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1995

Methods for

Measurements in electrostatics —

Part 1: Guide to basic electrostatics

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Committees responsible for this British Standard

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British Floor Covering Manufacturers' Association
British Plastics Federation
British Rubber Manufacturers' Association Ltd.
ERA Technology Ltd.
Electrical and Electronic Insulation Association (BEAMA Ltd.)
European Electrostatic Discharge Association
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Federation of Resin Formulators and Applicators Ltd.
Health and Safety Executive
Ministry of Defence
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Contents

Foreword

This Part of BS 7506 was prepared by Technical Committee PRI/25.

This Part is related to BS 5958 and BS EN 100015 which are codes of practice concerned with hazards arising from electrostatic phenomena.

Electrostatic problems are experienced in a wide spectrum of industry and measurements are made by technologists who are not necessarily experts in electrostatics. Part 2 of this British Standard describes methods for measuring electrostatic effects and quantifying the relevant properties of materials and gives guidance on implementation of the methods.

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 20, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

1 Scope

This Part of BS 7506 provides information and guidance on methods for making reliable measurements of electrostatic phenomena and the relevant properties of materials.

This Part comprises the following:

— review of basic electrostatics;

— outline of the range of problems caused by static;

— consideration of the role of materials and description of methods to minimize charge generation and achieve safe dissipation of static charge;

— consideration of electrostatic applications;

— recommendations for the control of the test environment conditions;

— general consideration of the basic recommendations for reliable measurement of electrostatic parameters.

2 References

2.1 Normative references

This British Standard incorporates, by reference, provisions from specific editions of other publications. These normative references are cited at the appropriate points in the text and the publications are listed on the inside back cover. Subsequent amendments to, or revisions of, any of these publications apply to this British Standard only when incorporated in it by updating or revision.

2.2 Informative references

This British Standard refers to other publications that provide information or guidance. Editions of these publications current at the time of issue of this standard are listed on the inside back cover, but reference should be made to the latest editions.

3 Definitions

For the purposes of this British Standard the following definitions apply.

3.1
antistatic material or treatment

a material or treatment which allows easy migration of charge so that when bonded to earth the material does not retain static charge or one which does not easily acquire charge by contact

NOTE An antistatic material will satisfy the quantitative requirements of either a dissipative or an astatic material (see **3.12** and **3.3**).

3.2
antistatic additive or filler

a substance added to a liquid or a solid in order to promote more rapid charge migration and so reduce its ability to retain significant electrostatic charge when in contact with earth

3.3
astatic material

a material with low tendency for charge separation by contact or by rubbing against other materials

NOTE As a means to control static risks it is essential that the maximum surface charge generated in an approved test procedure should remain below the relevant hazard threshold value.

3.4
bonding

the use of an additional independent connection between conductors to provide electrical continuity when this cannot otherwise be ensured

3.5
breakdown

the annihilation, at least temporary, of the insulating properties of an insulating medium under electric stress

3.6
breakdown voltage

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

3.7
charge decay

the migration of charge across or through a material leading to a reduction of charge density or surface potential at the point where the charge was deposited

NOTE It is usually measured by observation of the timescale for decay of surface voltage.

3.8
charge decay time constant

the time required for the local charge density or surface potential to fall to $1/e$ of its initial value

NOTE For characterizing materials the initial value should be the relevant hazard threshold value.

3.9
conductive material

a material of relatively high conductivity or charge carrier mobility. Materials of surface resistivity below 10^6 Ω or volume resistivity below 10^7 Ω·m are usually implied

3.10
conductivity

the reciprocal of resistivity ($S\text{m}^{-1}$, equal to $(\Omega\cdot\text{m})^{-1}$)

3.11
conductor

a material providing a sufficiently high conductivity that all parts of it are always at the same potential

3.12
dissipative material

a material which allows charge to migrate over its surface and/or through its volume in a time which is short compared to the timescale of the actions creating the charge or the time within which this charge will cause a problem. For normal applications the decay time constant for a patch of deposited charge downwards from the hazard threshold value should be within the range 0.01 s to 0.5 s

3.13
earth/earthing

electrical connection (bonding) of a conductor to the main body of the earth to ensure that it is at earth potential

3.14
earth bonding point

a dedicated point for connecting equipment and people to earth

3.15
electrostatic discharge (ESD)

the sudden transfer of electrostatic charge between bodies at different electrostatic potentials by direct contact or by breakdown

3.16
electrostatic discharge sensitive device (ESDS)

a discrete device, semiconductor, integrated circuit or other assembly that can be damaged by an electrostatic discharge directly to the device or nearby

3.17
ESD common earth bonding point

a common connection point to which all items in an ESD protected area are connected

3.18
ESD protected area (EPA)

an area with a defined boundary within which an ESDS can be handled without risk of damage from electrostatic discharges or fields

3.19
ESDS voltage sensitivity

the maximum voltage at which the ESDS does not suffer any ESD damage

3.20
ESDS voltage sensitivity of an assembly

the ESDS voltage sensitivity of the most sensitive device in an assembly will determine the sensitivity of the assembly

3.21
field work

handling ESDS within a temporary EPA with controlled boundaries

3.22
flammable material

a gas, vapour, liquid, dust or solid that can react continuously with atmospheric oxygen and that may, therefore, sustain fire or explosion when such reaction is initiated by a suitable spark, flame or hot surface

NOTE In normal usage gas and vapour are synonymous.

3.23
flammable mixture

a mixture of a gas, mist or suspension of dust with air (or air enriched with oxygen) in which combustion will propagate

3.24
flammable range

the range of concentrations in air of a flammable material within which combustion can occur

3.25
garment

a coat, jacket, smock, hood, trousers, overall or cap

3.26
ground

this is synonymous with earth

3.27
ground cord

a flexible electrical connection between the earth bonding point and the ESD earth facility

3.28
hazard threshold voltage

the minimum capacitively stored voltage at which an electrostatic hazard or risk will exist

3.29
hazardous area

an area in which flammable or explosive gas-air mixtures are, or may be expected to be, present in quantities such as to require special precautions against ignition

3.30
incendive

capable of igniting a prescribed flammable mixture

3.31
insulator

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

NOTE The charge decay time constant is generally greater than 10 s.

3.32
ion

an atomic or molecular particle carrying electrical charge

3.33
mass charge density

the net quantity of charge carried by unit mass of a material (C kg^{-1})

3.34
minimum ignition energy

the smallest amount of energy released in a spark that can ignite a mixture of a specified flammable material with air or oxygen, measured by a standard procedure

3.35
packaging material

any material in which ESDS are packed in intimate contact or close proximity for transportation or storage; including bags, boxes, crates, wraps, magazines, cushioning, foams, loose fill, etc

3.36
relaxation

the migration of charge over and/or through a solid, liquid or gaseous material causing a reduction in surface charge density and potential

3.37
relaxation time constant

charge decay time constant

3.38
shielding material

a material which when formed into an enclosure provides strong attenuation of fast electric field transients associated with spark discharges to, or in the vicinity of, the outside of the enclosure

3.39
shielding bag/container

a bag or container made from shielding material which provides protection for the storage or transport of ESDS

NOTE For normal applications it is necessary to provide 1 000 : 1 voltage attenuation ratio over the frequency range 10 Hz to 1 GHz between the inside and outside region. This may be affected by both the material and the construction.

3.40
surface charge density

the net quantity of charge per unit area of surface of a solid or liquid (C m^{-2})

3.41
surface resistivity

the resistance between opposing sides of a square on the surface of a material with account taken of all current flow paths

3.42
triboelectric charging

the separation of charge occurring at relative contact movement between two surfaces

3.43
volume charge density

the net quantity of charge per unit volume of a solid, liquid or gas (C m^{-3})

3.44
volume resistivity

the resistance between opposing sides of a cube of the material with account taken of fringing field effects

3.45
permittivity (absolute)

the quantity whose product by the electric field strength is the electric flux density or surface charge density

3.46
electric constant ϵ_0

the value of the permittivity in a vacuum, sometimes referred to as the permittivity of free space

3.47
relative permittivity

the ratio of the absolute permittivity to the electric constant. The permittivity is often taken to mean relative permittivity. It is also the ratio of the capacitance of an electrode system filled with a dielectric to that where the interelectrode space is free of all material (i.e. in a vacuum)

4 List of symbols

The following symbols are used in this standard:

Quantity	Symbol	Unit or value
Area	A	m^2
Capacitance	C	F
Charge	Q	C
Charge density	σ	Cm^{-2}
Conductivity	γ	$\Omega^{-1}m^{-1}$
Current	I	A
Electric field	E	V/m
Energy, potential energy	W	J
Ionic charge	ϵ	C
Ionic mobility	μ	$m^2V^{-1}s^{-1}$
Linear dimension (thickness, diameter)	d	m
Permittivity, relative	ϵ	1
Potential	V	V
Probability	P	1
Resistance	R	Ω
Temperature (Kelvin)	T	K
Time	t	s
Electric constant	ϵ_0	$8.85\ 10^{-12}$ Fm^{-1}
Base of natural logarithms	e	2.718282
Boltzmann's constant	k	$1.3804\ 10^{-23}$ J/K

5 Fundamentals of static electricity

5.1 General

The most common cause of electrostatic charge is contact electrification. Conducting objects can become charged by induction if they reside in an electric field produced by other charged objects or conductors at high potential in the vicinity. Any object can become charged if charged particles or ionized molecules accumulate on it.

5.2 Contact electrification

Contact electrification can occur at solid/solid, liquid/liquid or solid/liquid interfaces. Clean gases cannot be charged 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 dissimilar solids, initially uncharged and normally at earth potential, a small amount of charge is transferred from one material to the other when they make contact. The two materials are, therefore, oppositely charged and consequently there is an electric field between them. If the materials are then separated, work has to be done to overcome the attraction between the opposing charges and the potential difference between them, therefore, 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. In practice, surfaces are usually rough and so the charging is enhanced if the contact and separation involves rubbing since the area of real contact is increased.

Contact electrification in liquids is essentially the same process but it can depend on the presence of ions or sub-microscopic charged particles. Ions (or particles) of one polarity may be adsorbed at the interface and they then attract ions of opposite polarity forming 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.

5.3 Charging by induction

There is an electric field around any charged object. A conductor introduced into this field changes the distribution of potential in its vicinity and at the same time there is a separation of opposing charges in the conductor under the influence of the field. If it is insulated, the conductor takes up a potential, dependent upon its position in the field and is said to be charged by induction. By virtue of this potential, coupled with the separated charges that it carries, the conductor is capable of producing an electrostatic discharge, or spark. If, while it is in the field, the conductor is momentarily earthed, its potential is reduced to zero, but an imbalance of charges remains on it. Isolation from earth and removal of the, now insulated, conductor from the vicinity of the original charged object, however, makes the remaining charge available to provide a spark. This type of sparking can be hazardous, for example in the case of an insulated person moving about near electrostatically charged materials.

5.4 Charge transfer by conduction

Whenever a charged object makes contact with one that is uncharged, the charge is shared between them to the extent that their conductivities and capacities allow. This is a potent source of electrostatic charging and examples are 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 initially uncharged object.

5.5 Retention of charge

Even after separation in the charging process, electrostatic charges will quickly recombine 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 insulated from other conductors and from earth.

Pure gases 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.

In all cases 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 which accumulates on an insulator or an isolated conductor. Examples are when a steady stream of charged liquid or powder flows into an insulated metal container or a person walks across an insulating floor covering. The potential on the insulated conductor is 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 1 and the potential of the conductor is given by the equation

$$V = IR\,(1 - e\,(^{-\,t/CR})$$

where

V is the potential of the conductor;

C is its capacitance;

R is the leakage resistance to earth;

I is the electrostatic charging current;

t is the time from the commencement of charging

The maximum potential is reached when t is large and is therefore given by the following equation:

$$V_{\mathrm{max}} = IR$$

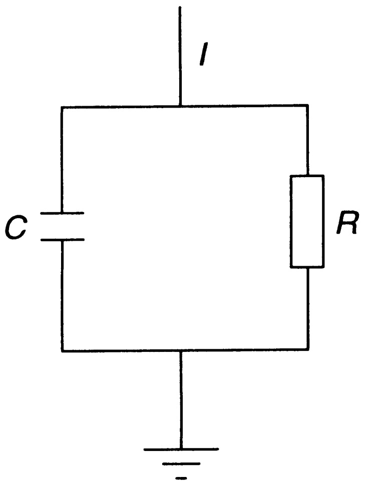


Figure 1 — Equivalent electrical circuit for an electrostatically charged conductor

The capacitance of an isolated object and its leakage resistance to earth or the rate of charge dissipation can be measured to establish if dangerous charges can accumulate.

There is an inherent assumption in the above calculation 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.

5.6 Charge migration in insulators

Insulators are poor conductors of electricity because there are few charge carriers free to migrate through the material. Both intrinsic and injected carriers are trapped within the structure. This is illustrated in Figure 2 where the carrier trap is represented as a potential well of depth W. The presence of an electric field distorts the well, easing release of the carrier in the field direction.

The carrier then proceeds by hopping from one well to the next. The free mobility of the carrier (between traps) may be quite high but the apparent drift mobility of the carriers through the material is governed by the rate of release from the traps. The probability of release from the well is increased by raising the temperature and can be expressed by an Arrhenius equation:

$$p = e^{-W/kT}$$

where

k is Boltzmann's constant;

T is the absolute temperature;

p is the probability.

The mean drift carrier mobility (or velocity per unit field), μ, is, therefore, described by:

$$\mu = \mu_0 e^{-W/KT}$$

where μ_0 is a constant.

The conductivity is given by:

$$\gamma = n\epsilon\mu$$

where n and ϵ are the carrier density and charge, respectively.

Under conditions of constant field and constant carrier density, the conductivity is single valued. This will be the case for a relatively conductive (or dissipative) material and the current I for an electric field E is given by:

$$I = \gamma E$$

The current is equivalent to the rate of loss of charge from a surface and, for a surface charge density σ (Cm^{-2}), the relationships between charge density; field E; conductivity γ; current I; and charge decay rate are:

$$E = \sigma/\epsilon\epsilon_0$$

$$I = \gamma\sigma/\epsilon\epsilon_0$$

$$\sigma = \sigma_0 e^{-\gamma t/\epsilon\epsilon,o}$$

where ϵ and ϵ_0 are the relative permittivity and electric constant respectively, and σ_0 is the initial value of charge density.

The decay is therefore exponential for these materials, with a time constant given by the product of the permittivity (absolute) and resistivity ($1/\gamma$) of the material.

Carriers having insulating materials, which have few intrinsic carriers, reduce the number available for conduction as well as, in the case of a charged material, causing a reduction in the driving field. The conductivity will decrease with time but the form of this decrease is unpredictable. A common form observed is a rapid loss of charge at short times followed by a slowing down in the rate, even in some cases to a constant residual charge level.

Since the mobility increases with temperature it is important to record the temperature when determining electrostatic parameters.

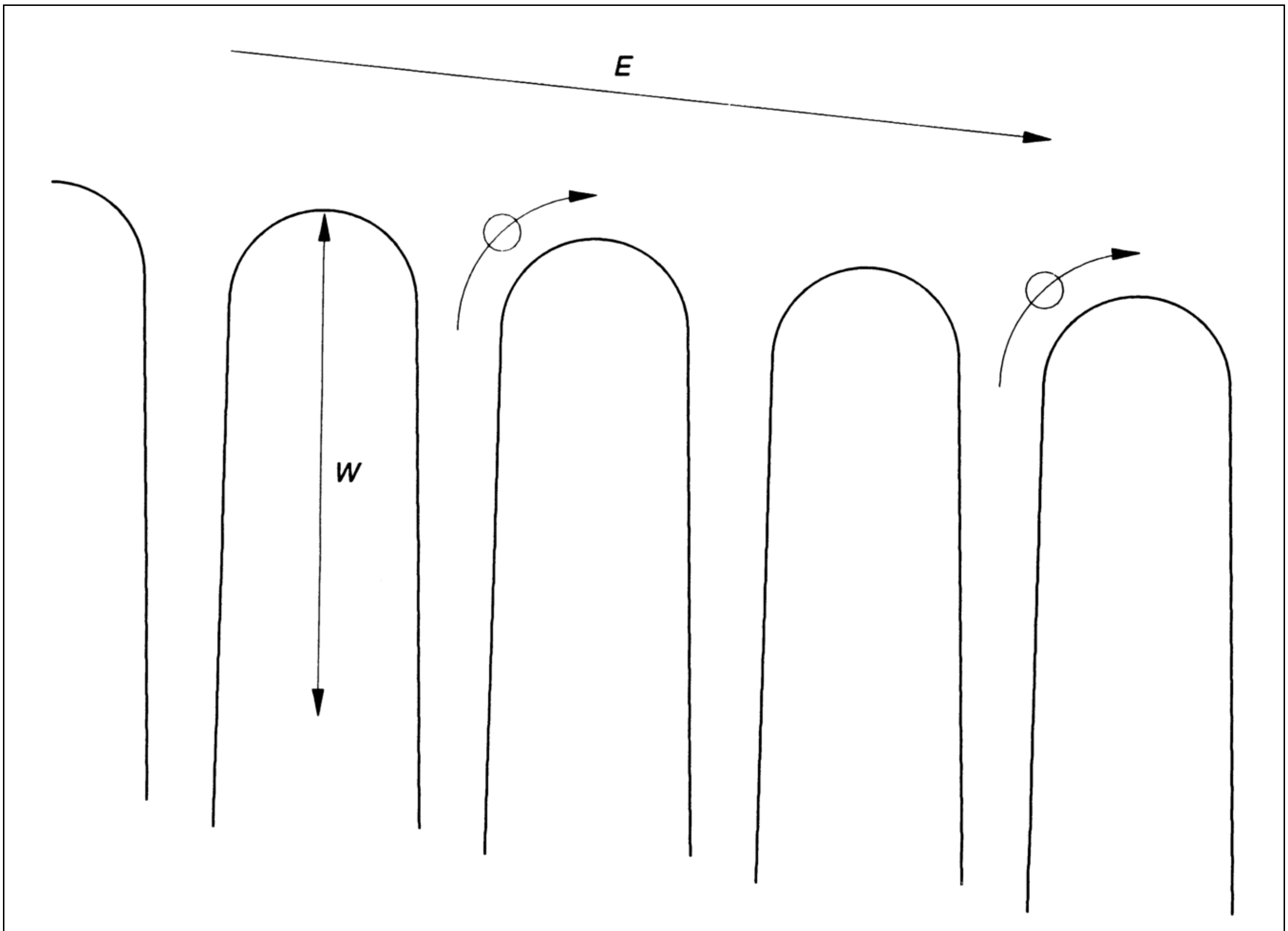


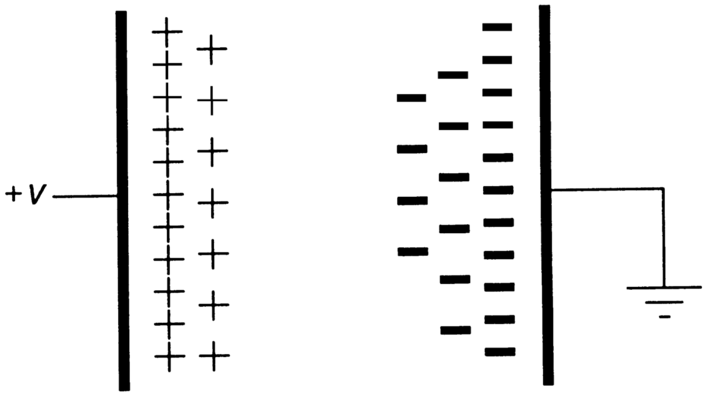
Figure 2 — Potential wells and charge migration

5.7 Electrical conduction in insulators

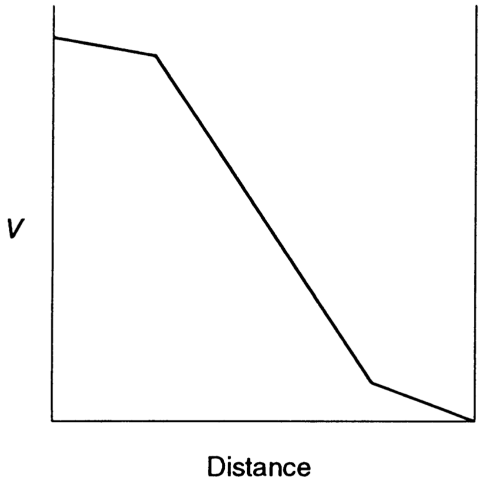
Application of a d.c. potential difference between the electrodes in a metal/insulator/metal or metal/dissipative material/metal sandwich results in an instantaneous, very high, capacitive charging current which decreases rapidly at a rate governed by the charging circuit impedance. Following this fast transient, the current decreases steadily to an equilibrium value. The magnitude and duration of the latter reduction in current are usually interrelated.

The current can decrease for a considerable time and over several orders of magnitude for a good insulator but for more dissipative materials both effects can be negligible.

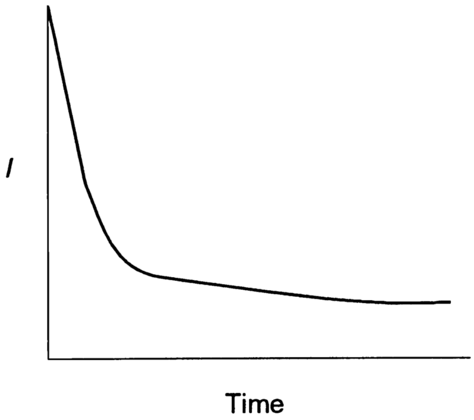
The passage of a steady electrical current through the electrode/insulator/electrode system requires equilibrium between the transfer of electrical carriers from the electrodes into and out of the insulator and the transport of carriers through the material. The rate of carrier transfer in each of these processes is governed by the electric field and attainment of current continuity necessary for the steady state results in the establishment of a space charge to generate the necessary local field. In a highly insulating solid, owing to the paucity of carriers, the carrier injection rate is higher than the rate of migration. Conversely, for a liquid containing some ionic species, the migration rate could be higher than the rate of injection. In either case, space charges accumulate adjacent to the electrodes either to retard or to stimulate the electrode transfer, respectively. This is illustrated schematically in Figure 3. Phenomenologically, therefore, the effects are the same, being a high initial current as the space charges are being established followed by a steady decrease to an equilibrium level.



a) Carrier injection and transport



b) Potential distribution



c) Current transient

Figure 3 — Schematic diagram of a metal-insulator-metal sandwich

Whatever the effect of temperature on the electrode injection processes, the dependence of the carrier drift mobility in insulators on temperature necessitates that all these effects are also temperature dependent. Indeed, at elevated temperature, the observed phenomena for good insulators can be reversed, that is, the transport current may be greater than the injection currents. However, consistent with the increased conductivity, both the magnitude and duration of the transient are reduced.

It is crucial to have some appreciation of these phenomena to enable the proper implementation of test procedures and unambiguous interpretation of the resultant data. It is important with regard to choice of electrodes, protection of current measuring devices from the initial capacitive surge, and the time at which the value of current is recorded.

5.8 Influence of environmental humidity

5.8.1 *General*

All materials adsorb atmospheric water to some degree and in the case of insulators this can significantly increase the rate of charge dissipation. Water absorbed on the surface of materials is the prime cause of a surface conductivity which is different from that in the bulk of the material. The effect, well known but still poorly understood, is that the conductivity increases with amount of water adsorbed; that is, 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.

In terms of the model of charge migration the water could contribute free carriers, influence the carrier trapping characteristics of the material, or both. If the effect was simply to provide carriers then a linear dependence of the conductivity on the concentration of adsorbed water could be expected. The water molecule, being highly polar, if adsorbed into the structure at the cartier trap could effectively reduce the depth of the potential well. Assuming that the depth of the well is reduced by an amount δ, which is linearly dependent on the relative humidity, the conductivity can be expressed by:

$$\gamma = \gamma_{\mathrm{o}}\, e^{-(\mathrm{W} - \delta)/\mathrm{kT}}$$

$$\gamma = \gamma_1\, e^{-\delta/\mathrm{k},1}$$

where γ_{o}, γ_1 and K_1 are constants.

This predicts an exponential dependence of the conductivity on relative humidity which is observed over a wide range of humidity and for a large number of insulating materials. Ideally, therefore, electrostatic parameters should be measured for at least two levels of relative humidity which are as widely spaced as possible. In this way the characteristics at any humidity can be predicted.

5.8.2 *Laboratory measurements*

Standardized laboratory measurements should be made at a temperature of 23 °C ± 2 °C and at relative humidities of (50 % ± 5 %) RH and between 10 % RH and 20 % RH. Specimens should be conditioned for at least 24 h under the prescribed conditions prior to measurement or for longer if required in relevant product standards. These conditions should be maintained while the measurements are being made.

It may be possible, owing to the special properties of the material, that these conditioning procedures may not be adequate to define the effect of the environment on a particular product. In this case the conditioning specified in the product specification is used.

5.8.3 *Industrial measurements*

Measurements under practical conditions clearly cannot easily be made at differing humidities but in this case the prevailing conditions should be recorded.

6 Problems and hazards associated with electrostatic charges

6.1 General

The electric field produced by an electrostatic charge can exert a mechanical force on objects which it envelopes. Films of material charged to a few microcoulombs per square metre can adhere to nearby metals while dust particles can be attracted by fields associated with charge densities an order of magnitude smaller than this. Breakdown of the insulating layers of a semiconductor can occur for voltages as low as 50 V and other forms of damage such as material fusion require only a few microjoules of energy. In general, charge retained on a liquid or a solid creates a problem if it is suddenly discharged to another body or more usually to earth.

Electrostatic discharges vary greatly in type and consequently their effect as causes of electrostatic problems can be very varied. Discharges between metal structures in the form of sparks, such as between a charged device and earth, are the most destructive although discharges from charged insulators can also be harmful. The several types slipped are loosely classified in **6.2, 6.3, 6.4, 6.5** and **6.6**.

6.2 Sparks

A spark is an electrical discharge between two conductors. 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 gives 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. As a guide, the breakdown strength for flat or large radius surfaces 10 mm or more apart is about 3 MV/m under normal atmospheric conditions.

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

$$W = QV/2 = CV^2/2 = Q^2/2C$$

where

W is the energy dissipated, in joules;
Q is the quantity of charge on the conductor, in coulombs;
V is its potential, in volts;
C is the capacitance to earth, in farads.

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 1.

Table 1 — Typical electrical capacitances

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

Approximate calculation of spark discharge energy can be made such as for an unearthed metal drum filled with powder from a grinding unit. In such a case the charging current, I, might be 10^{-7} A, the leakage resistance of the drum to earth, R, $10^{11}\Omega$ and its capacitance about 50 $_{\mathrm{p}}$F. The maximum voltage on the drum, reached in about 15 s, is given by the following equation:

$$V_{\mathrm{max}} = IR \approx 10 \text{ kV}$$

and the maximum energy released in a spark discharge is given by:

$$W_{\mathrm{max}} = CV^2/2_{\mathrm{max}} \approx 2.5 \text{ mJ}$$

The rise time, amplitude and duration of the current passing during the spark are important factors in determining the level of hazard. For example, a very fast high magnitude current pulse conveys energy adiabatically into an electronic device. The device cannot cope with the consequent rapid rise in temperature and is therefore damaged. On the other hand, the longer the duration of the high current pulse for a given energy, the greater the probability of igniting a flammable gas mixture. It is evident that inclusion of a high impedance in the discharge current path will reduce the potential hazard.

6.3 Corona

Corona discharges are 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 discharge arises due to the fact that the electric field locally 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, simply 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 energy density in the discharge is much less than in a spark and for this reason corona discharges are not normally incendive. However, in certain circumstances, for example if there is an increase in the potential of the pointed conductor, a corona can develop into a spark between it and another object.

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 while the field at the point is above the corona discharge threshold and so complete neutralization is not possible. Ionization by corona is a very useful means of reducing unwanted surface charge. Devices based on this principle and comprising an array of earthed, sharp electrodes are used for charge reduction in industry.

6.4 Brush discharges

These discharges can occur when rounded (as opposed to sharp) earthed conductors approach a charged insulating material, for example, between a person's finger and a plastics surface, or between a metal filling tube (dip-leg) and the surface of liquid inside a tank.

The discharges are of short duration and 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. In spite of this, the energy is quite concentrated and brush discharges can ignite most flammable gases and vapours. There is no definite evidence to show that even the most sensitive dusts can be ignited by brush discharges. It is probable, however, that these discharges are harmful to electronic systems.

6.5 Propagating brush discharges

Propagating brush discharges may occur from high resistivity plastics sheets, walls or coatings of equipment or containers with high charge density of opposite polarities on the two 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. 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 plant, for example during the bulking of charged high resistivity powder. Such discharges do not occur with layers of powder.

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 be calculated from the stored energy. The equivalent capacity, C, of a dielectric sheet of area, A, thickness, d, and relative permittivity, ϵ, retaining a surface charge density, σ, is given by the following equation:

$$C = \epsilon\epsilon_0 A/d$$

For a charge density σ, the total charge, $Q = \sigma\mathrm{A}$.

Taking as an example:

$d = 75\ \mu\mathrm{m}$, $A = 0.5\mathrm{m}^2$, $\epsilon = 2$ and a surface charge density, $\sigma = 10^{-3}\mathrm{C/m}^2$, the stored energy is given by:

$$W = CV^2/2 = Q^2/2C = Ad/2\epsilon\epsilon_0 \approx 1J$$

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 would have a catastrophic effect. It should be noted that the discharge of energy of this magnitude to earth via a person would produce considerable physiological reaction and is dangerous.

Propagating brush discharges can be avoided by ensuring that the breakdown voltage of all high resistivity walls and coatings is less than 4 kV so that the charge density that can be stably retained is limited.

6.6 Discharges from people

Charges on peoples' bodies commonly cause a hazard. A person who is insulated from earth can easily acquire and retain an electrostatic charge. The insulation from earth may be due to the floor covering or the soles of footwear 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 insulating packaging.

If an electrostatically charged person touches a conducting object (e.g. door handle, hand rail) 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. The levels of perception of electrostatic charge by people and their physical responses are shown in Table 2.

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 (about 1 mJ). Such discharges can damage electronic devices.

Table 2 — Perception levels and physical responses of people to discharges

Discharge energy mJ	Equivalent body voltage kV	Reaction
1	3.6	Perceptible
10	11.5	Definite sensation
100	36.5	Unpleasant shock
1 000	115.0	Severe, muscular spasm
10 000	365.0	Possibly lethal shock

7 Solutions

7.1 General

A brief review of problems and general approaches to their solution is useful as an introduction to the description of methods of measuring the relevant electrostatic properties of materials. It is generally the case that electrostatic problems are specific to the actual product, process or materials. A measurement of the electrostatic parameters is a necessary precursor to effective solutions.

7.2 Common approaches

The first principle is to avoid the use of highly insulating materials and ensure that all conductive materials or items of metal plant are earthed. 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. In the case of solids this means, for example, avoidance of sliding for solids or a reduction in linear velocity for liquids.

The enhancement of the rate of charge loss from an insulating material to ground is desirable and this can sometimes be achieved by increasing the local humidity or by the addition of antistatic additives. 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 fibres. 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. In general, charge 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 when 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. A pneumatically conveyed (fluidized) powder 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 charged species which can reduce, if not wholly neutralize, the problematic charge on the material.

It is important that people who work in areas of potential electrostatic hazard where there may be flammable atmospheres present and 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 (antistatic) footwear, whichever is practical for the particular industrial environment.

8 Applications dependent on electrostatic effects

The ink-jet printer and photocopier are two machines which contribute significantly to information technology. The electrographic process is entirely based on electrostatic effects and the ink-jet printer uses the precise deflection of accurately sized and charged ink drops. In the photocopier, the optical image is transformed into a charge pattern on a corona-discharge charged photoconductor which is subsequently developed by the adhesion of countercharged developer particles. The final stage is the transfer of the developed image on to the copy paper 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, ore bonification and plastics separation are all either viable or developing industrial processes. 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.

9 General aspects of measurements

9.1 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.

Some electrostatic measurements relate directly to basic physical parameters, for example, electric field, charge, surface and volume charge density, resistivity, capacitance, current, energy. Other measurements are more practical and 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.

Static electricity measurements often do not need to be particularly accurate. The order of magnitude may be quite adequate in many instances. More important 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 which may present risks to sensitive semiconductor devices and for measuring charge density on individual sides of thin films.

There are 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, such as for on-line measurement of charge density or charge decay rate.

The methods detailed in Part 2 of this standard are in general concerned primarily with providing reliable methods with adequate accuracy and precision rather than with the achievement of high accuracy. An introduction to each of the methods is presented in this Part of the standard to clarify some of the difficulties and enable confident implementation and unambiguous interpretation of the results.

9.2 Measurement of electric field

9.2.1 *General*

Measurements of electric field are made using fieldmeters of which there are two types: 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 of relatively low cost but their sensitivity and usefulness is limited. They have a finite input time constant and therefore can only be used for relatively short term measurements (tens of seconds) after zeroing in a zero electric field environment. Their readings will be in error if operated 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 field, 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 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 nulling mode. This is particularly useful for voltage follower probe applications.

9.2.2 *Application*

A measurement of the electric field can provide information on 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 will remain stable over extended periods of operation.

9.2.3 *Precautions*

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 need to 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. Air purging helps prevent particle deposition but it is necessary to check the fieldmeter zero reading from time to time.

The best approach for checking the fieldmeter zero setting is to mount the fieldmeter to look into a clean metal chamber in which the nearest surfaces are at least 50 mm away from the sensing aperture. This avoids the influence of contact potential and contamination effects.

9.3 Measurement of potential

9.3.1 *General*

Potentials arise on conducting 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 the electric field generated at an earthed fieldmeter or from the voltage 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.

9.3.2 *Surface potential*

9.3.2.1 *General*

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

An earth-bonded fieldmeter can be used as a voltmeter and gives easy measurement of surface voltage, even for very high voltages. The separation distance has to 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. However, the distance should not be so large that readings are affected by other nearby charges or earthed surfaces.

9.3.2.2 *Precautions*

The electric field between the surface or body and the fieldmeter will usually be non-uniform and the surface voltage is obtained by multiplying the observed electric field E by the separation distance and by a correction factor which depends on the physical arrangement. For a fieldmeter near a large plane conducting surface the electric field is uniform, there is no ambiguity and a correction factor can be obtained for a fieldmeter 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 fieldmeter without a guard plate for hand held 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 fieldmeter around to ensure all significant sources of charge are identified. Individual surface voltages can then be measured, possibly with shielding against other nearby sources. This approach avoids attributing voltage values to surfaces where the reading actually arises from a more significant nearby charge source.

In measurements involving insulating surfaces it is necessary to recognize 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 fieldmeter.

9.3.3 *Space potential*

9.3.3.1 *General*

The local space potential can be measured by the electric field at an earthed fieldmeter. The earthed fieldmeter perturbs the potential distribution by an amount which depends upon the effective fieldmeter diameter. The electric field, E, relates to the local space potential V for a fieldmeter diameter d as follows:

$$E = f\ V/d$$

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

9.3.3.2 *Precautions*

Care should be taken introducing an earthed fieldmeter into a highly charged environment to avoid initiating spark or corona discharges at the meter surface.

9.4 Measurement of charge

9.4.1 *General*

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 fieldmeter or voltage follower probe, or the current to earth can be integrated.

9.4.2 *Precautions*

Great care is needed with sensitive electrometer circuits to ensure high input leakage 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 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 are:

- — 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;

  NOTE This, for example, requires bonding the equipment to earth and when the operator is placing items into the pail, ensuring that the operator is bonded to earth and that 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 times long 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 incendive sparks.

9.5 Measurement of charge density

9.5.1 *Surface charge density*

9.5.1.1 *General*

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 an electric field at a nearby fieldmeter, can be determined. The thickness and relative permittivity of the material and the precise distance of the sensor from the surface should be known.

9.5.1.2 *Precautions*

Measurements to 5 % accuracy require the fieldmeter sensing aperture to be spaced at least 1.5 times the sensing aperture diameter from the sheet surface. The diameter of 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 the fieldmeter to be adequately high relative to the speed of the web coupled with an appropriate spatial resolution to detect any variation in the charge pattern on the surface.

9.5.2 *Volume charge density*

9.5.2.1 *General*

For a spherical chamber the boundary electric field and the maximum space potential relate to the mean charge density linearly and quadratically, respectively. The density of electrostatic charge in a volume may, therefore, 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.

9.5.2.2 *Precautions*

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 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.

9.6 Measurement of charge decay rate

9.6.1 *General*

The dissipation of charge from materials is a crucial 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 characterized by the charge decay time constant.

Traditionally, the ability of materials to conduct and hence dissipate charge is often assessed by measurement of surface or volume resistivity. This can be satisfactory for homogeneous materials. Unfortunately, many practical materials are not homogeneous and many have a voltage-dependent resistivity. Since static charges arise on surfaces by contact or rubbing actions, the appropriate way to assess the charge retention properties of materials is to simulate this practical situation by deposition of a patch of charge on the material and observe how quickly this is dissipated.

Charging of sheet material by rubbing can be very inconsistent and so a high voltage corona discharge is the simplest and most versatile way to charge the surface. This method is also applicable to powders. A short pulse of corona discharge from a number of discharge points produces a consistent pattern of charge with minimum risk of modifying the surface by the corona ionization. The usual method of observing the dissipation of the charge is by using a fieldmeter to record the decrease of the associated surface field.

9.6.2 *Precautions*

The area and density of charge and the proximity of earthed surfaces will affect the electric fields driving charge migration. Ideally, charge decay rates should 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 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 and a method of filling providing consistent packing density developed.

The charge decay rate on many materials is very dependent on the charge density; the higher the charge density the faster the decay. A very fast initial decrease can slow significantly as the charge density decreases. The best way to interpret the rate of decay, therefore, is in relation to the application of the material. For example, if the concern is the amount of charge retained by a powder during storage 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.

9.6.3 *Comments on existing standards*

One method described in Federal Test Standard 101C Method 4046.1, 1988 [1] and American National Standards Institute EIA-541-1988 [2] cannot be applied to non-homogeneous materials. The initial voltage of 5 kV is high and could cause breakdown within multilayer materials. The methodology is such that capacitance coupling from the mounting electrodes gives an immediate drop (which is not generally appreciated) to an actual test voltage of between 3 kV and 4 kV. The extent of this initial sharp drop depends upon geometric details. The tests can only be used with samples and are not applicable in-situ to installed surfaces or materials with earthed backing.

The data obtained by the method described in Part 2 of this standard have been compared with those obtained using FTS 101C for a variety of types of materials and with truly homogeneous materials very comparable decay times are observed. However for many common materials the test described in Part 2 of this standard yields much longer charge decay times than the FTS 101C method, the difference being attributed to non-homogeneity between the surface and bulk of these materials. The FTS 101C test apparently relates to the bulk material whereas the corona deposited charge migrates preferentially over the outermost surface of the material. The corona charging method has been found to be more flexible.

9.7 Measurement of resistance and resistivity

9.7.1 *General*

Electrical resistance is the physical property with the greatest range of values 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 may suffice in many cases. The resistance across the surface of a material can be different from that through the same material. Different forms of electrode system are required, but the principle remains the same.

Phenomenologically, 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 highly insulating materials the resistance recorded after 1 min 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.

9.7.2 *Precautions*

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 required for liquids and powders and a procedure for consistent packing is essential for the latter. 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 and great care taken with cleaning the insulators in contact with the product.

9.8 Measurement of chargeability

9.8.1 *General*

Charge is transferred between surfaces in contact so that when they separate a net positive charge remains on one surface and a net negative charge on the other surface. The quantity of charge is increased by increased contact pressure and by rubbing in proportion with the increased area of contact. The relative amounts and polarity of charge transferred between materials can be presented as a list, the triboelectric series, in which materials are sequentially expected to receive a positive charge with respect to the next one on the list. It should, however, be noted that two samples of the same material rubbed against each other can result in quite strong charging.

It is often necessary to measure chargeability to assess the currents which may arise in process operations or handling of individual products. 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. The methods given in Part 2 of this standard cover the commonest situations: rubbing of a material, transport of a web through a roller system, pneumatic conveying of powder 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.

9.8.2 *Precautions*

Fresh rubbing materials and clean roller systems should be used to avoid changes caused by contamination. Charge separation may be accompanied by charge dissipation. Also discharges can occur between the separating bodies. This needs to be recognized in practical measurements so that allowance can be made by observing changes with time and a correction made. Flowing products should fall directly, and at full test speed, into the Faraday pail. Ambient electric fields can influence the charge separation process and so these measurements should be made in a field free environment.

9.8.3 *Comments on existing standards*

There are several standards which describe methods for measuring the charging produced in special circumstances such as components in packaging or rubbing of materials. Inadequacies in these standards such as delay between charging and measurement, inappropriate cleaning of specimens or inadequate control of the test environment have been addressed in Part 2 of this standard.

9.9 Measurement of shielding

9.9.1 *General*

Many products including electronic devices and explosive detonators can be damaged by the discharge of stored electrostatic energy. A spark type discharge will cause a very fast collapse of a high electric field in its vicinity. As an example, voltages as high as 30 kV can be acquired by people moving about in electronic production areas and so the voltage involved in these sparks can range up to this value and the timescale for voltage collapse can be as short as 1 ns. The devices can be damaged by voltages as low as 50 V and so safe transport of such sensitive devices through environments where charge cannot be controlled requires packaging which provides shielding with a voltage attenuation ratio of around 1 000 : 1 over the frequency band from 10 Hz to 1 GHz. It is therefore necessary to be able to test shielding performance.

The method described in Part 2 of this standard overcomes the problems and limitations of existing methods by applying simultaneous and balanced positive and negative high voltage electric field pulses across a defined width of material. The pulse symmetry means that no net charge is transferred to the layer under test so that the layer can be isolated from earth. The test is equally valid for materials with surface or volume conductivity or with buried conducting layers. Because there is no net charge transfer to the layer, the signals observed opposite either of the pulse source electrodes contain no common mode component and observations may be made directly relative to earth. The signals observed are analysed into frequency components over the range from 10 Hz to 1 GHz. Peak signal amplitudes and the performance of the material is assessed from the ratio of the signals observed with and without the material for each component of frequency.

9.9.2 *Precautions*

High voltages are produced and so care should be taken to avoid touching the electrodes.

9.9.3 *Comments on existing standards*

When following the test method in EIA 541 the signal for measurement appears as the difference between the two probe signals and the higher the attenuation the smaller the difference signal which has to be measured in the presence of a large common mode, capacitively coupled, signal. Instrumentation for the reliable measurement of small difference signals from single shot events in the presence of large common mode signals up to the gigahertz frequencies involved in spark discharges is not generally available. The length of surface between the probes is not specified and the attenuation level needed (1 000 : 1) not stated with adequate clarity in terms of frequency. The measurement of room to room attenuation via window of test material method described in MIL-STD 285 [3] poses the problem of earthing window boundary for buried layer materials. The method in Part 2 provides a more meaningful test on materials which only need performance to about 1 GHz.

9.10 Measurement of current

9.10.1 *General*

There are several areas in which the measurement of current is relevant in electrostatics. Very small currents, usually less than nanoamps, arise from conduction through insulators. Larger currents of the order of microamps 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 currents up to several microamps although the determination of the increase of potential of a known capacitor presents an alternative method for all 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 should have a response risetime adequately shorter than the minimum risetime of the fastest discharge event to be measured. For spark discharges from conducting bodies this should be 1 ns or less.

9.10.2 *Precautions*

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

9.11 Measurement of energy

9.11.1 *General*

The determination of electrostatic energy released in a discharge is important for the assessment of the damage vulnerability of sensitive devices and the incendivity of mixtures of flammable materials in air. There is no method at present which is generally accepted 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 $CV^2/2$. The discharge of a known capacitor charged to a preset potential forms the basis of current methods to assess discharge effects.

The method for testing electronic devices is described in IEC 801-2 while the assessment of ignition energy of sparks is given in BS 5958.

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.

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 indication of incendivity. Ignitions seem to occur more readily if the surfaces are at a negative potential relative to the probe.

NOTE 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 ensure that ignition risks are small.

9.11.2 *Precautions*

The voltage before and after discharge should be measured because not all the initial energy may be released. The effect of electrostatic sparks can change greatly with risetime and duration. The risetime 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 test in IEC 801-2 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 should be greater than a certain minimum to reduce the cooling effect of the electrodes on the development of the flame kernel. Care should 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.

9.12 Measurement of capacitance

9.12.1 *General*

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:

$$C_2 = C_1(V_1 - V_2)/(V_3 - V_2)$$

9.12.2 *Precautions*

Care is needed when 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 approximately the normal operating voltage may be the most appropriate method.

Low values of capacitance should 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.

9.13 Measurement of breakdown voltage

9.13.1 *General*

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 hazard increases with increasing values of breakdown voltage.

The breakdown strength of insulators is dominated by defects within the material. The result is therefore greatly influenced by the area under test; the larger the area the greater the number of defects and hence the lower the value obtained.

An indication of the degree of hazard may be obtained as follows, for example, for polyethylene film.

a) The electric strength of polyethylene film is approximately 20 $\mathrm{MVm^{-1}}$ and so 4 kV will be sustained by a layer about 200 μm thick.

b) The capacitance of such a layer is approximately 90 $\mathrm{nFm^{-2}}$ and its stored energy at 4 kV is 720 $\mathrm{mJm^{-2}}$ so that up to approximately 7 mJ will be available from an area of 100 $\mathrm{cm^2}$ of the material.

9.13.2 *Precautions*

A simple circuit based on charging a capacitor has been developed to provide the test ramp voltage. Care should be taken to avoid electric shock since the circuit employs high voltage in association with large capacitances and relatively low protective resistances.

9.14 Calibration

In order to make reliable measurements, the instruments used should be calibrated in accordance with standard procedures.

Procedures are given in the annex of Part 2 of this standard for the calibration of instruments for the measurement of electric field, surface voltage, charge, charge decay and shielding capability.

List of references (see clause 2)

Informative references

BSI publications

BRITISH STANDARDS INSTITUTION, London

BS 5958, *Code of practice for the control of undesirable static electricity.*

BS 5958-1:1991, *General considerations.*

BS 5958-2:1991, *Recommendations for particular industrial situations.*

BS EN 100015, *Harmonized system of quality assessment for elctronic components. Basic specification: Protection of electrostatic sensitive devices.*

BS EN 100015-1:1992, *General requirements.*

IEC publication

INTERNATIONAL ELECTROTECHNICAL COMMISSION (IEC), Geneva

IEC 801, *Electromagnetic compatability for industrial-process measurement and control equipment.*

IEC 801-2:1984, *Electrostatic discharge requirements.*

Other references

[1] FED-STD-101C *Test procedures for packaging materials.* 1988 1).

[2] ANSI EIA-541-88 *Packaging material standards for ESD sensitive items.* AMERICAN NATIONAL STANDARDS INSTITUTE. 1988 1).

[3] MIL-STD 285 *Method of attenuation measurement for enclosures, electromagnetic shielding, for electronic test purposes.* 1956 1).)

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1) Available from BSI Customer Services.

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