BRITISH STANDARD

BS 5958 :
Part 1 : 1991

Code of practice for

Control of undesirable static electricity

Part 1. General considerations

Code de bonne pratique pour le réglage
d'électricité statique non voulue
Partie 1. Considérations générales

Richtlinie für die Regelung von
unerwünschter statischer Elektrizität
Teil 1. Allgemeine Überlegungen

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Foreword

This Part of BS 5958 was prepared under the direction of the General Electrotechnical Standards Policy Committee. It replaces BS 5958 : Part 1 : 1980 which is withdrawn.

This edition introduces technical changes to bring the standard up-to-date but it does not reflect a full review of the standard, which will be undertaken in due course.

Static electricity occurs commonly in industry and in daily life, and can be a source of danger as well as discomfort or inconvenience. The main hazard is that of explosions and fires initiated by electrostatic discharges, but shocks to personnel can also, on occasion, cause accidents. In addition, static electricity introduces operational problems during manufacturing and handling processes, e.g. by causing articles to adhere to each other or to attract dust. It is generated in many operations, including the flow of liquids or powders, the production of sprays and the contact and separation of solids. It therefore gives rise to problems in a wide range of industries, e.g. chemicals, pharmaceuticals, petroleum and textiles.

The purpose of this Part of BS 5958 is to provide recommendations for the control of static electricity. In some cases static electricity is an integral part of a process, e.g. paint spraying, but more often it is an unwelcome side effect and it is with the latter that this Part of BS 5958 is concerned. Often, static electricity will not be the only source of ignition present, and antistatic precautions should be formulated so as to be consistent with the measures required to deal with other ignition risks.

This Part of BS 5958 does not provide recommendations for the control of static electricity in the transport, handling, storage or testing of electrostatic sensitive electronic devices (ESDs) or circuits. Reference should be made to BS 5783(1) for this purpose.

Although lightning is a form of static electricity, it is not intended that this Part of BS 5958 be used to obtain guidance on the protection of structures against lightning. For this purpose, reference should be made to BS 6651.

BS 5958 is in two Parts. BS 5958 : Part 2 provides simple recommendations for controlling static electricity in a variety of specific operations, the justification for which should be sought in this Part of BS 5958. Static phenomena are encountered so widely that it is not possible to cover all cases and, if adequate guidance is not found in BS 5958 : Part 2, this Part should be consulted. If there is still doubt, expert advice should be sought; research on the subject continues and new information is still coming to light.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

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(1) BS CECC 00015 : Part 1 is in preparation and will supersede BS 5783 : 1987.

Section 1. General

1 Scope

This Part of BS 5958 gives basic information on the generation of undesirable static electricity in solids, liquids and gases, and also on persons, and describes how the charges produced give rise to discharges which may cause ignitions or electric shocks. It gives the methods available for minimizing such generation and for safely dissipating the charges produced. Section 4 deals with the principles of earthing and bonding as applied to avoid static electricity hazards. Appendix A gives guidance on the means of measuring or estimating the parameters which need to be taken into account when deciding upon the action to be taken to control static electricity.

NOTE. The titles of the publications referred to in this standard are listed on the inside back cover.

2 Definitions

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

2.1 antistatic; conductive

Used as an adjective to indicate that a material is, by virtue of its low resistivity, incapable of retaining a significant electrostatic charge when in contact with earth.

NOTE. The terms 'antistatic' and 'conductive' are frequently used as synonyms, hence the common definition. However, in contexts where they have specific meanings, e.g. in relation to footwear, this definition is qualified in the appropriate clauses of this Part of BS 5958.

2.2 antistatic additive

A substance added to a liquid or a solid in order to increase its conductivity so that it is incapable of retaining a significant electrostatic charge when in contact with earth.

2.3 bonding

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

2.4 breakdown strength

The minimum electric field strength in a medium at which electrostatic discharges can occur in a given situation.

2.5 conductivity

The reciprocal of resistivity.

2.6 conductor

A material possessing an electrical conductivity sufficiently high to render it incapable of retaining an electrostatic charge unless insulated from earth.

2.7 earthing

The electrical connection of a conductor to the main body of the earth to ensure that it is at earth potential.

2.8 flammable

Capable of being ignited.

2.9 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 1. Many liquids and solids, though regarded as flammable, nevertheless do not normally burn. The application of heat to such materials serves to release vapour that may burn with atmospheric oxygen. The heat of the subsequent reaction serves to release further vapour for combustion. Flame may propagate through suspensions of dusts by this mechanism.

NOTE 2. In normal usage 'gas' and 'vapour' are synonymous.

2.10 flammable mixture; explosive mixture

A mixture with air of a flammable material, in the form of a gas, droplets or dust, which is within the flammable range and therefore capable of being ignited.

2.11 flammable range

The range of concentrations in air of a flammable material, in the form of a gas, droplets or dust, between the lower and upper flammable limits.

2.12 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.

Hazardous areas are classified into the following three zones (see BS 5345 : Part 1).

(a) *Zone 0*: zone in which an explosive atmosphere is continuously present, or present for long periods.

(b) *Zone 1*: zone in which an explosive atmosphere is likely to occur in normal operation.

(c) *Zone 2*: zone in which an explosive atmosphere is not likely to occur in normal operation, and if it occurs it will exist only for a short time.

2.13 incendive

Capable of igniting a prescribed flammable mixture.

2.14 inert gas

A gas or a mixture of gases incapable of supporting the combustion of a flammable material.

2.15 ion

An atomic or molecular particle carrying electrical charge.

2.16 lower flammable limit

The concentration in air of a flammable material, in the form of a gas, droplets or dust, below which there is insufficient of the material to support and propagate combustion.

2.17 mass charge density

The nett quantity of charge carried by unit mass of a material.

2.18 minimum ignition energy

The smallest quantity of energy that can ignite a mixture of a specified flammable material with air or oxygen, measured by a standard procedure.

2.19 non-conductor

A material possessing an electrical resistivity sufficiently high to enable it to retain enough charge to give rise to electrostatic effects.

2.20 relaxation

The dissipation of an electrostatic charge by conduction.

2.21 relaxation chamber

A part of a liquid flow system which provides sufficient residence time for the charge on the liquid to be reduced to a safe level.

2.22 relaxation time

The time required for the charge or potential on a liquid or a solid to decay to 1/e of its original level (e is the base of natural logarithms).

2.23 surface charge density

The nett quantity of charge per unit area of the surface of a solid or a liquid.

2.24 surface resistivity (of a substance)

The resistance between the opposite edges of a square.

2.25 upper flammable limit

The concentration in air of a flammable material, in the form of a gas, droplets or dust, above which there is insufficient of the air to support and propagate combustion.

2.26 volume resistivity (of a substance)

The resistance at unit length and unit cross-sectional area.

Section 2. Fundamentals of static electricity

3 Electrostatic charging

3.1 General

The primary source of electrostatic charge is contact electrification, where two dissimilar materials are brought into contact and then separated, carrying equal and opposite charges. Conducting objects may also become charged by the process of induction from another charged object or objects in the vicinity. Objects can also receive charge by direct transfer either from other objects or by the impingement upon them of a stream of ions.

3.2 Contact electrification

Contact electrification can occur at solid/solid, liquid/liquid or solid/liquid interfaces. Gases cannot be charged in this way, but if a gas has solid particles or liquid droplets in suspension these may be charged by contact, so that such a gas can carry an electrostatic charge.

In the case of dissimilar solids, initially uncharged and at the same, normally 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 there is a potential difference between them which is of the order of 1 V. 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. This higher potential difference tends to drive charge back across the interface whilst any contact remains. 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 hold part, at least, of their charges. Because the clearance between the surfaces when in contact is extremely small, the potential generated on separation can easily reach many kilovolts despite the small amount of charge involved. For reasons not fully understood the charging is enhanced if the contact and separation involves rubbing.

Contact electrification in liquids depends on the presence of ions or sub-microscopic charged particles (the latter are usually less important). Ions (or particles) of one polarity are adsorbed at the interface and they then attract ions of opposite polarity which form a diffuse layer of charge close to the surface. If the liquid is then moved relative to the interface, it carries away 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 the separation, provided that the liquid is sufficiently non-conducting to prevent recombination. Such processes can occur at both solid/liquid and liquid/liquid interfaces.

3.3 Charging by induction

There is an electric field around any charged object. A conductor introduced into this field changes the distribution of potential in the field 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 its potential, coupled with the separated charges that it carries, the conductor is capable of an electrostatic discharge.

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. Removal of the conductor from the vicinity of the original charged object, however, makes the remaining charge available to provide a spark. This type of induction sparking can be hazardous, for example in the case of an insulated person moving about near electrostatically charged materials.

3.4 Charge transfer

Whenever a charged object makes contact with one that is uncharged, the charge is shared between them to the extent that their conductivities allow. This is a potent source of electrostatic charging when charged sprays, mists or dusts impinge upon a solid object, for example by settling. A similar transfer of charge can also take place when a stream of gaseous ions is incident upon an initially uncharged object.

4 The retention of electrostatic 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 by means of a non-conductor. It is shown in **13.2** that to retain a significant electrostatic charge a resistance to earth in excess of 10^6 Ω is required.

Pure gases under normal conditions are non-conductors and the suspended particles, or droplets, in dust clouds, mists or sprays can therefore retain their charges, often 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. This process is known as relaxation. The resistance and resistivity or conductivity values which are needed to produce hazardous situations depend greatly upon the system under consideration and will be discussed in section 3.

In many industrial processes there is a continuous generation of static electricity which accumulates on an insulated conductor, e.g. when a steady stream of charged liquid or powder flows into an insulated metal container. The potential on the insulated conductor is then the result of a balance between the rate of input of charge and the rate of leakage. The equivalent electrical circuit is shown in figure 1 and the potential of the conductor is given by the following equation:

$$V = IR\left[1 - e^{-\frac{t}{RC}}\right]$$

where

V is the potential of the conductor (in V);

C is its capacitance (in F);

R is the leakage resistance to earth (in Ω);

I is the electrostatic charging current (in A);

t is the time from the commencement of charging (in s).

The maximum potential is reached when t is large and is, therefore,

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

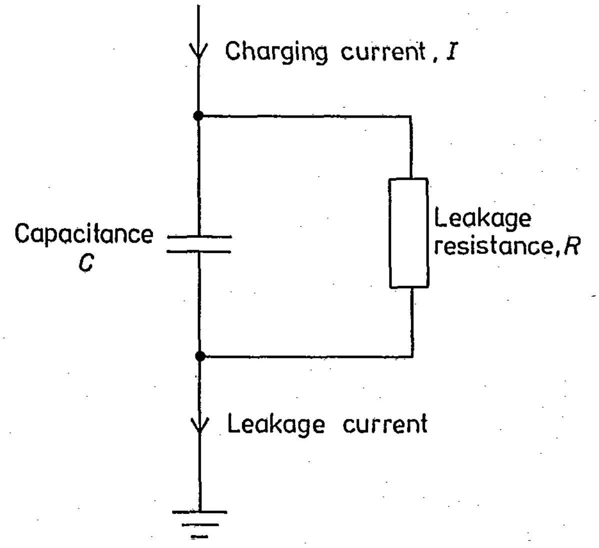

Figure 1. Equivalent electrical circuit for an electrostatically charged conductor

5 Electrostatic discharges

5.1 General

Charge retained on a liquid or a solid creates a hazard only if it is discharged to another body or, more usually, to earth. Electrostatic discharges vary greatly in type and incendivity. In this Part of BS 5958 they are classified as described in **5.2** to **5.6**, although the differentiation between the various types is not completely definite.

5.2 Sparks

A spark is a discharge between liquid or solid 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 a sharp crack.

A spark occurs between conductors when the field strength between them exceeds a level known as the breakdown strength, which depends upon the gap width. For flat or large radius surfaces 10 mm or more apart this field strength is about 3×10^3 kV/m and it increases somewhat as the gap decreases.

Because the bodies concerned in the discharge are conductors, all the charge is drawn into the spark, which in most practical cases dissipates almost all the available energy. Referring to the equivalent electrical circuit of figure 1, therefore, the energy of the spark is

$$E = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2$$

where

E is the energy dissipated (in J);

Q is the quantity of charge on the conductor (in C);

V is its potential (in V);

C is its capacitance (in F).

This is the maximum value of energy; the energy in the spark is less if there is resistance in the discharge path to earth, and the duration of the spark is then also greater.

Typical values for the capacitances of conductors are given in table 1.

A typical calculation of spark discharge energy is that involved when an unearthed metal drum is filled with powder from a grinding unit. In such a case the electrostatic charging current, I, might be 10^{-7} A. The leakage resistance of the drum to earth, R, is, for example, $10^{12}\Omega$ and its capacitance about

Table 1. Typical electrical capacitances

Object	Capacitance
	pF[1]
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
Major plant items (reaction vessels) immediately surrounded by earthed structure	100 to 1000
Human body	100 to 300

[1] 1 pF = 1 × 10^{-12} F.

50 pF. The maximum voltage on the drum is then

$$V_{\text{max}} = IR = 100 \text{ kV}$$

and the maximum energy released in a spark discharge would be

$$E_{\text{max}} = \tfrac{1}{2} CV^2_{\text{max}} = 250 \text{ mJ.}$$

The charge retained on the drum to give a potential of 100 kV is

$$Q_{\text{max}} = CV_{\text{max}} = 5 \times 10^{-6} \text{ C}$$

5.3 Corona

This is a form of discharge from a conductor when it is very small, pointed, or has a sharp edge, i.e. where a surface with a small radius of curvature exists. The discharge may be directed towards another object, or it may be dissipated into the atmosphere.

The field strength near the pointed feature is very large and falls off rapidly with increasing distance from it. The gas adjacent to the point is ionized and current can therefore leave the conductor. However, farther away from the point ionization is not complete and a low stable current is set up which is controlled by the gas conduction in this area. It is known as a corona discharge and is characterized by a hissing sound and, sometimes, by a faint glow.

A corona discharge may continue indefinitely or it may be in discrete short bursts. The energy density in the discharge is much less than in a spark. In certain circumstances, e.g. if there is an increase in the potential of the pointed conductor, corona can develop into a spark to another object.

5.4 Brush discharges

Brush discharge occurs from a charged non-conductor to a conductor. It takes the form of short spark-like discharges from discrete areas of the surface of the non-conductor. The total discharge often has a brush-like appearance. If the conductor to which the current is flowing is pointed, the discharge at the conductor will be in the form of corona.

The localized energy density in a brush discharge may be high enough to be incendive; empirical tests suggest, however, that the equivalent energy release is unlikely to exceed about 4 mJ.

5.5 Propagating brush discharges

This type of discharge is a development of the normal brush discharge which can occur from a high resistivity non-conductor in sheet form with large opposing charges on its two surfaces. Often the sheet is backed by a conductor, but the essential point is that the sheet is polarized and in the same state as the dielectric of a charged capacitor. If a conductor approaches the non-conductor surface the resultant electrostatic field promotes ionization across a large area of the surface. A discharge can then take place in which the charge from an extensive area of the non-conductor rapidly flows to the initial discharge point through the ionized gas adjacent to the surface. The result is an intense and highly energetic spark-like discharge which can be very dangerous.

5.6 Field emission discharges

The energy of this type of discharge is very small and it is likely to be of concern only when explosives are involved. The discharges described in **5.2** to **5.5** have all depended upon gas ionization brought about by high field strength, but it is believed that a different ionization process operates in field emission discharges, i.e. possibly the ejection of electrons from the surfaces; surface condition appears to be important. Discharges have been observed with a potential difference of 50 V if two conductor surfaces are brought within a distance of 10^{-3} mm of each other, which is equivalent to a field strength of about 5×10^4 kV/m. These figures compare with a field strength of about 3×10^3 kV/m for the more usual discharges, with a threshold potential difference of about 300 V.

6 Incendivity of electrical discharges

NOTE. The data given in clause **6** is only appropriate at ambient temperatures and pressures. At other temperatures and pressures the flammability and explosibility characteristics may change and specialist advice should be sought.

6.1 Flammability and explosivity

6.1.1 *Flammable mixtures*

In the combustion process a flammable material reacts with an oxidant to liberate energy. The oxidant is usually air but it can be another gas mixture, containing more or less oxygen than air, or some other oxidizing agent.

A mixture in air of a flammable material in the form of a gas, droplets or dust cannot burn unless its composition lies within two limits, known as the lower and upper flammable limits and normally expressed in terms of the concentration of flammable material in air. The range of concentrations between these limits is known as the flammable range, and any mixture within this range is termed a flammable mixture. The majority of gases have flammable limits within the range 2 % V/V to 10 % V/V. However, there are substances, e.g. acetylene, ethylene and hydrogen, whose flammable limits exceed this range (see BS 5345 : Part 1).

For a mixture of gas and dispersed dust the flammability characteristics of the gas/dust mixture should be considered.

In general, it is possible to avoid an explosion hazard due to an electrostatic discharge, or any other source of ignition, by eliminating any flammable mixture that is present. This can be done either by ventilation with air to reduce the concentration of the flammable material below the lower flammable limit or by adding inert gas. An inert gas is one containing little or no oxygen, such as boiler flue gas, and by its use the oxygen content of the atmosphere can be reduced to such a low figure that combustion is not possible at any concentration of flammable material in air. The required oxygen concentrations are, for example, about 11 % V/V for hydrocarbon gases and about 5 % V/V for hydrogen, compared with the normal atmospheric oxygen content of 21 % V/V. It is usual in practice to include a factor of safety; a maximum oxygen content of 8 % V/V is frequently specified for hydrocarbons.

6.1.2 *Explosives*

These are mixtures or compounds whose violent exothermic reaction can be initiated by electrostatic discharges or other sources of ignition without the intervention of air.

6.2 Ignition energy

Whether or not an electrostatic discharge will ignite a flammable mixture depends upon the composition and temperature of the mixture, the energy of the discharge and the distribution of this energy in space and time. In practice the most frequent source of ignition is a spark from an insulated conductor, and a spark is therefore the commonly accepted means of measuring ignition energies, using a voltage of at least 10 kV. For a given flammable material a graph of the lowest energy for ignition as a function of concentration in air takes the form shown in figure 2. The energy corresponding to the lowest point on this curve is called the minimum ignition energy and is the best general measure of the smallest quantity of energy needed to initiate an explosion or fire involving the flammable material in question.

A detailed review of ignition energy data for gases has been compiled by Lewis and Von Elbe of the US Bureau of Mines[1]. Most organic vapours and hydrocarbon gases in air have minimum ignition energies in the range 0.01 mJ to 1 mJ. Carbon disulphide and hydrogen in air have values in the region of 0.02 mJ, while explosives can have minimum ignition energies as low as 0.001 mJ.

Similar considerations apply to dust clouds or liquid droplet suspensions except that the minimum ignition energies are higher than those of gases because of the need to heat up the suspended matter present. For dust clouds the values range from less than 2 mJ to greater than 5000 mJ.

The minimum ignition energy of a dust cloud depends on the particle size distribution in the cloud, as well as on its chemical composition, although published data frequently do not specify the particle size. A decrease in particle size or an increase in the percentage of fines in general decreases the minimum ignition energy. In some cases this effect is very marked, as in the example given in table 2.

As a practical guide, experience suggests that the sensitivity of a dust cloud to ignition is realistically determined by using dust that has passed through a 200 mesh (75 μm) sieve. For a mixture of flammable gases and dusts take the minimum ignition energy of the mixture to be that of the most sensitive component.

6.3 Assessment of the incendivity of discharges

Sparks from insulated conductors constitute the most important electrostatic ignition risk. As discussed in **5.2**, sparks are of very short duration and, in many cases, virtually all the available electrostatic energy appears in the discharge. To assess the incendivity of such a discharge, therefore, it is usually valid to compare the stored energy, measured by $\frac{1}{2}CV^2$, with the minimum ignition energy of the combustible material in question. The comparison may not be valid if there is resistance in the discharge path, because part of the stored energy may be dissipated in the resistance and the duration of the spark may increase.

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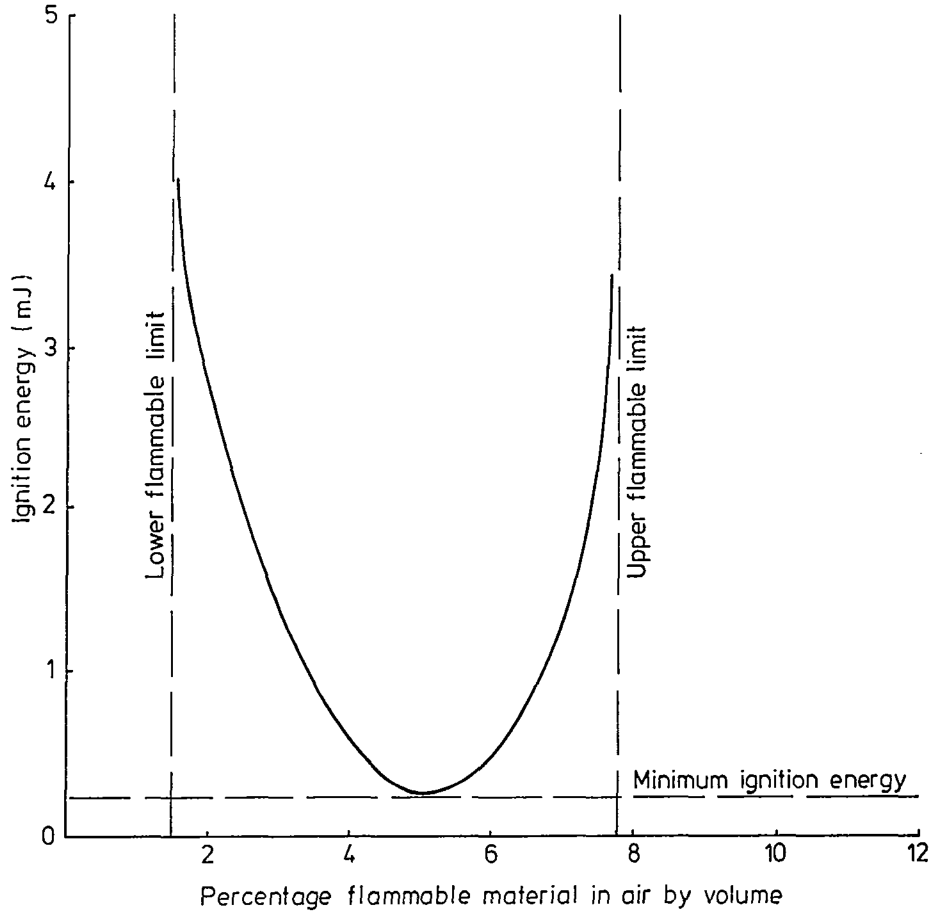
[1] *Combustion flames and explosions of gases,* Lewis and von Elbe, Academic Press Inc., 1961.



NOTE. This graph is purely diagrammatic and is not to be used in any assessment of incendivity.

Figure 2. Ignition energy as a function of flammable material concentration in air

Table 2. Example of dependence of minimum ignition energy on particle size of a dust

Particle size range	Minimum ignition energy
μm	mJ
710 to 1680	> 5000
355 to 709	250 to 500
180 to 354	50 to 250
105 to 179	< 10
53 to 104	< 10
5	< 10

The incendivities of corona discharges are less than those of sparks. The stored energy on a conductor, $\frac{1}{2} CV^2$, therefore tends to overestimate the ignition risk. The relatively low incendivity of corona allows it to be used in passive eliminators as a means of safely removing static electricity, although, if there is any possibility of the presence of a flammable mixture, it is essential that great care be taken in the design of the system.

There is no generally accepted method of determining the incendivity of brush discharges from non-conductors. Brush discharges have limited energy but can ignite most gases and vapours and some sensitive dusts. Brush discharges can be more incendive than corona. A propagating brush discharge from a high resistivity non-conducting sheet, with or without a metal backing, is highly incendive. Where a precise assessment of the incendivity of a brush discharge is required, ignition tests should be made using the flammable mixture of interest. In the case of a propagating brush discharge, if the total energy stored on the non-conductor can be estimated, it may be compared with the minimum ignition energy of the flammable atmosphere.

7 Physiological effects of electrostatic discharges

The smallest spark energy that a person can feel when a discharge occurs to or from his body is about 1 mJ, that is, a potential of about 2.5 kV if his capacitance is 300 pF. As the potential is increased, variations in response are observed. Some people find 10 mJ uncomfortable due to muscular contraction, whereas others can accept several hundred millijoules before they experience sharp muscular contraction. 1000 mJ, i.e. 1 J, affects everybody severely. In incidents in which people have been rendered unconscious the energy of the discharge was estimated to be several joules.

Since in most situations discharge energies are below 100 mJ, serious physiological shock is very rare. There are exceptions, e.g. a discharge to a person due to highly charged particulate matter collected in a non-conducting container can be as much as several joules (see **10.2.3**). Irrespective of whether the shock itself is harmful, the involuntary muscular reaction to a discharge may cause an accident through, e.g. the dropping of a tool or by precipitating a fall.

Section 3. Electrostatic hazards and their control

8 Electrostatics in liquids

8.1 Charge generating mechanisms

8.1.1 *Flow of single phase liquids through pipes*

When a liquid flows through a pipe, charge separation occurs (see **3.2**) and the liquid emerging from the pipe is charged. The amount of charge is dependent, amongst other things, upon the flow conditions. Turbulent flow generates more charge than laminar flow; for a single phase liquid the current generated is roughly proportional to the velocity in the case of laminar flow and to the square of the velocity in the case of turbulent flow. Because laminar flow problems are less severe, this Part of BS 5958 deals exclusively with turbulent flow conditions.

For single phase flow, the current generated by a liquid flowing through an infinitely long pipe, made of metal or of any material with a volume resistivity less than about 10^{12} Ω·m, does not change greatly with the conductivity and relative permittivity of the liquid. In practice, as the liquid leaves the pipe it is no longer subject to the charge separation process and charge relaxes back to the wall of the pipe through the emerging liquid. Therefore the net current carried by the liquid as it enters the receiving vessel decreases as the liquid conductivity increases. Also, as the flow rate decreases, the current decreases.

For single phase liquids whose conductivities are low enough for them to retain a dangerous charge, there are a number of empirical relationships giving maximum charging currents for infinitely long pipes. One of the widely used relationships is the Schön equation:

$$i_s = Kv^2d^2$$

where

i_s is the maximum streaming current (in μA);

v is the velocity of the liquid (in m/s);

d is the diameter of the pipe (in m);

K is a constant of 4 $\mu A{\cdot}s^2/m^4$.

This relationship approximately represents the current (in microamperes) generated in industrial scale pipes.

Liquid charging can also be expressed in terms of charge density. The Schön equation leads to the following approximate expression:

$$\eta \approx 5\, v$$

where

η is the charge density (in $\mu C/m^3$);

v is the linear velocity of the liquid (in m/s).

Thus, for linear velocities of 1 m/s and 10 m/s the charge densities are about 5 $\mu C/m^3$ and 50 $\mu C/m^3$ respectively.

For practical purposes the pipe can be considered to be of infinite length if

$$L > 3v\tau$$

and

$$\tau = \frac{\epsilon\epsilon_0}{\gamma} \times 10^{12}$$

where

L is the length of the pipe (in m);

τ is the relaxation time of the liquid (in s);

ϵ is the relative permittivity of the liquid;

ϵ_0 is the permittivity of free space (8.85×10^{-12} F/m);

γ is the conductivity of the liquid (in pS/m).

Very little data is available for charge generation during liquid flow in pipes made of materials having volume resistivities greater than 10^{12} Ω·m. It has been found that for liquids with conductivities in the range 1 pS/m to 100 pS/m the current leaving a polyethylene pipe decreases with increasing duration of the flow and finally reaches an equilibrium value in good agreement with that from a metal pipe. On this evidence, the expression for charge generation by a conducting pipe can be used to estimate the equilibrium generation by a non-conducting pipe. However, prior to the establishment of equilibrium, the current is greater than that for a conducting pipe, but this is unlikely to affect the degree of hazard in a sustained pumping operation.

8.1.2 *Flow of liquid/liquid or liquid/solid mixtures through pipes*

Whenever such mixtures are pumped through pipes, charge generation occurs in the same way as with a single phase liquid. The rate of generation may be greater than with a single phase because of the increased interfacial area, but it is not amenable to calculation.

8.1.3 *Flow of liquids through strainers and filters*

Strainers and gauzes are very coarse filters, usually with mesh numbers less than 350 (30 μm apertures), designed to remove large particles from liquids. They do not normally cause any significant current generation and can be ignored when handling single phase liquids. If a second phase is present they may aid its dispersion, thereby promoting increased charge generation elsewhere in the system.

Fine particle filters can be prolific generators of static electricity; in general, the more stringent the filtration requirement, the greater the charge generation. The current generated by very fine micronic filters can exceed, by several orders of magnitude, that produced by a pipeline. Typical charge densities in the liquid leaving such a filter can be in the range 10 $\mu C/m^3$ to 5000 $\mu C/m^3$. Unfortunately it is not possible to predict the charge generation of a fine particle filter; even apparently identical filters of the same type can give widely differing results.

Current generation in a fine particle filter depends upon flow rate, liquid conductivity, the type of ions in the liquid and, possibly, the state of the filter element surfaces. In general, generation increases with increasing flow rate. As the liquid conductivity increases from a very low level (0.1 pS/m), generation at first also increases. This is because the increasing ion concentration makes a positive contribution to both conductivity and charge generation.

However, the current emerging from the filter reaches a maximum and then declines with further increase in conductivity as the normal relaxation process carries charge back to the filter. The lack of predictability of the current generation is attributed to variations in the nature and concentration of the ions present and to the complexities of the liquid/filter element interface.

8.1.4 *Settling of solids or liquids in liquids*

Any settling process, such as that of water in hydrocarbon, generates charge. The process of charge generation in such systems is very complicated and has been studied only to a very limited extent. Low conductivity of the continuous liquid phase promotes the occurrence of a high settling potential by retarding relaxation.

8.1.5 *Splashing of liquid jets*

As liquid emerges from a pipe into a receiving vessel two processes may give rise to charged mist or spray.

In the first, the liquid is charged during its flow through the pipe as described in **8.1.1** and, if the liquid column is unbroken, part of the charge relaxes back to the pipe. If, however, the column breaks up into droplets, any remaining charge is distributed amongst the droplets. The resultant spray is therefore charged.

Secondly, if the jet hits an obstruction, additional charge can be produced by contact electrification at the point of impact and the resultant spray may therefore be highly charged. The magnitude of this charge is not predictable; it depends upon the nature and cleanness of the surface as well as on the type and concentration of ions in the liquid. In general, the more conducting the liquid, the greater the charge generation. For example, a water jet produces more charge than an oil jet, but water/oil mixtures may produce more than either water or oil.

8.1.6 *Ejection of liquid droplets from a nozzle*

A wet gas stream issuing from a nozzle can be highly charged. The liquid layer on the inside of the pipe is sheared by the gas stream and broken up into droplets. If the sheared layer has a charge as a result of its motion along the pipe surface, the droplets emerging from the nozzle are charged. The amount of charge depends, amongst other things, on the conductivity of the liquid and on the gas velocity.

8.1.7 Stirring and mixing

Any motion of a liquid in a container generates static electricity, to an extent dependent upon the conductivity of the liquid and the relative motion between the liquid and the solid surfaces with which it is in contact. Normally, the amount of charge generated is much less than that produced by the flow of a liquid through a pipe or a fine filter, because the turbulence is less, but a hazard can arise in some blending operations.

8.2 Discharges involving liquids

8.2.1 *General*

For some processes it is possible to calculate both charge generation and charge retention (see **5.2**) and hence to assess the degree of hazard due to a discharge and to decide upon countermeasures. In many other cases, however, calculations are impossible and measurements have to be relied upon. This usually involves the use of electrostatic voltmeters or electrostatic field meters to monitor the problem and to determine the critical parameters. Because charge generation is very variable it is important to be satisfied that the worst case has been tested.

8.2.2 *Discharges from liquids*

Charges that have been separated as a result of the flow of a liquid attempt to recombine. If the liquid has a low conductivity it can, however, retain the charge, irrespective of whether it is pumped into an earthed, conducting (normally metal) tank or into a non-conducting tank or container.

A measure of the rate of charge dissipation from a liquid in contact with earthed metal is its relaxation time, τ (in seconds), the expression for which was given in **8.1.1**. It is the time required for the potential of the liquid to fall to about 37 % of its original level as it decays exponentially. It is accepted in many applications that if a liquid has a conductivity greater than 50 pS/m, equivalent to a relaxation time of about 0.35 s, it is incapable of retaining a hazardous charge. Alcohols and ketones are normally in this category. In certain situations (e.g. agitation) a conductivity of 1000 pS/m may be required to prevent the retention of hazardous levels of charge. These situations are given in BS 5958 : Part 2 (e.g. clause **10**). Clean and white oils such as kerosene or gasolene, however, normally have conductivities below 50 pS/m and are therefore able to retain a significant charge.

When a liquid is charged, electric fields exist both within the liquid and in the space around it. If these fields are high enough, discharges can occur. Discharges within the liquid are, in general, not an ignition hazard, but they may bring about chemical changes altering the specified properties of the liquid or causing corrosion of the plant involved.

Discharges in the atmosphere can be hazardous. Within a tank, the field strength between the liquid surface and earthed walls or structure can exceed the breakdown strength. It is rarely possible to estimate the energy of the resultant discharges and, in any event, this energy cannot be compared with the minimum ignition energy determined using metal electrodes.

It is sometimes possible to avoid a hazardous situation by controlling the rate of charge input to the tank so as to keep the field strength at the liquid surface below the breakdown value. This field strength can, in principle, be calculated from the input current given information on the conductivity of the liquid, the size and shape of the tank and of any internal structure, and the ullage of the liquid.

Charge retention on liquids is similar in both conducting and non-conducting containers although in the latter case relaxation may be controlled by the resistivity of the container. A non-conducting container can be expected to increase the possibility of discharges from a liquid, but little quantitative data is available on this subject.

8.2.3 *Discharges from solids*

Both non-conductors and conductors with a resistance path to earth greater than $10^6\ \Omega$ can become charged through the agency of a liquid by many processes. These include:

(a) flow of a liquid past them (the charge may be due to contact electrification between the liquid and the object, or to charge transfer from a liquid already carrying charge; examples are an insulated metal flange, an insulated section of metal pipe in a non-conducting pipeline or a length of non-conducting pipeline itself). The level of liquid conductivity in which a hazardous situation could result is given in the relevant clauses of BS 5958 : Part 2;

(b) collection of charged liquid, as when charged liquid is poured into an unearthed can;

(c) immersion of a conducting object in charged liquid (the object takes up the potential of the point where it is situated in the liquid; an example is an unearthed metal component in a sampling or ullaging system);

(d) settling of charged mist or spray on the object, e.g. an unearthed object in the vicinity of a steam leak.

The possibility of charging by induction should always be borne in mind where there are insulated conductors in the vicinity of charged liquid.

As described in clause **5**, the discharges from conductors are usually sparks and are potentially hazardous. The energy can be calculated using the procedure given in **5.2**. In some cases, e.g. an empty can floating in a liquid, the conductor may be mobile, and the calculation is then complicated because the capacitance is variable.

Discharges from non-conductors are considered in clause **10**.

8.2.4 *Charge retention on mists and sprays*

Suspensions of charged droplets retain their charge by virtue of the insulation provided by the surrounding atmosphere. When the mist or spray is being produced continuously, as, for example, when washing a tank with water or injecting steam, the charge density builds up to an equilibrium value where the rate of input of charge is equal to the rate of loss by processes such as settling or impingement of the droplets on the structure of the tank.

There is an electric field both within and around a charged cloud of mist or spray. The field strength at any point depends on the charge density, the size and shape of the cloud and the size and shape of the vessel, if any, containing the cloud. Insulated conductors within or near the cloud can be charged by induction or by the settling of droplets and are then capable of yielding incendive sparks to earth. With very high charge densities complete ionization could occur in the atmosphere between the droplets, leading to a lightning type discharge, but there is no evidence that this occurs in industrial situations. Corona discharges are possible, more especially from earthed projections to the cloud, and these are believed to contribute to the establishment of an equilibrium charge density in the cloud.

An important example of a charged mist is that produced during the water washing of the cargo tanks of tankers. One type of insulated conductor in this process is provided by isolated slugs of water produced as the water jets entering the tank break up.

8.3 Precautions against static electricity from low conductivity liquids

8.3.1 *General*

Measures to avoid ignitions due to static electricity (and any other sources of ignition) are necessary if the presence of a flammable mixture is known or suspected. One type of precaution is to eliminate the flammable mixture by ventilation with air or by inerting (see **6.1.1**). Alternatively, the space in which the flammable mixture could form can be removed, for example by means of floating roof tanks as used in the oil industry. In the absence of the possibility of a flammable mixture there may still be a risk of serious physiological shock; this can be eliminated by bonding and earthing both conductors and personnel.

If the presence of a flammable mixture is possible, electrostatic discharges should be controlled. The methods available are:

(a) bonding and earthing of conductors, including personnel,

(b) minimizing electrostatic charge generation,

(c) maximizing charge dissipation.

In some cases, these measures either singly or in combination may not be entirely adequate and they should then be supplemented by appropriate operational procedures and design features to avoid discharges.

Bonding and earthing are considered in detail in section 4. The other methods are dealt with in **8.3.2** and **8.3.3**. Because of the very wide range of possibilities, precise and totally comprehensive advice is difficult to give. Each application should be considered on its merits.

8.3.2 *Control of charge generation*

8.3.2.1 *Flow rate*

The generation of electrostatic charge increases with the rate of flow of liquids. Also, high velocities encourage the entrainment and dispersion of a second phase, such as water, thereby increasing charging in pipeline systems as well as allowing subsequent charge generation by settling in tanks. The point of entry into a tank should be at a low level and the flow velocity should be kept low until the incoming stream no longer breaks through the liquid surface.

A flow velocity of 1 m/s is recommended in the filling of storage tanks with low conductivity liquids (conductivities less than about 50 pS/m) when any second phase may exist in the pipe. A second phase is most likely to be present in the initial stages of a filling operation. It is not possible at present to make a general statement on the upper limit of velocity or flow rate to cover all tank filling operations when no second phase is present. In the light of present knowledge it is undesirable in any case for the pipeline velocity to exceed 7 m/s, but in some instances it might need to be as low as 2 m/s.

Flow rate limitations for various tank filling operations are given in BS 5958 : Part 2.

8.3.2.2 *Free fall*

The splashing and impingement on surfaces associated with the free fall of low conductivity liquids are sources of electrostatic charging. Free fall should be avoided in tanks, either by arranging for bottom entry of the liquid or by the use of a fill pipe extending to the bottom of the tank.

8.3.2.3 *Agitation and mixing*

Mechanical mixing or agitation of low conductivity liquids with air, steam, gas or jet nozzles should be kept to a minimum because of the charge which may be produced on the mist or spray formed above the liquid.

8.3.2.4 *The presence of immiscible components*

The presence of a second liquid phase, commonly water, in a low conductivity liquid may increase electrostatic problems. As already indicated (see **8.3.2.1**) the flow velocity should be kept at about 1 m/s whilst the second phase is present. Efforts should be made to eliminate it, by reducing the water bottoms in tanks as much as possible and by draining down thoroughly any water-flushed pipelines.

8.3.3 *Charge dissipation*

8.3.3.1 *Relaxation*

When a liquid is highly charged, e.g. after passage through a fine particle filter, most of the charge can be dissipated by allowing the liquid to pass slowly through a relaxation chamber. This may be a small tank or, more frequently, a length of large-diameter pipe. For liquids with conductivities down to 2 pS/m the residence time in the relaxation chamber should be 3τ where τ is the relaxation time of the liquid (in seconds), and for less conductive liquids it should be 100 s.

The charge on the liquid entering any metal container relaxes in a similar manner. Relaxation in non-conducting tanks is controlled by the relaxation time of the material of the tank. In such cases charge can be dissipated by arranging for the liquid to be in contact with earthed metal, usually an earthed metal plug at the bottom of the tank, or any earthed metal components, such as the fill pipe, extending to the bottom of the tank.

8.3.3.2 *Antistatic additives*

These additives increase the conductivity of liquids. The addition of such an additive to raise the conductivity to 50 pS/m or more decreases the relaxation time sufficiently to remove any electrostatic hazard in a conducting system.

8.3.3.3 *Ionization*

Radiation may be used to promote ionization of the atmosphere adjacent to the liquid surface to facilitate the leakage of charge from the liquid. This method can rarely be employed in practice because it usually requires a prohibitively large number of radioactive sources and it can only relax the charge on the liquid near the surface.

8.3.4 *Operational and design features*

Whenever there is the possibility of the presence of a flammable mixture, any metallic object lowered into a tank, e.g. ullaging or sampling equipment, should be earthed and any person using such equipment should be earthed. However, if a low conductivity liquid is being pumped into the tank, a discharge may occur between the descending earthed equipment and the liquid surface as they approach each other. Therefore, dipping, ullaging or sampling should be avoided whilst pumping is in progress and time should be left for relaxation on completion of pumping. For a single phase liquid in a metal tank a period of 3τ or 100 s, depending on conductivity, is sufficient (see **8.3.3.1**). However, if the liquid contains a second immiscible phase, such as water, in suspension the delay should be 30 min to permit settling of the second phase and the relaxation of any settling potential.

A similar hazard exists if there are conductive earthed metal projections downwards into a tank which could discharge to the liquid surface as it rises towards them. Such projections should be avoided, unless it can be shown that charging is not at a dangerous level.

Earthing of conductors is the most commonly used precaution against static electricity and is usually comparatively simple to arrange. In a few instances, however, an unearthed conductor may inadvertently be present, for example an empty can floating in a liquid. The geatest care should be taken to ensure the absence of such potential insulated conductors.

9 Electrostatics in powders

9.1 General

The movement of particulate materials generates static electricity. The amount of charge generated on, and the incendivity of discharges from, a material are a function of its physical form.

The charge per kilogram generally increases with decreasing particle size but recent evidence suggests that electrostatically charged granules release discharges of higher energy than powders.

If a system contains only granules then their size precludes the formation of an ignitable dust cloud. The potentially most hazardous situation occurs when granules and fine powder are intermixed. The granules can be the source of higher energy discharges and the fine powder can be dispersed into a flammable dust cloud.

Electrostatic effects associated with granules are not yet fully understood and it is only possible to give general guidance on electrostatic hazards associated with powders.

Clause **9** is concerned with powders, i.e. particulate solid matter with particle sizes up to about 200 μm. Specialist advice should be sought for systems containing intermixed granules and powder.

Contact electrification occurs extensively in powders. The charging characteristics are often determined at least as much by surface contamination of the particles as by the chemical composition of the powder itself and charge generation is usually difficult to predict. Electrification can be expected whenever a powder comes into contact with another surface, e.g. in mixing, grinding, sieving, pouring, micronizing and pneumatic transfer.

The amount of charge carried by a powder in suspension in a gas cannot exceed a level at which the field strength at the surface of each particle is sufficient to produce ionization of the atmosphere around it, because ionization allows the powder to lose charge. This field depends on the particle size and shape and on the surface charge density. For well dispersed particles the surface charge density that can remain on a particle is of the order of 10 μC/m^2. As the particles approach each other more closely the field strength at the boundary of the cloud increases, discharges occur and hence the total charge carried becomes less.

The charge carried by unit mass of powder is usually the critical parameter in considering electrostatic phenomena involving powders. In the case of spherical particles it is given by the following equation:

$$q = \frac{3\sigma}{dr}$$

where

q is the mass charge density (charge to mass ratio) (in µC/kg);

σ is the surface charge density (in µC/m^2);

d is the density of the powder particles (in kg/m^3);

r is the radius of a particle (in m).

A given powder in suspension in air retains its maximum mass charge density when it is well dispersed. It is also evident from this relationship that for a given mass, a larger amount of charge can be carried when the particle size is small.

For the purposes of this Part of BS 5958 it is helpful to divide powders into three groups depending on the volume resistivity of the material of which the particles are composed. These groups are:

(a) low resistivity powders, e.g. metals having volume resistivities up to about 10^6 Ω·m;

(b) medium resistivity powders, e.g. many organic powders, such as flour, having volume resistivities in the approximate range 10^6 Ω·m to 10^9 Ω·m;

(c) high resistivity powders, e.g. certain organic powders, many synthetic polymers and some minerals, such as quartz, having volume resistivities above about 10^9 Ω·m.

In practice, low resisitivity powders are rarely encountered. Even metal powders do not remain conductive for very long because oxide films on the particles increase their effective resistivity sufficiently to put them into the medium resistivity category. This Part of BS 5958 is therefore predominantly concerned with medium and high resistivity powders. Problems can arise with low resistivity powders if they are insulated from earth, e.g. in a non-conducting container.

Measurements with medium resistivity powders indicate that their mass charge densities depend on the process to which they have been subjected and on their degree of fineness, rather than on their chemical compositions. The charge density is far greater in grinding or micronizing operations than in sieving or pouring. One reason for this is that the former types of operation produce much smaller particles.

Table 3 gives measured data on the charge levels on medium resistivity powders emerging from different processes.

Table 3. Charge generation on medium resistivity powders

Operation	Mass charge density
	µC/kg
Sieving	10^{-3} to 10^{-5}
Pouring	10^{-1} to 10^{-3}
Scroll feed transfer	1 to 10^{-2}
Grinding	1 to 10^{-1}
Micronizing	10^2 to 10^{-1}
Pneumatic conveying	10^3 to 10^{-1}

When a medium resistivity powder comes to rest in bulk, the charge retained depends on the resistance between the powder and earth. If the powder is in an earthed container or in contact with earthed metal components, charge retention is determined by the volume resistivity of the bulk powder, which includes the inter-particle resistances and is measured as described in **A.3**. The relaxation time of a bulked powder is given by the equation:

$$\tau = \epsilon \, \epsilon_0 \, \rho$$

where

τ is the relaxation time (in s);

ϵ is the relative permittivity of the powder;

ϵ_0 is the permittivity of free space (8.85×10^{-12} F/m);

ρ is the volume resistivity of the powder (in Ω·m).

For a volume resistivity of 10^{12} Ω·m this gives a relaxation time of about 20 s, so that, even making no allowance for contact resistance between the particles, medium resistivity powders at the upper end of the resistivity range can retain their charge for an appreciable period.

The charge generated on high resistivity powders depends much more on their mode of transfer, i.e. whether in suspension or semi-bulked, than on the process to which they have been subjected. Not only are their volume resistivities very high, but they are also very hydrophobic and in bulk they are capable of retaining charge for hours or even days even when in contact with earthed metal. Charge retention is in many instances controlled by the field strength, and the surface charge density may therefore be of the order of 10 µC/m^2.

9.2 Discharges involving powders

9.2.1 *Ignition energy*

The processes of charge generation and retention in powders are in general not sufficiently well defined to permit calculations to be made of the energies kely to be involved in discharges, and tests using e system in question are the most reliable means assessing the risks.

here the spark energy can be calculated, e.g. in ischarges from insulated conductors in the icinity of charged powders, it may be compared ith the minimum ignition energy of the powder, easured by the method described in **A.6**. There is nother commonly used procedure for measuring inimum ignition energies of powders in which a apacitor is discharged through a transformer to a park gap; the result is quoted in terms of the nergy lost from the capacitor, making no llowance for losses in the transformer. The use of e result of this type of test in comparisons with ischarge energies understates the hazard and hould be avoided.

.2.2 *Discharges from dust clouds*

n principle, discharges can occur within dust louds or from dust clouds to earth when the field trength due to the charged particles is high nough. Recent work has indicated that the ischarges are of a corona or brush type. Spark or ightning type discharges have not been observed n dust clouds of the size encountered in industrial perations. On the basis of the evidence so far, the isk of an ignition due to a discharge from a dust loud is very low, except for sensitive atmospheres, minimum ignition energy less than 25 mJ), e.g. ery fine dust suspensions or flammable gas nixtures.

.2.3 *Discharges from bulk powders*

he probability of an electrostatic discharge ncreases as the powder settles out in bulk form, hus concentrating the charge and increasing the ield strength in the surrounding space.

n the case of low and medium resistivity powders ρ less than 10^9 Ω·m) most of the charge relaxes as he particles settle and make contact with each ther, provided that the powder is in an earthed netal container or in contact with earthed metal. n these circumstances electrostatic discharges apable of igniting flammable atmospheres (gases, apours or dusts) whose ignition energy is greater han 0.2 mJ will not occur. In a non-conducting ontainer, relaxation may be slower and a lischarge to earth would be potentially more ncendive depending upon the resistivity of the ontainer.

High resistivity powders do not dissipate their harges by conduction when they enter a container, whether or not the container is conducting. Low energy discharges occur from the bulking point (where the particles first contact the heap) to the wall of the container. However, the energy readily available to such a discharge by conduction within the powder is limited, and experience so far is that this type of discharge to the walls of the container does not ignite dusts with minimum ignition energies greater than 10 mJ. It is important when using this criterion to know accurately the minimum ignition energy of the dust cloud.

NOTE. There is some evidence that there may be a scale effect whereby the longer discharges possible in a large silo (linear dimensions 5 m) are more energetic.

9.2.4 *Discharges from solids and from personnel*

Insulated conductors in powder handling systems are readily charged by contact electrification. For example, an isolated length of metal pipe or ducting can be charged to a high potential by the flow of powder through it and is then capable of energetic sparking to earth. Powders in suspension or in bulk can also charge insulated conductors in their vicinity by induction or by sharing charge with them. Thus, the pouring of a powder into an unearthed metal container can result in a spark from the container dissipating a charge equivalent to the total charge accumulated inside the container.

It is a feature of certain types of powder processing operations that personnel come into close contact with the powders, e.g. when sampling or during transfer of powder from one container to another. If the person concerned is not earthed he constitutes an insulated conductor and can collect a significant charge by induction or charge sharing.

Non-conducting solids and containers in contact with charged powders are potentially hazardous. It is possible in some circumstances for a highly energetic propagating brush discharge to occur. This subject is dealt with in more detail in **10.2.3**.

9.3 Precautions against static electricity from powders

9.3.1 *General*

When an ignition risk exists in a powder handling system, the precautions needed to avoid a static electricity hazard depend, to some extent, on the presence of other potential ignition sources in the system. If the latter necessitate explosion protection, e.g. explosion vents, an explosion suppression system or inert gas, then precautions against electrostatic ignitions can often be limited to the earthing of metal components and, where appropriate, personnel, because the energies of discharges from non-conductors in the system are likely to be comparatively low and incapable of igniting the powder. This does not apply, however, if a mixture with a low minimum ignition energy is present, such as a flammable gas mixture; an example is the pouring of a powder into a flammable solvent. Earthing of plant and personnel is also effective in avoiding physiological shocks.

Earthing and bonding are considered in detail in section 4. In the handling of powders, the presence of the powder itself can increase the resistance to earth of metal components and it is necessary therefore to ensure that earthing is adequate when the plant is dirty as well as when clean. This applies particularly to floors.

When further precautions are judged to be necessary, control of both generation and dissipation of charge should be considered.

9.3.2 *Control of charge generation*

Systems handling powders are less amenable to design for the control of static electricity generation than those handling liquids because the details of the process are often determined by factors, such as the flow properties of the powder, which can rarely be modified enough to have a significant effect on charge generation. With high resistivity powders, some reduction may be possible by using high density (semi-bulked) flow rather than low density flow. However, control of charge generation can seldom be used as the primary means of minimizing static electricity risks in powder handling systems.

9.3.3 *Charge dissipation*

9.3.3.1 *Humidification*

Normal atmospheric air is a poor conductor of electricity irrespective of its relative humidity. Humidification is therefore ineffective as a means of dissipating the charge from a dust cloud of any kind.

High relative humidity is capable of decreasing the surface resistivity of many non-polymeric powders and hence of facilitating charge relaxation in the bulked powder when in an earthed metal container. However, a relative humidity in excess of 60 % may be needed and it is often impracticable to operate powder processing units at this high level of humidity. For some polymeric materials an increase in relative humidity can increase the rate of charge generation. The use of relative humidity to control electrostatic charging should not be undertaken without careful consideration.

9.3.3.2 *Ionization*

The electrical conductivity of the gas in which a powder is suspended can be increased by ionization, produced either by corona discharge from pointed conductors or by the use of radioactive sources. In practice, however, such systems are not widely used for removing the charge from powders except, occasionally, for preventing dust deposition on surfaces. It is difficult to provide the ionization required throughout the relatively large volume of dust cloud enclosures owing to ion losses and recombination. Also, the total charge to be dissipated is often greater than the charge that can be transferred by a radioactive ionization system. Similar considerations apply to the use of ionization for removing charge from bulked powders.

Localized discharges from pointed, earthed, conducting probes or wires can be of value in both dust clouds and bulked powders when the surface charge density approaches 10 μC/m^2 and the electric field strength is close to the breakdown value, a situation likely to be encountered with high resistivity powders. Such earthing probes or wires placed at the bulking point as a powder enters a container can reduce the energy of individual discharges to a low level. If the powder enters a non-conducting container it can also provide a safe route to earth for the accumulating charge, thereby avoiding propagating brush discharges (see **10.2.3**).

Where substances with very low minimum ignition energies are involved, e.g. hydrocarbon gases, it is difficult, in large containers, to avoid incendive discharges by means of rods and wires. The ignition problem should then be dealt with by other means, such as inert gas or explosion venting; if necessary, rods can be used in these systems to avoid physiological shocks.

9.3.3.3 *Antistatic additives*

In the case of powders there is no equivalent to the antistatic additives available for reducing the resistivity of liquids. Such additives are used in the case of solid polymers but are not normally present at the stage when these materials are being handled as granules.

10 Electrostatics in high resistivity solids

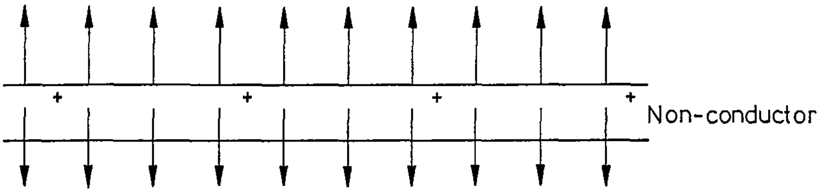
10.1 Charge generation

Non-conducting materials are being used increasingly in equipment and structures in a multiplicity of forms including pipes, containers, sheets, coatings and liners. This subclause is concerned with those having volume and surface resistivities in excess of about 10^{12} Ω·m and 10^{12} Ω, respectively, and therefore capable of retaining charge for long periods (relaxation times greater than about 20 s). Most synthetic polymers fall into this category.

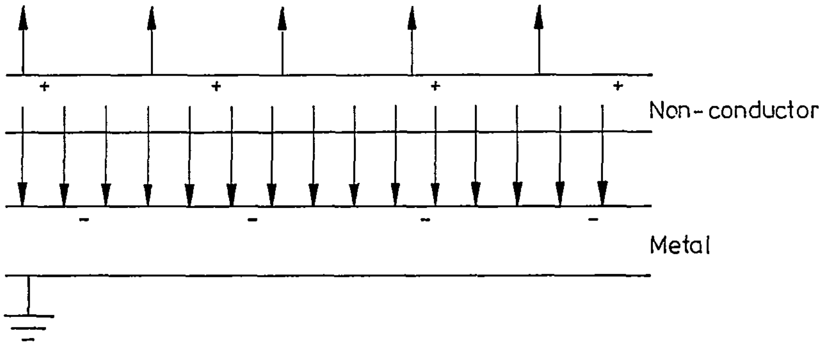
These materials are readily charged by contact electrification and also by sharing charge with other charged bodies. The contact electrification is often a consequence of the process in which the material is being used; for example, the pneumatic transfer of a powder or the flow of a liquid through a plastics pipe generates charge on the inner surface of the pipe. Alternatively the charging can be due to something extraneous to the operation, such as rubbing of the external surface of a plastics pipe. Charge sharing is often associated with the introduction of charged powder into a high resistivity container and the sharing process then involves discharges from the powder to the container.

Owing to their very high resistivities, the maximum charge that can be retained on these non-conductors is determined not by conduction, but by the breakdown strength of the atmosphere adjacent to the charged surface. Theoretical considerations indicate that when the surface is remote from earthed metal the maximum charge density in air at normal temperatures and pressures is about 30 $\mu C/m^2$. The precise maximum depends on many factors including the shape of the surface.

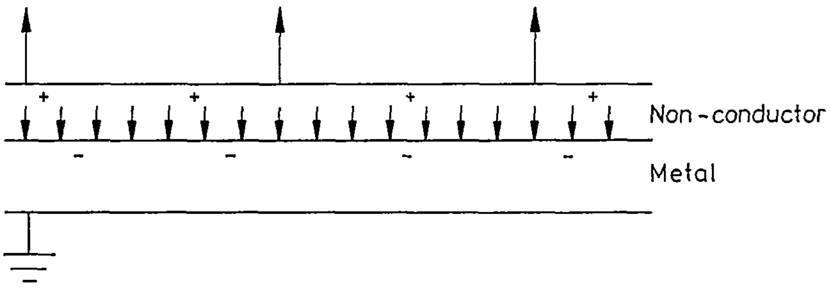
In the case of extended sheets of a high resistivity non-conductor, the charge density for breakdown depends on whether there is earthed metal either near or in contact with the side of the sheet opposite that where the charge resides. In the absence of metal, the field due to the charge is directed outwards from the sheet roughly equally on both sides, as shown diagrammatically in figure 3(a). The presence of earthed metal behind the sheet causes a redistribution of the field so that much of it is directed towards the metal, leaving less going outwards from the surface. This is illustrated in figure 3(b), where the density of the arrows is an indication of the field strength.



(a) Isolated sheet



(b) Sheet with adjacent earthed metal at rear



(c) Sheet backed by earthed metal

Figure 3. The electric field due to a charged sheet of a high resistivity non-conductor

In these circumstances a charge density much greater than 30 $\mu C/m^2$ can be accommodated on the non-conductor surface before discharges commence. The field outwards from the surface is least when the sheet is in contact with the metal as a coating or liner (see figure 3(c)) and the maximum charge density before discharge is correspondingly greater. This maximum charge density increases as the thickness of the coating or liner becomes less.

10.2 Discharges involving high resistivity materials

10.2.1 *General*

Charged high resistivity materials can give rise to discharges either directly from their surfaces or through the agency of insulated conductors, by induction or charge sharing.

The usual type of discharge from a high resistivity surface is a brush discharge as described in **5.4**. The diversity of discharge characteristics and the state of knowledge concerning them are such that no general quantitative measure is available of the incendivity of the discharge. The form of the discharge depends on the design of the equipment in which the material is incorporated, more particularly on the proximity of earthed metallic structure.

A number of cases are considered in **10.2.2** to **10.2.6**.

10.2.2 *Surfaces remote from earthed metallic structure*

It is known that brush discharges from high resistivity surfaces can ignite flammable gas mixtures with minimum ignition energies less than about 4 mJ. Mixtures with greater minimum ignition energies can be ignited in some circumstances. For example, contamination may make the surface more conductive so that it behaves as a conductor and the total charge in the contaminated area can then be released as a spark to earth which may be highly incendive.

10.2.3 *High resistivity non-conducting containers near earthed metallic structures*

In addition to the types of discharge mentioned in **10.2.2**, the much more serious hazard associated with propagating brush discharges may be encountered when a container made of high resistivity material is mounted close to an earthed metal structure in a powder handling system. As the container is filled with highly charged powder, discharges occur from the bulking point of the powder to the inside surface of the container, and from the metal structure to the outside of the container. This leads to polarization across the wall of the container with consequent very high surface charge density and stored energy density. The container wall in effect acts like the dielectric of a charged capacitor. A propagating brush discharge (see **5.5**) can then occur if an earthed conductor or person approaches the interior surface, for example to clean it.

10.2.4 *High resistivity non-conducting coatings on metals*

The risk of an incendive discharge from a thin high resistivity non-conducting coating on an earthed metal surface is usually less than that from an isolated thin sheet of a similar material. As described in **10.1**, a greater surface charge density is required to initiate a discharge from the coating and the form of the discharge is likely to be less incendive because of the smaller discharge gap and the smaller area from which charge can be drawn.

The probability of an incendive discharge depends on the surface charge density and on the thickness of the coating, becoming less as the coating becomes thinner.

A completely safe thickess cannot be recommended, but very thin layers, such as paint films and thin epoxy coatings, are unlikely to present a hazard. Often these very thin films break down electrically before a hazardous surface charge density is reached, allowing the charge to flow to the earthed metal backing.

If the charge density is very high and electrical breakdown does not take place across the coating, the approach of an earthed conductor may precipitate a propagating brush discharge liberating virtually all the energy stored in the polarized coating.

It is also known that the separation of a high resistivity non-conducting coating from its substrate metal can cause incendive discharges between the two. The same type of discharge can also occur when a high resistivity liner is removed from an earthed metal container.

Another consequence of the comparatively small field outwards from a thin coating on earthed metal is that it is much less likely to attract dust than a similar isolated film.

10.2.5 *High resistivity non-conducting films*

Polymer films readily acquire charge whilst being processed and this is particularly troublesome when the film is wound on to a reel. Personnel approaching the reel can experience shocks and the discharges are capable of igniting flammable gas mixtures. The breakdown value of the atmosphere limits the surface charge density, which rarely exceeds 10 $\mu C/m^2$. Discharges to the atmosphere leave charge patterns on the film surface, known as

Lichtenberg figures, which involve high positive and negative charges adjacent to each other. The resultant fields can anchor dust to the surface.

Occasionally film acquires polarization charges, i.e. equal and opposite charges on the two surfaces of the film. Although such charges may reach higher surface densities than the usual single surface charges, they do not give additional problems in most circumstances.

10.2.6 *Insulated conductors*

Both unearthed metal plant and unearthed personnel near charged high resistivity non-conducting components or structures can be charged by induction or charge sharing and they are then sources of incendive sparks to earth. The close proximity of a charged high resistivity non-conducting material to an insulated conductor is highly dangerous because it combines the possibility of the long-term retention of a large amount of charge with the possibility of virtually all of the stored energy being released as a highly incendive spark.

10.3 Precautions against discharges from high resistivity solids

10.3.1 *General*

The occurrence of discharges from high resistivity materials can, in principle, be avoided by either minimizing the generation of static electricity or encouraging its dissipation. In practice, the measures that can be taken are mostly in connection with charge dissipation; the principal measures are considered in **10.3.2** to **10.3.6**.

10.3.2 *Reduction of resistivity*

Many items fabricated from polymeric materials, e.g. rubbers, are being made available commercially in conducting forms by the incorporation of suitable additives, such as carbon black. The electrical requirements for antistatic and conducting products made from polymeric materials are given in BS 2050.

The resistivity required to prevent the retention of charge and the production of undesirable effects depends on the nature of the effect, e.g. whether it is dust contamination or ignition risk, and on the rate of accumulation of charge on the material. Surface and volume resistivities below about 10^8 Ω and 10^6 Ω·m respectively, are generally regarded as producing no undesirable effects except possibly in relation to explosives. In many applications, however, surface and/or volume resistivities below about 10^{11} Ω and 10^{10} Ω·m respectively, may be sufficient under normal ambient conditions.

10.3.3 *Humidification*

With many materials, including cotton, cellulose acetate, paper and gelatin, increased humidity brings about a marked reduction in resistivity and is helpful in reducing electrostatic effects. Many polymeric materials, however, are highly hydrophobic and with these it would be necessary to raise the relative humidity to the impracticably high levels of 80 % r.h. or even 90 % r.h. to ensure reliable relaxation of charge to earth.

10.3.4 *Ionization*

It is possible to assist the neutralization of the charge on the surface of high resistivity materials by ionization of the atmosphere near the charge. As usual with this technique care is required in the presence of substances with low minimum ignition energies, such as flammable gas mixtures, but it is valuable in avoiding shocks to personnel.

An important application of ionization is in the handling of high resistivity films. The following three types of static eliminator based on ionization are available.

(a) *Passive.* Corona discharges from earthed sharp needles, fine wires or conductive tinsel in the field of the film provide ions to neutralize the charge on the film. A disadvantage of the passive eliminator is that the charge density on the film has to reach a threshold before it can operate, and this threshold is too high for complete safety unless the device is sited well away from earthed metalwork which attracts a significant proportion of the field originating on the film. It may, however, be used safely in flammable mixtures with minimum ignition energies greater than about 0.2 mJ, but not in more sensitive, e.g. oxygen enriched, atmospheres.

(b) *High voltage.* Ionization at a needle tip is produced by applying a high voltage to it; commercial systems commonly use a 5 kV to 10 kV mains frequency supply to a row of points. There are 'shockless' versions which are safe to touch, and encapsulated designs, some of which are intended for use in flammable atmospheres, but expert advice should be obtained before employing such devices in this situation.

(c) *Radioactive.* Ionization is produced by means of a radioactive source; the maximum ion current is usually quite low. Radioactive ionization itself does not present an ignition hazard, but discharges to the installation are possible which necessitate precautions in flammable atmospheres. Passive eliminators are often used for this purpose.

For dissipating charges from awkwardly shaped objects, ionized air blowers using either high voltage or radioactive sources are available.

10.3.5 *Earthing*

The earthing and bonding of metalwork are dealt with, in general, in section 4. Particular care is needed in systems incorporating metals and high resistivity non-conductors. Components whose earthing could be overlooked are, e.g. a length of metal pipe suspended between two sections of non-metallic pipe, the internal metal wire reinforcement in a non-metallic hose, wire mesh wrapped around pipe cladding, and small components, such as valves, insulated by high resistivity packing materials.

Dangerous discharges involving high resistivity containers can be avoided by earthing their contents. In the case of liquids this should be done by means of an earthed plug at the base of the container, or by any earthed metal reaching near to the bottom (see **8.3.3.1**). Even so, a risk may remain, associated with charge on the wall of the container. In the case of powders the technique, described in **9.3.3.2**, of applying earthed rods or wires at the bulking point is effective. However, this method involves ionization and should not be used in the presence of flammable gas mixtures or sensitive dust clouds.

10.3.6 *The use of earthed metal meshes*

A degree of protection against static electricity can be achieved by incorporating an earthed metal mesh into a high resistivity material or by wrapping such a mesh around its surface.

An internal mesh permits the flow of some charge to earth but the high resistance of the non-conductor keeps the rate of charge transfer at a low level. The mesh does, however, increase the capacitance of the system so that more charge is needed to produce a breakdown field at the surface. Improved safety is therefore the result of control of field strength rather than of earthing.

An earthed wire mesh on the surface provides a path to earth for charge, but with highly charged materials the transfer of charge to the mesh probably involves corona discharges. In a properly designed system these discharges are unlikely to be incendive to most flammable mixtures, but the possibilty of their igniting more sensitive mixtures cannot be excluded.

With both internal and external meshes a failure to earth the mesh may result in a high energy discharge. The use of meshes in conjunction with high resistivity non-conductors is best considered on an individual basis and not as part of normal earthing procedures.

11 Static electricity in gases

The movement of pure gases or of a mixture of gases, such as the atmosphere, generates little, if any, static electricity. Gases can, however, carry electrostatic charges on suspended liquid or solid particulate matter and it is with charges of this type that this clause is concerned. The particles may be extraneous matter, such as rust or water droplets, or they may be a condensed phase of the gas itself, such as carbon dioxide 'snow', liquefied gas mists or the droplets in wet steam.

Charging is due to contact electrification of the particles and separated charge may therefore be left on items of equipment, e.g. pipes or nozzles, with which the gas makes contact. The particles in the gas may also share their charge with any object on which the gas impinges, and the gas stream may induce a potential on any insulated conductor in its vicinity.

Examples where extraneous matter is involved are the charging of the nozzles of large industrial vacuum cleaners and of pipework in systems used for the pneumatic transport of small articles. Ignition of flammable mixtures and serious shocks to personnel are both possible unless the equipment in question is made of metal and earthed. The pneumatic transport of powders is a particular case of the carriage of charge by gases, where the particulate matter is present at a comparatively high concentration; this subject has been considered in detail in clause **9**.

The escape or release of any compressed gas containing particulate matter, e.g. jets of compressed air carrying water or rust issuing from orifices, valves or flange leaks, is potentially hazardous. Because of their low minimum ignition energies, the release of hydrogen/air or acetylene/air mixtures requires particular care if they contain entrained particles.

The release of liquefied carbon dioxide results in a mixture of the gas and carbon dioxide snow which can be highly charged; potentials up to 12 kV have been measured on the nozzle and on an insulated metal object on which the gas stream impinges. This could be a hazard when using carbon dioxide for inerting if suitable precautions are not taken. Liquefied petroleum gases (LPG), such as liquid propane, are similar to carbon dioxide in that they form a mist as they are rapidly expanded. LPG is normally handled in closed systems where there is no release to the atmosphere and the gas concentration within the system is always well above the upper flammable limit. However, flammable concentrations can occur outside the system, e.g. during the filling of liquid propane bottles.

In all systems handling gas, the main precaution is to bond together and earth all metallic equipment in the system and also any metallic parts on which the gas may impinge outside the system. The use of non-conductors should be avoided where there is any possibility that they could retain charge, either generated on them by contact electrification or imparted to them by a gas stream in their vicinity.

12 Static electricity on personnel

12.1 Charge generation

The volume resistivity of the human body is low enough for it to act as a conductor. If a person insulated from earth becomes charged, therefore, he can give rise to sparks which may be sufficiently energetic to ignite flammable mixtures or to cause electric shocks to himself or others. His insulation may arise because he is wearing insulating footwear or because he is standing on an insulated floor. The body can be charged by contact electrification, or by induction or charge sharing involving other charged objects or, more particularly, the clothing being worn.

Examples of charge generating mechanisms are:

(a) rising from a chair or brushing against a wall (the initial charge separation is between the outer surface of the clothing and the other surface involved; the body is then charged by induction);

(b) walking on an insulating floor, such as a carpet made of high resistivity material (the initial charge separation is between the floor and the footwear, and the body is then charged by sharing in the case of conducting footwear, or by induction in the case of insulating footwear);

(c) removal of an outer garment, where the contact electrification is between the inner and outer layers of clothing and the body is then charged by sharing or by induction;

(d) pouring of liquids or powders from a container held by a person (the liquid or powder carries away charge of one polarity leaving an equal and opposite charge on the body);

(e) contact with charged material, as when sampling a highly charged powder.

When there is a continuous charge generation process, the maximum body potential is limited to about 50 kV by electrical leakage and sparking.

12.2 Discharge involving personnel

12.2.1 *Sparks from the body*

The total stored energy on a charged person is given by the expression $\frac{1}{2} CV^2$ as derived in **5.2**. A typical body capacitance is in the range 100 pF to 300 pF. Not all the energy stored on the body is released in the spark discharge, the amount depending on the circumstances of the discharge. Consideration should be given to the need for precautions when the minimum ignition energy is less that about 100 mJ, e.g. in the presence of flammable gas mixtures and sensitive dust clouds.

12.2.2 *Sparks from clothing*

It will be seen from **12.1** that in many cases clothing becomes charged, but there is little chance of serious sparking direct from clothing if the wearer is earthed, because only a small proportion of the field due to the charged clothing is directed outwards from the person. Also sparks from clothing are limited by the resistivity of the material. Consequently, the energy of any discharge is small and unlikely to be dangerous except in atmospheres with very low minimum ignition energies, as when enriched with oxygen, or in handling explosives.

If an article of clothing is removed, however, its charge is more readily available and a dangerous spark is more likely to occur, either directly or by induction from it.

12.3 Precautions against static electricity on personnel

12.3.1 *Discharges from the body*

Static electricity discharges from a person can be minimized by providing an adequately conducting path between the person and earth through his footwear and the floor. Leather soled footwear is usually sufficiently conductive for this purpose in normal humidity conditions, although it may fail if very dry.

BS 7193 gives requirements for two types of rubber footwear, both of which are effective, provided that the floor does not impede the dissipation of charge: these are electrically conducting and antistatic footwear. Antistatic footwear is intended for use in situations where protection is also required against dangerous electric shock in the event of apparatus becoming defective when operating at voltages of up to 250 V to earth; conductive footwear is for use where there is no such danger of electric shock. The resistance of both types of footwear may increase in use and, in addition, insulating layers, e.g. of oil or wax, can be formed on their soles. Therefore, the footwear should be tested regularly.

Specifications for conducting flooring materials and for such floors after laying are given in BS 2050 and BS 3187, respectively.

12.3.2 *Discharges from clothing*

In general, clothing made from any material can be worn provided that the wearer is earthed either directly or through approved antistatic or conducting footwear and floors; exceptions are in areas where explosives are handled, where there are highly flammable gas mixtures, e.g. oxygen-enriched atmospheres, and in the manufacture of solid state devices. In such cases garments made of high resistivity materials should not be worn, and conductive outer garments should be earthed. Clothing can be made conductive by treatment with antistatic agents, but the effect of some of these is temporary and they should be reapplied at regular intervals, at least after each washing. Many antistatic agents, and also conductive clothing made from natural fibres such as cotton, flax or linen, rely on the presence of atmospheric moisture.

Clothing should not be removed in areas where flammable gas mixtures or low minimum ignition energy dust clouds are present (see **12.2.2**).

Section 4. Earthing and bonding

13 Earthing and bonding

NOTE. For information concerning earthing and bonding in potentially explosive atmospheres for purposes other than the control of static electricity, reference should also be made to the appropriate clauses of BS 5345 : Parts 1 and 4 and BS 5501 : Part 1.

13.1 General

The most common source of danger from static electricity is the retention of charge on a conductor, because virtually all the stored energy can be released in a single spark to earth or to another conductor. The accepted method of avoiding the hazard is to connect all conductors to each other and to earth by electrical paths with resistances sufficiently low to permit the relaxation of the charges. Similar earthing and bonding techniques are also associated with electricity power supply systems and lightning protection installations, although the criteria for their design are not necessarily the same. The present discussion is concerned only with protection against static electricity.

13.2 Criteria for the dissipation of static electricity from a conductor

13.2.1 *Basic considerations*

The maximum resistance that will prevent the retention on a conductor of a dangerous amount of charge depends upon the rate at which the conductor is receiving charge. The same principles apply to both earthing and bonding; the condition that has to be satisfied in all cases is that the total resistance to earth should not exceed an acceptable maximum.

In electrical terms, the majority of situations is adequately represented by the circuit shown in figure 1, where R is the resistance to earth from the conductor. As stated in clauses **4** and **5** the maximum potential and the maximum stored energy on the conductor are

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

and

$$E_{\text{max}} = \tfrac{1}{2} C V^2_{\text{max}} = \tfrac{1}{2} C I^2 R^2$$

where the symbols have the meanings assigned to them in clauses **4** and **5**.

An incendive discharge occurs when two conditions are satisfied; these are:

(a) that the potential of the conductor reaches a value such that the associated field strength exceeds the breakdown strength of the atmosphere;

(b) that the energy released in the spark exceeds the minimum ignition energy of any flammable material present.

With few exceptions, earthing installations are intended to prevent all discharges that could be incendive, and the first of these conditions is, then, the one to be satisfied, irrespective of spark energy, i.e. $IR <$ potential required to initiate an incendive discharge.

A potential of at least 300 V is considered to be necessary to initiate an incendive discharge in normal industrial operations, but in explosive manufacturing plant, 100 V is considered to be hazardous. Taking the latter figure, therefore, the requirement for the safe dissipation of static electricity is as follows.

$$R < \frac{100}{I}\ \Omega$$

13.2.2 *Practical criteria*

In the development of earthing specifications, each situation, i.e. each individual value of I, cannot be considered separately. It is known that charging currents range from 10^{-11} A to 10^{-4} A, and the corresponding values of R are $10^{13}\ \Omega$ and $10^{6}\ \Omega$. Taking the maximum value of I leads to the conclusion that a resistance to earth of $10^{6}\ \Omega$ will ensure safe dissipation of static electricity in all situations. In most industrial operations I does not exceed 10^{-6} A and a resistance to earth of $10^{8}\ \Omega$ is therefore safe in many situations.

Conductors in good contact with earth have a resistance to earth far less than $10^{6}\ \Omega$ and, for practical convenience, a much lower resistance is often specified as the maximum permitted earthing resistance. The following are amongst the factors to be considered in choosing a resistance value for this purpose.

(a) The resistance between metals in good contact rarely exceeds a few ohms. A value less than 100 Ω is readily attainable and is unlikely to deteriorate with time to a level above $10^{6}\ \Omega$ unless the plant is subject, for example, to serious corrosion.

(b) Resistances of the order of thousands of ohms across apparent metal/metal contacts suggest contamination by corrosion products or paint, and there is some risk that the resistance might in time rise above $10^{6}\ \Omega$.

(c) The resistance specified to avoid static electricity hazard should be compatible with that required for other reasons. In order to provide protection against lightning or to meet the requirements for earthing associated with an electricity power supply system, resistance to earth as low as 1 Ω may be needed. BS 6651 and BS 7430 should be consulted for details of the precise requirements.

For reasons such as these, and for convenience in monitoring, maximum resistance to earth in the range 10 Ω to 100 Ω have been specified for electrostatic earthing systems for conductors. The particular value chosen is, to a degree, an arbitrary one. 10 Ω has the advantage of being equal to the value prescribed for lightning protection of existing plants and will be used in the remainder of this discussion. A clear distinction should, however, be made between a value such as this, chosen for reasons of practical convenience, and the value of 10^6 Ω which is in fact the upper limit for the resistance to earth of a conductor.

The criterion of 10 Ω is generally suitable for wholly metallic systems but cannot always be applied to systems involving non-metallic, e.g. plastics, components, which are becoming increasingly common. Requirements for earthing are therefore now required to cover a variety of different situations. A number of possibilities are considered in **13.3** and **13.4**.

13.3 Earthing requirements in practical systems

13.3.1 *All-metal systems*

13.3.1.1 *Fixed structures*

The main structure of a metal plant and the major components mounted on it such as reactors, mills, blenders or tanks, and also items such as pipelines, are permanent installations normally with bolted or welded joints. They are usually in direct contact with the electricity power supply earthing system and their resistance to earth to protect against lightning should, where applicable, be less than 10 Ω. There is, in general, no difficulty in establishing and maintaining a resistance to earth of 10 Ω or less, and little risk of this deteriorating to a value above 10^6 Ω. For these reasons a prescribed maximum resistance of 10 Ω is acceptable to avoid static electricity hazards and, in most instances, this will be achieved without special earthing connections. These connections are to be recommended only when the plant design and usage make it difficult to maintain a low resistance to earth without them.

Plants are being developed which incorporate major items not in direct electrical connection with the main structure, e.g. items on flexible or vibratory mountings or on load cells. These should have special earthing connections to ensure a resistance to earth below 10 Ω, unless a higher prescribed resistance can be accepted (see **13.3.2**).

A pipeline is sometimes a temporary installation possibly less well connected to the structure of the plant and incorporating lengths of non-conducting pipe, and special earthing connections may then be needed.

In the past, the use of bonding connectors across all joints in a metal pipeline has been recommended in some guidelines. The general application of this principle can cause practical difficulties and such bonds should be used only when the design is such that the 10 Ω criterion may be exceeded.

13.3.1.2 *Transportable metal items*

These are items of equipment, including drums and road and rail tankers, which cannot be permanently connected to earth through the main plant structure. In many cases, their resistance to earth may be well below 10^6 Ω, but, for example when standing on the dry concrete floor or on pneumatic tyres, it may not be adequately controlled and may well rise above 10^6 Ω in use. To meet this situation, the resistance to earth of these types of equipment should be kept below 10 Ω by the provision of suitable earthing connections. The minimum essential requirement is that such earthing should be in position at any time when a flammable mixture may be present and the item may retain an electrostatic charge, such as during the filling or emptying of a container with a flammable liquid.

13.3.2 *Metal plant with non-conducting elements*

Plant of metal construction has always contained some non-conducting items which could affect electrical continuity and earthing; examples are lubricating oils and greases, and, more recently, components made of high resistivity non-conductors such as polytetrafluoroethylene or polyethylene. Normally, all metallic parts of the plant are earthed either directly or through suitable earthing connections and all paths to earth have resistances less than 10 Ω. Problems arise when this solution presents difficulties owing to the design of the equipment in question.

As already mentioned (see **13.2.2**) a resistance to earth of less than 10^6 Ω (or more generally $100/I$ Ω) is adequate for the relaxation of static electricity, and in many cases advantage can be taken of this; an important example is the oils and greases used in the lubrication of rotating shafts, stirrers, etc. In the past, the use of conducting brushes pressing on rotating shafts has been recommended, but they are difficult to adjust and maintain and their long-term effectiveness is doubtful. Tests have shown that the resistance across a lubricating film in a bearing is unlikely to exceed 10^3 Ω, so that it is in fact capable of dissipating static electricity without special earthing devices. The same approach can be applied to other plant items where the resistance to earth is less than 10^6 Ω but where a 10 Ω limit is difficult to achieve, such as roller conveyors or scroll feeds. In such cases a maximum resistance to earth of 10^6 Ω can be specified provided that:

(a) the resistance calculated using the volume resistivity of the non-conductor and the dimensions of the leakage path is less than 10^6 Ω; and

(b) tests made in normal operations are in reasonable agreement with the calculations and indicate that the resistance will remain stable and less than 10^6 Ω.

This approach removes the need for many special earthing devices to meet a 10 Ω criterion and enables effort and resources to be concentrated on situations where such a level of resistance to earth is justified.

When high resistivity polymers are involved as the insulating elements, a resistance in excess of 10^6 Ω is almost inevitable and the only solution is to provide an earthing connection between the isolated conductor and adjacent earthed metal components. The appropriate maximum resistance would be 10 Ω; examples are ball valves with polytetrafluoroethylene packing and seals, pipe spacing rings insulated by polytetrafluoroethylene coated gaskets, isolated metal pipeline sections between plastics connectors and metal nozzles at the end of plastics lines (see BS 5351).

A major problem is the detection of plant items which may be insulated. In many cases a non-conducting component within a piece of equipment is not visible and may not be detected by external resistance testing. It is essential that any design change involving the incorporation of non-conducting materials be studied in detail to ascertain whether its presence will cause the insulation of any metallic component.

13.3.3 *High resistivity non-conducting materials*

Materials such as glass and high resistivity polymers are increasingly being used as major items of equipment. The considerations in **13.2** concerning the appropriate criteria for resistance to earth to avoid electrostatic hazard can be extended to these materials. The basic condition to be satisfied is that the resistance (in ohms) to earth from every part of the non-conductor should be less than $100/I$. However, the provision of the large number of closely spaced contacts with earth required to meet this condition is impracticable, and the non-conductors will therefore retain their charge for long periods.

The discharges from high resistivity non-conductors are of comparatively low energy, although they may be sufficient to ignite sensitive flammable mixtures. In practice, however, there may be surface contamination with a conducting material, e.g. water, and if this does not cover the whole surface and is not in contact with earth, it constitutes an insulated conductor which can be the source of a high energy spark. Also, these non-conducting systems often contain metal components which will give rise to sparks if not earthed; examples are the connecting bolts and backing flanges in a plastics pipeline and the metal mesh extending throughout some types of non-conducting wall cladding.

Because of their electrostatic properties and the general fire risk the use of high resistivity non-conductors in association with flammable mixtures or flammable liquids in bulk should be avoided whenever possible. There are, however, situations where such materials are virtually essential (for handling highly corrosive liquids, for example) in areas from which flammable mixtures cannot be wholly excluded.

Ideally, all isolated conductors in a non-conducting system should be earthed, but effective earthing in many cases requires the extensive use of special earthing devices and an unrealistic degree of inspection and maintenance. The general recommendation that all conductors in high resistivity non-conducting systems should be earthed is therefore open to question. The measures taken to maintain safety will depend on the individual installation, and no general earthing specification can be prescribed.

Lack of earthing alone is not sufficient to produce an ignition. The risk depends also on:

(a) the probability that the non-conductor will become charged;

(b) the probability of an incendive spark from conductors;

(c) the probability of a flammable mixture being present.

Condition (c) can be considered in terms of the hazardous areas developed in connection with flammable gases (see BS 5345 : Part 1) and defined in **2.12**; for convenience, the same concept is taken here to apply also to dusts.

The overall principle adopted is to evaluate the probability of an ignition induced by static electricity and by means of the techniques most appropriate to the system in question, including earthing, to reduce this probability to a level no greater than that from other sources of ignition, e.g. electrical equipment, and also to a level acceptable to the user. In zone 0 or zone 1 areas this necessitates the elimination of the static electricity hazard by preventing generation and retention on both non-conductors and conductors by whatever technique is appropriate; the avoidance of the flammable mixture by inerting should also be considered. In nearly all cases earthing in some form would be involved. However, in a zone 2 area, if static electricity is not a normal feature of the operation, and if the accidental generation of a dangerous level of static electricity is very improbable, the overall ignition probability may be so low that earthing of isolated conductors in non-conducting systems solely for the control of static electricity can be dispensed with.

13.3.4 *Conductive and antistatic materials*

Materials are increasingly becoming available which combine the desirable properties of polymers, such as corrosion resistance, with a low enough volume resistivity to prevent the retention of dangerous levels of static electricity, provided that they are in contact with earth (see **10.3.2**). A resistance to earth of the order of 10 Ω is not applicable. The basic requirement is for a resistance (in ohms) to earth of less than $100/I$ and this is often in the range of 10^4 Ω to 10^8 Ω. For general use a maximum value of 10^6 Ω is probably the most appropriate, but if it cannot be met, $100/I$ would be acceptable. Values above 10^8 Ω, however, are acceptable only in special circumstances after assessment of the hazard.

13.3.5 *Summary of earthing requirements*

For practical convenience, an appropriate value for the maximum resistance to earth from all parts of fixed metal equipment is 10 Ω, although a resistance up to 10^6 Ω can be accepted, provided that it can be maintained. Special earthing connections are not normally required unless, for example, equipment is mounted on insulating supports, or if high resistivity contamination may develop across a joint.

Transportable metal items should have a resistance to earth of 10 Ω or less, provided by a special earth connection.

The use of high resistivity materials (polymers) for the construction of plant for use in the presence of flammable mixtures is not generally recommended and should rarely be encountered. No generally applicable resistance value to earth can be suggested and safety measures should be developed for each individual plant to reduce the hazard to an acceptable level. In a zone 2 area where the risk of electrostatic generation is sufficiently low, earthing of metal components solely for the control of static electricity may not be necessary.

Antistatic or conductive type materials can be used to avoid the retention of static electricity. The most appropriate maximum value for the resistance to earth from all parts of such equipment is 10^6 Ω although values up to 10^8 Ω may be acceptable in some cases.

A brief review of earthing resistance recommendations is given in table 4.

13.4 The establishment and monitoring of earthing systems

13.4.1 *Design*

At the design stage, the plant should be examined to ascertain the possible electrostatic hazards, and the earthing requirements should be determined using the guidance given in **13.3**. Where no other form of earthing exists it should be achieved by connections to copper rods or plates driven into or buried in the ground. However, special earthing devices, such as bonding cables, straps or brushes should be kept to the minimum essential. Where they are required, cables or straps to meet the 10 Ω maximum resistance criterion should be connected to threaded studs or bosses welded or brazed to the metalwork of the structure.

Important features in the design of earthing devices are:

(a) they should be recognized as such and accepted as essential to the safe operation of the plant;

(b) they should be clearly visible, or else essential to the correct functioning of the plant, so that any shortcoming is quickly detected;

(c) they should be robust and should be sited so that they are not affected by high resistivity contamination, for example by corrosion products or paint;

(d) they should be easy to install and to replace;

(e) cables for earthing transportable items should be equipped with a robust clip capable of penetrating through paint or rust layers. The clip should be attached before the operation commences and should remain in place until it has been finished and all dangerous electrostatic charges have been eliminated.

13.4.2 *Monitoring*

The checking of earthing as a protection against static electricity should be recognized as quite distinct from that for other reasons, such as the maintenance of earthing systems associated with electricity power supply and lightning protection installations. Checks should be made before the plant is brought into use, at each scheduled maintenance, and after any other maintenance or modification.

The basis of monitoring is the measurement of the resistance between the different parts of the plant and earth, but it is important that this should be supplemented by visual inspection. This will help to detect any incipient malfunction of the earthing devices and to minimize the risk of modifications leading to the insulation of a conductor.

Where resistances to earth greater than 10 Ω are permitted, the stability of the resistance is a critical feature. The monitoring system should be capable not only of monitoring these higher resistances but also of bringing to light any changes of resistance.

Table 4. Summary of recommended earthing resistances for the control of static electricity

Clause reference	Type of installation	Electrical area classification	Recommended maximum resistance to earth	Comments
			Ω	
13.3.1.1	Main metal plant structure	Zones 0, 1, 2	10	Earthing normally inherent in the structure
13.3.1.1	Large fixed metal plant items (reaction vessels, powder silos, etc.)	Zones 0, 1, 2	10	Earthing normally inherent in the structure. Occasionally items may be mounted on non-conducting supports and special earthing connections may then be required
13.3.1.1	Metal pipelines	Zones 0, 1, 2	10	Earthing normally inherent in the structure. Special earthing connections may be required across joints if there is doubt that the 10 Ω criterion will be satisfied
13.3.1.2	Transportable metal items (drums, road and rail tankers, etc.)	Zones 0, 1, 2	10	Special earthing connections are normally required
13.3.2	Metal plant with some non-conducting elements (rotating shafts, stirrers, etc.)	Zones 0, 1, 2	10^6	In special cases a limit of $100/I$ Ω may be acceptable, but in general if a 10^6 Ω criterion cannot be satisfied, a special earthing connection should be used to obtain a resistance to earth of less than 10 Ω
13.3.3	High resistivity non-conducting items with or without isolated metal components, e.g. bolts in plastics pipeline	Zones 0, 1, 2	No generally applicable value	The general electrostatic ignition risk and the fire hazard normally preclude the use of such non-conducting materials unless it can be shown that significant charge accumulation will not occur. In the absence of charge accumulation, earthing is not required in zone 2 areas
13.3.4	Items fabricated from conductive or anti-static materials	Zones 0, 1, 2	10^6 to 10^8	

NOTE. This table should be read in conjunction with the indicated paragraphs in the text.

Appendix

Appendix A. Guidance on methods for measuring or estimating various parameters

A.1 General

The measures recommended for the control of undesirable static electricity depend to a considerable extent upon a knowledge of particular characteristics of the medium involved, e.g. the conductivity of a liquid or resistivity of a powder. In some instances the required information can be obtained from the appropriate manufacturer but, to cover the situation where such information is not readily available, appendix A has been included in this standard.

Measurements made in flammable atmospheres should be carried out strictly to the requirements of the appropriate parts of BS 5345.

A.2 The electrical conductivity of a liquid

A.2.1 *General*

The electrical conductivity of a liquid indicates whether or not it is capable of retaining a hazardous electrostatic charge. For liquids with conductivities above about 10 000 pS/m, the measurement can be made using traditional a.c. bridge methods. Below this level, such methods are difficult to use and specialized equipment is required. Two methods of measurement are described in **A.2.2** and **A.2.3**: method A for routine use in the field and method B for more precise measurements in the laboratory.

Low conductivity liquids do not strictly obey Ohm's law, and to obtain reproducible results the conditions of measurement should be carefully selected and controlled.

In particular:

(a) the liquid should be uncharged at the time of the measurement. If it has been charged, adequate time should be allowed for relaxation and for the establishment of ionic equilibrium; the resultant conductivity is called the 'rest conductivity' meaning that the liquid is electrically at rest, although not necessarily quite motionless;

(b) the measurement process should not lead to ion depletion, and significant polarization voltages should not be allowed to develop.

These requirements impose limits on the applied voltage, the electrode spacing and the duration of the test, which may not be as well satisfied in method A as in method B.

A.2.2 *Method A, for routine use*

Proprietary instruments are available which are intended for use mainly in the range 50 pS/m to 600 pS/m, although some are scaled well below this range. They include instruments for dipping into storage tanks and open containers and for recording continuously the conductivity of liquid flowing in a pipeline. Each should be used in accordance with the manufacturer's recommendations.

Precautions should be taken to avoid sample contamination, which will usually give a high, and hence optimistic, result; errors from this source are more likely at low conductivities, below about 10 pS/m. Contamination is most likely when a sample is transferred from the bulk supply to the instrument by means of a sample bottle or can. If contamination of the container is suspected it should be rinsed several times with a mixture of equal parts by volume of toluene and of acetone. It should next be rinsed with *n*-heptane and finally it should be rinsed several times with the liquid to be tested.

A similar cleaning procedure should be applied to the measuring cell of the conductivity meter if it has been used for testing a high conductivity liquid or has been in contact with aqueous material.

Precautions should be taken to avoid errors due to charge in the liquid resulting from previous movement. For instruments dipped into tanks or open containers, such errors are likely only with very low conductivities; if such errors are suspected, readings should be repeated at five-minute intervals until a constant value is obtained. A continuous conductivity meter should be installed in such a way that:

(a) any charge in the liquid is relaxed before it enters the measuring cell; and

(b) charge generation due to flow through the cell has a negligible effect on the reading.

This becomes progressively more difficult as the conductivity decreases, and, so far, continuous meters have only been available for conductivities above 50 pS/m.

The precision of method A measurements, especially at low conductivities is expected to be inferior to that of method B.

A.2.3 *Method B, for precision laboratory use*

A.2.3.1 *Summary of method*

This is suitable for use with organic liquids having conductivities down to 0.1 pS/m.

A d.c. voltage is applied to a pair of electrodes in a test cell containing a sample, under such conditions that depletion of ions and polarization at the electrodes are negligible. The maximum current through the cell is measured and the conductivity of the sample is then calculated from the values of the voltage and the current and a cell constant.

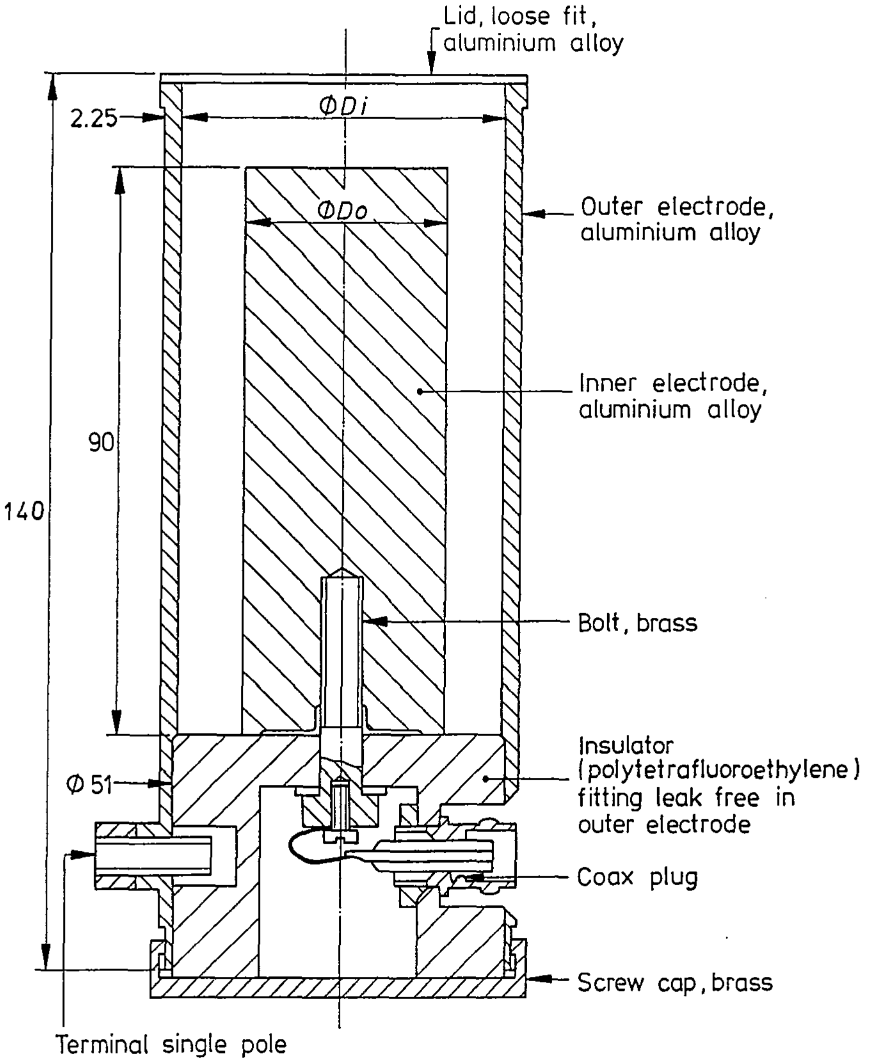
A.2.3.2 *Apparatus*

The following apparatus is required.

(a) *The test cell.* A recommended design is shown in figure 4, for which the cell constant is 1.00 $m^{-1} \pm 1$ %.

If another design of cell is used, the electrode spacing should not be less than 1 mm and the voltage gradient across the gap should not exceed 1.6 V/mm; precision will deteriorate as the electrode spacing is decreased. It will be necessary to determine the cell constant using a liquid of known conductivity. If the design of the cell does not provide screening of the liquid, the live electrode and the ammeter input lead, a separate earthed screen should be placed around the cell.

(b) *Electrical circuit.* The cell is included in the circuit shown in figure 5. The voltage source provides a constant d.c. voltage which, for the cell of figure 4, should be in the range 9 V to 11 V. A battery or a well regulated, low ripple voltage supply is suitable. If the latter is used, line variations should be effectively suppressed, so as to avoid irregular results when measuring conductivities below 10 pS/m.



All dimensions are in millimetres.
The scale is 1:1.

Figure 4. Main features of liquid conductivity cell design

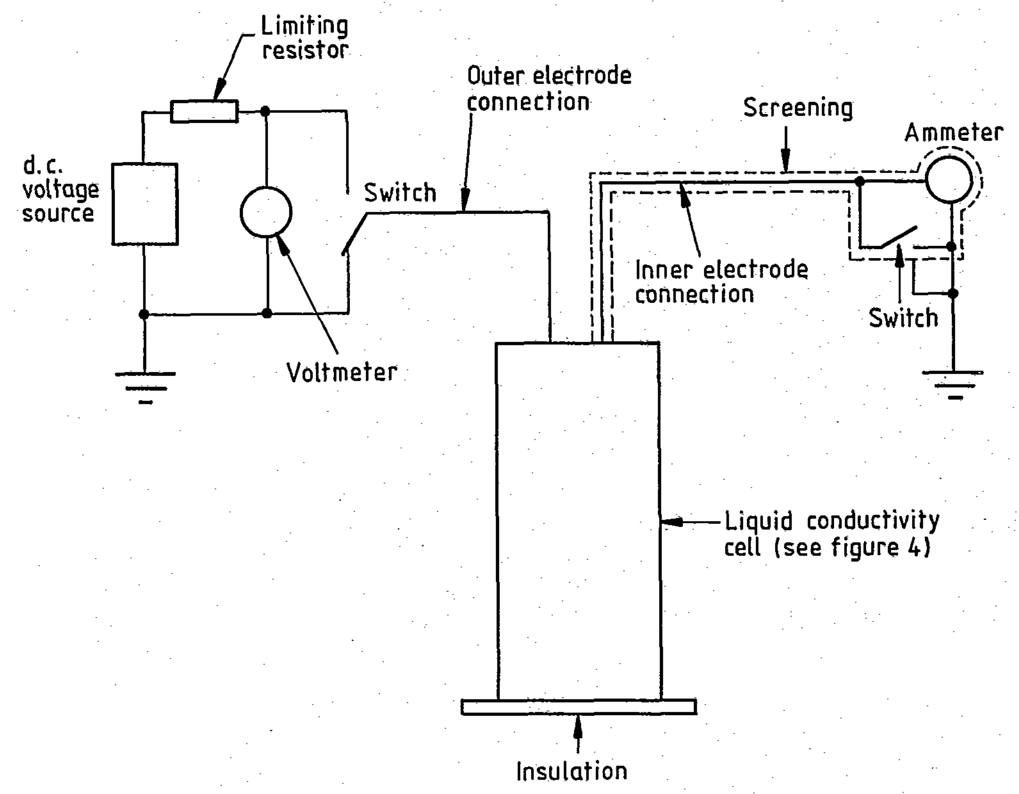


Figure 5. Arrangement of the equipment for liquid conductivity measurement

The voltmeter should be capable of measuring the applied voltage with an accuracy of at least 2 % and the ammeter should have a lowest measuring range of at most 10^{-12} A full scale deflection.

A.2.3.3 *Procedure*

(a) *Solvents.* The procedures given below are to be followed.

(1) Toluene-acetone mixture. Mix equal volumes of toluene and acetone.

(2) *n*-heptane. Prepare by percolating high purity *n*-heptane, e.g. analytical reagent quality, through silica gel. After treatment, the *n*-heptane should have a conductivity, measured by this method, of less than 0.03 pS/m.

(b) *Preparation of test cell.* The procedures given below should be followed for preparing the test cell. The cleaning procedure depends largely on the nature of the sample to be measured. If the sample is believed to contain the same ionic material at the same concentration as the sample measured in the previous test, the cell need only be rinsed a few times with treated *n*-heptane.

If the sample to be measured either has ionic material different from that in the previous test, or it is at a much lower concentration, rinse the cell thoroughly five times with fresh toluene-acetone mixture and then once with treated *n*-heptane.

When the cell has been used for testing samples with high conductivities (more than, say, 1000 pS/m), or when solutions containing surface active materials have been measured, cleaning the cell may be difficult. In such cases dismantle the cell and place all parts, except the plug removed from the outer electrode, in a Soxhlet apparatus containing boiling toluene-acetone mixture and leave if for several hours. Then rinse all parts with treated *n*-heptane before assembly, and rinse the cell again after assembly.

If it is required to measure both low conductivities (less than 1 pS/m) and high conductivities (greater than 1000 pS/m), it is advisable to keep one cell solely for the low conductivity samples.

After the cell has been cleaned, it should be checked by measuring the conductivity of the treated *n*-heptane, which should be less than

0.03 pS/m. If the result is greater than 0.03 pS/m, repeat the cleaning procedure using the toluene-acetone and *n*-heptane solvents, and check again with treated *n*-heptane. If this fails, check the electrical leakage of the cell itself by carrying out the measurement procedure with the cell empty and dry. The result should be less than 0.01 pS/m; a typical result would be 0.0002 pS/m. If the result is greater than 0.01 pS/m, clean the cell using the Soxhlet procedure described above.

(c) *Sampling the liquid and loading the cell.* Clean all equipment using the same procedure as for the cell. To avoid loss of active components from the sample by transfer to the wall of the container, keep the storage time in the container and the surface/volume ratio as small as possible. Avoid unnecessary pouring of the sample from one container to another.

Flush the cleaned cell three times with the sample, empty it completely and then fill it. When using the cell of figure 4, load it with 100 mL of sample.

(d) *Measurements.* Place the cell on a piece of insulating material with a resistance to earth greater than 10^7 Ω. With the switch turned to earth and the ammeter short circuited, make the electrical connections to the cell. Where it can be adjusted, set the voltage supply at 10 V (if using the cell of figure 4) and set the ammeter so that the voltage drop across its input resistance is less than 0.1 V.

Allow some time for any charge on the liquid to relax, if the conductivity is expected to be below 1 pS/m. The presence of this charge can be detected by switching the ammeter into the circuit; if the reading is small compared with that expected for the actual measurement, the influence of the charge can be neglected. After such a check short circuit the ammeter again.

When relaxation is complete, turn the switch to the voltage supply and, after a fraction of a second, switch the ammeter into the circuit. Take the maximum current reading, which is normally reached within 1 s or 2 s, and then turn the switch to earth and short circuit the ammeter. Finally, measure the temperature of the sample with a clean thermometer.

The measurement procedure should be repeated with fresh cell fillings until a constant current reading is obtained.

A.2.3.4 *Calculation of result*

The conductivity of the sample at the measurement temperature is given by the equation

$$\gamma = k \frac{I}{V} \times 10^{12}$$

where

γ is the electrical conductivity (in pS/m);

k is the cell constant (in m^{-1}). For the cell of figure 4, $k = 1.00\ \text{m}^{-1} \pm 1\ \%$;

I is the measured current (in A);

V is the applied potential difference (in V).

A.3 The volume resistivity of a powder

A.3.1 *General*

This test is designed to measure the volume resistivity of a bulked high resistivity powder in order to assess its ability to retain static electricity. For this purpose it is sufficient to know the order of magnitude of the resistivity. The equipment is suitable for measuring volume resistivities in the range 10^7 Ω·m to 10^{14} Ω·m.

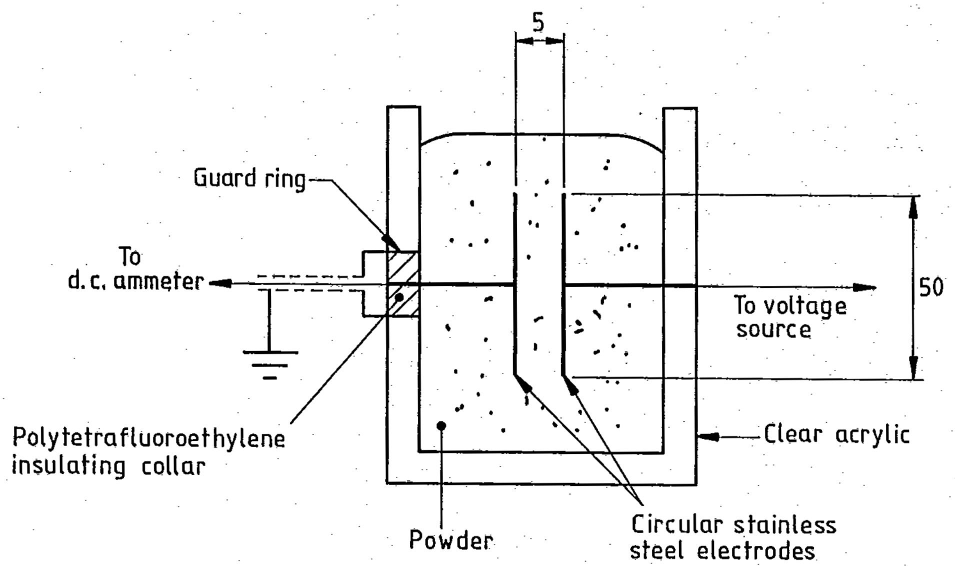
A.3.2 *Summary of method*

A sample of the powder is placed between two parallel electrodes and a high potential is applied to it. The resistance is derived by measuring the resultant current and the volume resistivity calculated from it using the dimensions of the electrode system.

A.3.3 *Apparatus*

The powder is placed in a resistivity cell; the essential details and typical dimensions of such a cell are shown in figure 6. For powders with resistivities towards the lower end of the resistivity range, the resistance between the electrodes can be determined with a commercial instrument such as an insulation tester or a megohmmeter.

For higher resistivity powders the cell is included in a circuit such as that shown in figure 7, where the test potential is provided by a 500 V to 1000 V d.c. source with an inbuilt current limiting resistor for safety purposes. The resultant current is measured by a d.c. ammeter with a range of 10^{-12} A to 10^{-4} A, depending on the resistivity of the powder involved. The earthed guard ring around the low voltage lead from the cell prevents any leakage current that might flow around the walls of the cell from reaching the electrometer, and this guard can be extended to screen the lead to the electrometer. In order to avoid the flow of a dangerously high current if, for example, the powder proved to be highly conductive, or the positive electrode were shorted to earth, a 1 MΩ resistor is put in series with the d.c. source.



All dimensions are in millimetres.

Figure 6. Main features of the powder resistivity cell design

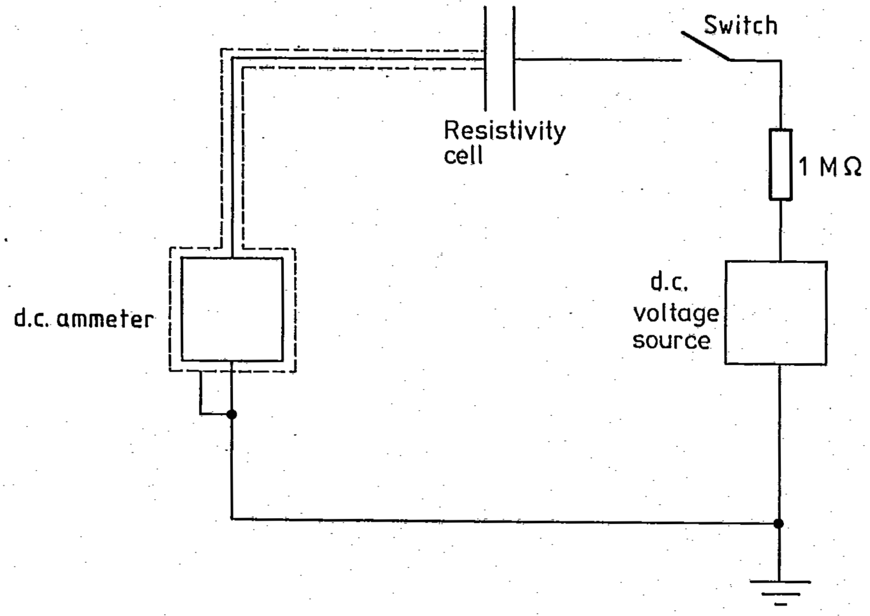


Figure 7. Arrangement of the equipment for the measurement of the resistivity of a powder

A.3.4 *Procedure*

The procedures given below are to be followed.

(a) *Preparation of the sample.* The measured resistance of the powder will depend upon the degree of compaction of the sample. Reproducible results are usually obtained if, after filling, the powder is tamped down by gently knocking the cell on the bench. Ideally, the compaction should be similar to that occurring in practice and, as an alternative to tamping, it may be possible to achieve this by pressing the powder with an appropriate weight.

(b) *Measurements.* Comparative measurements should always be made at the same temperature and relative humidity, preferably those obtaining when the powder is in use.

In the electrometer circuit of figure 7, apply a potential between 500 V and 1 kV to the cell and allow sufficient time for initial polarization transients to decay before measuring the steady current. The precautions normal for high voltage equipment should be taken.

If a commercial instrument is used for measuring the resistance between the electrodes, the manufacturer's instructions should be followed.

A.3.5 *Calculation of result*

The volume resistivity of the powder is given by the following equation.

$$\rho = R\frac{A}{l} = \frac{V}{I}\frac{A}{l}$$

where

ρ is the volume resistivity (in Ω·m);

R is the resistance of the powder (in Ω);

V is the applied potential (in V);

I is the measured current (in A);

A is the area of each electrode (in m^2);

l is the distance between the electrodes (in m).

Thus, for the dimensions given in figure 6,

$$\rho = 0.393\frac{V}{I} \text{ (in } \Omega\cdot\text{m).}$$

This equation is adequate for deriving the order of magnitude of the resistivity. It assumes a uniform current density between the electrodes and no distortion of the current flow at the edges of the electrodes. The error due to edge effects could be reduced by adopting a guard ring format for the electrodes as in dielectric test cells.

A.4 Mass charge density of a powder

A.4.1 *General*

One means of assessing the electrostatic hazard due to powder in a powder handling plant is to measure the mass charge density of the powder. For this purpose an estimate of the order of magnitude of the charge density is adequate. The following simple test method can be used at any point in the system where the powder can be diverted from the plant into a collector. A critical point is where the powder moves from the main units, e.g. mills, pneumatic transfer lines, to air/powder disentrainment or storage units, e.g. cyclones, filter bags, silos.

A.4.2 *Summary of method*

A quantity of charged powder is collected in an insulated metal container. The potential induced on the container is measured. The quantity of charge on the powder is equal to that repelled towards earth from the container, which is calculated from the measured potential and the capacitance of the container and measuring system. Alternatively, the current draining to earth from the container in a measured time is noted in order to obtain the quantity of charge. Division of the charge by the mass of powder yields the mass charge density.

A.4.3 *Apparatus*

The essential features of the apparatus are shown in figure 8. A conveniently sized metal container is insulated from earth and placed so as to collect powder issuing from the plant. Between the container and earth is connected either an electrostatic voltmeter or a current electrometer having an input impedance such that the leakage current is insignificant compared with the charging current; typical values are 10^{12} Ω to 10^{14} Ω. This simple system is usually entirely adequate, but if the readings are unsteady or fluctuating, screening of the container and of the lead to the instrument may be helpful.

It should be remembered that if the voltmeter system is used the container constitutes an insulated conductor and appropriate precautions should be taken.

A.4.4 *Procedure*

Before the test is started, earth the container by connecting it momentarily to a convenient earthed point.

Allow the powder to flow into the container for a convenient period of time and measure either the final voltage or the current flowing to earth. Determine the mass of powder by weighing the container and its contents and subtracting the mass of the container.

If the voltmeter system is used, the capacitance of the container/measurement system is required. This can be measured by normal a.c. bridge methods.

A.4.5 *Calculation of result*

A.4.5.1 *From voltage measurement*

The mass charge density of the powder is given by the following equation.

$$q = \frac{VC}{m} \times 10^{-6}$$

where

q is the mass charge density (in µC/kg);

V is the measured potential (in V);

C is the measured capacitance (in pF);

m is the mass of powder (in kg).

Also, the average rate of charge input to the container is given by the following equation.

$$I = \frac{VC}{t} \times 10^{-12}$$

where

I is the rate of charge input (in A);

t is the time of flow (in s);

V is the measured potential (in V);

C is the measured capacitance (in pF).

A.4.5.2 *From current measurement*

The mass charge density is given by the following equation.

$$q = \frac{It}{m} \times 10^{6}$$

where the symbols have the same meanings as described in **A.4.5.1**.

A.5 Measurement of charge density and potential by means of an electrostatic field meter

A.5.1 *General*

Methods of investigating the distribution of electrostatic charges or potentials usually rely upon the detection and measurement of the associated electrostatic fields. Many commercial field meters are available for such measurements. The types of meters and some examples of their use for the assessment of electrostatic hazards are considered in **A.5.2** and **A.5.3**.

A.5.2 *Apparatus*

In most modern field meters, an insulated metal plate is used as a field-sensing probe. The potential induced in this plate is measured, and indicates the strength of the electric field. In practice, the induced potential is low and, relative to the charges

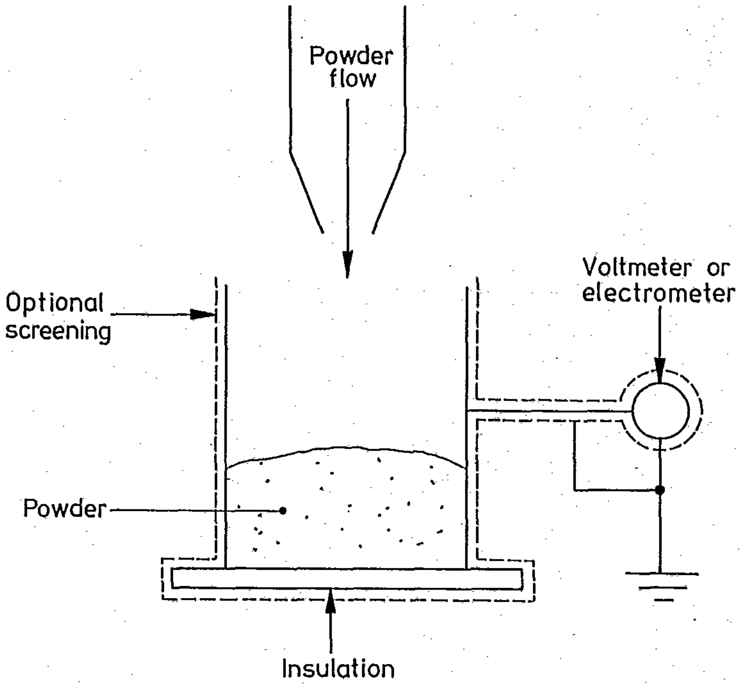


Figure 8. Arrangement of the equipment for the measurement of mass charge density of a powder

in its vicinity, the plate behaves essentially as an earthed conductor.

In the simplest form of meter, a d.c. system is used to measure the potential, and care is required to maintain a very high degree of insulation (greater than, say, 10^{12} Ω) of the probe from earth, and to prevent drift in the instrument zero due to the collection of charge on the probe. Frequently, the 'field mill' principle is used, in which a rotor alternately exposes and shields the probe, so that an a.c. signal is generated. This reduces the problems of insulation and zero drift. Instruments based on radioactivity are also available, but these are used more for qualitative than for quantitative tests.

A.5.3 *Procedure*

A.5.3.1 *General*

Quantitative interpretation of field measurements has to take account of the geometrical arrangement of the field meter, the charged object or objects and any nearby conductors. The reading of a calibrated meter gives the average field strength over the area of the probe, but care is needed in its interpretation. The field may have been badly distorted by the presence of the probe, or it may be part of a highly non-uniform field distribution. Examples of the use of field meters are given in **A.5.3.2** to **A.5.3.4**.

A.5.3.2 *Qualitative use*

Any field meter can be used qualitatively in the diagnosis of electrostatic problems, e.g. to locate a centre of high charge density, or to check on the efficiency of a static eliminator. It is useful to bear in mind two significant field strength levels:

3×10^3 kV/m:	the breakdown strength of air in large gaps, which sets an upper limit to the fields observable in air;
10 kV/m:	electrostatic forces generally have no appreciable effect unless the field exceeds this level.

A.5.3.3 *Measurement of surface charge density on high resistivity sheet materials*

In this application it is important to surround the probe with a guard ring to define the area under examination. Figure 9 shows the basic arrangement of equipment for measurements on an isolated sheet carrying a uniform distribution of charge.

The guard diameter should be at least ten times greater than that of the active area of the probe. The probe/guard assembly is held parallel to the surface of the sheet in a region well away from metal objects such as rollers and brackets. With this arrangement:

$$\sigma = \epsilon_0 K$$

where

σ is the surface charge density (in C/m^2);

K is the measured field strength (in V/m);

ϵ_0 is the permittivity of free space (8.85×10^{-12} F/m).

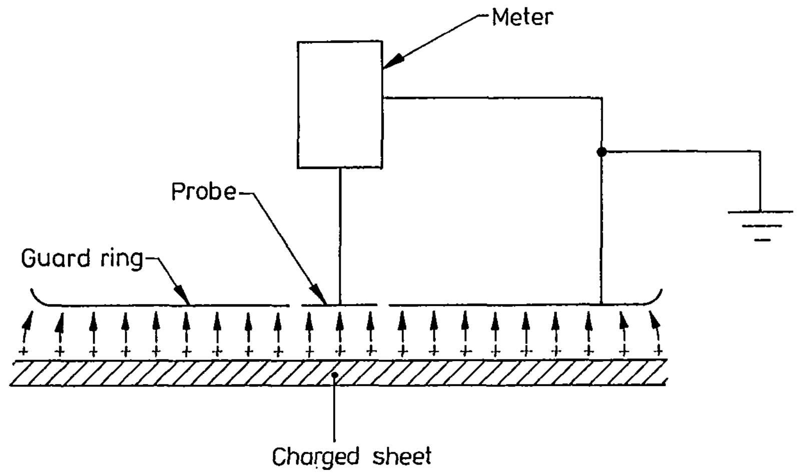


Figure 9. Arrangement of the equipment for the measurement of the surface charge density on a high resistivity non-conducting sheet

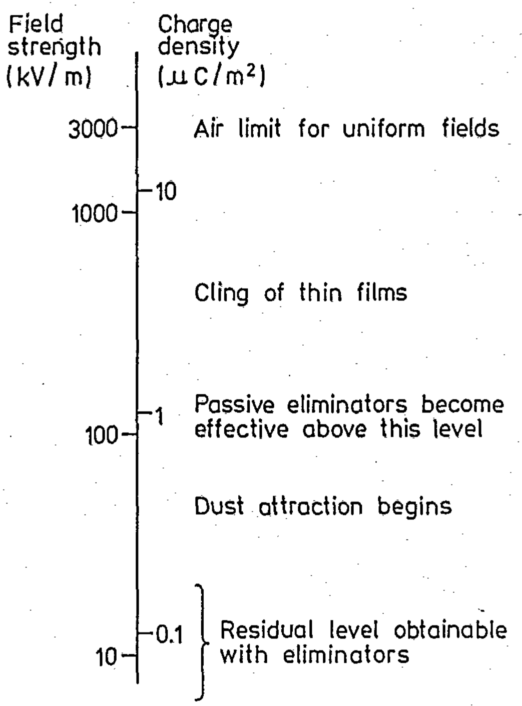


Figure 10. Guide to field strength/surface charge density relationship for high resistivity sheets

The result is virtually independent of the distance from the probe to the surface, but anomalous readings may be obtained with a non-uniform charge distribution, unless the probe/surface distance is small compared with the diameter of the active part of the probe.

Figure 10 is a chart of the relationship between σ and K with an indication of the phenomena to be expected at various levels. It applies only in the absence of conductors which would attract a proportion of the field due to the charge on the sheet.

The charge density obtained with the arrangement of figure 9 is the algebraic sum of the densities of all charges present, whether they are on the upper or lower surface of the sheet or trapped within it. If charge is present on both surfaces, but not within the volume of the sheet, that on the upper one can be measured with the arrangement in figure 11, where the lower surface is in contact with an earthed metal plate. The same method is applicable to a coating on metal with a charge on its outer surface.

In the arrangement of figure 11, the charge density on the upper surface is given by:

$$\sigma = \frac{a + b/\epsilon}{b/\epsilon}\epsilon_0 K$$

where

σ is the surface charge density (in C/m^2);

K is the measured field strength (in V/m);

ϵ_0 is the permittivity of free space (8.85×10^{-12} F/m);

a is the thickness of the sheet (in m);

b is the distance between the probe and the surface (in m);

ϵ is the relative permittivity of the material of the sheet.

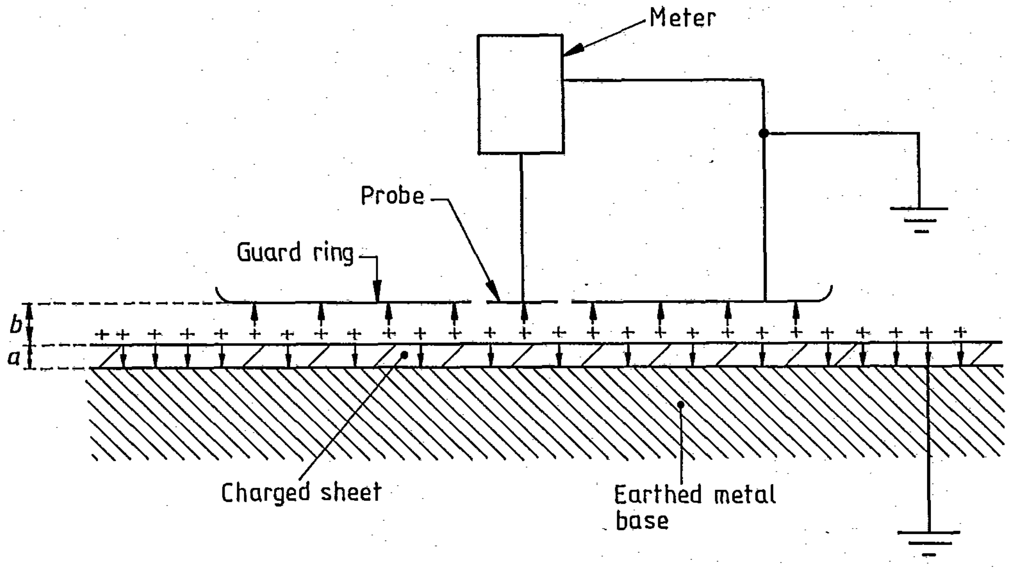


Figure 11. Arrangement of the equipment for the measurement of the surface charge density on a sheet with charges on both sides

A.5.3.4 *Measurement of potentials*

If the field pattern associated with a system of charges is known, an observation of the field strength at one place can be used, in principle, to derive surface and space potentials in the system. In some cases, the field pattern can be obtained by mathematical modelling, or a correlation between field and potential values may be established experimentally. The procedures are complicated and each situation requires individual treatment. Two important cases are mentioned briefly in (a) and (b) below:

(a) *Liquid surface potential.* A measurement of the vertical field strength is made by means of a field meter suspended at a known distance above the surface of the charged liquid. To a first approximation, it can be assumed that the field between the surface and the probe is uniform. The potential of the surface is then given by:

$$V = Kx$$

where

V is the surface potential (in V);

K is the measured field strength (in V/m);

x is the distance between the probe and the surface (in m).

When quoting a potential derived in this way, an estimate should also be given of the uniformity of the field.

It should be remembered that the introduction of the field meter may trigger sparking, and appropriate precautions should be taken if there is any possibility of a flammable mixture.

(b) *Space charge potential.* For a large vessel containing a uniform distribution of charge throughout its volume, experimental and theoretical studies have shown that a field meter introduced into the volume on the end of an earthed metal tube gives a reading which is proportional to the potential which would exist at the probe position if the field meter and tube were absent altogether (J.M. van de Weerd, 1971)[1]. For a tube of diameter about 100 mm, the potential is given by:

$$V = kK$$

where

V is the potential (in V);

K is the measured field strength (in V/m);

k is a constant with a value 0.12 m.

Potentials at other points may then be computed assuming a uniform charge distribution. An alternative approach is to set the field meter probe in the wall of the vessel.

Precautions should be taken where flammable mixtures may be involved.

A.6 Minimum ignition energy

A.6.1 *General*

The purpose of the test is to obtain information on minimum ignition energy which can be used to assess the ignition risk due to static electricity discharges. Test techniques are available for both flammable gases and dusts. The minimum ignition energies of gases are comparatively low and in the following ranges:

gas/oxygen mixtures: 0.002 mJ to 0.1 mJ;

gas/air mixtures : 0.01 mJ to 1.0 mJ.

Since these levels are below the energies frequently available in electrostatic discharges, it is normal to assume that flammable gases present an electrostatic hazard, and there is then no need to measure their minimum ignition energies. If, in a particular application, an accurately measured value is needed, suitable techniques are described by Lewis and von Elbe.

In contrast to gases, the minimum ignition energies of powders can be very large, covering a range from less than 2 mJ up to 5000 mJ or more, and measured values are required for hazard assessments. The procedure described is, therefore, that applicable to powders.

NOTE. This test is intended for use with the normal range of flammable powders and should not be used for highly reactive materials or detonating deflagrating explosives.

A.6.2 *Summary of method*

The type of discharge in the majority of electrostatic ignitions is a spark from an insulated conductor. In the test method, sparks are produced by the discharge of a capacitor and, since virtually all the stored energy on the capacitor appears in the spark, the energy (in joules) released is given by

$$\tfrac{1}{2}CV^2$$

where

C is the capacitance in the circuit (in F);

V is the potential at the moment of discharge (in V).

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[1] *Static electrification*, J M Van de Weerd. Inst. of Physics Conference. Ser. No. 11, p.158, 1971.

[2] 1 bar = 10^5 N/m^2 = 10^5 Pa.

Sparks of various energies are produced in suspensions of the dust under test, and the occurrence of ignitions is recorded; a range of dust concentrations is explored to cover the most readily ignitable mixture in air.

Consistent results may not be achieved until experience of the method has been gained, owing to the difficulty of making adequate dust dispersions. As a check that reasonable results are being obtained, tests should be made using anthroquinone powder passing a 200 mesh sieve; its minimum ignition energy should be less that 10 mJ. Minimum ignition energy of powders is normally measured by experts at specialist laboratories.

A.6.3 *Apparatus*

A diagram of the apparatus is shown in figure 12. Powder in the dispersion cup is dispersed by a blast of air injected through the pipe at the base and directed downwards by the conical deflector over the end of the pipe. The air is released by a solenoid valve from an air reservoir having a volume of about 50 mL, where it is held at a pressure between 3 bar[1] and 4 bar. Sparks pass between the hemispherical metal electrodes; the electrodes separation can be varied but should be not less than 6 mm.

The sparks are produced by the electrical circuit shown in figure 13. The high d.c. voltage should be applied in such a manner as to slowly raise the potential of the capacitor until a spark occurs, and the cycle is then repeated, giving a regular series of sparks. A current-limiting resistor with a valve between 10^8 Ω and 10^9 Ω is included in the circuit. The potential across the capacitor is measured by an electrostatic voltmeter with a decoupling resistor in series having a value between 10^8 Ω and 10^9 Ω.

A.6.4 *Procedure*

Procedures given below are to be followed.

(a) *Preparation of the sample.* The sensitivity of the powder to ignition depends not only on its chemical composition but also on its physical form and water content.

The sample for test should have a particle size distribution representative of the finest cloud that can be formed with a flammable concentration. With few exceptions, the sample should be sieved so that all particles have a size less than 75 μm (passing a 200 mesh sieve). The water content of the powder should be the minimum encountered during the normal processing and use of the powder.

(b) *Measurements.* The general procedure is to make tests with sparks at standard energy levels; those recommended are 500 mJ, 100 mJ, 25 mJ, 10 mJ and 1 mJ. If a more precise measure of the minimum ignition energy is needed, tests can be made at intermediate energy levels.

The settings for sparks of the required energy are determined before any powder is placed in the ignition chamber. After choosing a capacitor of appropriate value, select a voltage in the range 10 kV to 30 kV and then adjust voltage and electrode separation by trial until sparks of the required energy, given by $\frac{1}{2} CV^2$, occur at the maximum possible electrode spacing (not less than 2 mm). In this expression, V is the voltage at which the spark occurs and C is the total capacitance at the high voltage electrode, which can be measured by normal a.c. bridge methods.

To make an ignition test, earth the high voltage electrode and load a quantity of prepared powder of the order of 0.5 g to 1.0 g into the dispersion cup. Then switch the d.c. voltage supply into the circuit and as sparks start to pass between the electrodes disperse the powder by operating the solenoid valve. Note whether ignition occurs and flame propagates away from the spark gap.

The first tests should be at a spark energy of 500 mJ. If there is an ignition reduce the ignition energy to 100 mJ, and continue in this way down the energy range until ignition does not occur.

If, at any energy level, there is no ignition, the test should be repeated 10 times. If there has still been no ignition, further tests should be made varying the quantity of powder, before concluding that ignition does not occur at the spark energy in question.

The precautions normal for the use of high voltage equipment should be taken throughout the test procedure, and the operator should be protected from the dust ignition.

NOTE. Other methods which give comparable results can be used.

(c) *Quotation of results.* The minimum ignition energy (in millijoules) should be quoted in the following manner:

$$E_1 < \mathrm{E_{min}} < E_2$$

where

E_1 is the energy of the spark which failed to ignite the dust cloud (in mJ);

E_2 is the spark energy at which the dust cloud just ignited (in mJ).

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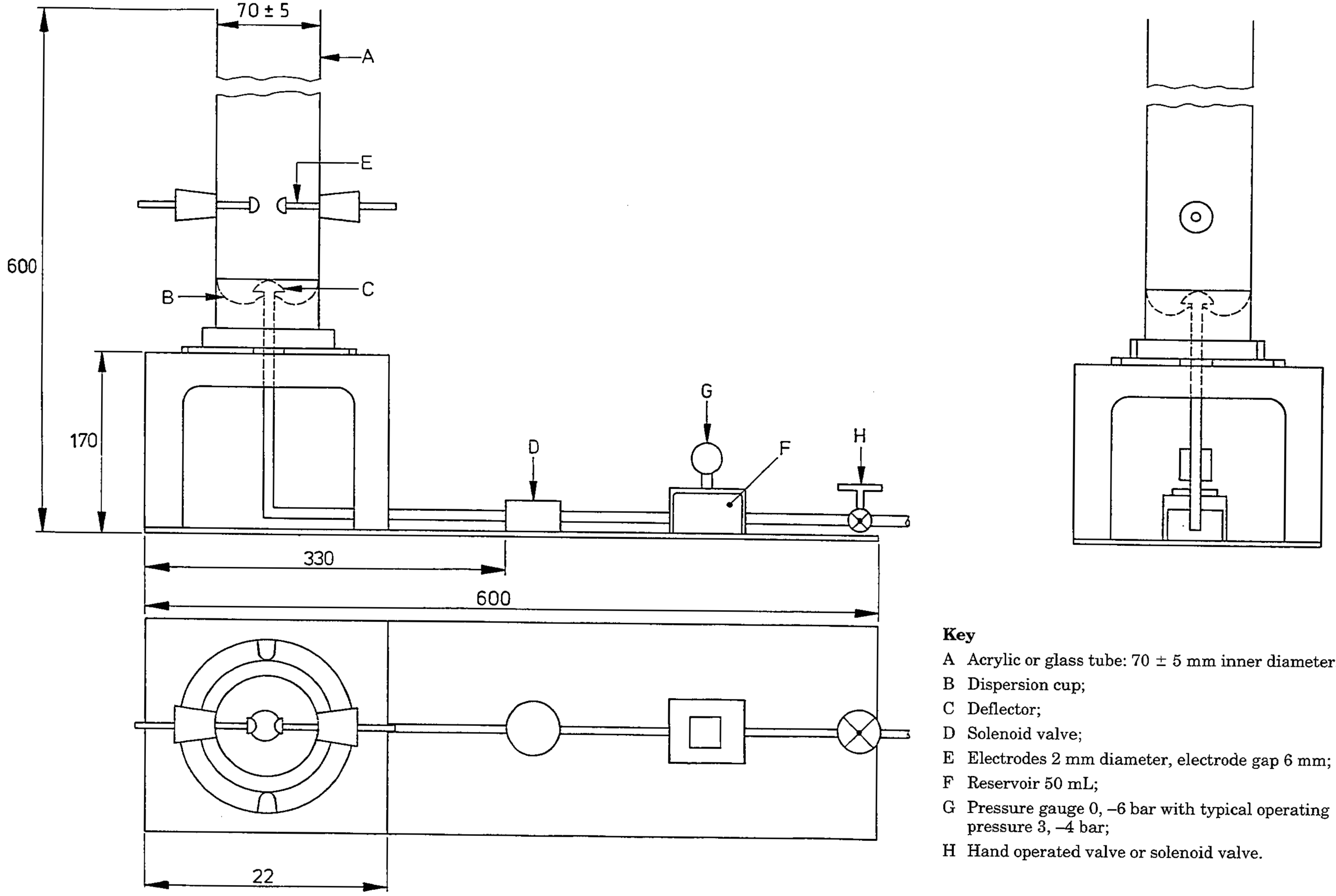
[1] 1 bar = 10^5 N/m^2 = 10^5 Pa.



Key

- A Acrylic or glass tube: 70 ± 5 mm inner diameter;
- B Dispersion cup;
- C Deflector;
- D Solenoid valve;
- E Electrodes 2 mm diameter, electrode gap 6 mm;
- F Reservoir 50 mL;
- G Pressure gauge 0, –6 bar with typical operating pressure 3, –4 bar;
- H Hand operated valve or solenoid valve.

All dimensions are in millimetres.

Figure 12. Main features of the apparatus for the determination of the minimum ignition energies of dusts

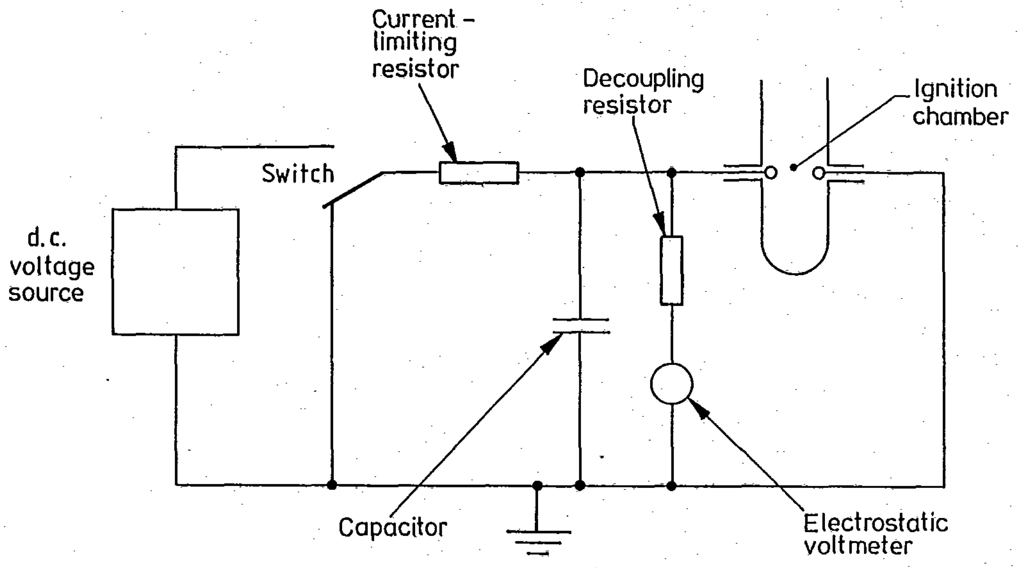


Figure 13. Arrangement of the equipment for the production of sparks of known energy

A.6.5 *Interpretation of results*

A chart is given in figure 14 to provide guidance on the precautions which would be appropriate with powder suspensions in air. It should be supplemented by reference to the appropriate clauses of this Part of BS 5958.

A.7 Resistance to earth from metallic and non-metallic objects

A.7.1 *General*

In many installations, particularly those containing non-conductors, there is a need to check that the various parts of the system are adequately earthed. For this purpose, instrumentation is required to measure resistances in the range $10^5\ \Omega$ up to say $10^9\ \Omega$, between earth and metal components which may be partially insulated from earth, and between earth and any part of the surface of an object made of non-conducting material.

A.7.2 *Summary of method*

A direct voltage is applied between earth and the object under test and the ensuing current to earth is measured. Some non-conductors do not obey Ohm's law, so that the measured resistance to earth depends on the applied voltage. A value of about 500 V is taken as standard in this method, although a lower voltage may be used in some circumstances (see **A.7.3**).

A.7.3 *Apparatus*

For resistances up to $10^8\ \Omega$, measurements should preferably be made using a proprietary insulation tester or megohmmeter having a nominal open circuit voltage of 500 V d.c.

Minimum ignition energy of the powder (mJ)	
500	Low sensitivity to ignition: Earth plant when ignition energy is at or below this level.
100	Consider earthing personnel when ignition energy is at or below this level.
25	The majority of ignition incidents occur when ignition energy is below this level. The hazard from electrostatic discharges from dust clouds should be considered.
10	High sensitivity to ignition. Take the above precautions and consider restrictions on the use of high resistivity materials (plastics). Electrostatic hazard from bulk powders of high resistivity should be considered.
1	Extremely sensitive to ignition. Precautions should be as for flammable liquids and gases when ignition energy is at or below this level.

NOTE. The above guidelines may not ensure safety in particular situations, e.g. in the case of powders in large non-conducting containers (see **9.2.3**) or handling and storage of granules or flakes.

Figure 14. Guide to electrostatic precautions for powders

Alternatively, and for higher resistances, a circuit such as that shown in figure 15 may be used. The voltage source is a battery or a rectified power source, and a current limiting resistor, r, is included. Its value should be such that when the maximum permissible resistance to earth, R is being measured, the potential applied to the object under test is not less than 400 V, i.e. r should be about $R/4$.

The voltmeter should have a range of 0 V to 500 V, and the range of the ammeter depends on the resistance being measured, e.g. 0 A to 10^{-6} A for 10^9 Ω. With suitable switching, a single multifunctional meter may be used. Measurements using the above instrumentation may produce incendive sparks and tests should not, therefore, be made in flammable atmospheres. If tests are required under these conditions, specialized equipment and techniques should be used (see BS 5345). The use of low voltage equipment is acceptable if a maximum limit on resistance only is being sought; because of possible deviations from Ohm's law it may give an abnormally high result and hence cause a satisfactory piece of equipment to fail the test.

The earth connection should be a buried electrode, a water pipe or part of the metallic structure of a building.

It is important to ensure that the lead to the object under test be adequately insulated from the operator and from any earthed object other than that being tested. This can be confirmed from the meter readings before contact is made with the surface.

A.7.4 *Procedure*

The procedures given below are to be followed.

(a) *Electrical contact with the object.* If the object is metallic, a simple metal/metal contact presents no difficulty.

If the object is made of non-conducting material, e.g. a polymer treated to have some degree of conductivity, precautions may be required to ensure satisfactory electrical contact. The contact should then be made by means of an electrode consisting of a metal disc of 50 mm diameter conforming in shape to the surface being tested. The surface beneath the electrode should be coated with a conductive medium; suitable media are a conductive silver lacquer, aqueous colloidal graphite, which may be allowed to dry, or a conductive liquid such as those given in table 5.

In the absence of a conductive medium a high result can be expected, but provided that this falls below the permissible maximum resistance, and no minimum is specified, direct contact between the surface and the electrode is acceptable.

In some tanks constructed of polymeric materials a partially conductive inner layer is protected from contact with the liquid contents by a thin non-conductive gel coat. To measure the resistance to earth of the conductive layer, a sharp-pointed electrode may be used to penetrate the gel coat and make contact with the underlying layer.

(b) *Measurements.* The measurement is made by contacting the object under test with a suitable lead or electrode and observing the current on the ammeter. Before the test is carried out the object should be allowed to reach equilibrium with it surroundings and both the temperature and the relative humidity should be recorded at the time of the measurement.

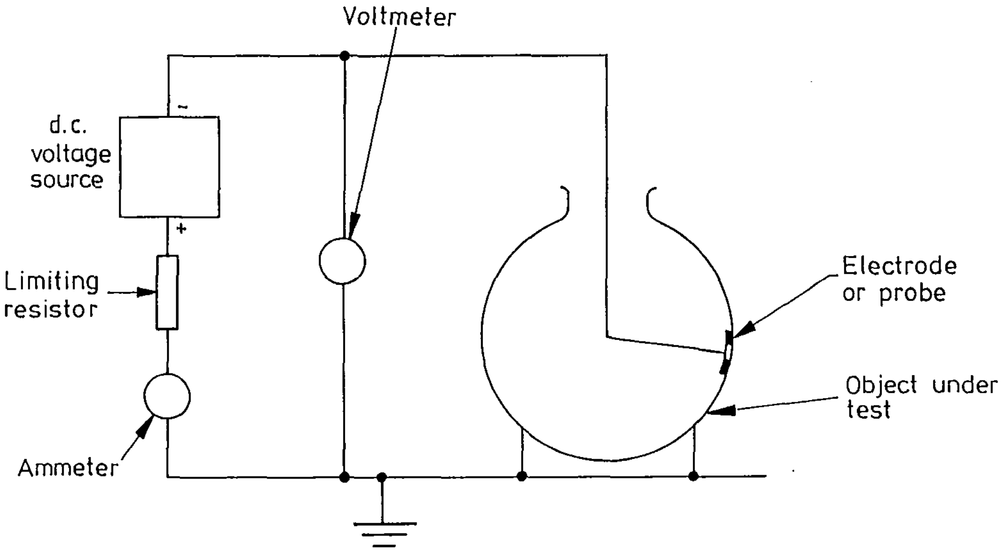


Figure 15. Arrangement of equipment for the measurement of resistance to earth

Table 5. Suitable conductive liquids to ensure that objects made of non-conducting materials have satisfactory electrical contact

Conductive liquid	Parts by mass
Anhydrous polyethylene glycol, molar mass 600	800
Water	200
Wetting agent (detergent)	1
Potassium chloride	10

A.7.5 *Calculation of result*

The resistance to earth is given by the following equation:

$$R = \frac{V}{I}$$

where

R is the resistance (in Ω);

V is the applied potential (in V);

I is the measured current (in A).

A.8 Personnel resistance monitor

A.8.1 *General*

The manufacture of a shoe sole material to have the desired degree of conductivity after moulding is difficult to control, especially after the addition of inner soles and liners. The conductivity of the finished product can, subsequently, be affected in use by exposure to certain chemicals or physical conditions. There is therefore a need to measure, under normal conditons of use, the total resistance between a person and earth through his footwear, to check that it is appropriate to the circumstances.

A.8.2 *Summary of method*

A small constant current is arranged to flow through the person from his hand through his footwear to an earthed metal plate on which he stands. A voltmeter display a reading proportional to the potential drop across the person and is calibrated to give the required resistance directly.

A.8.3 *Apparatus*

In order to make the measurement, current is passed through the person from a conducting handle which he grasps to an earth plate on which he stands. This imposes limits on the voltage and current that can be used, or which could arise under fault conditions.

A monitoring instrument can be designed either to give a meter indication of the resistance or conductance, a 'go/no go' signal at a specified limit value, or both. A high level of insulation is required, particularly at the operating handle, to avoid faulty low readings by partial short circuiting. The operating handle and its associated switches should be of robust construction.

Equipment of this type is available commercially. The basic circuit of a highly stabilized monitor suitable for a permanent installation is shown in figure 16. The meter gives a linear indication from zero to 2 × 10^8 Ω with an accuracy of ± 2 % of full scale deflection (FSD). Amplifiers A2 and A3 form a current generator producing, through R2, R3 and R4, a current which is constant and proportional to V_{ref}/R2. Adjustment of this current is provided by the 'Span' preset. The balance preset trims the circuit and ensures that changes in input resistance do not affect the constant current. Additional optional circuitry is included to provide 'Red' (dangerous) and 'Grn.' (safe) indicator lamps; the operating point for these lamps can be set to any value in the range.

To make a measurement, the person is put in place of R4 through operation of the relay RL A1 and his resistance to earth is displayed directly on the meter.

Since the equipment is mains operated, it should be sited outside hazardous areas.

A.8.4 *Procedure*

The person under test stands on the earth plate, grasps the operating handle and depresses it to close the test circuits. His resistance is shown on the meter, and if it exceeds the preset limit, the 'Red' (dangerous) lamp is illuminated and a buzzer sounds.

A.8.5 *Interpretation of result*

BS 7193 specifies two classes of soling material which will dissipate static electricity:

(a) antistatic footwear has a resistance between 5 × 10^4 Ω and 5 × 10^7 Ω;

(b) conducting footwear has a resistance less than 1.5 × 10^5 Ω.

Testing of these properties is to be by methods described in BS 2050. The voltage specified for use in these tests is not less than 200 V, which is much higher than can be permitted in a personnel tester. Some rubbers give results dependent on the test voltage, so the precise resistance levels given in BS 7193 are not directly applicable to a low voltage test.

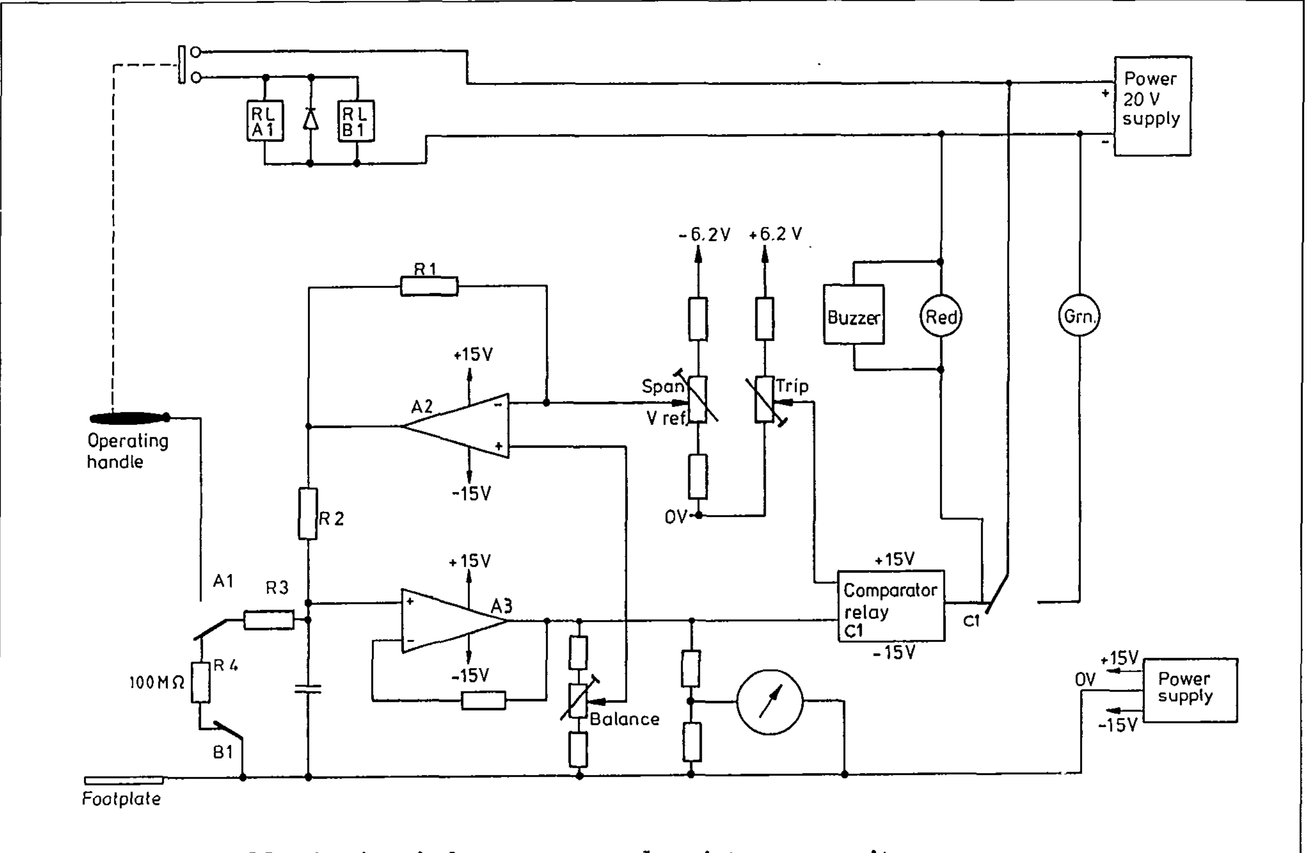


Figure 16. Typical basic circuit for a personnel resistance monitor

Under practical conditions, realistic values for personnel resistance determined by means of a monitor are as follows:

(1) antistatic: $1 \times 10^5\ \Omega$ to $1 \times 10^8\ \Omega$;

(2) conducting: less than $1 \times 10^5\ \Omega$.

A.9 Electrical resistivity of textiles

The following British Standards give details of test procedures for the determination of electrical resistivities for specific textile products.

BS 6524	Method for determination of the surface resistivity of a textile fabric
BS 6654	Method for determination of the electrical resistivity of textile floor coverings

A.10 Surface and volume resistivities of rubber, plastics and other insulating materials

The following British Standards give details of test procedures for the determination of surface and volume resistivities for rubber, plastics and other electrical insulating materials.

BS 903	Physical testing of rubber
	[1]Part C1 Determination of surface resistivity
	[2]Part C2 Determination of volume resistivity
BS 2782	Methods of testing plastics
	Part 2 Electrical properties
	[2]Method 230A Determination of volume resistivity
	[1]Method 231A Determination of surface resistivity
BS 2044	Methods for determination of resistivity of conductive and antistatic plastics and rubbers (laboratory methods)
BS 6233	Methods of test for volume resistivity and surface resistivity of solid electrical insulating materials

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[1] BS 903 : Part C1 and BS 2782 : Method 231A are issued as a single publication.

[2] BS 903 : Part C2 and BS 2782 : Method 230A are issued as a single publication.

Publication(s) referred to

BS 903	Physical testing of rubber [1]Part C1 Determination of surface resistivity [2]Part C2 Determination of volume resistivity
BS 2044	Methods for determination of resistivity of conductive and antistatic plastics and rubbers (laboratory methods)
BS 2050	Specification for electrical resistance of conducting and antistatic products made from flexible polymeric material
BS 2782	Methods of testing plastics Part 2 Electrical properties [2]Method 230A Determination of volume resistivity [1]Method 231A Determination of surface resistivity
BS 3187	Specification for electrically conducting rubber flooring
BS 5345	Code of practice for the selection, installation and maintenance of electrical apparatus for use in potentially explosive atmospheres (other than mining applications or explosives processing and manufacture) Part 1 General recommendations Part 4 Installation and maintenance requirements for electrical apparatus with type of protection 'i'. Intrinsically safe electrical apparatus and systems
BS 5351	Specification for steel ball valves for the petroleum, petrochemical and allied industries
BS 5501	Electrical apparatus for potentially explosive atmospheres Part 1 General requirements
BS 5783	[3]Code of practice for handling of electrostatic sensitive devices
BS 5958	Code of practice for control of undesirable static electricity Part 2 Recommendations for particular industrial situations
BS 6233	Methods of test for volume resistivity and surface resistivity of solid electrical insulating materials
BS 6524	Method for determination of the surface resistivity of a textile fabric
BS 6651	Code of practice for protection of structures against lightning
BS 6654	Method for determination of the electrical resistivity of textile floor coverings
BS 7193	Specification for lined lightweight rubber overshoes and overboots
BS 7430	Code of practice on earthing

J M Van de Weerd, *Static electrification*. Inst. of Physics Conference. Ser. No. 11. p.158, 1971.

Lewis and von Elbe, *Combustion flames and explosions of gases*. Academic Press Inc., 1961.

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[1] BS 903 : Part C1 and BS 2782 : Method 231A are issued as a single publication.

[2] BS 903 : Part C2 and BS 2782 : Method 230A are issued as a single publication.

[3] Referred to in the foreword only.

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