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Electrostatics

Part 1: Electrostatic phenomena — Principles and measurements

National foreword

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Electrostatics –
Part 1: Electrostatic phenomena – Principles and measurements

Electrostatique –
Partie 1: Phénomènes électrostatiques – Principes et mesures

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ELECTROSTATICS –

Part 1: Electrostatic phenomena – Principles and measurements

FOREWORD

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IEC/TR 61340-1, which is a technical report, has been prepared by IEC technical committee 101: Electrostatics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
101/344/DTR	101/355/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 61340 series, published under the general title *Electrostatics,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

Static electricity has been known for around 2 500 years but until recently had little impact on humankind. More recently in the last century the nature of static electricity became better understood and the principles of charge separation and accumulation could be described. Despite this improved understanding, it remains difficult to predict with certainty the polarity and magnitude of charges built up in any situation due to the many factors involved, and to, many electrostatics remains a “black art” rather than a science.

The development of modern materials, especially polymers, and their nearly ubiquitous application in fields such as floor materials, furnishings, clothing and engineering materials, has made static electricity an everyday phenomenon. In some industries, such as electronics manufacture and processes using flammable materials, unintended and invisible electrostatic discharges can lead to substantial component damage or unreliability, or fires or explosions. In everyday life, experience of electrostatic shocks to personnel has become commonplace. This has led to increasing need to understand such phenomena, and to specify materials, equipment and procedures for use in preventing and controlling electrostatic problems in the human environment.

This technical report gives an overview of the field of electrostatics and has been prepared to give the user a view of the background, principles, methods of measurement and industrial applications prepared in conformity with IEC TC101 publications.

ELECTROSTATICS –

Part 1: Electrostatic phenomena – Principles and measurements

1 Scope

This part of IEC 61340, which is a technical report, describes the fundamental principles of electrostatic phenomena including charge generation, retention and dissipation and electrostatic discharges.

Methods for measuring electrostatic phenomena and related properties of materials are described in a general way.

Hazards and problems associated with electrostatic phenomena and principles of their control are outlined.

Useful applications of electrostatic effects are summarized.

The purpose of this technical report is to serve as a reference for the development of electrostatics related standards, and to provide guidance for their end-users.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60079-10-1, *Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres*

IEC 60079-10-2, *Explosive atmospheres – Part 10-2: Classification of areas – Combustible dust atmospheres*

IEC 61000-4-2, *Electromagnetic compatibility (EMC) – Part 4-2: Testing and measurement techniques – Electrostatic discharge immunity test*

IEC 61340-5-1, *Electrostatics – Part 5-1: Protection of electronic devices from electrostatic phenomena – General requirements*

IEC 61340-5-2, *Electrostatics – Part 5-2: Protection of electronic devices from electrostatic phenomena – User guide*

IEC 60243-1, *Electrical strength of insulating materials – Test methods – Part 1: Tests at power frequencies*

IEC 60243-2, *Electric strength of insulating materials – Test methods – Part 2: Additional requirements for tests using direct voltage*

IEC 61241-2-3, *Electrical apparatus for use in the presence of combustible dust – Part 2: Test methods – Section 3: Method for determining minimum ignition energy of dust/air mixtures*

BS EN 13821, *Potentially explosive atmospheres. Explosion prevention and protection. Determination of minimum ignition energy of dust/air mixtures*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
antistatic additive
antistatic filler, antistatic treatment
substance added to, or process applied to a liquid or solid in order to reduce its tendency to acquire a charge by contact and rubbing, or to promote more rapid charge migration and so to reduce its ability to retain significant charge when in contact with earth

3.2
antistatic
[AC1⟩ refers to the property of a material that inhibits or limits triboelectric charging ⟨AC1]

3.3
bonding
electrical connection between two or more conducting objects that reduces the potential difference between them to an insignificant level

3.4
breakdown
failure, at least temporarily, of the insulating properties of an insulating medium under electric stress

3.5
breakdown voltage
voltage at which breakdown occurs, under prescribed conditions of test or use

3.6
charge decay
neutralization or migration of charge across or through a material leading to a reduction of charge density or surface potential at the point where the charge is deposited

3.7
charge decay time
charge relaxation time
time taken for charge to decay from a specified value to a specified lower value

Note 1 to entry: The specified lower value is commonly one tenth or 1/e of the starting value (e = 2,718).

3.8
conductivity
ability of the substance to conduct electrical current expressed as $\text{S} \times \text{m}^{-1}$

3.9

conductor or conductive material

object or material providing a sufficiently high conductivity so that potential differences over any parts of it are not sufficiently large as to be of practical significance

Note 1 to entry: In general this is a material having a resistance below about $10^5\ \Omega$ but different standards may define different resistance ranges for this term.

3.10

dissipative material

material which allows charge to migrate over its surface and/or through its volume in a time that is short compared to the timescale of the actions creating the charge or that will cause an electrostatic problem

Note 1 to entry: In general a material having a resistance approximately $10^5\ \Omega$ and below approximately $10^{11}\ \Omega$ is considered to be dissipative. Different standards may disagree on the exact values of the limits.

3.11

earth, earthing ▌AC1⟩ , grounding ⟨AC1▐

ground

electrical connection (bonding) of a conductor to the main body of the earth to ensure that it is at earth potential (▌AC1⟩ *text deleted* ⟨AC1▐)

3.12

electrostatic discharge

ESD

transfer of charge by direct contact or by breakdown from a material or object at a different electrical potential to its immediate surroundings

3.13

explosion groups

flammable gaseous atmospheres subdivided into explosion groups I, IIA, IIB and IIC to define their inflammability

Note 1 to entry: The most sensitive explosion group is Group IIC.

Note 2 to entry: See [9] to [11][1] for definitions of classification method.

3.14

flammable substance

substance in the form of gas, liquid, solid or mixture of these, capable of propagating combustion when subjected to a sufficiently strong ignition source

3.15

hazard threshold voltage

minimum electrical potential of capacitive stored charge that may give rise to an electrostatic hazard

3.16

hazardous area

area in which flammable substance is, or may be expected to be, present in quantities such as to require special precautions against ignition

Note 1 to entry: Hazardous area zones are defined in IEC 60079-10-1 and IEC 60079-10-2.

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[1] References in square brackets refer to the bibliography.

3.17
insulator
insulative material
material with very low mobility of charge so that any charge on the surface will remain there for long time

Note 1 to entry: Connecting an insulator to earth does not help charge migration.

3.18
minimum ignition energy
MIE
smallest amount of energy released in a capacitive electrical spark that can ignite a mixture of a specified flammable material with air or oxygen, according to a defined procedure

3.19
relaxation of charge
migration or neutralization of charge over and/or through a solid, liquid or gaseous material causing a reduction in surface charge density and energy

Note 1 to entry: If the potential of a surface is defined then this is also reduced.

3.20
surface charge density
σ_s
net quantity of charge per unit area of surface of a solid or liquid

3.21
surface resistivity
Ω
[AC1⟩ resistance between opposing sides of a square on the surface of a material ⟨AC1]

3.22
triboelectric charging
electrical charging process in which charge is generated by the contact and separation of two surfaces which may be solid, liquid or particle-carrying gases

3.23
volume charge density
σ_v
net quantity of charge per unit volume of a solid, liquid or gas

3.24
volume resistivity
$\Omega \times \mathrm{m}$
[AC1⟩ resistance between opposing sides of 1 m^3 of the material ⟨AC1]

4 Fundamentals of static electricity

4.1 General

Generally, electrostatic charge on a material, product or object is the result of:

- contact and rubbing;
- charge transfer;
- induction in an electric field;

- effect of polarization;
- photoelectric effect;
- pyroelectric effect;
- piezoelectric effect;
- ionization and ions adsorption;
- electrochemical processes.

However, the primary source of electrostatic charge is triboelectric charging. If two previously uncharged substances come into contact, charge transfer will, in general, occur at their common boundary. If a gas containing solid particles or liquid droplets in suspension becomes charged by contact and separation, then the gas can be seen as carrying an electrostatic charge. On separation, each surface will carry an additional charge of equal magnitude but of opposite polarity. Conducting or dissipative objects can become charged by induction if they reside in an electric field produced by other charged objects or conductors at high potential in their vicinity. Any object can become charged if charged particles or molecules accumulate on it.

It is very important to have some appreciation of these phenomena in order to enable the proper implementation of test procedures and unambiguous interpretation of the resultant data. It is also important with regard to choice of electrodes, protection of current measuring devices from the initial capacitive surge and the time at which the value is recorded. The latter should, of course, be appropriate to meet the practical circumstance for which the data are required. Further comments are included in this technical report with the descriptions of the individual test methods, where considered necessary.

4.2 Contact electrification

Contact electrification can occur at solid/solid, liquid/liquid or solid/liquid interfaces. Clean gases cannot charge materials in this way. If a gas contains solid particles or liquid droplets in suspension, however, these may be charged by contact so that such a gas can carry an electrostatic charge by virtue of these particles.

In the case of solids of different materials, initially uncharged and normally at earth potential, charge is transferred from one material to the other when they make contact. When they separate, a net positive charge remains on the one surface and a net negative charge on the other surface. The quantity of charge is increased by the size of the contact areas and the size is affected by the contact pressure. Additional rubbing also increases the effective contact area.

The relative amounts and polarity of charge transferred between materials can be presented as a list, referred to as the triboelectric series. A material is expected to charge positively against materials lower in the series, and negatively against materials higher in the series. It should be noted that the position of a material in the triboelectric series is an approximation, dependent on test conditions, and that two samples of the same material rubbed against each other can result in quite strong charging.

Examples of triboelectric series are shown in Table 1.

Table 1 – Example of triboelectric series

Item	Charge
Rabbit fur Glass Human hair Polyamide (nylon) Wool Fur Silk Aluminum Paper Cotton Steel Wood	Positive
Rubber Acetate rayon Polyethylene (PE) and polypropylene (PP) PET PVC Polyurethane PTFE	Negative

The two materials are oppositely charged and consequently there is an electric field between them. If the materials are then separated, measures shall be taken to overcome the attraction between the opposing charges and the potential difference between them increases linearly with distance. This higher potential difference tends to drive charge back to any point of residual contact. In the case of two conductors, the recombination of charges is virtually complete and no significant amount of charge remains on either material after separation. If one material, or both, is a non-conductor, the recombination cannot take place completely and the separating materials retain part of their charge. There may only be a small amount of charge involved but, because the distance between the charges when the surfaces are in contact is extremely small, the potential generated on separation can easily reach many kilovolts. Realistic surfaces are usually rough and so the charging is enhanced if the contact and separation involves rubbing and/or pressure, since the area of real contact is increased by these actions. Note that the real area of contact can be quite different in size from the appearing area of contact. They can differ by a magnitude or more.

Contact electrification in liquids is essentially the same process but it can depend on the presence of ions or sub-microscopic charged particles (the latter are usually less important). Ions (or particles) of one polarity may be absorbed at the interface and they then attract ions of opposite polarity which form a diffuse layer of charge in the liquid, close to the surface. If the liquid is then moved relative to the interface, it carries away some of this diffuse layer, thereby bringing about separation of the opposing charges. As in the case of solids, a high voltage is generated because of the work done to bring about separation, provided that the liquid is sufficiently non conducting to prevent recombination. Such processes can occur at both solid/liquid and liquid/liquid interfaces.

4.3 Charging by induction

There is an electric field around any charged object. A conductor or dissipative material introduced into this field changes the distribution of electric field in its vicinity and at the same time there is a redistribution of charges in the material under the influence of the field (see

Figure 1a). If it is isolated from earth, the conductor takes up a potential, dependent upon its position in the field. The material is capable of producing an electrostatic discharge by virtue of this potential.

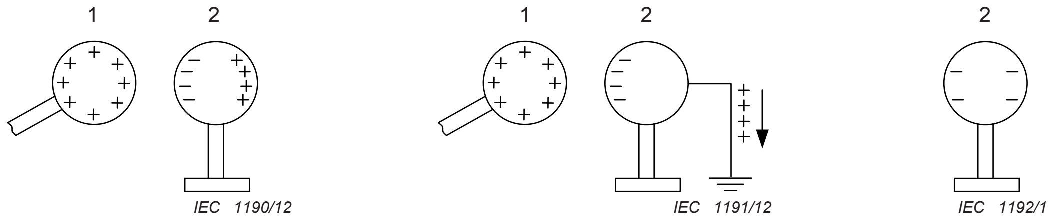


Figure 1a) – Move the charged object (1) close to an uncharged object (2)

Figure 1b) – Connect the uncharged object (2) to ground momentarily. The uncharged object is charged, but assumes ground potential

Figure 1c) – Remove the earth connection and then the first object; the conductor remains charged (negatively in this example)

Figure 1 – Charging by induction

If, while it is in the field, the material is momentarily earthed, its potential is reduced to zero and an imbalance of charge remains on it (Figure 1b). When the electrical field is removed from the object the net charge remains (Figure 1c). If the material is isolated from earth and the electric field is removed, the material then has a charge available to provide an electrostatic discharge. The conducting object after this process is said to be charged by induction. A discharge from such an object can be hazardous, for example in the case of an isolated person moving in the area of electrostatically charged materials.

4.4 Charge transfer by conduction

Whenever a charged object makes contact with another object (Figure 2), the total charge is shared between them to the extent that their conductance and capacitance allow. This is a potent source of electrostatic charging and examples include charged sprays, mists or dusts impinging or settling on solid objects. A similar transfer of charge can also take place when a stream of gaseous ions is incident upon an object.

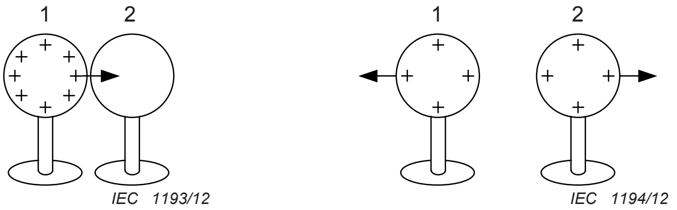


Figure 2a) – A charged object has contact with an uncharged object. Positive charge transfer to the uncharged object

Figure 2b) – Charged objects will be separated

Figure 2 – Charge transfer by conduction when objects 1 and 2 are conductors

4.5 Retention of charge

Even after separation in the charging process, electrostatic charges will quickly re-combine either directly or via the earth unless they are prevented from doing so. If a charge is on a non-conductor, it is retained by virtue of the resistance of the material itself. To retain charge on a conductor it has to be isolated from other conductors and from earth.

Pure gases, like air, under normal conditions are non-conductors and the suspended particles or droplets in dust clouds, mists or sprays can often retain their charges for very long periods, irrespective of the conductivity of the particles themselves.

The charge leaks away at a rate determined by the resistances of the non-conductors in the system and the capacitances of the conductors. This process is known as relaxation. The resistance, resistivity, conductivity or charge decay rate values which are needed to produce an electrostatic problem depend greatly upon the system under consideration.

In many industrial processes there is often a continuous generation of static charge that accumulates on an insulator or an isolated conductor. Examples are when a steady stream of charged liquid or powder flows into an isolated metal container, or a person walks across an insulating floor covering. The potential on the isolated conductor is then the result of a balance between the rate of input of charge and the rate of dissipation. The equivalent electrical circuit is shown in Figure 3 and the potential of the conductor is given by the equation:

$$V = V_o \times e^{\frac{-t}{RC}} + I \times R \times (1 - e^{\frac{-t}{R \times C}}) \qquad (1)$$

where

V is the potential of the conductor (V);

V_0 is the initial potential;

R is the resistance to ground (Ω);

T is the time from the commencement of charging (s);

C is its capacitance (F).

The maximum potential is reached when $t >> RC$, and is given by:

$$V_{\text{max}} = I \times R \qquad (2)$$

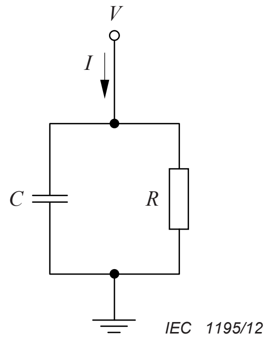


Figure 3 – Equivalent electrical circuit for an electrostatically charged conductor

The capacitance of an isolated object and its “resistance to ground” or the rate of charge dissipation can be measured to establish if significant charges can accumulate. This cannot be done for dusts and mists while suspended in air.

There is an inherent assumption here that the resistance, or the charge relaxation rate, of an insulating material is single valued. This is not always the case. The value of resistance for a given potential difference can vary with time and, similarly, the rate of charge dissipation can be a function of the electric stress (or amount of charge). These effects can also be greatly influenced by the temperature and the ambient humidity.

4.6 Influence of environmental humidity

4.6.1 General

Materials absorb atmospheric water to some degree and in the case of insulators this can increase the rate of charge dissipation greatly. Water absorbed on the surface of materials is the principal cause of a surface conductivity that is different from that in the bulk of the material. The effect, well observed but still poorly understood, is that the conductivity increases with the amount of water absorbed, i.e. in practical terms, the conductivity increases with increasing relative humidity. The effect is observed even under relatively dry (RH < 20 %) conditions where the water can only be present in molecular form and no free liquid water layer exists.

4.6.2 In situ measurements

When making measurements under practical conditions, it is often not possible to control humidity. As the results are likely to be influenced by environmental humidity, it is important to record the environmental conditions at the time of measurement.

4.7 Electrostatic discharges

4.7.1 General

An electrostatic discharge occurs when the electric field exceeds the breakdown strength of the atmospheric gas, which is usually air. As a guide, the breakdown strength for flat or large radius surfaces 10 mm or more apart is about 3 MV/m (30 kV/cm) under normal ambient conditions.

Electrostatic discharges vary greatly in type and depend in a detailed way on the system in which the discharge is initiated. The several types of discharges can be classified as described in 4.7.2 to 4.7.6, although the differentiation between the various types is not completely definite.

4.7.2 Spark discharges

A spark is an electrical discharge between two conductors at different potentials. It is characterized by a well-defined luminous discharge channel carrying a high density current. Ionization of gas in the channel is complete over its whole length. The discharge is very rapid and can give rise to an audible “crack”. The discharge observed between a person’s finger and a large metal object is a typical example.

The potential difference between the conductors necessary to produce a field which exceeds the electric strength of the ambient atmosphere depends upon both the shape and the distance between the conductors.

The current passing in a spark is limited only by the impedance in the external circuit and so nearly all the charge on the electrodes is drawn into the discharge. The spark in most practical cases, therefore, dissipates almost all the available energy which is given by:

$$W = \frac{1}{2} \times Q \times V = \frac{1}{2} C V^2 = \frac{1}{2} \frac{Q^2}{V} \tag{3}$$

where

W is the energy dissipated (J),

Q is the quantity of charge on the conductor (C),

V is its potential (V);

C is the capacitance to earth (F).

This is the maximum amount of available energy. Any resistance in the discharging circuit reduces the energy in the spark and increases its duration. Typical values for the capacitances of conductors are given in Table 2.

Table 2 – Typical electrical capacitances

Object	**Capacitance** $\times 10^{-12}$ F
Very small metal items (screw, nail)	1 to 10
Small metal items (scoop, hose nozzle)	10 to 20
Small containers (bucket, 50 l drum)	10 to 100
Medium containers (250 l to 500 l)	50 to 300
Human body	100 to 300
Major plant items (reaction vessels) closely surrounded by earthed structure	100 to 1 000
Cars	800 to 1 200

4.7.3 Corona discharges

This type of discharge is associated with conductors with sharp points or edges. They can occur when such a conductor is earthed and moved towards a highly charged object or, alternatively, if the conductor is raised to a high potential. The discharges arise due to the fact that the electric field located at the sharp surface is very high and above the breakdown stress (3 MV/m). Since the field away from the conductor decreases rapidly with distance, the region of ionization does not extend far from it. It may be directed towards the charged object or, in the case of a high potential conductor, it may simply be directed into space.

Corona discharges are difficult to see, but under subdued lighting a glow can be seen adjacent to the point. Outside this ionized region ions can drift away, their polarity being dependent on the field direction.

The field from a charged surface producing corona discharges on adjacent, earthed, sharp points attracts ions of opposite polarity from the discharge and can, therefore, reduce the charge on the surface. This process will only continue, of course, while the field at the point is above the corona discharge threshold and so complete neutralization is not possible.

Corona discharge can also transfer charge to a surface or object. This effect may be used intentionally or may accidentally cause a hazard, for example by charging an isolated metal part to high potential.

4.7.4 Brush discharges

These discharges can occur when grounded conductors approach a charged insulating material (for example, between a person's finger and a plastic surface or between a metal filling tube and the surface of liquid inside a tank).

The discharges are short duration events which, under suitable circumstances, can be seen and heard. Unlike spark discharges, they tend to involve only a small fraction of the charge associated with the system and the discharge does not necessarily bring the two objects to the same potential.

4.7.5 Propagating brush discharges

The difference between brush discharge and a propagating brush discharge is that the first is mainly an air gap discharge and the second is essentially a surface discharge. The reason for the second being a surface discharge is that the electrostatic field mainly is bound to a thin insulating layer and not outgoing as in the first case. This requires a breakdown voltage of the thin layer that greatly exceeds the breakdown voltage of a corresponding air gap. Propagating brush discharges can be avoided by ensuring that the breakdown voltage across all high resistivity walls and coatings is less than 4 kV. The maximum permissible breakdown voltage increases with increasing dielectric thickness and for specific application the permissible breakdown voltage may be greater than 4 kV. The discharge can be triggered either by a conductive object approaching the surface or by a breakdown of the dielectric. Should the field in the dielectric, from the charge on its surface reach the breakdown value of the dielectric, a spontaneous discharge occurs resulting in a puncture of the plastic sheet/ coating. Starting from this puncture (or the discharge to the approaching object), a very high electric field is created parallel to the surface of the dielectric, which initiates a series of strong surface discharges, thereby releasing most of the surface charge.

A dielectric sheet with charges of opposite polarity on its surfaces is the equivalent of a parallel plate capacitor with the dielectric sheet between the plates. The energy released in propagating brush discharges can, therefore, easily be estimated from the stored energy. The equivalent capacitance C_e, for a dielectric sheet of area A, thickness d, permittivity ε_0 = 8,854 × 10^{-12} Fm^{-1} and the relative permittivity ε_r, retaining a surface charge density σ, is:

$$C_\mathrm{e} = \varepsilon_\mathrm{r} \times \varepsilon_0 \times \frac{A}{d} \tag{4}$$

for a charge density σ, the complete charge q.

Taking as an example:

d = 75 µm, A = 0,5 m^2, ε_r = 2 and a surface charge of density, $\sigma = 10^{-3}$ C/m^2, the stored energy is:

$$W = \frac{1}{2} \times C_\mathrm{e} \times V^2$$

$$W = \frac{1}{2} \times \frac{q^2}{C_\mathrm{e}}$$

$$W = \left[A \times \frac{d}{2} \times \frac{1}{\varepsilon_r \times \varepsilon_0} \right] \times \sigma^2 = 1\mathrm{J}$$

4.7.6 Cone discharges

This type of discharge has been experienced when, for instance, high resistivity granules are fed into a silo. When feeding charged particles, such as plastic granules, into a silo, there is an accumulation of charge at the heap. The field from this charge exerts repulsive forces on the similarly charged particles, which are falling onto the heap. As the gravitational forces on the particles act against the repulsive forces, there is an increase of the charge density of the bulk material at the heap. If charged particles continue to fall onto the heap after the field strength in that region has reached the breakdown value for air, discharges will occur in a direction towards the conducting walls of the silo, which is grounded.

4.8 Mechanical forces in an electrostatic field

The electric field produced by an electrostatic charge can exert a mechanical force on objects which it envelops. Films of material charged to a few micro coulombs per square meter can adhere to nearby metals while dust particles can be attracted by fields associated with charge densities an order of magnitude smaller than this.

For example, the force acting on a charged particle near a flat, grounded plate can be calculated from Coulomb's law:

$$F = \frac{q^2}{16 \times \pi \times \varepsilon_r \times \varepsilon_0 \times d^2} \tag{5}$$

where

q is the charge of the particle;

d is the distance to the plate.

5 Electrostatic problems and hazards

5.1 General

Electrostatic discharges vary greatly in type and their effect as causes of electrostatic problems can be very different. Discharges between metal structures in the form of sparks, and propagating brush discharge are amongst the most energetic and potentially destructive. Discharges from charged insulators can also be harmful and can ignite flammable gas mixture or causes damage to electronic components. Breakdown of the insulating layers of a semiconductor device can occur for voltages lower than 50 V and other forms of damage such as local fusion of semiconductor material requires only a few micro-joules of energy. In general, charge retained on a liquid or a solid creates a problem if it is suddenly discharged to another body or to ground.

In medical clean rooms that are used for surgery and during production of pharmaceuticals, one might have special requirements concerning contamination control. This can also implicate that static electricity has to be controlled to avoid charging of particles.

5.2 Electronic components and systems

5.2.1 General

Electrostatic discharge (ESD) is a serious threat to electronic components and systems. Electronic components have a wide range of susceptibility to ESD. Examples of the most susceptible types include semiconductors, magneto-resistive (MR) heads and thin film resistors. An electrostatic potential, as low as 10 V, can cause the failure of certain components.

Due to this high susceptibility, it should be assumed that all types of electrostatic discharges can harm sensitive electronic components.

5.2.2 Types of failure

ESD damage can result in catastrophic failure and latent defects.

Catastrophic damage can result in failure or degradation of a component, causing the component or system to cease functioning or fall outside its specification.

A component with a latent failure may have changes in its characteristics that do not necessarily take it outside its specification. However, it can become weakened by the ESD event. A component with latent damage may be more susceptible to a succeeding ESD or any other stress. It is therefore an increased possibility that such a component will fail prematurely.

Soft errors occur when a programmed component is exposed to an ESD, or from the electrical noise generated from the ESD event changing the stored data. A false signal might appear in the system, due to conducted or radiated electromagnetic interference sourced by an electrostatic discharge.

The damage level of a component is either voltage- or power-related, depending on the type of damage mechanism. Different types of components and semiconductor families are susceptible to different kinds of damage mechanisms.

One of the most common damage mechanisms is related to breakdown or puncture of the oxide insulation, the dielectric, or the semiconductor junction (burn-out or short circuit). Another common damage mechanism is related to the melting or sublimation of metallization due to high currents resulting from the ESD.

Examples of components particularly susceptible to dielectric breakdown include MOSFET (discrete, gate-oxide breakdown), MOS IC, ICs with metallization crossovers and capacitors (particularly MOS). Typical failure mode is an electrical short circuit or increased leakage current (degraded I-V characteristic).

Examples of components particularly susceptible to metallization damage include HF-transistors and ICs. A typical failure mode is open circuit.

As all of these damage mechanisms are dependent on the geometrical size of the dielectric layer, other insulation layer, metallization width and thickness, etc., it is assumed that the trend of ESD sensitivity of semiconductors increases with time. However, for some types of components, improved ESD-protection circuits are fabricated at the device pins that reduce the device ESD sensitivity.

5.2.3 Problems and threats at different life cycle periods

All electronic systems in use are vulnerable to electrostatic discharges. A direct hit by a strong discharge to any part of a system can create currents and energies high enough to damage components if the discharge currents are not drained directly to ground.

Even a discharge in the vicinity of a system can damage the system. The discharge creates an electromagnetic field that might induce currents in the system. These currents can be damaging or they can cause “soft-errors”, i.e. the information is degraded by invalid pulses. The programming of certain components can also be irreversibly changed.

A discharge might occur against a cable or remote equipment far from the system and the disturbance (high voltage pulse) can be conducted into the system.

During the manufacture of electronic devices, handling of sensitive electronic components and assemblies is very delicate. In such an environment there are many threats to electronics: charged operators, clothes, ungrounded machine parts, plastic bags and bins, plastic components, etc. The most damaging discharge is a spark discharge. Such a discharge can occur from a charged operator touching a printed circuit board.

A charge on a component itself might also be damaging. A plastic encapsulated semiconductor is easily charged by rubbing its surface with, for instance a finger or a plastic bag. This charge on the surface of the plastic housing induces a voltage on the conductors of the semiconductor and on its terminals. By touching a terminal with a metallic tool or a finger a fast discharge occurs. As the capacitance of the terminal is small and the capacitance of the tool or finger (operator) is much larger, the discharge is very fast and causes a high current. Even if the discharge has very low energy content, the high current can be damaging to the very small circuit elements it may pass.

During the manufacture of components there are additional problems arising from electrostatic charge. Semiconductors have to be extremely clean during the manufacture and the surface has to be protected. If the semiconductor is charged, it attracts dust from the air. The same type of problem exists in other parts of electronics, for instance contamination of disks and disk drives and of electro-optics.

The level at which a component is damaged by an electrostatic discharge depends on the design of the component and the characteristics of the discharge. Discharges of many kinds might occur, but three types, human body model (HBM), machine model (MM) and charged device model (CDM), have been defined as being representative for most types, even if they do not cover all possible variables that influence a discharge. The models are used to define a withstand voltage, which is the maximum voltage, as applied in the respective model, that a component can withstand without sustaining damage.

5.3 Electrostatic ignition – Hazards

5.3.1 General

Electrostatic discharges may ignite flammable gases, dust and vapours or mists. It is the intense heat of a discharge channel that is responsible for the ignition.

5.3.2 Spark discharges from conducting objects

Approximate calculation of spark discharge energy can be made, for example, for an ungrounded metal drum filled with powder from a grinding unit. In such a case the charging current, I, might be 10^{-7} A. The resistance to ground of the drum, R, could be 10^{11} Ω and its capacitance about 50 pF. The maximum voltage on the drum, reached in about 15 s, is then:

$$V_{\mathrm{max}} = I \times R = 10\ \mathrm{kV}$$

The maximum energy, W, released in a spark discharge would be:

$$W = \frac{1}{2} \times C \times \mathrm{V}_{\mathrm{max}}^{2} = 2{,}5\,\mathrm{mJ}$$

The rise time, amplitude and duration of the current passing during the spark are all important factors in determining the level of hazard. A very fast, high magnitude, current pulse conveys energy adiabatically and may most easily ignite a gas-air mixture. Conversely, a longer duration discharge has been found to sometimes increase the probability of ignition of a flammable dust cloud. Inclusion of high impedance in the discharge current path to sufficiently reduce the discharge current and increase the discharge duration can reduce the potential hazard to most flammable mixtures.

5.3.3 Corona discharges from conducting objects

The energy density in the discharge is much less than in a spark and for this reason corona discharges are not normally [AC1⟩ incendive ⟨AC1]. However, in certain circumstances, for example if there is an increase in the potential of the pointed conductor, corona can develop into a spark between it and another object.

5.3.4 Brush discharges from insulating surfaces

If the energy is quite concentrated, brush discharges can ignite most flammable gases and vapours. This is dependent on the polarity of the discharge and the electrode configuration.

There is, as yet, no evidence to show that in most practical cases even the most sensitive dusts can be ignited by brush discharges.

5.3.5 Propagating brush discharges from insulating surfaces

The high surface charge density required for the onset of propagating brush discharges may typically be generated at those locations where powder particles hit high resistivity walls or coatings such as in pneumatic transport of powder through pipes made of low charge dissipation (high resistivity) materials or through metal pipes with a lining of such material. Propagating brush discharges have also been observed and proven when conductive liquids were pulsating through insulating hoses whose surface was not wet table. Another circumstance could be where considerable rubbing occurs between a packaged product and the inner surface of the package. High surface charge densities may also result from the deposition of ions on high resistivity (low dissipation) walls or coatings. Large quantities of ions may be generated within the plant, for example, during the bulking of charged high resistivity powder. Such discharges do not occur with layers of powder.

Since most of the charge is released in a single discharge the stored energy may be compared with the minimum ignition energy of a given powder to judge the ignition probability of propagating brush discharges. Discharges of such energy passing directly into electronic systems or devices could have a catastrophic effect. It should be noted that the discharge of energy of this magnitude to ground via a person would produce considerable physiological reaction and is dangerous.

5.3.6 Discharges from people

Charges on people's bodies commonly cause a hazard. A person who is insulated from ground can easily acquire and retain an electrostatic charge. The insulation from ground may be due to the fact that the floor covering or the soles of their footwear is made from an insulating material. There are many mechanisms that can cause a person to become charged and the following are a few examples: walking across a floor; rising from a seat; removing clothing; handling plastics; pouring from, or collecting charged material in a container; or standing close to charged objects, e.g. a moving belt or highly insulated packaging.

If an electrostatically charged person touches a conducting object (e.g. door handle, handrail, etc.) a spark will occur at the point of contact. Such sparks may not be seen or heard and may not even be felt by the person.

A potential of 3 kV on a typical body capacitance of 200 pF gives a stored energy of 0,9 mJ. Sparks of this energy from people are capable of igniting gases (hydrogen/air, 0,02 mJ), vapours (hydrocarbon/air, 0,2 mJ) and even some of the more sensitive dusts (< 1 mJ). It is certainly the case that such discharges can damage unprotected electronic devices.

5.3.7 Ignition potential of electrostatic discharges

5.3.7.1 General

When electrostatic discharge is expected in hazardous areas it shall be taken into consideration whether the ignition potential is capable of igniting the surrounding atmosphere.

5.3.7.2 Spark discharges

The ignition danger caused by a spark discharge may be assessed by comparison of the energy released in a spark with the minimum ignition energy (MIE) of the surrounding atmosphere (see 5.3.2).

5.3.7.3 Corona discharges

The energy density in this discharge is normally not ⟦AC1⟩ incendive ⟨AC1⟧. (see 5.3.3).

5.3.7.4 Brush discharges

There is as yet no evidence to show that even the most sensitive dust (except primary explosives) can be ignited by brush discharges. However, there is a theoretical possibility because brush discharges can have equivalent energies up to 4mJ (see 5.3.4).

However, flammable gases and vapours may be ignited by brush discharges.

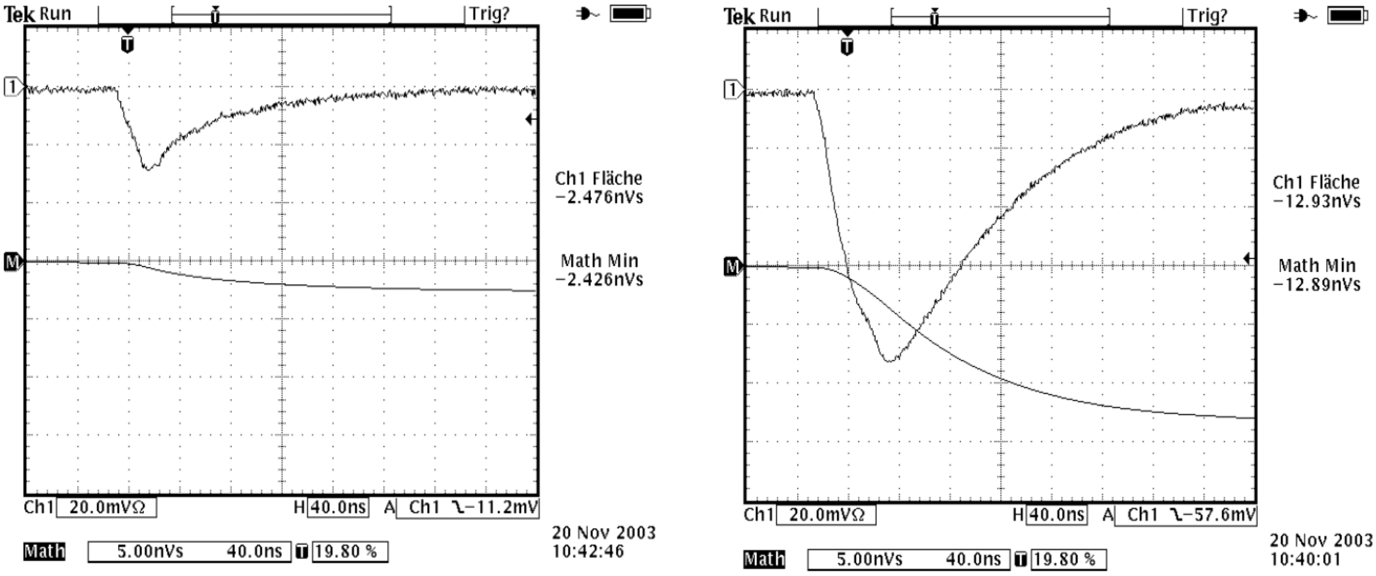
An estimation of the probability of brush discharges causing the ignition of a gas or vapour can be made by considering the amount of charge transferred in a single brush discharge.

The minimum charge transfer for brush discharges to cause ignition of gases and vapours in different explosion groups is estimated as

- 60 nC for explosion groups I or IIA,
- 30 nC for explosion group IIB,
- 10 nC for explosion group IIC.

More information on explosion groups can be found in IEC 60079-10-1 and IEC 60079-10-2.

Brush discharges occurring in the nanoseconds region shall be registered with a suitable measuring device. Figure 4 provides two examples. Examples of such devices are rapid storage oscilloscopes (bandwidth ≥ 300 MHz, sample rate ≥ 1 GS/s) with a high frequency shunt resistor.



IEC 1196/12

IEC 1197/12

Figure 4a) – Weak discharge < 20 nC

Figure 4b) – Strong discharge > 60 nC

Figure 4 – Examples of brush discharge waveforms measured with a fast digital storage oscilloscope

The relationship between charge transfer in a brush discharge and the probability of ignition takes no account of the spatial or temporal distribution of energy in the discharge. These values should only be regarded as an approximation and should not be used as an absolute determination of safety for all materials in all applications.

5.3.7.5 Propagating brush discharges

There is evidence that propagating brush discharges are capable of igniting flammable gases and vapours as well as most dusts (see 5.3.5).

5.3.7.6 Cone discharges

A proven fact is that cone discharge may ignite flammable gases and vapours. It cannot be excluded that some dusts can be ignited as well.

5.4 Physiological sensation

A well-known phenomenon, particularly on days with low air humidity, is the electrical shock felt when touching a conducting object after having been charged by, for instance, walking on a rug or rising from a car seat.

The levels of perception of electrostatic charge by people and the physical responses are shown in Table 3.

Especially when handling highly chargeable objects, an isolated person can be charged to high levels. Examples of such situations include:

- making a bed: the sheets are charged and the person receives an induced potential, which is neutralized in a spark discharge by touching a grounded object;
- packing or unpacking when highly chargeable packing materials are used.

Table 3 – Typical perception levels and physical responses of people to discharges based on a body capacitance of 200 pF

Discharge energy mJ	Reaction	Body potential V
0,1	Perceptible	1 000
0,9	Definite sensation	3 000
6,4	Unpleasant shock	8 000

A person can feel the same sensation when touching a charged object.

Examples of this include:

- taking off a sweater: the sweater is charged to a high level and discharges (as brush discharges) to the person;
- a truck with insulated, plastic wheels charges to high levels when driven and can cause a very unpleasant shock.

5.5 Simulation of electrostatic discharges

5.5.1 General

Electrostatic discharges are generally simulated using a simple circuit in which the electrostatic charge is initially stored as a voltage on a capacitor. When a simulated discharge is required, the stored electrostatic energy is discharged through a circuit to a load, which may be a spark discharge or an electronic device under test. The discharge is normally defined in terms of the output current waveform, I, although the stored electrostatic energy is often also an important parameter.

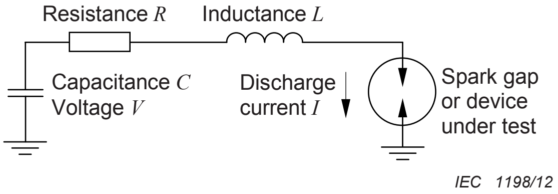


Figure 5 – Circuit for simulation of electrostatic discharges

This simple circuit model can generate a wide variety of waveforms for different purposes, depending on the values of the capacitance, C, the resistance, R and the inductance, L. All circuits have all these components although in practice some may be present as unintentional but unavoidable "stray" components. In many circuits, the small stray components can have a significant effect on the final output waveform simulation.

The output current is given by:

$$I = \frac{V_0}{2 \times L \times \omega} \times \left[e^{-(\sigma+\omega)\times t} - e^{-(\sigma-\omega)\times t} \right] \qquad (6)$$

where

$$\sigma = \frac{R}{2 \times L} \qquad (7)$$

and

$$\omega = \left[\frac{R^2}{4 \times L^2} - \frac{1}{L \times C} \right]^{0,5} \qquad (8)$$

If ω is a real number, then the circuit gives a unidirectional waveform, typically having a fast rising edge and longer exponential decay.

If $\omega = 0$, then the circuit is critically damped and a short, unidirectional waveform occurs. If ω is a complex number, then the output waveform is a damped "ringing" sinusoid.

5.5.2 Capacitive discharges for ignition energy measurements

Capacitive discharge circuits are used for the measurement of ignition energy of flammable atmospheres. In a typical circuit, the capacitance is controlled in order to determine the stored energy. The circuit resistance R and inductance L are usually maintained at low "stray" values.

In many cases, it is the stored energy rather than the output waveform which is the parameter of interest. Typically the output waveform is a damped sinusoid.

In some cases an inductance, L, or resistance, R, may be included in the circuit. This is the case for some apparatus for measurement of ignition sensitivity of dust clouds, where an inductance of 1 mH is often specified. Typical values are given in Table 4.

5.5.3 Human body model

An important electrostatic discharge model which simulates a discharge of a charged person to the device or system under test is called the human body model (HBM). This model is the most commonly used both for testing the ESD sensitivity of electronic components and systems during manufacture and operation. This model also finds applications in assessing other situations where electrostatic discharges from the human body may occur, for example in assessment of the ignition sensitivity of pyrotechnic dusts.

In this case the capacitance C is chosen to be representative of the typical range of the human body. A resistance R is introduced into the circuit, but the inductance L is limited to the "stray" value. The output waveform is of unidirectional form with a fast rise time and long slow decay time. Typical values are given in ⟦AC1⟩Table 4⟨AC1⟧.

5.5.4 Machine model

A class of model used in determining the ESD sensitivity of electronic components simulates a discharge of a large metal object, such as a part of a machine. This model is called the machine model (MM).

In this case, the capacitance C, the inductance L and the output waveform are usually defined. The waveform is typically a ringing sinusoid of defined frequency, rise time and amplitude. Typical values are given in ⟦AC1⟩Table 4⟨AC1⟧.

5.5.5 Charged device model

The charged device model (CDM) simulates the situation where a small charged device or object approaches a grounded surface and an ESD event takes place as a result. It is used for measuring ESD sensitivity of electronic devices. Typically, the capacitance of the device is small and the circuit inductance L and resistance R are defined by "stray" values. The model is typically defined by its waveform, which is characteristically a very short and fast unidirectional discharge. Typical values are given in Table 4.

Table 4 – Typical values used in ESD simulation models

Model	Application	*R* Ω	*C* pF	*L* nH
Ignition energy measurements	Dust cloud ignition	Stray	5 – 1 000	Stray or 1mH
	Vapour ignition	Stray	5 – 1 000	Stray
Human body model (HBM)	Electronic device test	1 000 – 3 000	100 – 300	Stray
Machine model (MM)	Electronic device test	8,5 (typical)	200	0,5 (typical)
Charged device model (CDM)	Electronic device test	< 10 (typical)	3 – 30 (typical)	< 10 (typical)

6 General solutions to problems and hazards

6.1 General

While it is not the objective of this technical report to discuss specific electrostatic problems, a brief review of solutions to problems is useful as an introduction to the description of methods of measuring the relevant properties of materials. It is generally the case that electrostatic problems are specific to the actual product, process or materials and circumstances. A measurement of the electrostatic parameters is a necessary precursor to effective solutions.

The handling of electrostatic sensitive components is described in IEC 61340-5-1 and IEC 61340-5-2 and the avoidance of hazards due to electrostatic electricity is described in [4]. Common approaches are summarized in 6.2.

6.2 Common approaches

In many cases, it is necessary to define an area in which special precautions are necessary. This may be an ESD protected area in electronics manufacture or a flammable atmosphere zone in a process industry. It is necessary for all personnel working in these areas to understand the need for electrostatic control, where the boundaries of the area are located and what precautions should be taken into account within the area.

The first principle is to avoid the use of insulating materials and to ensure that all conductive materials or items of metal are grounded. If charging is inevitable, as is usually the case, the degree of charging can sometimes be limited by minimizing the number of contact and separation events. This means avoidance of rubbing for solids and a reduction in linear velocity for liquids should be performed. Ionization by corona is a very useful means of reducing unwanted surface charge on insulating objects. Devices based on this principle and comprising an array of grounded, sharp electrodes are used for charge reduction in the electronics industry.

As the amount of charge is highly dependent on the air humidity (surface humidity) a general solution to get lower charge levels is to keep the air humidity as high as possible with regard to other risks. For instance, the humidity in electronic manufacturing plants is often regulated to 40 % RH to 60 % RH. For most cases, the use of high relative humidity is not a primary safety measure to control static electricity, but only a secondary one.

The enhancement of the rate of charge loss from an insulating material to ground can be achieved by the addition of an antistatic additive.

A common practice for solid insulators is to form a conductive matrix within the material by the addition of carbon or metallic particles, flake or fibers. It should be appreciated, however, that these systems are effective only while electrical continuity is maintained throughout the matrix and that, consequently, they are often sensitive to mechanical distortion and temperature changes. Also, in the present context, they can present a measurement problem. Charge, in general, cannot migrate from the insulating continuum to the conductive matrix and so the indicated charge-dissipative or conductive characteristics are very different between charge applied to, or contact with, the former and the latter. The procedure employed should be considered carefully in implementing any test.

The most common circumstances where electrostatic problems arise are where the material is either an electrical insulator or is not in good electrical contact with ground. Pneumatically conveyed dust is a typical example of the latter since even metallic particles retain charge when suspended in air. In this case, ionization of the ambient atmosphere can provide charges which reduce, if not wholly neutralize, the problematic charge on the material.

The accumulation of metallic dust on active ionizers may lead to hazardous sparks. It is therefore recommended to use passive or radioactive ionizers when metallic dusts are present. It is important for safety and operational efficiency that passive and active ionizers be regularly cleaned and checked for faults in accordance with manufacturer’s instructions.

One of the most common problems is an ungrounded conductor, often a small metal object or part of an assembly, which can accumulate charge and give rise to an [AC1⟩ incendive ⟨AC1] or otherwise damaging discharge. The preferred solution is to ground the object and prevent charge accumulation.

A potentially charged ungrounded metal or conductive object should never be grounded in the presence of a flammable atmosphere. To do so would be to risk a discharge that could ignite the atmosphere.

It is very important that people working in areas of potential electrostatic hazard, where flammable atmospheres may be present, and certainly those who handle sensitive electronic systems, should be prevented from becoming electrostatically charged. This can be achieved by grounding personnel through a conductive wrist strap or by having a conducting floor and ensuring that people wear low-resistance conducting footwear, whichever is practical for the particular industrial environment.

The floor shall be reasonably clean and a regular functional control shall exist, otherwise the grounding by shoe/floor will not work.

For protection of sensitive electronics, particularly during transportation, it is recommended to use ESD protective packaging to shield the electronics from electrostatic field and direct electrostatic discharge originating outside the packaging. The packaging material in contact with the device should also not be insulating and should not cause significant electrostatic charging of the packaging or device.

7 Useful applications of electrostatic effects

The ubiquitous photocopier and inkjet printer are two machines which contribute enormously to information technology. The electrographic process is entirely based on electrostatic effects and the inkjet printer uses the precise deflection of accurately sized and charged ink drops. In the former process, the optical image is transformed into a charge pattern on a corona charged photoconductor which is subsequently developed by the adhesion of counter-charged developer particles. The final stage is the transfer of the developed image on to the copy paper, again, by means of an electrostatic field.

Corona charging of dust particles, the electrical properties of the captured effluent dust layers and the generation of stable high electric fields all contribute to the efficiency of electrostatic precipitators.

Electrostatic painting, crop spraying, flocking and ore beneficiation and plastics separation are all either viable or burgeoning industrial processes. It is certainly the case that effective implementation of any means to control and utilize electrostatic effects is crucially dependent on quantitative data for the electrostatic parameters and relevant materials properties.

Additional electrostatic applications include electrostatic printing assistance, electrostatic moisturing and electrostatic oiling.

8 General aspects of measurements

8.1 General

Measurements are used to provide understanding of electrostatic phenomena, to analyse and derive solutions to problems and to design and develop systems and devices based on electrostatic processes.

This clause describes general methods of measurement which will allow unambiguous data of sufficient accuracy to be produced. Correct interpretation of the data is most important and this can only be obtained by understanding the basic phenomena and having an awareness of the influence on them of the local environment.

Some electrostatic measurements relate directly to basic physical parameters, for example electric field, charge, surface and volume charge density, resistivity, capacitance, current and energy. Other measurements are more practical and so require test methods in which practical situations are simulated with agreed geometric arrangements and dimensions. Examples include chargeability, charge decay, earth bonding resistance and shielding capability.

Measurements of electrostatic charge and field often do not need to be particularly accurate. A value to within an order of magnitude is sufficient in many instances. What is important however is reliability – the confidence that the observations made are real and are correct to an accuracy which is appropriate. There are instances where high resolution and stability may be needed, for example in obtaining estimates of the rate of decay of charge on an insulating material from short time observations when the surface charge and potential may be high but the rate of change very small.

There are instances where high sensitivity is needed, for example for measuring the low potentials that may present risks to sensitive semiconductor devices and for measuring charge density on individual sides of thin films. There are also some instances where high accuracy may be needed, for example where difference measurements need to be made between two or more measurements of electric field, for example for on-line measurement of charge density or charge decay rate.

The methods presented are, in general, concerned primarily with the correctness of method rather than with the achievement of high accuracy. An introduction to each of the methods is presented here to clarify some of the difficulties and enable confident implementation and unambiguous interpretation of the results.

8.2 Electric field

8.2.1 General

Measurements of the electric field are made using two types of field meters: induction probes and field mills.

Induction probe instruments involve a sensing surface connected to a high input impedance amplifier with a capacitor to earth. Such instruments are simple and relatively low cost but their sensitivity and usefulness is limited. They have a finite input time constant and this means they can only be used for relatively short-term measurements (tens of seconds) after zeroing in a zero electric field environment. Their readings are seriously upset by operation in the presence of ionized air.

A field mill is so called because an earthed rotating shutter is used to modulate the electric field observed at the sensing surface. The alternating signal generated depends only on the area of the sensing surface and the value of the input capacitor so long as the rate of modulation of the observed electric field is suitably faster than the input time constant. Phase sensitive detection generates an output signal showing the strength and polarity of the observed electric field.

An alternative arrangement uses a vibrating chopper to modulate the electric field at the sensing surface. In such instruments, a voltage is usually fed back to the input so the instrument works in a null mode. This is particularly useful for voltage follower probe applications.

8.2.2 Application

A measurement of the electric field can provide information on the magnitude and polarity of surface potential, surface or volume density of charge or local space potential.

The induction probe responds continuously to observed fields. The measured field produces a response which is relative to previously observed fields and so it is essential that these instruments be switched on or zeroed in a region free of electric fields and measurements made within a relatively short time after re-zeroing. The field mill is not affected by the electric field present when it is switched on and, since the chopper presents a continuous earth reference, the zero remains stable over extended periods of operation.

It is important that the instrument is properly bonded to earth and that the stability of the zero reading over times comparable to expected time needed for measurement is checked. The presence of other earthed surfaces within the field of view should also be checked.

Surfaces around the sensing region shall be kept clean. This is particularly important with high sensitivity instruments and in work involving insulating particles. Insulating particles readily become charged and any such particles deposited around the sensing region will offset the instrument zero. Clean air purging helps prevent particle deposition but it is necessary to check the field meter zero reading from time to time.

The field meter zero setting can be checked by covering the aperture with an earthed metal plate.

The induction probe or field mill distorts the electric field by its presence. In addition, the instrument's response is an integral of the field or potential over a poorly defined sensitive region. These effects may be significant and should be taken into consideration.

8.3 Potential

8.3.1 General

Potentials arise on objects, on charged surfaces or within a volume containing a space charge. The first can be measured using an electrostatic voltmeter but they can all be determined either by an earthed field meter or from the potential needed to provide a null electric field signal at the field sensor. Such measurements should require no removal of charge and should be made without significant change of electric field at the surface tested as this may alter the distribution of charge present.

8.3.2 Surface voltage

Measurement with an electrostatic voltage follower probe is preferable with the probe mounted close to the surface so that the response is not affected by any other nearby electrostatic charges. The main limitations arise from the difficulty of covering large potential ranges and risks of electrical breakdown if response speed cannot follow sudden changes of surface potential. The advantages are the good accuracy of potential measurement, independence of probe spacing and the low effective capacitance loading by the probe.

An earth-bonded field meter can be used as a voltmeter and gives easy measurement of surface potential - even for very high voltages. The separation distance shall be known and should be large enough to avoid increasing the capacitance which would depress the potential to be measured. The distance should also be large enough to avoid discharges between the charged surface and the earthed meter. The distance should not be so large, however, that readings are affected by other nearby charges or earthed surfaces.

Precautions:

- The electric field between the surface or body and the field meter will usually be non-uniform and the surface potential is obtained by multiplying the observed electric field E (V/m) by the separation distance (m) and by a correction factor which depends on the physical arrangement. For a field meter near a large plane conducting surface, the electric field is uniform and there is no ambiguity and a correction factor can be obtained for a field meter by itself or with a guard plate. A guard plate only achieves a moderate flattening of the correction curve. It is generally easier to use a field meter without a guard plate for handheld measurements.

- If the surface is not a large plane, it is necessary to establish the relationship between the electric field, the separation distance and the potential. This may be done either empirically or by computer modelling.

- When studying static risks in complex work areas, it is advisable to move the field meter around to ensure all significant sources of charge are identified. Individual surface potentials can then be measured, possibly with shielding against other nearby sources. This approach avoids attributing potential values to surfaces where the reading actually arises from a more significant nearby charge source.

- In measurements involving insulating surfaces, it needs to be recognized that such surfaces may be transparent to electric fields. The effective location of charge sources can be established by varying the position of the observing field meter.

8.3.3 Space potential

The local space potential can be measured by the electric field at an earthed fieldmeter. The earthed field meter perturbs the potential distribution by an amount which depends upon the effective field meter diameter. The electric field, E (V m^{-1}), relates to the local space potential V (volts) for a field meter diameter d (m) as:

$$E = f \times \frac{V}{d} \tag{9}$$

where f is a constant approximately equal to 1. This relationship remains true so long as the field meter is several diameters away from nearby earthed surfaces and structures. This may be tested using a battery powered field meter and raising it to the potential at which the electric field reading is zero, that is, by using it as a voltage follower.

Care should be taken that introducing an earthed field meter into a highly charged environment does not initiate spark or corona discharges at the meter surface.

8.4 Charge

The net electrostatic charge on a product or quantity of material may be measured by dropping it into an isolated conducting chamber known, as a Faraday pail, and measuring the charge induced on the outside of the pail by means of an electrometer amplifier. Alternatively, the increase in voltage of the pail in relation to its capacitance can be measured using an electrostatic field meter or voltage follower probe, or the current to earth can be integrated.

Great care is needed with sensitive electrometer circuits to ensure high input resistance, to eliminate noise from any connecting cable and to minimize input bias currents. For measurements based on an increase in pail voltage, the capacitance of the pail needs to be much larger than that of the charged item. This approach is simple and suitable for measurements down to 1 pC. When collecting large quantities of charge in industrial studies, safety may be critical and the integration of current may be a simple way to keep the pail reliably close to earth.

Practical precautions needed for reliable measurement include:

- a pail deep enough to ensure that all introduced charge couples to the pail and essentially none outside;
- good shielding of the pail against the influence of any charges in the local environment;
- avoidance of influence of any local charges on the charging process being studied. This, for example, requires bonding the equipment to earth when the operator is placing items into the pail, ensuring that the operator is bonded to earth and that his clothing cannot contribute any electric fields at the charging process;
- avoidance of leakage and trapped charge effects on any insulation mounting the pail and in connections and cabling to any external charge measurements circuits;
- ensuring that zero and charge readings are stable for longer times compared to the times involved in making measurements.

Safety should also be ensured by seeing that the charged pail can be safely earthed without causing [AC1⟩ incendive ⟨AC1] sparks.

8.5 Charge density

8.5.1 Surface charge density

A charged sheet of insulating material which is well away from any other earthed surfaces produces the same electric field normal to each surface which is related to the algebraic sum of the charge densities on the two surfaces. The charge densities on individual sides of the sheet can be measured by resting the sheet against an earthed surface. Charge on the surface against the earthed surface will produce no external field and so the charge on the outside surface, which will be less closely coupled and will produce a electric field at a nearby field meter, can be determined. The thickness and relative permittivity of the material and the precise distance of the sensor from the surface should be known.

Measurements to 5 % accuracy require the field meter sensing aperture to be spaced at least 1,5 times the sensing aperture diameter from the sheet surface. The surrounding plane guard plate should be at least 9 times the separation spacing. For 1 % accuracy measurements, the surrounding surface needs to be at least 15 times the sensing aperture diameter.

Observation of small scale charge patterns requires the use of sensing apertures and separation distances of dimensions similar to the pattern size.

Measurements on moving webs require the response speed of fieldmeter to be adequately high relative to the speed of the web, coupled with an appropriate spatial resolution in order to detect any variation in the charge pattern on the surface.

8.5.2 Volume charge density

For a spherical chamber and a uniform charge distribution, the boundary electric field and the maximum space potential relate to the mean charge density linearly and quadratically, respectively. For a uniform charge distribution, therefore, the density of electrostatic charge in a volume may be obtained from the electric field at the boundary or from the maximum space potential within a simple chamber sampling the local atmosphere.

For chambers of complex shape, computer modelling can be used to give values of electric fields at boundaries and the distribution of potential through the volume.

The chamber could be either the overall vessel containing charge or a small sampling vessel ventilated to sample the local atmosphere. Care is needed in the design of a sampling chamber in order to balance good atmosphere transfer against effective shielding of the electric field, created at the outer surface of the chamber by the charge in the larger vessel. The shielding efficiency of sampling chamber boundary can be tested in the absence of space charge by measuring internal readings when the sampling chamber is raised to a high potential. The penetration of external fields can be quite significant if the sampling chamber is to be lowered into the central regions of large scale distributions of electrostatic charge, where the local space potential may be several tens of kilovolts.

8.6 Charge decay

The dissipation of charge from materials is a factor in the control of electrostatic effects. The measurement of the rate of self-dissipation of charge is, therefore, an important parameter. The dissipation performance is indicated by the charge decay time.

Traditionally, the ability of materials to conduct and, hence, dissipate charge has been assessed by measurement of surface or volume resistivity. This can be satisfactory for homogeneous materials. Unfortunately, many practical materials are not identifiable as being homogeneous and many have a resistivity dependent upon position, be that directional or voltage-driven. Since static charges arise on surfaces by contact or rubbing actions, the best way to access the charge retention properties of materials is to simulate this practical situation by depositing a patch of charge on the material and observing how quickly it dissipates.

Charging of a material by rubbing is a very simple and practical way to charge a solid material surface. This method often has the benefit that it may simulate real life conditions. However, charging using this method can be very inconsistent. Powders, granules and flakes of material may be easily charged, simulating real life conditions, by tumbling or simulated flow.

Deposition of charge using high-voltage corona discharge is often a simple and versatile way to charge materials or surfaces. This method is applicable to solid surfaces, powders or granules and liquids.

Conducting and dissipative materials or objects, having resistivity of less than about 10^{11} Ω may be charged by induction or by direct connection to a high voltage source.

The usual method of observing the dissipation of the charge is by using a field meter to record the decrease of the associated surface field.

Materials and surfaces used to provide a discharge path for objects placed thereon can also be assessed by observing the voltage decay of a charged metal plate placed upon the material or surface.

The charge decay rate on many insulating materials is heavily dependent on the charge density – the higher the charge density, the faster the decay. A very fast initial rate of charge decay can slow radically as the charge density decreases. The best way to interpret the rate of decay, therefore, is in relation to the application of the material.

If the concern is the amount of charge retained by a powder during storage, for example, then the long-term characteristic is important. In a dynamic charging situation, such as pneumatic transfer of material, the important factor is the short-term charge migration rate with cleaning the insulators in contact with the product.

The area and density of charge and the proximity of earthed surfaces will all affect the electric fields driving charge migration. Ideally, therefore, charge decay rates need to be measured under two extreme conditions to assess the influence of nearby earthed surfaces. An edge contact for the sample with an open backing promotes preferential migration over the surface while transport through the sample will be preferred for a sample supported on an earthed plate. With installed materials, of course, it is necessary to observe the charge decay using the installation earth.

Care should be taken to minimize the handling of materials and causing any changes to the surface properties. Powders should be placed in a suitable container.

8.7 Resistance and resistivity

Electrical resistance is the physical parameter with the greatest range extending over some 30 orders of magnitude from metals to almost perfect insulators. The resistance and resistivity of both solids and liquids have been measured for a considerable time and a large number of methods have been described in the standards literature. It is evident that no single method will be applicable over the whole range but, in the context of electrostatics, simply placing the sample between a pair of electrodes and measuring the current for a given voltage will probably suffice in most cases. The resistance across the surface of a material can be different from that through the same material owing to the effect of absorbed contaminants, in particular, water. A different form of electrode system is clearly required but the principle remains the same.

A continuously decreasing current (or increasing resistivity) is observed for highly insulating materials under constant electric field. Also, for these materials, the current can increase non-linearly with increasing voltage. These factors make the concept of resistivity invalid and interpretation of experimental observations difficult. It is general practice that for these highly insulating materials the resistance recorded after a specified time is the accepted value.

Measurement of the resistance, under practical circumstances such as from the surface of an installed structure to the building earth, or through protective footwear, is sometimes required. In these cases, the principle to be used is that the electrode system should, as near as possible, be representative of the actual application,

It is important that good contact is made between the electrodes and the sample. Soft, electrically conductive materials or metal foils backed by a soft material are often used. Special cells are evidently required for liquids and powders. In those situations where the resistance of the product is similar to that of the insulating components of the measuring system, guard electrodes to divert stray currents should be used. Great care is required when filling with powders to use a method which provides consistent packing density.

8.8 Chargeability

It is often necessary to measure chargeability to assess the currents that may arise in process operations or handling of individual products. It is the case that the greater the work done on the product, the larger the charge. For instance, grinding produces more charge than sieving of powder, and pumping a liquid through a filter produces more charge than laminar flow. Other common situations include: rubbing of a material, transport of a web through a roller system, pneumatic conveying of powder, flow of liquids through pipes and people walking on insulating flooring.

The charge resulting on one component of the system may be measured directly by use of a Faraday pail, or indirectly by observation of the electric fields or potentials created by this charge. Because of the equality in the magnitude of charge on the test surface and on the rubbing material, there is the option of measuring charge on either.

Fresh materials shall be used to avoid changes caused by contamination.

Charge separation may be accompanied by charge dissipation. Discharges can occur between the separating bodies. The balance of charge measured is the result of the balance of charging and discharge processes. The charge measurement should therefore be made as soon as practicable after charge generation. For example, flowing products under test should fall directly into a Faraday pail measurement system.

Ambient electric fields can influence the charge separation process and so these measurements should be made in a field free environment.

8.9 Current

There are several areas in which the measurement of current is relevant in electrostatics. Very small currents, usually less than a few nano amperes, arise from conduction through insulators. Larger currents of the order of microamperes are produced by flowing, charged products while large currents of amperes can be generated in electrostatic discharges. Commercially available electrometers provide a convenient means for the measurement of the first two although the determination of the increase of potential of a known capacitor presents an alternative method for all three current levels. With spark discharge currents it is necessary to ensure that all the charge flow passes through the measurement shunt and for the shunt to have a low resistance so that the voltage generated by current flow is small compared to the source voltage. The reactive impedance of the shunt should be negligible in comparison to its resistance so that the voltage across the shunt is an accurate measure of instantaneous current flow. The transient recording system shall have a response rise time adequately shorter than the minimum rise time of the fastest discharge event to be measured. For spark discharges from conducting bodies this should be 1 ns or less.

Care needs to be taken with the maximum voltage excursion of the measuring system and means of shorting to earth without sparking should be provided in areas where flammable gases may be present.

A convenient way to keep the inductance low is to form a 1 Ω (e.g.) input resistor from ten 10 Ω resistors in parallel. Surface mount resistors are useful to achieve a shunt with low reactive impedance for frequencies up to 1 GHz. A series resistance of 50 Ω should connect to the input of the 50 Ω cable connected to the detector which should have a 50 Ω input impedance to earth. The 50 Ω resistors are necessary to match the characteristic impedance of the cable at its terminations to prevent signal reflections distorting observed waveforms. It should be noted that the 50 Ω input impedance halves the observed voltage. Great care is needed with earthing and shielding to avoid spurious observations of fast transient discharge events. It is useful to check whether negligible signals arise if the discharge event takes place directly to the earthed surface rather than to the probe.

8.10 Energy in capacitive discharges

The determination of electrostatic energy released in a discharge is important for the assessment of the damage vulnerability of sensitive devices and the $\text{AC}_1\rangle$ incendive $\langle\text{AC}_1$ of mixtures of flammable materials in air. There is no method that is generally accepted at present for the direct measurement of this energy. The most general way to determine the stored electrostatic energy is by measurement of the voltage, V, and capacitance, C, of the charged object, the energy being given by 0,5 CV^2. The discharge of a known capacitor charged to a preset potential, therefore, forms the basis of current methods to assess discharge effects. The method for testing powered electronic equipment is described in IEC 61000-4-2 while the determination of minimum ignition energy of dust/air mixtures is given in BS EN 13821.

8.11 Ignition energy

8.11.1 General

The energy required to ignite flammable gases or dust clouds is smaller if the discharging circuit includes resistive and inductive components which extend the duration of the discharge. The test generally accepted to be most representative does not use additional inductors. The minimum ignition energy (MIE) for a particular vapour/air or dust/air mixture is found by repeated testing with progressive reduction of spark energy until ignition is not obtained. The powder is dispersed into the air in the vicinity of the spark gap by a short puff of compressed air and the spark discharge applied a few tens of milliseconds later. A large number of observations is required for each set of conditions. The method of determination of minimum ignition energy of dust/air mixtures is given in IEC 61241-2-3.

A convenient method for assessing the incendivity of sparks from charged surfaces is to draw a spark to an earthed, spherical electrode which is enclosed within an insulating chamber fed with a controlled flammable gas mixture. The device is called an ignition probe. Ignition of the flammable mixture bathing the electrode gives a direct incendivity indication. Ignitions seem to occur more readily if the surfaces are at a negative potential relative to the probe. The occurrence of ignition will indicate that conditions are within the boundaries for ignition risk. Ignition is, however, a statistical process and so many tests are required without ignitions to be sure that ignition risks are small.

The voltage shall be measured both before and after the discharge, because not all the initial energy may be released.

The effect of electrostatic sparks can change greatly with rise time and duration. The rise time of air sparks between metal conductors is observed to be faster for lower voltages and even faster with a closing rather than stationary spark gap. The IEC test specifies the use of both a spark discharge from a charged electrode approaching a sensitive circuit and direct contact of the electrode, ensuring the correct current waveform by means of a fast relay. The instantaneous discharge current will be higher for the direct contact and this is, therefore, a more severe test of the device.

Reliable measurement of ignition energies for flammable vapour/air or dispersed dust/air mixtures requires the components to be well mixed and the concentrations properly defined at the ignition electrodes. The gap between the spark electrodes shall be greater than a certain minimum to reduce the cooling effect of the electrodes on the development of the flame kernel. Care shall be taken with the discharge circuit and its components to ensure that the discharge is really capacitive. Optimization of flow rates and timing of the ignition discharge in relation to the dispersion of the dust cloud requires considerable experience.

Good ventilation of the general region is needed when using the ignition probe to avoid build-up of a large volume of flammable atmosphere and risk of a large scale explosion if ignition occurs.

8.11.2 Equivalent energy

The ignitability of a flammable substance to an electrostatic discharge is characterized by minimum ignition energy. The power density (temporal factor) and spatial spread (spatial factor) of electrostatic discharge are also important factors in determining the ignition probability of an electrostatic discharge. However, except for spark discharges, it is not easy to obtain the total energy of electrostatic discharge. Much less easy is it to determine how much of that energy contributes to ignition. For that reason, spark discharge is used to measure ignition energy because the discharge provides high energy density both temporally and spatially and then facilitates determination of discharge energy. In an electrostatic discharge other than the spark discharge, the equivalent energy for that electrostatic discharge is defined as X J when the discharge ignites a flammable atmosphere with the minimum ignition energy X J. Since equivalent energy is experimentally determined in comparison with ignition energy, it is convenient in analysing the risk of ignition. Note that the discharge energy other than spark discharge referred to hereafter corresponds to this equivalent energy. Recently, in view of how effective a specific electrostatic discharge is at igniting a flammable atmosphere, this equivalent energy may also be referred as effective energy (see [7] and [8]).

8.12 Charge transferred in electrostatic discharges

8.12.1 General

WARNING charge transfer measurements should never be made in the presence of flammable atmospheres.

The quantity of charge transferred in an electrostatic discharge can be measured for all types of discharge. One application of charge transfer measurement is the prediction of ignition probability. There is some evidence that the probability of a discharge igniting a flammable atmosphere can be related to the quantity of charge transferred in the discharge [7]. It should be noted that any relationship between charge transfer and ignition probability may be limited to the specific materials from which discharges are generated and the specific measuring system used. The reason for this is that discharges differ in the spatial and temporal distribution of energy. For example, a brush discharge may be less likely to cause ignition than a spark discharge in which the same quantity of charge is transferred because the energy associated with the transfer of charge is distributed through a larger volume of gas. Although limit values have been established for the minimum charge transfer required to ignite gases of different sensitivity, the limit values should be regarded as a general guide only. Particular care shall be exercised when considering the safety of materials for which charge transfer measurement results are close to the specified limit values.

The basic arrangement for measuring charge transferred in electrostatic discharges is shown in Figure 6.

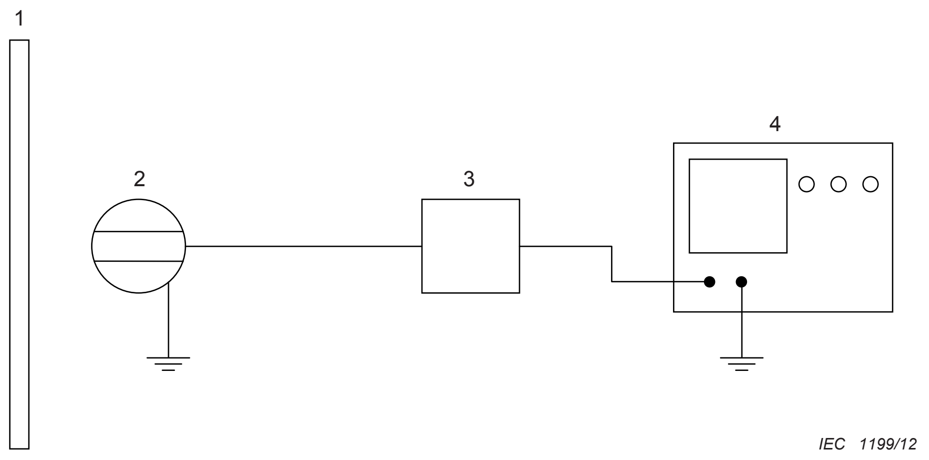


Figure 6a) – Basic arrangement

Figure 6b) – Measurement circuits with capacitor

Figure 6c) – Measurement circuits with resistor

Key

1	charged object or surface
2	spherical, bi-component discharge electrode
3	measuring circuit
4	digital storage oscilloscope (e.g. 1 GHz bandwidth)
5	connection to electrode
6	connection to oscilloscope
7	capacitor (e.g. 20 nF)
8	resistor (e.g. 0,25 Ω)

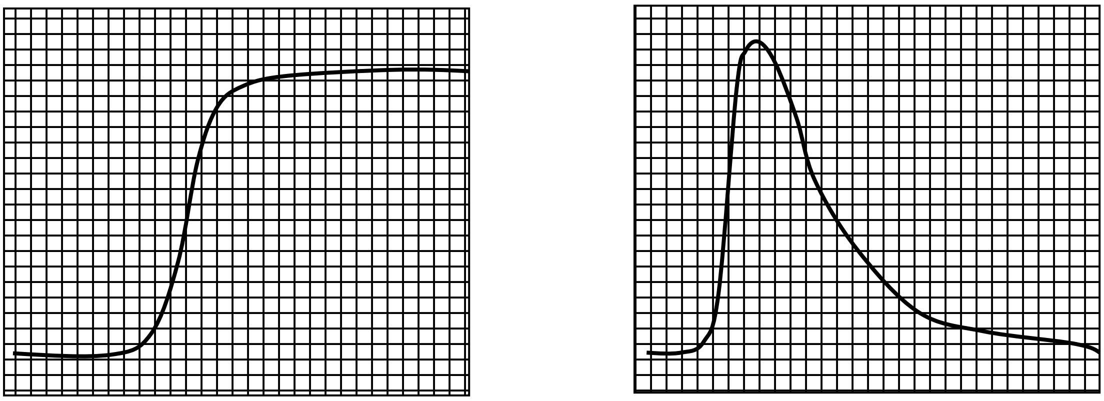
Figure 6 – Basic arrangements for measuring charge transferred in electrostatic discharges with alternative measuring circuits

8.12.2 Discharge electrode

The size and geometry of the electrode should be suitable for the application for which the measurements are being made. For example, the optimum diameter to produce discharges that are incendiary to typical hydrocarbon gases from highly charged surfaces is about 30 mm. For surfaces with lower charge density, a smaller diameter electrode, 2 mm for example, may be more suitable, particularly if the ignition of very sensitive gases such as hydrogen is of concern. Electrodes of diameter significantly less than 2 mm should be avoided as they are likely to induce corona discharge. Electrodes of more than 10 mm diameter should ideally be bi-component, with the central core connected to the measuring system and the outer sheath connected to earth. The use of bi-component electrodes is necessary to avoid the effect of charge induced on the electrode before a discharge occurs.

8.12.3 Measuring circuit

The measuring circuit can be based on one of two components: a capacitor or a resistor, typical values being 20 nF and 0,25 Ω respectively. An oscilloscope essentially measures potential difference with respect to time. Each of the alternative components will produce a different voltage/time trace on the oscilloscope as shown in Figure 7.



IEC 1202/12

Figure 7a) – Capacitor measuring circuit

IEC 1203/12

Figure 7b) – Resistor measuring circuit

NOTE These are idealized representations of oscilloscope traces and, in practice, the voltage/time trace may display ringing and other artefacts.

Figure 7 – Oscilloscope voltage/time traces

A capacitor in the measuring circuit produces a step function trace on the oscilloscope. The charge transfer in coulombs can be calculated by multiplying the amplitude of trace in volts by the value of the capacitance in farads.

AC1⟩ A resistor in the measuring circuit produces a pulse. The measuring system of the oscilloscope is used to integrate the voltage with respect to time to produce a value in volts × second (V × s) that can then be divided by the value of the resistor in ohms, to give the charge transfer in coulombs. ⟨AC1

8.12.4 Alternative charge transfer measuring arrangements

Commercial instruments, referred to as handheld coulomb meters, are available that provide a self-contained system for measuring charge transfer. The instruments are generally easy to use and provide a direct read-out of the charge transfer value. Handheld coulomb meters are useful for identifying potential sources of incendiary discharges, but in using them consideration should be taken of the following:

a) if the discharge electrode is fixed, it may not be the optimum size for the application;

b) if the discharge electrode is a solid sphere, measurements may be susceptible to induced charges;

c) if no graphical display is provided, there may be no way of determining if the measurement is of a single discharge or the accumulated charge from multiple discharges.

8.13 Capacitance

Capacitance can be measured using alternating voltage bridge instruments or by measuring voltage changes when charge is shared between a known and an unknown capacitance. For charge sharing between two capacitors C_1 and C_2 with initial voltages V_1 and V_2 and a final common voltage V_3, the unknown capacitance C_2 is given by:

$$C_2 = C_1 \cdot \frac{V_1 - V_2}{V_3 - V_2}. \tag{10}$$

Care is needed in measuring the values of capacitors used to provide energy for spark discharges because dielectric relaxation may affect the rate at which charge is available, so the effective capacitance may be less than that measured by low frequency methods. In this situation, measurement by charge sharing via a spark discharge and using a capacitor of known high quality at around the normal operating voltage may be the most appropriate method.

Low values of capacitance shall be obtained by measuring the difference of readings with the active lead just not contacting the test item, and then just in contact, with no other change to connection arrangements, to allow for the capacitance of connecting leads.

8.14 Electric strength

The measurement of the electric strength of thin films or layers of insulation is an important factor in assessing the possibility of sustaining propagating brush discharges on the material. The important parameter is the breakdown voltage and the critical value is about 4 kV.

The breakdown strength of insulators is dominated by defects within the material. The result is, therefore, greatly influenced by the area under test. The number of defects increases and, hence, breakdown strength reduces with increasing area. Conversely, a smaller area gives a greater breakdown voltage and greater apparent hazard. As a guide, the breakdown strength of polyethylene is about 20 MVm^{-1}, so 4 kV will be sustained by a layer some 200 μm thick. The capacitance of a plate capacitor having such layer-type dielectric is about 90 nF m^{-2} and the stored energy (0,5 CV^2) at 4 kV is 720 mJ m^{-2}. Some 7 mJ of energy is, therefore, in principle available from an area of 100 cm^2 of the material. A test electrode area of a few square centimetres will provide a realistic estimate of the hazard.

A simple circuit based on charging a capacitor has been developed to provide the test ramp voltage. Care shall be taken to avoid electric shock since the circuit employs high voltage in association with large capacitances and relatively low protective resistances. Test methods are given in IEC 60243-1 and IEC 60243-2.

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