a horizontal line across the graph from the design density to the 30 $\mu C.kg^{-1}$ position, we see it now just crosses the lower 80% limit line.

In other words, simply by increasing the charge to mass ratio from zero to 30 $\mu C.kg^{-1}$, instead of having a situation in which the fill weight of powder will not fit in the sack for one in a hundred fills, we now have a situation in which the fill weight will not fit for one in ten fills. And if the increase in charge was as a result of a reduction in humidity (which is quite possible) the increase in down time could simply be interpreted as "the filling machine is playing up today"! The answer of course is to ensure the powder is never highly charged, and one way would be to use a static eliminator as for the previous example.

b) Tablet Blister Packing

Tablets are filled in blister packs by heat forming the blisters in a thermoplastic web, placing one tablet in each blister and then closing the blisters by laying and sealing a second web over the first. Figure 22 illustrates the tablet blister packing problem DEKRA investigated and solved.

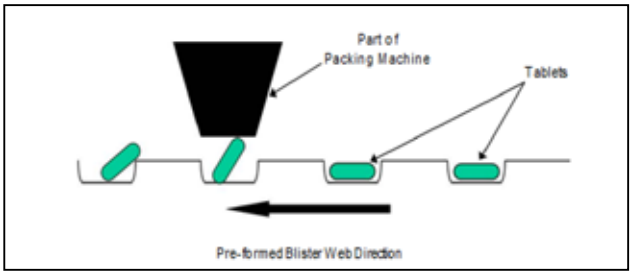


Figure 22: Blister Packing Problem

In the illustration the blisters have already been formed in the thermosplastic web, tablets have already been placed in the blisters and the web is moving from right to left. As a tablet passes under a machine part which is close to the web, charge causes the tablet to be lifted, not completely out of the blister but just enough so that as the web moves on the tablet is left part way out of the blister and resting on one side. Then, when the displaced tablet passes under another machine part close to the web, it is caught and crushed between the machine part and the blister side.

That is exactly what we saw happening when we went on site to investigate the problem. However, for the pharmaceutical company concerned it was worse than that. Every time a tablet was caught and crushed, it jarred the whole web causing all the tablets already in open blisters to jump out, most ending up on the floor! Clearly, tablets cannot be swept up off the floor and put through the machine again, so not only did this problem lead to machine down time and loss of packing productivity, it also led to considerable wastage of an expensive product.

Having observed the problem, trials were carried out with an off-the-shelf static eliminator. This demonstrated the effectiveness of the proposed solution, but the anodised aluminium case and unsuitable plastics of the static eliminator meant the pharmaceutical company would not permit it to be installed for production runs, only for trials. Hence, Chilworth designed and fabricated the stainless steel and PTFE static eliminator shown in Figure 14, which was then fitted as a solution to the problem. Indeed, the blister packing machine manufacturer also began fitting this solution to some new machines after that.

4.2.4 Product Quality

a) Dust Adhesion

Just one example of dust adhesion being a problem was where a car manufacturer needed to paint a plastic moulding. Dust on the part could not even be removed with a compressed air gun, which resulted in a poor paint finish. The problem here is that moulded plastic parts are in such intimate contact with the mould that after de-moulding they are almost always highly charged. For some plastics this charge will not be lost for several weeks even under ideal conditions, and in practice it may never be lost. This charge can lead to dust being so strongly attracted to the surface that once it settles even compressed air will only move it around on the surface and never detach it altogether. The solution in this case was to use a long range static eliminator (a blower type) to neutralise the charge on the plastic parts in the first place and hence limit dust attraction. This could also be supported by a static eliminating compressed air gun (a combined static eliminator and compressed air gun) immediately before painting. The static eliminating compressed air gun ensures that as dust is moved by the compressed air, simultaneous static elimination prevents it being attracted to another part of the surface, allowing it to be completely detached.

b) Powder Bottle Filler

A small bottle was being filled with powder, but charge on the bottle and the powder meant there was always some powder down the side of the bottle. The contaminated appearance of the filled bottle was perceived as a product quality problem. In this case a special, point-source static eliminator was installed at the bottle filling head to neutralise static charge and avoid the poor appearance.

5. Beneficial Applications of Process Safety

As with electrostatic problems, there are so many beneficial applications that it is only possible to select and highlight a few to give a feel for the range. However, if these prompt any ideas for new applications, discussion with an expert is recommended.

5.1 Liquid Atomisation

If a liquid with finite conductivity is delivered into a region in which there is an electric field, the liquid will become charged by induction and will accelerate away from the source. This can be seen diagrammatically in Figure 23.

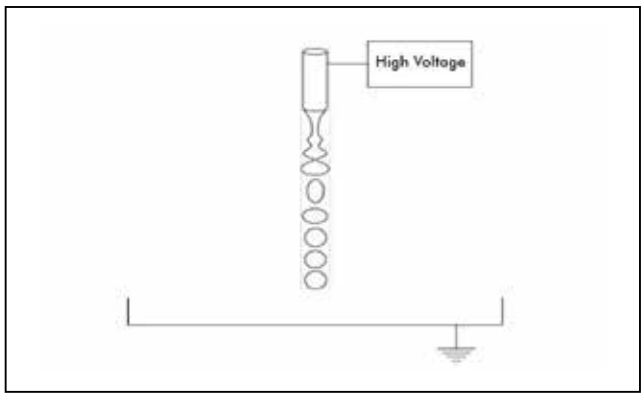


Figure 23: Diagram Showing Electrostatic Atomisation

Looking at Figure 23, if a negative high voltage is applied to the conducting tube through which the liquid is delivered, liquid carrying an excess of negative charge will accelerate towards the earthed collection target. In doing so the liquid will "neck down" to form a relatively long, thin cylinder of liquid, or ligament. Whenever a cylinder of liquid is formed like this, instabilities will develop leading to break-up of the liquid into drops which are approximately twice the diameter of the ligament from which they were formed.

When the ligament has been formed by electrostatic forces, as described above, it is very stable, such that the resulting spray has an exceptionally narrow drop size spectrum. Furthermore, the diameter of the ligament can be controlled by controlling the electric field (applied voltage, and distance from earth), the liquid flow rate, and the liquid conductivity.

Hence, within a window of stability, a spray with a well-controlled and defined median drop size, and very narrow spectrum of drop sizes, can be produced. Depending on the chosen spray parameters it is possible to produce drops ranging from single microns (or even sub-micron) to perhaps 150 – 200 µm.

The flow rate from a single ligament as shown in Figure 23 is relatively low, so multiple ligament nozzles can be used to increase the total flow rate. Multiple ligaments can be produced not from multiple small apertures, but from slots. For example, Figure 24 is a photograph of an annular electrostatic spray with an annulus diameter of about 5 mm.

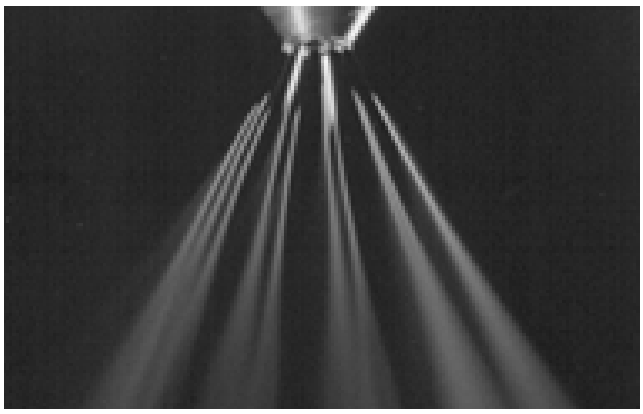


Figure 24: Annular Electrostatic Spray Nozzle

In a multi-ligament nozzle, provided each ligament is exposed to the same electric field and each is delivering the same liquid flow rate, each will be providing drops with the same narrow drop size spectrum centred on the same median. Hence, much of the effort in nozzle design is ensuring the flow rate in all ligaments is the same and each sees the same field. The drop size in the photograph is about 50 µm.

Increasing the size of annular nozzles becomes self-limiting after a while as the space charge in the spray tends to reduce the field at the nozzle. However, this can be overcome by constructing linear nozzles. These use a linear slot, though the same rules apply: ensure each ligament carries the same flow rate and each is exposed to the same electric field and the nozzle as a whole will produce well controlled, narrow drop size spectra. And as an indication of flow rate, a 50 cm long linear nozzle will handle about 1 Tonne/day when producing 50 µm drops.

Although the flow rates are not particularly high, they are comparable to many speciality chemical processes. Furthermore, the basic process of generating narrow drop size spectra can provide the basis for too many uses to describe in full. Hence, there follows a short list of applications and potential applications for electrostatic atomisation, some of which have been well developed, and some of which have been taken no further than the realms of laboratory trials and await further development.

a) Coating and finishing

The narrow drop size spectrum has been used to produce some exceptionally fine coatings down to 1 μm and less in thickness. Furthermore, trials have shown that coatings from linear nozzles can be switched on and off entirely under electronic control.

b) Spray Drying

If the solvent is allowed to evaporate before the drops land, leaving behind a previously dissolved solid,the result is a dry powder. Obviously, in this case the quality of the dry powder reflects the quality of the spray from which it was formed - controllable and narrow particle size spectra. In fact, given the range of drop sizes that can be produced, spray drying from electrostatic sprays offers the possibility of producing high quality powders direct from solution without size reduction and classification steps.

c) Microencapsulation

Under some circumstances, three parallel slots can be used to produce ligament formed from two, coaxial liquid streams. If the outer liquid solidifies before landing, microcapsules will be formed.

d) Drug Delivery

Given the small particle sizes that can be produced by electrostatic sprays, in principle they could be delivered to the deep lung for effective delivery of all kinds of systemic treatments. It would normally be expected that to assist this, charge would first have to be removed from the particles (a process which has been demonstrated), though it is possible that non-zero residual charge could help target a particular location.

e) Spinning

If the solvent from a solution is allowed to evaporate from the ligaments before they break into droplets, the result is fibres. This technique has been used to produce 50 mm polyvinyl alcohol fibres for use in liquid crystals displays, though it may also be possible to produce fibres from materials that could not normally be spun. Melts, rather than solutions, can also be used to produce fibres by this technique, though of course in this case the liquid must cool and solidify before the ligament breaks up.

5.2 Electrostatic Separation of Materials

If materials stick to an earthed conducting surface as a result of their charge, they will fall off at a time determined by their rate of charge decay. Hence, materials with long charge decay times can be separated from materials with short charge decay times. Also, charged materials falling through an electric field formed between two electrodes will accelerate towards one electrode or the other leading to a spectrum of materials from the most negatively charged at one extreme through to the most positively charged at the other. One particularly useful way of using this technique is to tribocharge a binary mixture of materials against a third material chosen such that one will charge positively and one negatively. Then when the mixture is dropped through the field, one material will move in one direction while the other moves the opposite way.

DEKRA Process Safety designed and demonstrated an automatic plastic separation process using a combination of these techniques for one client with the laboratory scale experimental rig in Figure 25.

What can be seen in Figure 23 is just one stage of the multi-stage separation process, in which a carbon fibre corona brush charges mixed plastic chip before it is dropped on to an earthed metal drum. The drum rotation speed is such that the plastic with the shorter charge decay time has lost so much charge by the time



Figure 25: Experimental Laboratory Scale Plastics Separation Rig

the drum has rotated 180° that it all drops off. However, the material with the longer charge decay time remains stuck until it is removed from the surface using a brush.What can be seen in Figure 23 is just one stage of the multi-stage separation process, in which a carbon fibre corona brush charges mixed plastic chip before it is dropped on to an earthed metal drum. The drum rotation speed is such that the plastic with the shorter charge decay time has lost so much charge by the time the drum has rotated 180° that it all drops off. However, the material with the longer charge decay time remains stuck until it is removed from the surface using a brush.

The whole multistage separation process was very successful. As required by the project it was demonstrated that the client's materials could be automatically separated from post-consumer plastic waste (real waste, taken from a waste treatment plant) after washing in water (to simulate the current washing and pre-separation based on flotation). What was surprising was the purity of the client's materials which was obtained: better than 99%.

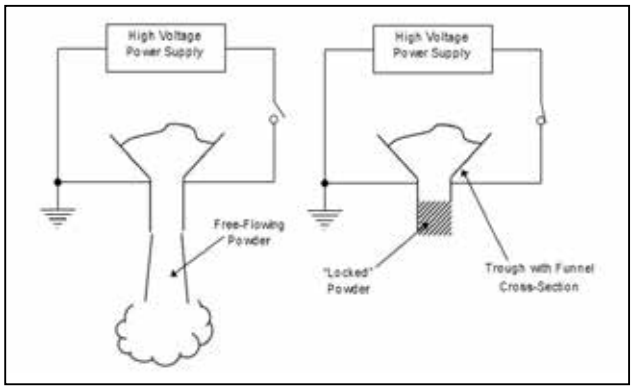


Figure 26: Diagram Illustrating the Electrostatic Valve

5.3 Electrostatic Valve

If a normally free flowing, modest conductivity powder is exposed to an electric field, given the right combination of field strength and powder conductivity, the powder particles will lock and cease to flow. This concept forms the basis of an electrostatic valve for powders, as illustrated in Figure 26.

There are two main potential advantages with this arrangement. The first is that unlike most conventional valves, when the electrostatic valve is "open" (the powder is flowing), there is nothing at all in the flow path. Hence there is nothing to impede flow, nor is there anything to become contaminated with retained powder.

The second advantage is that, although the diagram illustrates a conventional mechanical switch, in reality the field can be switched on and off entirely electronically with no moving parts. That means flow can be for anything from very short pulses through to permanently on. Between these two extremes it is possible to control the average flow rate, again under fully electronic control, by applying pulsed flow for defined periods and at defined intervals.

Figure 27 shows an actual laboratory trials electrostatic valve, fully "closed", and "closed" after a short "open" pulse, in order to illustrate the flow rate flexibility.

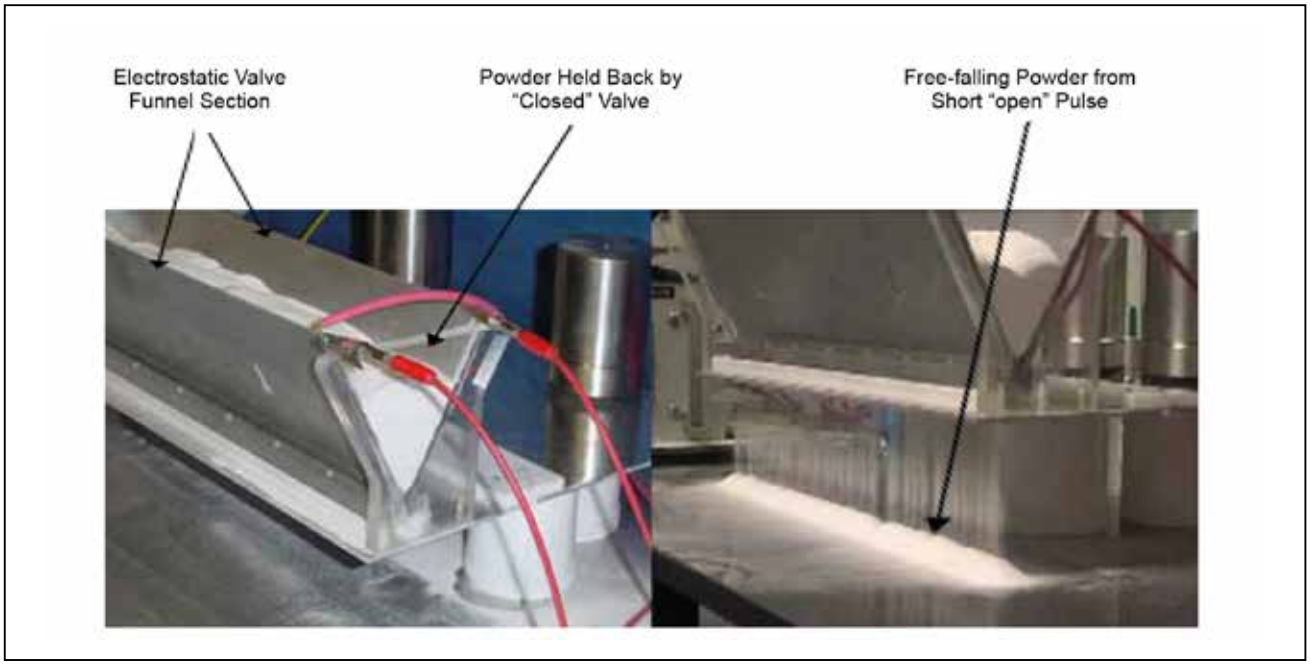


Figure 27: Laboratory Trials Electrostatic Valve with Aluminium Oxide Powder

5.4 Powder Transport and Deposition

We have seen how induction charging occurs (see Section 2.2.3). Figure 1 showed diagrammatically how charge will be separated (induced) when anything other than a very good insulator is exposed to an electric field. Then, when the object touches one field boundary (electrode) charge will be lost leaving a net charge of the same polarity as the electrode which was touched. If the object then stays within the field (unlike the illustration of Figure 1) it will be repelled from the electrode it touched and attracted towards the other. Once it touches the other electrode its charge polarity will be reversed, and so on. The result is that such an object will oscillate backwards and forwards between the two electrodes.

Of course, if the electrodes are not parallel, the trajectory with each cycle of the oscillating object will tend to carry it towards the more divergent end of the electrode system, as illustrated in Figure 28. This forms the basis of one type of electrostatic powder transporter.

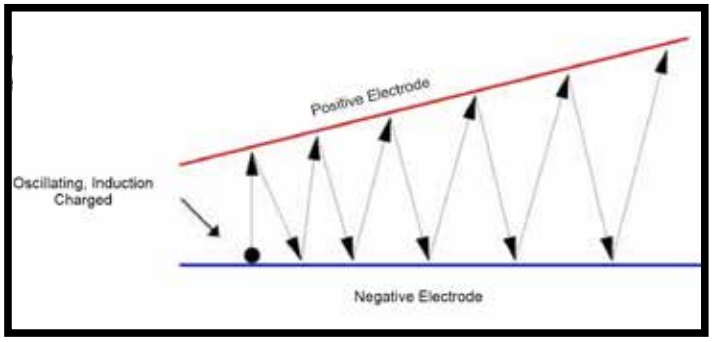


Figure 28: Induction Powder Transporter Concept

When powder of an appropriate resistivity is placed at the narrow end of this transporter and the field applied, all the particles oscillate between the two electrodes producing a cloud which gradually moves towards the divergent end. This concept has been proposed as a means of distributing powder over some surfaces for the purpose of visualising fingerprints. However, DEKRA has used it, together with an electrostatic valve, to develop a powder deposition device for one client.

The brief in this case was to develop a system capable of producing a very uniform but very diffuse distribution of powder on a web surface as part of a production process. DEKRA proposed the device shown in cross section in Figure 29 and described below.The electrostatic valve delivers powder to the space between the Powder Transport Electrodes at an electronically controlled average flow rate, but as a series of pulses at one second intervals.

The Powder Transport Electrodes then carry the powder as a cloud towards the slot. As it does so, both the powder delivery pulses and any lengthwise non-uniformities in flow through the valve are removed by the randomising effect of the transport oscillations. Hence, by the time powder reaches the slot it is in the form of a very uniform cloud both spatially and temporally. Some powder passes through the slot and produces the coating. Powder which passes the slot is brought back by the convergent electrodes on the other side.

Laboratory scale trials worked extremely well and a full scale, 1.2 m wide unit was constructed for use on a factory production line. Figure 30 shows the core of the production scale powder deposition unit, though on the factory production line much of this was hidden inside an earthed outer housing and powder delivery system designed to maintain the level in the electrostatic valve.

Figure 31 shows the uniformity of results obtained with this unit by zooming in on two randomly selected 1 mm x 1 mm squares. It should be noted that for visualisation purposes the deposition density seen in Figure 31 was made much higher than the production requirement, achieved by slowing the web speed.It would be quite impossible in a short document such as this to deal with the full range of possible electrostatic applications in detail, or even just those with which DEKRA has been involved. Hence, this section simply lists very briefly a number of other applications and application types which have been proposed and/or developed.

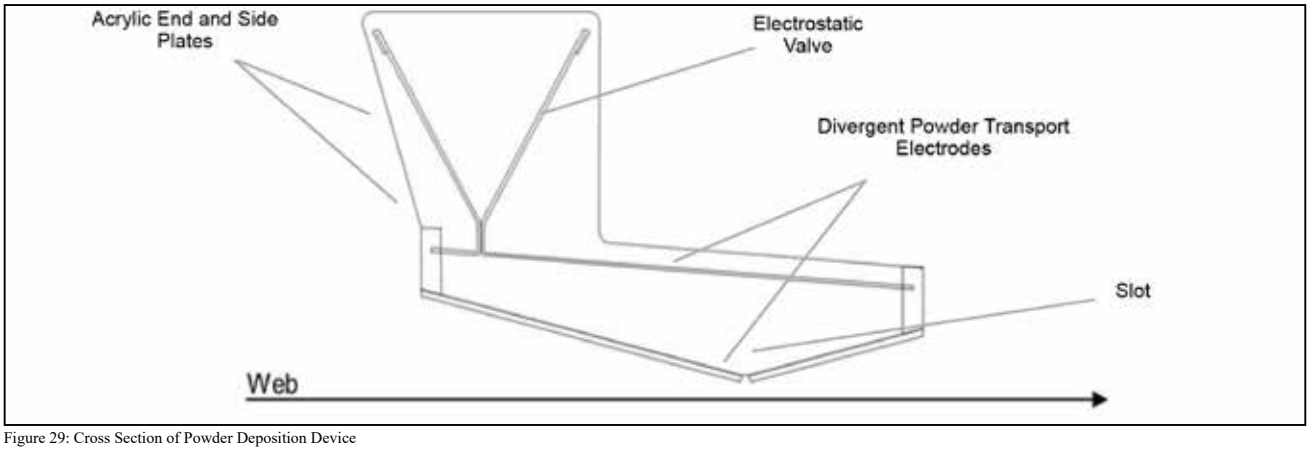


Figure 29: Cross Section of Powder Deposition Device

5.5 Other Electrostatic Applications

a) Electrostatic Precipitation

This is probably the oldest patented application of electrostatics, and is used for removing particulates from gases. Electrostatic precipitators are often, though not exclusively, seen treating flue gases.

b) Pinning

Electrostatic forces can be used to temporarily hold items in place while some other operation is carried out. This is referred to as "pinning". Amongst other things, it has been used to hold paper in place on plotters, and to hold plastic sheets together whilst welding them.

c) Powder Coating

Powder coating involves capturing highly charged powder on the item to be coated, and then fusing the powder to form a coherent, conformal coating. It is widely used as a solvent-less means of providing a decorative and protective finish with minimal waste as over-sprayed powder can be collected and re-used.

d) Flocking

Flocking involves charging short fibres and depositing them on an adhesive-coated surface. The effect of the electric field on the fibres is such that they stand vertically against the surface on which they are deposited. The result is the velvet-like surface of flocked decorative wall and floor coverings.

e) Photocopying and Laser Printers

Photocopying is achieved by producing a latent image in charge on a cylinder, which then attracts toner particles to form a loosely bound image. The toner is transferred to paper where it is fused to form a permanent image. Laser printers work in a similar way. Photocopiers and laser printers are, of course, extremely widely used, but similar techniques have been proposed simply as a means of accurately dosing small quantities of powder.

f) Surface Corona Treatment

The chemistry of many modern plastic surfaces makes them very difficult to print on. For some materials the surface can be chemically altered by exposing it to corona, permitting printing but with no visually obvious change.

g) Assisted Filtration

As it is necessary to filter out finer and finer particulates for some applications, the filter media must become increasingly dense, eventually making the pressure drop across them very high, even for modest flow rates. By using charged material for the filter medium, particulates can be captured even if they could physically fit through the medium pores. This permits increased filter efficiency without excessive pressure drops; a principle used in HEPA filters.

h) Electrostatic Clutch

If powder particles are suspended in an insulating liquid, exposure to an electric field can cause them to lock, in the same way as for the electrostatic valve described in Section 5.3. In effect, the viscosity of the liquid suspension can be changed from low to very high (virtually solid) simply by application of an electric field. And if the electrodes are two discs, one on a shaft driven by a motor, and the other on a drive shaft, the assembly is an electrostatic clutch under electronic control.

i) Pump

If ions are injected into a liquid and accelerated under the influence of an electric field, they can carry the liquid along with them. The resulting "ion drag" pump has no moving parts yet under ideal conditions can produce liquid heads of 1 m – 2 m, although flow rates tend to be quite modest.

j) Other Applications?

If any of the applications in Section 5 have prompted ideas for new applications, discussion with an expert is recommended. No idea will be considered too outrageous. Some may already have been tried. And there could be some very special benefits awaiting those who choose to develop the concepts.



Figure 30: Production Scale Powder Deposition Unit

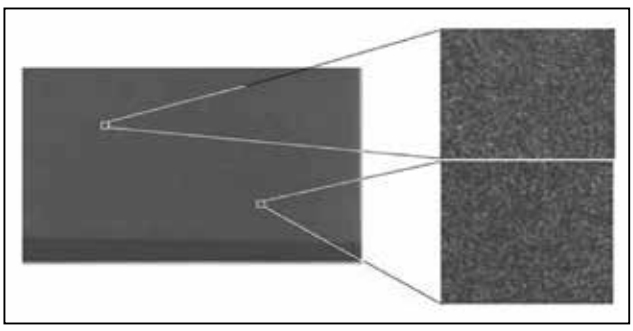


Figure 31: Photograph Showing Uniformity of Powder Deposition in Full-Scale Trials

6. Measurements and Instrumentation in Electrostatics

This section briefly describes the operation and form of some common instrumentation used in electrostatics. A more theoretical discussion of most of the variables referred to in this section can be found in Sections 2.3 and 2.4.

Of course, measurements must always be carried out with care, but it is especially important in electrostatics to be sure that the measurement you are making is not significantly changing the variable being measured. In case of any doubts in this respect expert help should be sought.

6.1 Electric Field and Surface Potential

Electric field meters come in varying forms. The lowest cost options rely solely on induction, but can be subject to reading drift. Apart from the generally low cost, these can usually be recognised by the fact that they will have a "zero" button or switch, which must always be operated while pointing the instrument at a known good earth, prior to starting measurements or taking any critical readings.

One of the most popular types of field meter which does not suffer from drift is sometimes referred to as a field mill, because of the form of rotating vane on the front of the instrument which is the way the drift problem associated with simpler induction types is avoided.

An example of a Field Mill is the JCI 131 Adverse Conditions Field Meter, shown in Figure 32, together with a simplified specification.

JCI 131 Specification	
Full scale (4 ranges)	2, 20, 200 cr 2000 kV.m^{-1}
Accuracy	± 1% FSD
Frequency capability	3 Hz (70 Hz for high frequency)

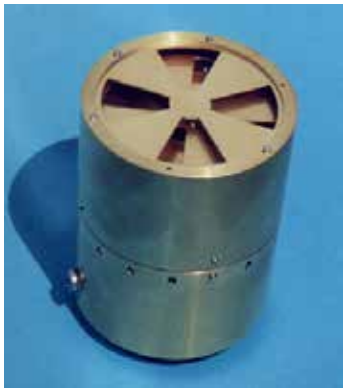


Figure 32: JCI 131 Adverse Conditions Fieldmeter

The JCI 131 is a relatively large instrument which, as the name implies is designed for adverse conditions including direct exposure to rain outdoors. It is therefore used mainly for outdoor monitoring and research purposes. It therefore has no display on the unit itself, simply providing the measurement in the form of an electronic signal which would normally be connected to a remote base unit with a display. The high frequency version is capable of monitoring mains frequency AC fields, and its base station is designed to resolve mains frequency field components from slowly changing, essentially DC, fields.

The JCI 131 has been used as the basis of a lightning warning system, and for long term remote monitoring has an option whereby its continued operational health can be monitored. For many situations, a smaller, hand held meter is more convenient, and it is in this category that most induction type field meters fall. However, field mill types are also available as hand held units, such as the JCI 140, Static Monitor, shown in Figure 33.

JCI 140 Specification	
Full scale (2 ranges)	2 or 20 kV
Accuracy:	± 2% FSD
Frequency capability:	120 Hz (400 Hz for high frequency option)

The JCI 140 is referred to as a Static Monitor because although it is essentially a field meter, it is calibrated to display the electrical potential on a plane surface 100 mm away, since for most people surface voltage is a more meaningful reading than field strength. Nevertheless, there is a simple factor which can be used to convert the Static Monitor reading to electric field, and there is also a version with almost identical appearance calibrated to give a field reading on the display. The JCI 140, being a small hand-held unit, is particularly convenient for diagnostic investigations and monitoring.



Figure 33: JCI 140 Static Monitor

6.2 Potential Measurements on Conductors

In electrostatics currents are rarely as much as 1 μA, so normal voltmeters, even with high voltage adaptor probes, often drain any charge from a conductor before a reading can be taken.

However, the Static Monitor principle can be used with a special adaptor to measure voltages on conductors while drawing almost no current. A plate in the adaptor is raised to the same potential as the item to be measured by making a direct wire connection.

The JCI 140 is clamped in the correct position relative to the plate, such that the Static Monitor reading gives the plate voltage directly. The JCI 148 Voltmeter adaptor, with a JCI 140 in place, is shown in Figure 34.



Figure 34: JCI 148 Voltmeter Adaptor (for JCI 140)

JCI 148 Specification (with separately purchased JCI 140)	
Full scale (2 ranges)	2 or 20 kV
Accuracy	± 2% FSD
Input leakage resistance	$>10^{14}$ Ohms

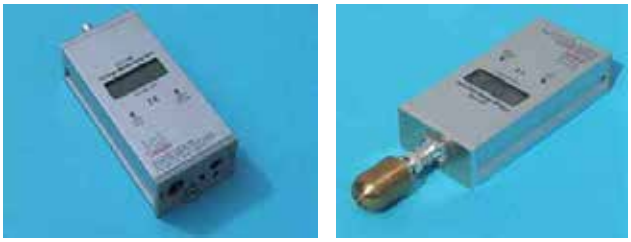


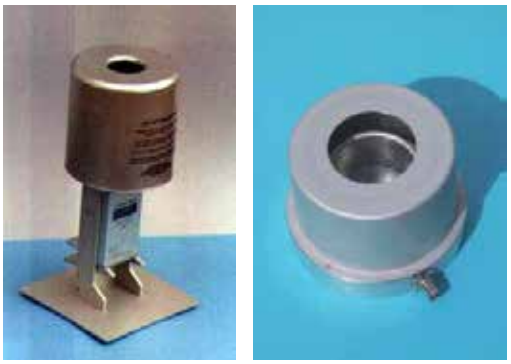
Figure 35: JCI 178 Charge Meter (with and without discharge electrode)

6.3 Charge Measurement

Charge on an isolated conductor can be measured using a charge meter. Essentially, this is an instrument which has a large capacitor at its input, such that when connected to an isolated conductor all the charge is transferred to the capacitor. A sensitive and high input impedance voltmeter then measures the voltage on the capacitor, such that charge can be determined and displayed. Charge measurement is one of the ranges on relatively expensive electrometers, though lower cost, dedicated charge meters are also available. One is the JCI 178, pictured in Figure 35.

Also seen in Figure 35 is the discharge electrode accessory for the JCI 178. This is a special electrode used to measure how much charge was transferred in an electrostatic discharge. This is often important information when assessing electrostatic hazards and problems.

JCI 178 Specification	
Full scale (2 ranges)	20 or 200 nC (other ranges available)
Accuracy	±5% FSD



a) JCI147 Faraday Pail Adaptor for JCI140

b) JCI150 Faraday Pail for use with JCI 178

Figure 36: Faraday Pails

It is sometimes also important to measure the charge on small items and or insulating materials, such as powders. Clearly it would be pointless connecting a charge meter to an insulator, and quite impossible to connect it to a powder! The only way to measure charge on materials of this type is to place them inside a specially shielded container known as a Faraday Pail. A charge meter connected to the Faraday Pail can then be used to determine total charge, whether the items in the pail are insulators or conductors.

It is sometimes necessary to construct Faraday Pails specially to suit the size or quantity of objects or materials to be placed in them. However, some suitable for common, small scale applications are available as standard and can be seen in Figure 36 above.

6.4 Charge Decay Time

For most people who are having to deal with unwanted charge, what they really need to know is how quickly the charge will be lost when the charged item or material is in contact with a good earth. For that reason, measurement of charge decay time is a particularly useful and intuitively understood measurement for a wide range of material types.

Various companies have made instruments to make this measurement, but there is little doubt that the most sophisticated and all-embracing instrument to date is the JCI 155v6 Charge Decay Analyser, seen to the right.

The JCI 155v6 permits easy adjustment of all relevant parameters and shows the charge decay curve on its large format, built-in display. It can also be operated from a computer, to which all data can also be transferred. It can be used to measure charge decay time on solids, films, powders and liquids (the latter requiring special sample holders).

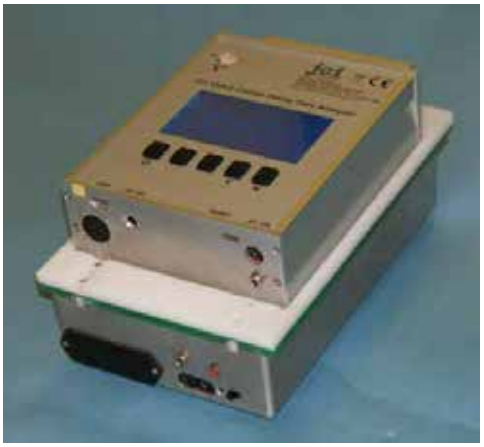


Figure 37: JCI 155v6 Charge Decay Analyser on JCI 176 Charge Measuring Support

6.5 Capacitance Loading

Capacitance Loading is probably less readily understood for most people than charge decay time. However, it is effectively a measure of how problematic charge will be on a particular material, and in many situations it is therefore another important quality control or quality assurance measurement for materials.

Furthermore, by using the JCI 176 in conjunction with the JCI 155v6 (as standard the two are supplied together), the JCI 155v6 automatically gives capacitance loading alongside charge decay time data.

6.6 Resistivity and Conductivity

Compared with charge decay time, resistivity is less easy to understand at an intuitive level, and also has the shortcoming that each measurement can only be carried out at one discrete voltage. Nevertheless, some standards do point towards resistivity measurements.

Resistivities (and conductivities) are measured by using a suitable cell with two active electrodes, between which resistance is measured. The resistance is then converted to resistivity or conductivity by the use of an appropriate cell constant, taking account of the cell geometry.

By way of example, Figure 38 shows a powder resistivity cell and a liquid conductivity cell. However, other cells are available in different sizes and also to determine volume and surface resistivities of solids, films and fabrics as per the guidance of a number of national and international standards.



a) Powder Resistivity Cell



b) Liquid Conductivity Cell

Figure 38: Two DEKRA Test Cells

6.7 Chargeability

It is often useful to quantitatively determine a material's propensity for acquiring charge. However, as a rule so many variables affect charge acquisition that the only practical way of doing this is to carefully define a charge generation method which can be used in the laboratory and then determine how much charge is gained when the material under test is subjected to that regime. That means a number of chargeability tests have been defined, each addressing a particular issue.

In the case of powders, DEKRA Process Safety has found it useful to mostly standardise on one method in which pneumatic conveying is used as the charge generation method. Here, powder is passed down a short (1 m) pneumatic conveying line and the amount of charge acquired determined when it is caught on a filter. The powder flow rate and the air flow rate can be adjusted, and different materials can be used for the conveying line. Furthermore, the results can then be compared with a published range of charging rates for pneumatic conveying and other charge-generating process operations. The test apparatus can be seen in Figures 39 and 40.

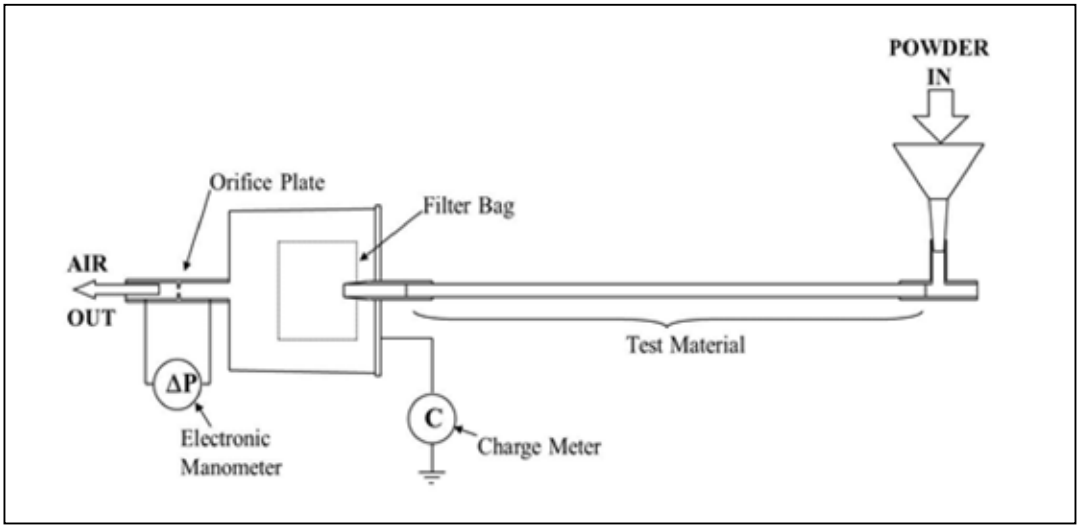


Figure 39: Diagram of DEKRA Powder Chargeability Apparatus

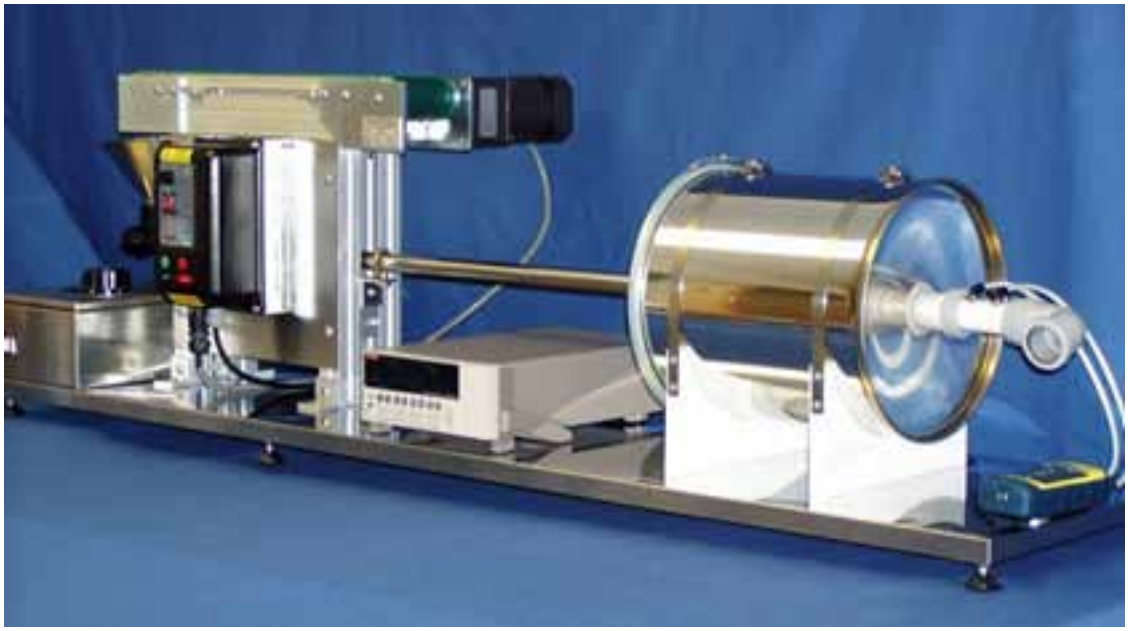


Figure 40: Photograph of DEKRA Powder Chargeability Apparatus

7. Concluding Remarks

It would be quite impossible to fully do justice to the diversity of applications, problems and hazards arising from static electricity in such a short document. However, it is to be hoped that whichever aspect of electrostatics is relevant, enough will be found in these pages to at least provide a grounding. For many situations that may be enough. For others it may be enough to indicate the complexity of the phenomena involved and point to the need for further reading. For some it may even awaken ideas of new beneficial applications of static electricity, or a hitherto unthought-of mechanism for a particularly intractable problem and the need to talk to an expert to take it any further. Whichever it is, it is to be hoped that what has been found in these pages has proved interesting.

This has been an overview covering many of the electrostatic issues we encounter in our visits to industry. We have also explained how it can be used in practical applications such as photocopying and how it can pose a hazard in many industrial processes. We have aimed to provide an understanding of the complex nature of electrostatics but, as in all areas of technical knowledge, it is often necessary to obtain assistance from the experts, DEKRA JCI (contact details below).

For assistance with all aspects of electrostatics (hazards, problems and applications) please free to contact us at www.dekra-process-safety.co.uk

For further reading consideration might be given to the following books and publications:

CLC/TR 50404: "Electrostatics – Code of practice for the avoidance of hazards due to static electricity", CENELEC, 2003.
IEC 60079-32-1: "Explosive Atmospheres – Electrostatic hazards – Guidance", IEC, Currently in draft (September 2012) but publication expected soon.
NFPA 77: "Recommended Practice on Static Electricity", NFPA, 2007.
Britton, L. G.: "Avoiding Static Ignition Hazards in Chemical Operations", AIChemE, 1999.
Chubb, J.: "An Introduction to Electrostatic Measurements", Nova Science, 2010.
Cross, J.: "Electrostatics: Principles, Problems and Applications", Adam Hilger, 1987.
Lüttgens, G., Glor, M.: "Understanding and Controlling Static Electricity", Expert Verlag, 1989.
Moore, A. D.: "Electrostatics and its applications", John Wiley, 1973.
Taylor, D. M., Secker, P. E.: "Industrial Electrostatics: Fundamentals and Measurements", Research Studies Press, 1994.
Walmsley, H. L.: "The Avoidance of Electrostatic Hazards in the Petroleum Industry", J. Electrostatics, 27, Elsevier, 1992.

DEKRA Process Safety
Phi House
Southampton Science Park
Southampton, Hampshire
United Kingdom
SO16 7NS

process-safety-uk@dekra.com
www.dekra-process-safety.co.uk

Tel : +44 (0)23 8076 0722
Fax : +44 (0)23 8076 7866