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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

Static electricity occurs commonly in industry and in daily life, and can be a source of danger as well as of 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, for example 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 code of practice 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 code 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.

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

The code is in two Parts. Part 1 deals with general considerations as detailed in clause 1.

Part 2* will provide simple recommendations for controlling static electricity in a variety of specific operations, the justification for which should be sought in Part 1. Static phenomena are encountered so widely that it is not possible to cover all cases and, if adequate guidance is not found in Part 2, Part 1 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.

* In course of preparation.

British Standard Code of practice for

Control of undesirable static electricity

Part 1. General considerations

Section one. 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 four deals with the principles of earthing and bonding as applied to avoid static electricity hazards. An appendix 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.

2. References

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

3. Definitions

For the purposes of this code, the following definitions apply.

3.1 antistatic; conductive. (*As an adjective.*) Used 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 above. However, in contexts where they have specific meanings, for example in relation to footwear, the above definition is qualified in the appropriate clauses of this code.

3.2 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.

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

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

3.5 conductivity. The reciprocal of resistivity.

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

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

3.8 flammable. Capable of being ignited.

3.9 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.

3.10 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.

3.11 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.

3.12 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).

Zone 0 In which an explosive gas-air mixture is continuously present, or present for long periods.

Zone 1 In which an explosive gas-air mixture is likely to occur in normal operation.

Zone 2 In which an explosive gas-air mixture is not likely to occur in normal operation, and if it occurs it will exist only for a short time.

3.13 incandive. Capable of igniting a prescribed flammable mixture.

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

3.15 ion. An atomic or molecular particle carrying electrical charge.

3.16 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.

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

3.18 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.

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

3.20 relaxation. The dissipation of an electrostatic charge by conduction.

3.21 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.

3.22 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).

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

3.24 surface resistivity. *Of a substance.* The resistance between the opposite edges of a square.

3.25 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.

3.26 volume resistivity. *Of a substance.* The resistance at unit length and unit cross-sectional area.

Section two. Fundamentals of static electricity

4. Electrostatic charging

4.0 Introduction. 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.

4.1 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.

4.2 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.

4.3 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.

5. 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 14.2 that to retain a significant electrostatic charge a resistance to earth in excess of $10^6 \Omega$ 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 three.

In many industrial processes there is a continuous generation of static electricity which accumulates on an

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insulated conductor, for example 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 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,

$$V_{\max} = IR$$

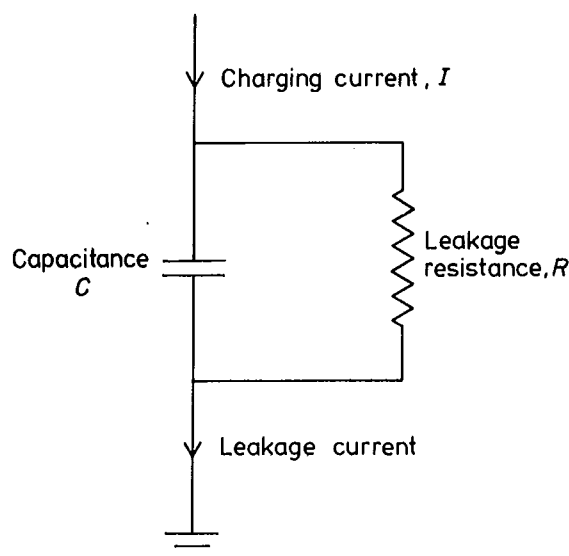


Figure 1. Equivalent electrical circuit for an electrostatically charged conductor

6. Electrostatic discharges

6.0 Introduction. 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 incidence. In this code they are classified as described in the following paragraphs, although the differentiation between the various types is not completely definite.

6.1 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

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

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.

Table 1. Typical electrical capacitances

Object	Capacitance
	pF*
Small metal items (scoop, hose nozzle)	10 to 20
Small containers (bucket, 50 litre drum)	10 to 100
Medium containers (250 litres to 500 litres)	50 to 300
Major plant items (reaction vessels) immediately surrounded by earthed structure	100 to 1000
Human body	100 to 300

*1 pF = 1×10^{-12} F.

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 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 50 pF. The maximum voltage on the drum is then

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

and the maximum energy released in a spark discharge would be

$$E_{\max} = \frac{1}{2} CV_{\max}^2 = 250 \text{ mJ}$$

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

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

6.2 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, for example if there is an increase in the potential of the pointed conductor, corona can develop into a spark to another object.

6.3 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; effectively, each discharge is a small spark limited by the quantity of charge that can flow to it over the surface. 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 incandescence; empirical tests suggest, however, that the energy release is unlikely to exceed about 4 mJ.

6.4 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.

6.5 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 so far 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.

7. Incendivity of electrical discharges

NOTE. The data given in this clause are, strictly speaking, only appropriate to normal atmospheric temperatures. If higher temperatures are involved, specialist advice should be sought.

7.1 Flammability and explosivity

7.1.1 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 detailed information).

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.

7.1.2 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.

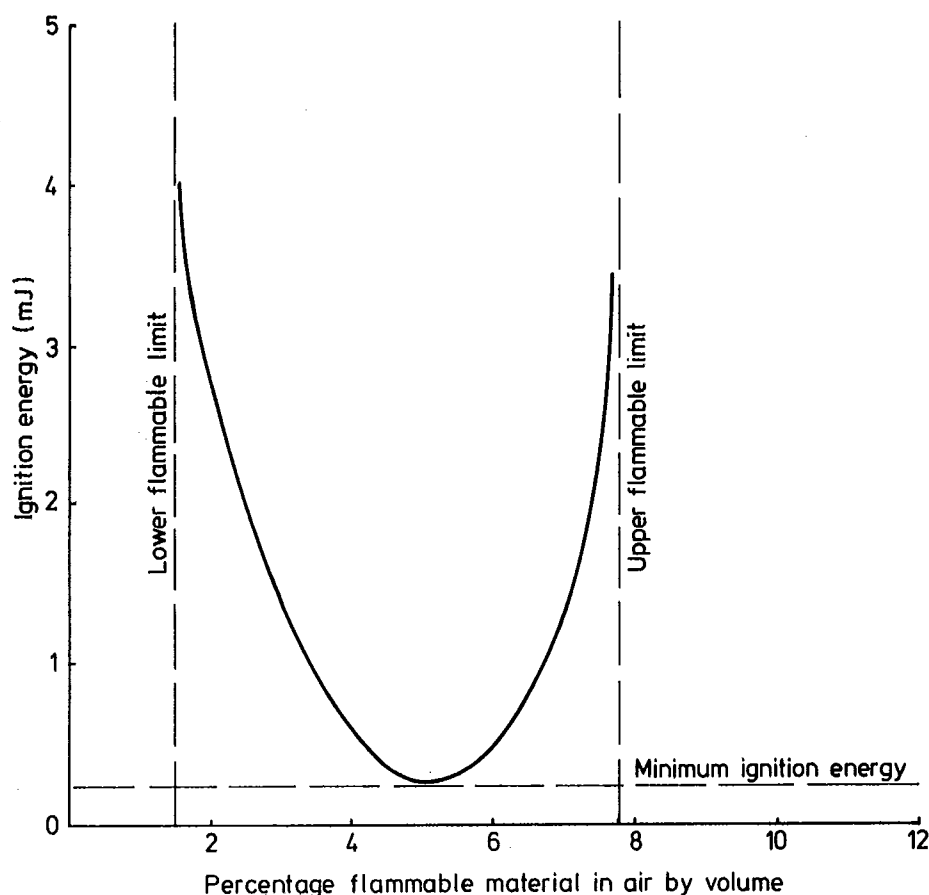
7.2 Ignition energy. Whether or not an electrostatic discharge will ignite a flammable mixture depends upon the composition and temperature of the mixture, the energy of the discharge and the distribution of this energy in space and time. In practical situations the most frequent source of ignition is 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*. 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.

*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

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.

7.3 Assessment of the incendivity of discharges. Sparks from insulated conductors constitute the most important electrostatic ignition risk. As discussed in 6.1, 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.

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 over-estimate 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 the brush discharges from non-conductors. Usually the rate of release of energy is comparatively low because the high surface resistivity impedes the flow of charge but, due to the presence of high energy density cores, 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.

8. 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; for example 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 11.2.3). Irrespective of whether the shock itself is harmful, the involuntary muscular reaction to a discharge may cause an accident through, for example, the dropping of a tool or by precipitating a fall.

Section three. Electrostatic hazards and their control

9. Electrostatics in liquids

9.1 Charge generating mechanisms

9.1.1 Flow of single phase liquids through pipes. When a liquid flows through a pipe, charge separation occurs (see 4.1) 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 code will deal 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 $10^{12} \Omega \text{ m}$, 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 the maximum charge generation. One such relationship leads to the following approximate expression for the charge density on the liquid leaving an infinitely long pipeline:

$$\eta \approx 5 \nu$$

where η is the charge density (in $\mu\text{C}/\text{m}^3$) and ν 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 $5 \mu\text{C}/\text{m}^3$ and $50 \mu\text{C}/\text{m}^3$ respectively.

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

$$L > 3\nu\tau$$

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

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
($8.85 \times 10^{-12} \text{ F/m}$)

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

Very few data are available for charge generation during liquid flow in pipes made of materials having volume resistivities greater than $10^{12} \Omega \text{ m}$. 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.

9.1.2 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.

9.1.3 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 micron 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 $10 \mu\text{C}/\text{m}^3$ to $5000 \mu\text{C}/\text{m}^3$. 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.

9.1.4 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.

9.1.5 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 9.1.1 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.

9.1.6 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.

9.1.7 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.

9.2 Discharges involving liquids

9.2.1 General. For some processes it is possible to calculate both charge generation and charge retention (see 6.1) 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.

9.2.2 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 , the expression for which was given in 9.1.1. 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 in this category and so also are all black petroleum oils (containing residual material) and crude oils. Clean or white oils, such as kerosene or gasoline, 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 few quantitative data are available on this subject.

9.2.3 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 low conductivity 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);
- (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 6, the discharges from conductors are usually sparks and are potentially hazardous. The energy can be calculated using the procedure given in 6.1. In some cases, for example 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 11.

9.2.4 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.

9.3 Precautions against static electricity from low conductivity liquids

9.3.1 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 7.1.1). 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 four. The other methods are dealt with in 9.3.2 and 9.3.3. 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.

9.3.2 Control of charge generation

9.3.2.1 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 will be given in Part 2 of this code which is in course of preparation.

9.3.2.2 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.

9.3.2.3 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.

9.3.2.4 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 9.3.2.1) the flow velocity should be kept at about 1 m/s whilst the second phase is present. Efforts should be made to eliminate it, for example by reducing the water bottoms in tanks as much as possible and by draining down thoroughly any water-flushed pipelines.

9.3.3 Charge dissipation

9.3.3.1 Relaxation. When a liquid is highly charged, for example 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, 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.

9.3.3.2 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.

9.3.3.3 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.

9.3.4 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. Dipping, ullaging or sampling should therefore 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 9.3.3.1). 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 greatest care should be taken to ensure the absence of such potential insulated conductors.

10. Electrostatics in powders

10.1 General. In this code the term powder means particulate solid matter with particle sizes ranging from those in fine dust to granules or chips. The behaviour of powders has to be considered both when the particles are in suspension as a cloud and when they have settled as a bulked powder.

10.2 Charge generation. 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 a dissimilar surface, for example 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, allowing charge to leak away. This field depends on the particle size and shape and on the surface charge density. For well dispersed particles the maximum surface charge density that can remain on a particle is about $10 \mu\text{C}/\text{m}^2$. 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:

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

where

q is the mass charge density (in $\mu\text{C}/\text{kg}$)

σ is the surface charge density (in $\mu\text{C}/\text{m}^2$)

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 and σ approaches $10 \mu\text{C}/\text{m}^2$. It is also evident from this relationship that a larger amount of charge can be carried when the particle size is small.

For the purposes of this code 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 $10^6 \Omega \text{ m}$;

(b) medium resistivity powders, e.g. many organic powders, such as flour, having volume resistivities in the approximate range $10^6 \Omega \text{ m}$ to $10^{12} \Omega \text{ m}$,

(c) high resistivity powders, e.g. many synthetic polymers and some minerals, such as quartz, having volume resistivities above about $10^{12} \Omega \text{ m}$.

In practice, low resistivity powders are rarely encountered. Even metal powders do not remain conductive for very long because oxide films on the particles increase their