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OF THE NATIONAL INSTITUTE
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Recommendations for Requirements for Avoiding Electrostatic Hazards in Industry 2007

JNIOSH

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Technical Recommendations of
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Preface

The basics of preventing electrostatic hazards include the following:

(1) grounding and bonding;

(2) removing nonconductors; making nonconductors antistatic (dissipative);

(3) making workers antistatic and grounding them (making their clothes antistatic and their bodies grounded.);

(4) control charge generation (slow processing);

(5) preventing flammable/explosive atmospheres;

(6) safety management system;

These specific antistatic measures are not necessarily difficult. Nevertheless, disasters caused by electrostatic hazards still occur. Such disasters seem to occur as a result of a lack of understanding that static electricity is hazardous or from insufficient countermeasures or poor safety management, although the risk of static electricity is well understood and antistatic measures are taken.

Our objective, as reported here, is to prevent electrostatic disasters. It is important that all employees understand the risk posed by static electricity and basic electrostatic safety, and thereby help to build a safe, reliable working environment. In brief, our objective is to raise the level of safety with regard to static electricity in Japan. To this end, the following items are presented:

(1) basic understanding of static electricity (the basics for performing risk assessment of static electricity);

(2) identification and evaluation of the risk of static electricity;

(3) measures against the risk of static electricity;

(4) maintenance of measures and management for safety.

A sufficient understanding of the basics is paramount to conducting electrostatic measures, and measures must be based on the basics. Such knowledge will equip employees with a thorough understanding of such measures and prevent workers from engaging in incorrect behaviour that could cause accidents. Moreover, such basic knowledge is indispensable to electrostatic risk assessment. Raising the understanding level of electrostatic safety will eventually help prevent accidents, which is an objective of this document.

When previous versions of these recommendations were published in 1978 and 1988, the hazard control and safety management were based on compliance with guidelines and standards. However, whatever measures may be taken, static electricity remains a threat as long as there is matter. Therefore, as long as flammable substances are used, "absolute safety (zero-risk)" is an impossibility. In such a situation, risk assessment is essential. The risk assessment requires that hazards be identified and evaluated in advance to determine whether or not the risks were tolerable and, if they were not, which protective measures would be taken to reduce the risks until they were at a tolerable level. This is a risk-reducing control system for safety as a safety technology established in Europe as shown in some EC directives, so-called the Seveso directives I and II, with some serious disasters as a turning point. In Japan, the revised Industrial Safety and Health Law, put into effect in April 2006, included a provision in Article 28-2 stipulating that efforts be made to perform risk assessment. This document also adopts the risk assessment; therefore, antistatic measures (risk-reducing measures) shown in this document are specified on the precondition that risk assessment be performed. In this point, this document is different from the previous versions. This document specifies risk evaluation for static electricity and universal risk-reducing measures, which may be useful in identifying hazards in various processes. We hope that employees and managers of companies subject to the hazards of electrostatic build-up will find the information provided by this document to be useful for risk reduction and incorporate it into their safety manuals.

The scope and purpose of this document are stated in Chapter 1. The terms and definitions used in this document are presented in Chapter 2. Chapter 3 elaborates the basics of electrostatic safety in order to describe how static electricity develops, resulting in electrostatic discharge and the ignition of flammable matter, and to understand the risks and significance (physics) of the measures. Chapter 4 outlines the risks of static electricity and a brief summary of general antistatic measures. Chapters 5 to 7 contain the fundamentals of antistatic measures, such as grounding and bonding conductors and making workers and nonconductors antistatic. Chapters 8 to 11 deal with liquids, powders, solids, and gases, respectively, and prescribe antistatic measures for various processes. The appendices present measures to prevent the formation of explosive atmospheres when antistatic measures are unfeasible; Control indicators required for risk assessment; Basic methods of measuring static electricity; and various numerical data required for risk analysis. Moreover, this document contains solutions to a broad variety in hazards associated with static electricity in chemical processes. As a help for risk assessment, the scientific grounds for such measures and methods with references are contained.

Antistatic measures also entail some complications. There may be specific processes to which the recommendations in this document are inapplicable or cases in which antistatic measures are unfeasible. In such cases, expert advice would be needed to avoid providing erroneous solutions.

This document offers supplementary references in the form of separate booklets: TR–84–1: *Recommended Standards of Construction of Appliances used for Protection against Electrostatic Hazards*, and TR–85–3: *A supplement-Applications for Safety Measures to Selected Processes and Facilities.*

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Chapter 1

Scope and purpose

1.1 Scope

(1) This document describes the basics for risk assessment for static electricity. It deals with solids, liquids, gases, powders, and persons and how they can be charged, resulting in an electrostatic discharge that sometimes leads to the ignition of a flammable atmosphere. Countermeasures are described to prevent incendive electrostatic discharge. The recommendations apply to the identification, evaluation, and control of the risks for the purposes of preventing fires and explosions in industry.

(2) The recommendations apply to factories and locations in which flammable atmospheres exist, such as those in which flammable substances are manufactured or handled.

(3) The recommendations do not directly apply to measures against electrostatic hazards involving electronic devices or hospital operation rooms, clean rooms, computer rooms, and high-pressure oxygen therapy room. The basic concepts in these recommendations, however, may be adapted to those areas as well.

1.2 Purpose

The purpose of this document is to assist the user in controlling the hazards associated with the generation, accumulation and discharge of static electricity by providing the following fundamentals:

(1) Basic understanding of electrostatic phenomena;

(2) Identification and assessment of electrostatic hazards;

(3) Techniques for control, countermeasures for the hazards, and selected applications for industrial operations;

(4) Safety management involving control and measurements for electrostatic hazards.

Chapter 2

Definitions

The basic terms used in this document with regard to static electricity and electrostatic safety are defined here. The units used are the SI Unit System. However, if there is any non-SI unit that is in common use and familiar, that unit may be used. Symbols of physical quantity in italics represent scalars, while those in bold font represent vectors.

2.1 Charge

Symbol: Q or q, Unit: coulomb C = ampere second A·s

An electric charge is the quantity of a static electricity having positive or negative polarity. It is the most basic physical quantity serving as the source of the Coulomb force, the formation of an electric field, and all other electrical and electrostatic phenomena. The minimum electric charge is the charge of an electron that is the elementary charge and negative, $-e$, $e = 1.6 \times 10^{-19}$ C, and the charge of an object is an integral multiple of the elementary charge.

2.1.1 Space charge

Symbol: Q or q, Unit: coulomb C = ampere second A·s

A charge in a space volume.

2.2 Charge density

2.2.1 Surface charge density

Symbol: σ, Unit: $\mathrm{C/m^2}$

A charge per unit surface area.

2.2.2 Space charge density

Symbol: ρ, Unit: $\mathrm{C/m^3}$

A charge per unit volume. When charged liquid drops or powder is distributed in space, the charge density is defined as a space charge density.

2.2.3 charge-to-mass ratio

Symbol: Q/m or Q_m, Unit: C/kg

It is defined as the charge of powder per unit mass.

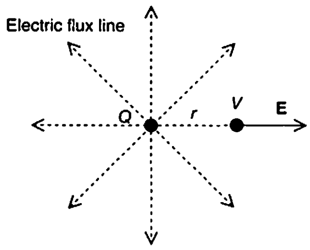


Figure 2.1: Potential and electric field due to a point charge

2.3 Potential

Symbol: ϕ or V, Unit: volt V = joule/coulomb J/C

The potential at a point in space is defined as the energy required to move a unit charge from infinity to the point ($W = QV$: $Q = 1$ C). In other words, it is the electrical potential energy of a unit charge in an electrostatic field at that point. In general, the potential is the voltage on the basis that the earth is the reference (0 V).

2.4 Voltage

Symbol: V, Unit: volt V

It is the potential difference between two points.

2.5 Electric field

Symbol: E, $\mathbf{E}$, Unit: volts/meter V/m

An electric field refers to a space having such a nature as to make an electrical force act on charges. The electrical force (Coulomb force) $\mathbf{F}$ on charge Q by electric field $\mathbf{E}$ is expressed by

$$\mathbf{F} = Q\mathbf{E} \tag{2.1}$$

and the electric field can also be defined as the Coulomb force working on a unit electric charge. This electric field is formed by charges. For example, the electric field due to the point charge Q as shown in figure 2.1 is from Gauss' theorem[1],

$$E = \frac{Q}{4\pi\varepsilon_0 r^2}. \tag{2.2}$$

Here, r is the distance from the point charge. The direction of the electric field is outwards for that produced by the positive charge and inwards for that produced by the negative charge. Moreover, potential V at position r from that point charge is, from the definition given in 2.3,

$$V = -\int_{\infty}^{r} E dr = \frac{Q}{4\pi\varepsilon_0 r}. \tag{2.3}$$

Moreover, the electric field can be expressed as the inclination of the potential (potential gradient).

$$\mathbf{E} = -\nabla V. \tag{2.4}$$

---

[1] This theorem holds that the total electric flux D ($D = \varepsilon_0 E$) leaving a closed surface equals the total electric charge within the closed surface. In this example, $4\pi r^2 \varepsilon_0 E = Q$.

Here, ∇ (nabla) is as follows at Cartesian coordinates x, y, and z,

$$\nabla = \mathbf{i}\frac{\partial}{\partial x} + \mathbf{j}\frac{\partial}{\partial y} + \mathbf{k}\frac{\partial}{\partial z}. \tag{2.5}$$

i, **j**, and **k** are the unit vectors in directions x, y and z, respectively. Since, in this example, they become the spherical coordinates with point symmetry,

$$E = -\frac{\partial V}{\partial r}. \tag{2.6}$$

The dielectric breakdown field in the ambient air is about 3 MV/m (30 kV/cm). In a uniform electric field, an electrostatic discharge occurs when the electric field exceeds this level.

2.6 Current

Symbol: $I, \mathbf{I}$, Unit: Ampere A = coulomb/second C/s

A current is a charge that flows through a cross section per unit time.

$$I = \frac{dq}{dt} \tag{2.7}$$

The direction in which a positive charge flows is positive. A current generated through the electrification of static electricity in industrial processes is of the order of tens of micro-amperes at most.

2.7 Resistance

Symbol: R, Unit: ohm Ω

As known through Ohm's law ($R = V/I$), resistance represents the difficulty with which current flows. The resistance of a conductive material does not depend on the applied voltage, while the resistance of a nonconductive (insulating) material generally dose, and Ohm's law may then not be applied.

2.8 Surface resistivity

Symbol: ρ_s, Unit: Ω (Ω/square or $\Omega/\square$ may be used.)

It is defined as the resistance between two mutually opposite sides of a square; each of the sides of the square has the unit length of the surface of an object. The surface resistivity is the resistance between electrodes at $L_1 = L_2$ in Figure 2.2. When electrodes with a length of L_1 are placed at distance L_2 as shown in this figure, the surface resistance R_s between electrodes then is

$$R_s = \rho_s \frac{L_2}{L_1}. \tag{2.8}$$

2.9 Volume resistivity

Symbol: ρ_v, Unit: ohm·meter Ω·m

It is the resistance between two mutually opposite planes of a cube; each of the sides of the cube has the unit length inside a body. It is the reciprocal of the conductivity. Resistance R of a material whose length L and cross section S is

$$R = \rho_v \frac{L}{S}.$$

In this sense, the word "resistivity" refers to volume resistivity.

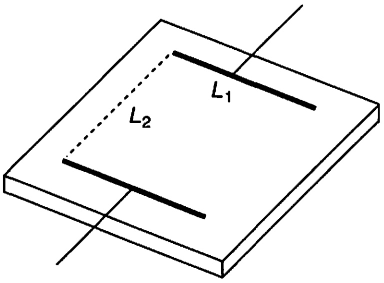


Figure 2.2: Surface resistivity and resistance

Table 2.1: Capacitances of practical conductive objects

Object	Capacitance (pF)
Small metal objects (such as a shovel, flange, or nozzle)	10–20
Small containers (bucket, 50 L drum)	10–100
Medium-size containers (250–500 L)	50–300
Plants and equipment	100–1000
Persons	100–300

1 pF = 1×10^{-12} F

2.10 Leakage resistance

It refers to the resistance between a point on a body or material to the earth. The leakage resistance on a floor, therefore, refers to the totality of the resistance, consisting of all related resistance paths from the point to the earth, i.e., the contact's resistance, the earth's resistance, and the materials' resistance.

2.11 Capacitance

Symbol: C, Unit: farad F = coulomb/volt C/V

It is the charge required to increase 1 V of the conductor's potential.

$$C = \frac{Q}{V}. \tag{2.9}$$

The capacitance increases with increasing the permittivity and the size of the body and decreases the distance between conductors. For example, the capacitance between parallel plane electrodes with distance d and area A is expressed by $C = \varepsilon A/d$. Table 2.1 shows the capacitances of typical conductive objects to ground.

2.12 Permittivity

Symbol: ε, Unit: F/m

In a cube, each of the sides of which is a unit length in a substance, it is defined by the capacitance between two mutually opposite planes. The permittivity of free space is $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m. The permittivity of a nonconductive material is expressed as

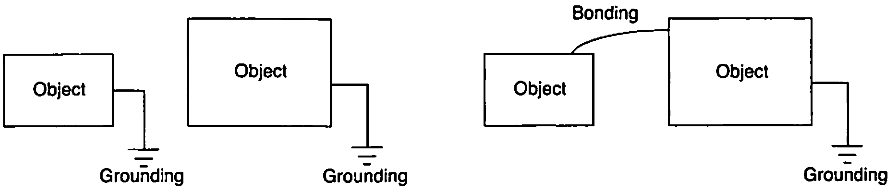
$$\varepsilon = \varepsilon_r \varepsilon_0$$

by using the relative permittivity (electric constant) ε_r which depends on the materials. Since the relative permittivity of a gas is almost 1, the permittivity can be represented by ε_0. The relative permittivities of main substances are shown in Tables D.6 and D.7.

Table 2.2: Electrostatic properties of conductors and nonconductors

	Volume resistivity ρ_v (Ω·m)	Surface resistivity ρ_s (Ω)
Conductive	$\rho_v < 10^3$	$\rho_s < 10^6$
Charge-dissipative *	$10^3 \leq \rho_v < 10^8$	$10^6 \leq \rho_s < 10^{10}$
Nonconductive	$\rho_v \geq 10^8$	$\rho_s \geq 10^{10}$

*conductive materials (2.17) are within this range.



(a) (b)

Figure 2.3: Grounding and bonding (a) grounding each, (b) bonding to a grounded object

2.13 Conductivity

Symbol: σ, Unit: siemens/meter S/m

It is the ratio of current density J to electric field E, $J = \sigma E$. It is the reciprocal of the volume resistivity.

2.14 Charge relaxation

It is a phenomenon in which a charge generated in or on a body is lost from it due to electrical conduction. When no such charge relaxation occurs or the relaxation is smaller than the charge generated, charge accumulation occurs.

2.15 Conductor and nonconductor

Conductors and nonconductors differ in electrostatic properties, and their ranges are defined as conductive, (charge-)dissipative, and nonconductive by using resistivity as shown in Table 2.2[2]. Electrostatic conductors are conductors and charge-dissipative bodies, such as bodies made of metals, conductive substances (conductive liquids, solids, and powders), or dissipative materials and human bodies.

2.16 Bonding

Bonding is the act of connecting an object to be grounded with a grounded conductor nearby via a conductive wire (resistance $\leq$ 1 kΩ), resulting in equalising the potential difference between the object and the earth. It is used when direct grounding is difficult or inefficient (figure 2.3).

2.17 Conductive materials

Conductive materials are rubber, plastic, fibre, or other materials whose conductivity has been increased by adding carbon black, metal powder, or other conductive materials.

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[2] Note that they differ in range from conductors, semiconductors, and insulators in electrical properties.

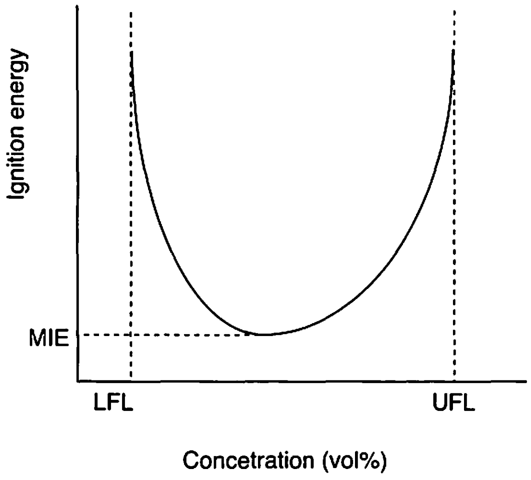

Figure 2.4: Typical relationship between minimum ignition energy and the concentration of a flammable mixture

2.18 Antistatic materials

Antistatic materials are materials having the function of preventing electrostatic accumulation. In addition to the conductive materials listed in 2.17, there are materials that reduce charge accumulation by using corona discharge. Materials that use corona discharge are often found in work clothes, carpets, bags, and other fibre products.

2.19 Antistatic additives

Antistatic additives are agents to increase the conductivity of solids, liquids, and powders with low conductivity (high resistivity).

2.20 Electrostatic discharge

Electrostatic discharge is an ionised gas phenomenon generated when the local electric field on a charged object reaches the dielectric breakdown field of ambient air.

2.21 Ignition limit and minimum ignition energy

To ignite flammable gas, vapour, dust, or hybrid mixtures (gas or vapour including dust), there is a lower limit (lower flammable limit (LFL) or lower explosive limit (LEL)) and an upper limit (upper flammable limit (UFL) or upper explosive limit (UEL)) of its concentration. Controlling the concentration toward the outside of the range between the limits can prevent the generation of an explosive atmosphere. As shown in Figure 2.4, the plot of the ignition energy follows a U-shaped curve that reaches its minimum at a concentration near that when flammable substances and oxygen (or air) reach the stoichiometric composition. The minimum is called the minimum ignition energy (MIE)[3]. The minimum ignition energy ranges roughly between about 0.001 and 1 mJ for gases and vapours and between about 1.0 and 5,000 mJ for dusts. The minimum ignition energy decreases as the pressure and temperature rise and, for dust, as its particle size decreases.

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[3] Since the curve in Figure 2.4 plots the minimum ignition energies at different concentrations, the minimum of that curve is sometimes referred to as the lowest minimum ignition energy (LMIE).

Table 2.3: Classification of hazardous areas [3–5]

Zone 0	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour or mist is present continuously, for long periods, or frequently.
Zone 1	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour, or mist is likely to occur occasionally in the course of normal operation.
Zone 2	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour, or mist is not likely to occur in course of normal operation but, if it does, will persist for a short period only.
Zone 20	An area in which combustible dust, as a cloud, is present continuously or frequently during normal operation in sufficient quantity to be capable of producing an explosive concentration of combustible dust in a mixture with air.
Zone 21	An area in which combustible dust, as a cloud, is occasionally present during normal operation in a sufficient quantity to be capable of producing an explosive concentration of combustible dust in a mixture with air.
Zone 22	An area in which combustible dust, as a cloud, may occur infrequently and persist for only a short period or in which accumulations of layers of combustible dust may give rise to an explosive concentration of combustible dust in a mixture with air.

The definitions are still under discussion in IEC

2.22 Equivalent energy

The ignitability of a flammable substance to an electrostatic discharge is characterised by the minimum ignition energy. Discharge incendivity (discharge energy) must therefore be discussed in consideration of the power density (temporal factor) and spatial spread (spatial factor) of an electrostatic discharge. However, except for a spark discharge, it is not easy to obtain even the total energy of an electrostatic discharge. It is much less easy to determine how much of that energy contributes to ignition. For that reason, the spark discharge is used to measure the ignition energy because the discharge provides high energy density both temporally and spatially and then facilitates the determination of discharge energy. In an electrostatic discharge other than the spark discharge, the equivalent energy for the incendivity (ignitability) for that electrostatic discharge is defined as X J when the discharge ignites a flammable atmosphere with the minimum ignition energy X J [1]. Since the discharge energy (equivalent energy) is experimentally determined by contrasting it with the ignition energy, it is convenient for analysing the risk of ignition. Note that the discharge energy, other than spark discharge referred to hereafter, corresponds to this equivalent energy. Recently, in view of how effectively a specific electrostatic discharge can ignite a flammable atmosphere with a minimum ignition energy, this equivalent energy is also referred to as effective energy [2].

2.23 Hazardous areas

This document employs the classification in the International Electrotechnical Commission (IEC) standards (IEC 60079 series [3]). Hazardous areas are classified as in Table 2.3.

2.24 Classification of flammable gas groups

The IEC standards classify flammable gases into IIA, IIB, and IIC depending on the minimum ignition current (MIC) to be measured with an IEC spark test. Typical gases used in the

Table 2.4: Classification of gas groups (equipment groups)

Group	Typical gas	Maximum safe gap*	MIC ratio**	MIE
IIA	propane	> 0.9 mm	> 0.8	> 0.25 mJ
IIB	ethylene	0.5–0.9 mm	0.45–0.8	0.02–0.25 mJ
IIC	hydrogen	< 0.5 mm	< 0.45	< 0.02 mJ

*The maximum clearance between two parallel metal surfaces to prevent an explosion.
**The ratio to the MIC (Minimum ignition current) for methane.

classification thresholds are propane (IIA), ethylene (IIB), and hydrogen (IIC). The minimum ignition energies of selected gases in ambient air are 0.25 mJ (propane), 0.07 mJ (ethylene), and 0.016 mJ (hydrogen). The ranges of minimum ignition energy for flammable gas groups IIA, IIB, and IIC are shown in Table 2.4. This document uses this classification as an indicator of antistatic measures. Group IIC includes few gases, such as hydrogen, acetylene, carbon disulfide, dichlorosilane, and trichlorosilane.

2.25 Risk assessment

The conventional practice of ensuring safety in Japan has been based on the concept that it suffices to set and follow standards. In other words, the concept is that safety standards are to be observed and set forth by law. Risk assessment, on the other hand, holds that individuals identify hazards in advance and take action to prevent them. This document also specifies antistatic measures (risk reduction measures) on the precondition that risk assessment be performed as something that has already been a global standard[4] in safety technology. As long as flammable substances or products are handled, absolute safety cannot be ensured regardless of the measures taken. It is, therefore, important to assess the risk scientifically, rationally, and exhaustively and reduce the risk until it reaches a tolerable level .

The following terms regarding risk assessment are defined according mainly to ISO/IEC Guide 51: 1999 *Safety aspects – Guidelines for their inclusion in standards.*

2.25.1 Safety

Safety is the freedom from unacceptable risk. In this sense, the meaning of "safety" differs from the general sense. For the purpose of this document, safety is freedom from unacceptable risk, and safety measures are involved with risk reduction..

2.25.2 Risk

Risk is a combination of the probability of the occurrence of harm and its severity. In the field of electrostatic safety, this refers to a combination of the probability of the occurrence of electrostatic hazards and subsequent damage. This combination can be calculated in various manners. The most frequently used method is to multiply the probability of the hazards by the numerical level representing the degree of the damage.

2.25.3 Harm

Physical injury or damage to people's health or damage to property or the environment.

2.25.4 Hazard

This refers to a potential source of harm.

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[4] Risk assessment has been made obligatory (a regulation requiring effort) since April 2006 by the Industrial Safety and Health Law as well.

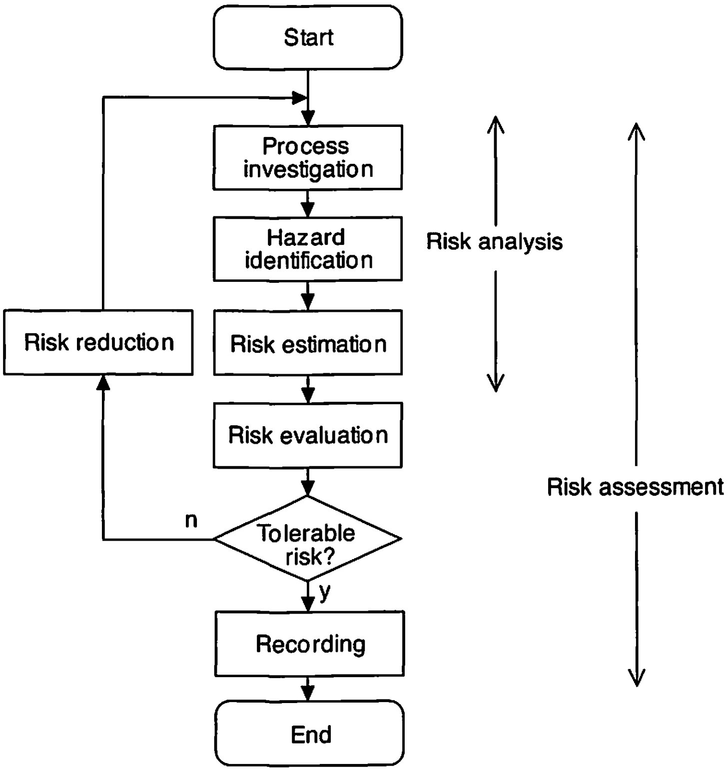

Figure 2.5: Risk assessment procedure

2.25.5 Tolerable risk

A tolerable risk is that under given conditions according to the values of society in the current age. This term means that the ideal is to reduce the post-project residual risk to a widely acceptable risk but that the risk has reached a tolerable level in reality in view of convenience, cost, techniques, and other matters. It does not suffice to reduce the risk to a tolerable level: It is imperative to work to reduce the risk to a level as low as reasonably practicable (ALARP) (more specifically, as long as the cost of risk reduction is proportional to the effect of improvement obtained) as proposed in the HSE (Health and Safety Executive) in UK.

2.25.6 Risk reduction measure

This refers to a measure to reduce a risk to a tolerable level.

2.25.7 Residual risk

This means a risk remaining after some risk reduction measures have been taken.

2.25.8 Risk analysis

Systematic use of available information to identify hazards and to estimate the risk. This estimate prioritises specific measures.

2.25.9 Risk evaluation

This means the act of evaluating whether a tolerable risk has been achieved on the basis of a risk analysis.

2.25.10 Risk assessment

Of all processes in risk analysis and risk evaluation, risk assessment is the process of reducing the risk to a tolerable risk. This includes recording as well. The procedure for risk assessment is as shown in Figure 2.5.

Chapter 3

Fundamentals of electrostatics for safety

This chapter is an outline of the basics of electrostatics for safety, which includes the mechanisms of the generation of static charge and the generation of electrostatic discharge caused by the charge. The chapter also contains basic safety information of electrostatics required for risk assessment in practical situations and industrial processes that are subject to electrostatic discharges that can lead to fires and explosions.

3.1 Static electrification

To prevent hazardous accumulation of static charge and to conduct antistatic safety measures (risk reduction measures), knowledge of charge generation and the factors that affect it is required. Static charge is generated mainly by charge separation. When charges are separated for some reason, the resultant charge of either the positive or the negative polarity becomes excessive on the surface of a body that was originally electrically neutral. This excessive charge results in static electrification when the separated charge accumulates on the surface of the body.

3.1.1 Charge separation

Charge separation is the main mechanism of charge generation. As shown in Figure 3.1, the mutual contact of two electrically neutral bodies with different materials (solid-solid, solid-liquid, liquid-liquid, or liquid-gas) will result in the charge transfer at the interface to form a double layer[1]. In this state, the body is still electrically neutral. The mechanism of the charge transfer is not thoroughly understood; however, it is known that, when metals contact each other, electrons

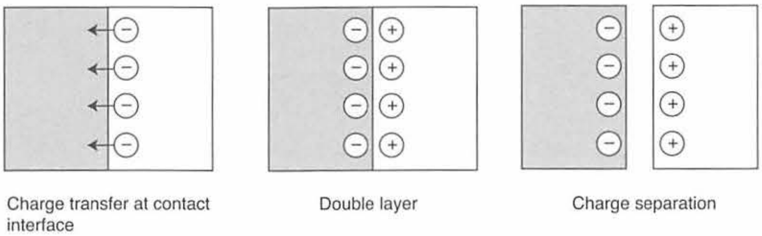

Figure 3.1: Charge separation

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[1] This is the charge distribution generated at the interface with two layers having the same charge of mutually opposite polarity. The total charge is zero.

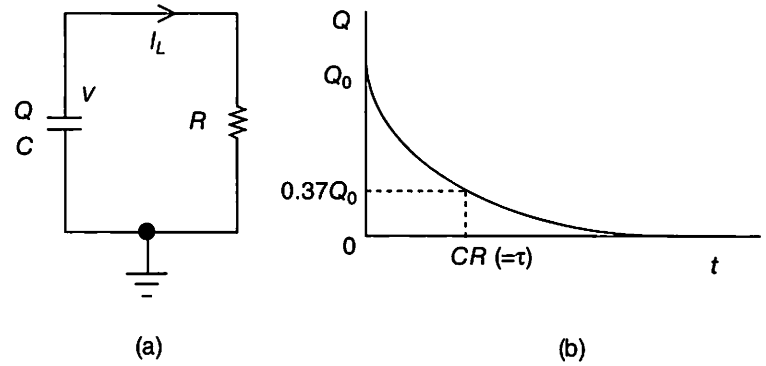

Figure 3.2: Circuit model of charge relaxation

as carriers move due to the difference in the energy state (Fermi level) between the two bodies at the interface. If some kind of work separates these bodies, the charge on the interface remains. This charge separation provides the positively and negatively charged bodies.

For example, the electrification in the roller transport of film or paper and the pipe transport of liquid or powder is caused by the charge separation at the time of contact and separation at their interfaces.

3.1.2 Charge relaxation

When static charges are generated in or on a body, not all of the charges are accumulated there. Some of them dissipate if the body is electrically grounded. This phenomenon is called charge relaxation. Charge relaxation can be expressed in an electrical circuit[2] composed of capacitance C and leakage resistance R of a body (Figure 3.2a). At the initial charge of Q_0 of the body, when the charge generation has stopped at time 0 seconds, its charge Q after t seconds is expressed as

$$Q = Q_0 \exp\left(-\frac{t}{\tau}\right), \tag{3.1}$$

$$\tau = CR = \varepsilon\rho. \tag{3.2}$$

Therefore, the charge of the body decreases exponentially with time due to charge relaxation. This means that a charged body will lose its charge gradually, and finally, it loses all of it if the charge generation can be eliminated. Here, C, R, ε, and ρ are the capacitance, leakage resistance, permittivity, and resistivity of the body, respectively. Moreover, τ is called the charge relaxation time (or charge relaxation constant) and is the time at which the charge becomes $1/e$ (about 37%) of the initial charge. For reference, the manner in which Equation (3.1) is derived is shown in footnote[3]. Equation (3.1) reveals that the charge relaxation depends on the capacitance (permittivity) and leakage resistance (resistivity) of the body and that the larger they are, the longer the relaxation time is. In the case of a conductor or other substance whose charge relaxation is ohmic[4], charge relaxation follows Equation (3.1), while the charge relaxation of many insulators (such as liquids with low conductivity) may not follow it.

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[2] Since this model defines capacitance, more accurately, a charged body is a conductor (with its surface potential being the same one).

[3] From Figure 3.2a, the charge relaxation current (leakage current) I_L can be expressed as

$$I_L = -\frac{dQ}{dt} = \frac{Q}{CR} = \frac{Q}{\tau}.$$

Solving this equation in terms of charge Q gives Equation (3.1).

[4] A substance complying with Ohm's law. In this case, it means that the charge relaxation contains no electric conduction depending on voltage.

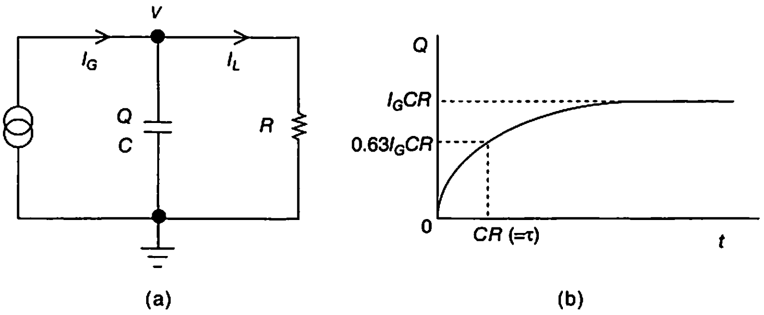

Figure 3.3: Circuit model of charge accumulation

3.1.3 Charge accumulation

Charge Q of static electricity is determined by charge generated (charge separation) I_G per unit time and charge dissipated (charge relaxation) I_L. The change in the resultant charge per unit time becomes

$$\frac{dQ}{dt} = I_G - I_L. \tag{3.3}$$

Representing this in the form of a circuit model, it will be as shown in Figure 3.3a. This means that static electrification is determined by the equilibrium between the charge separation and the charge relaxation (Figure 3.3b). When the charge relaxation is high enough, static charge, if any, does not accumulate on or in the body, resulting in lower charging. Conversely, low charge relaxation will accumulate charge on or in the body, resulting in higher charging, which may lead to electrostatic hazards. For example, when a liquid transfers through a pipe, and if the pipe is made of metal and grounded, the charge relaxation time becomes short (I_L in Equation (3.3) increases); thus, the charge generated in the pipe can instantaneously leak to the earth[5]. Conversely, when an insulating pipe is used or a metal pipe is ungrounded, it results in no charge relaxation, therefore charges generated accumulate on the pipe as well. This charge accumulation appears as the form of static electrification, thus becoming a potential disaster. Therefore, to increase charge leakage (that is, to reduce the capacitance of the body or reduce its leakage resistance) reducing that accumulation is an important measure to prevent electrostatic hazards.

We then obtain the steady-state value of charge accumulation. What is obtained is the steady-state value and the charge does not change with time, therefore, part of Equation (3.3) becomes $dQ/dt = 0$, and then $I_L = I_G$. This I_G flows through leakage resistance R so that the potential V of a charged body at the steady state becomes,

$$V = I_G R. \tag{3.4}$$

From the relationship, $V = Q/C$, the charge of the body becomes,

$$Q = I_G CR = I_G \tau. \tag{3.5}$$

As a reference, Equations (3.4) and (3.5) can also be derived as in footnote[6]. Equation (3.4)

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[5] The charge of the pipe itself leaks. However, low-conductive liquids leak hardly any liquid charge.

[6] Equation (3.3) becomes

$$\frac{dQ}{dt} = I_G - \frac{Q}{CR}.$$

Assuming that $Q = 0$ at $t = 0$, the charge t seconds later becomes

$$Q = I_G CR[1 - \exp(-t/CR)].$$

This equation is shown in Figure 3.3b. It is found that the steady-state charge of this equation is the same as Equation (3.5).

Table 3.1: Examples of various electrification phenomena due to charge separation

Cause of charge separation	Examples
Friction between different kinds of bodies	Friction between belt and roller and between powder and bag
Peeling of adhered bodies	Peeling of paper, film, or other objects; release of moulded plastics
Flowing: Selective adsorption of positive or negative ions to solid walls	Pipe transport of liquids and filters in flowing liquid
Spraying or eruption: Friction with a nozzle or crack	Eruption due to spraying and leakage
Sedimentation/floatation: Sedimentation of different kinds of liquids, solids, or powder in liquid	Sedimentation and floatation of water drops, foreign matter, and other substances in liquid;
Collision between different kinds of objects	Pneumatic transport of powder

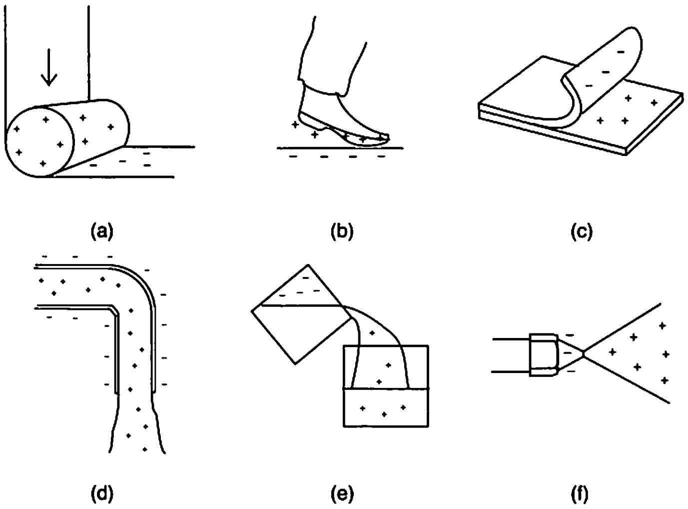

Figure 3.4: Examples of electrification: (a) friction with rollers, (b) walking as a person wears insulating shoes or on an insulating floor, (c) peeling of film, (d) pipe transport of liquid or powder, (e) transfer of liquid or powder into an insulating container, (f) liquid or powder spraying

serves as the basis for the leakage resistance required for the static safety measures for conductors described later.

3.2 Various types of electrification

3.2.1 Charging by charge separation

Most charging that taking place in many industrial processes is electrification by charge separation that occurs when bodies contact each other or are separated, such as by contact, friction, collision, peeling, flowing, fluidisation, agitation, mixing, spraying, atomisation, eruption, sedimentation, floatation, pulverisation, or dripping. Many examples of electrification are shown in Table 3.1 and Figure 3.4.

3.2.1.1 Factors affecting charge separation

The generation of a charge due to charge separation in general is affected by the material of the body, foreign matter, surface state, electrification history, contact area, pressure, and separation

Table 3.2: Example of triboelectric series

Metal	Fibre, Textile	Natural matter	Synthetic resin
+	+	+	+
		Human hair and fur	
		Glass	
		Mica	
	Wool		
	Nylon		
	Rayon		
Lead			
	Silk		
	Cotton	Cotton	
	Hemp		
		Lumber	
		Human skin	
	Glass fibre		
Zinc	Acetate		
Aluminium			
		Paper	
Chromium			
			Ebonite
Iron			
Copper			
Nickel			
Gold		Rubber	Polystyrene
	Vinylon		
Platinum			Polypropylene
	Polyester		
	Acrylic		
			Polyethylene
	Polychloride vinylidene	Celluloid	
		Cellophane	
			Polyvinyl chloride
			Polytetrafluoroethylene
−	−	−	−

The triboelectric series has been determined for pure materials. This table, therefore, serves as a guide alone.

speed.

(1) Materials
The materials of two bodies contacting each other and separating affect the magnitude of the charge generated (which rises as the triboelectric series shown in Table 3.2 are farther apart; in this table, vertically) and the polarity.

(2) Foreign matter
The inclusion of foreign matter affects the generation of static electricity, generally increasing its magnitude, e.g., two-phase liquid.

(3) Surface state
The surface state (surface roughness or contamination, oxidation, or corrosion of water, oil, or other matter) affects the generation of static charge. In general, a rough, contaminated, or oxidised surface tends to increase the magnitude of electrification.

(4) Electrification history
In general, electrification tends to peak at the first contact and separation and to decline gradually as contact and separation are repeated.

(5) Contact area and pressure
Electrification rises as the contact area increases. As an increase in contact pressure increases the contact area, electrification tends to rise.

(6) Separation speed after contact
The separation speed is related to charge relaxation during the separation. As a result, it affects the charge accumulation. In general, as this rises, the charge increases.

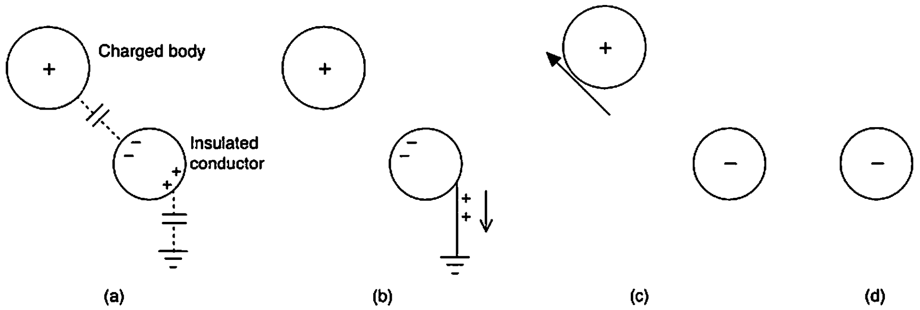

Figure 3.5: Electrostatic induction: Under electrostatic induction (a); Grounding an insulated conductor causes a charge transfer (discharge) with the same polarity as the charged body that may lead to an electric shock (b); Disconnecting the ground and releasing the charged body (c); The conductor charged by the discharge remains, and its polarity is the opposite of that of the charged body (d).

3.2.2 Electrostatic induction and induction charging

In addition to charging due to the charge separation in contact and separation, charging can also occur due to electrostatic induction. This phenomenon is proper only to conductors[7]. If an electrically insulated conductor, which is electrically neutral, is close to a charged body, non-uniform charge distribution on the conductor surface is created, resulting in a rise in potential. This is electrostatic induction. As shown in Figure 3.5a, as the insulated conductor comes close to a positively charged body, the surface of the conductor close to the charged body develops negative charges, while the opposite side develops positive charges[8]. In addition, as a conductor is grounded as shown in Figure 3.5b, the charge of the same polarity as the charged body goes into the earth. Releasing the charged body after disconnecting the grounding results in the conductor being charged with the opposite polarity of the charged body as shown in Figure 3.5c. This is called induction charging. However, releasing the charged body without grounding it will return the conductor into its earlier uncharged state because no true charge was transferred.

For example, when a worker wearing insulating shoes approaches a flexible intermediate bulk container filled with powder, film in the roller process or any other charged body, the induction will cause the worker to develop charge separation in the sides closest to and farthest from the charged body (Figure 3.5a). When the charged body becomes into contact with a grounded conductor, a discharge will occur, resulting in an electric shock (Figure 3.5b), and, at this moment, the worker will be charged. Afterward, the worker will leave the location (Figure 3.5c). Since the worker was charged at that time (Figure 3.5d), he/she will undergo a second electric shock when touching a grounded conductor again in a distant location.

3.3 Electrostatic discharge and ignition

3.3.1 Electrostatic discharge

As described in 3.1, the difference between charge generation and relaxation per unit time causes charge accumulation, resulting in electrification. However, the lack of charge relaxation does not result in infinitely high electrification. Rather, when an electric field created by an electrostatic charge reaches the dielectric breakdown electric field E_b, a gas discharge occurs, resulting in part of the charge being lost and electrification being limited. A circuit model representing this is as shown in Figure 3.6a. Here, this model can be applied when the charged body is a conductor.

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[7] Human bodies can be regarded as conductors in electrostatics; thus, they can also be influenced by induction.

[8] This is because, although the surface potential of a conductor is the same all over the surface (the tangent component of the electric field is zero at the surface), the presence of a charged body will cause the generation of a tangent component of the electric field on the conductor surface. To cancel this electric field, the charge will be redistributed on the surface instantaneously. Note also that the charge is only redistributed (separated as shown in Figure 3.5a) but the total charge remains unchanged.

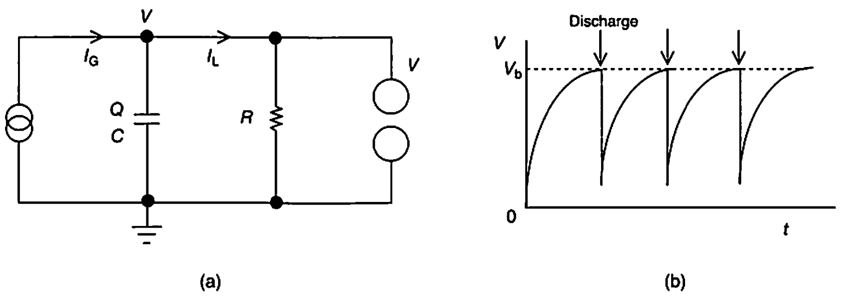

Figure 3.6: Charging and discharge

When charge separation (charge generation) continuously occurs and when the potential of the body reaches a potential V_b (onset or inception voltage), which gives a discharge inception field, a discharge will occur intermittently and, at that time, most of the charge will disappear (will be neutralised) (Figure 3.6b). This can be applied as a model of spark discharge in a discharge between conductors to be shown in 3.3.5 later. If the charged body is an insulator, a spark discharge will not occur, instead, various different types of discharge will occur. For static safety measures, it is important to understand the mechanisms whereby various discharges are generated as well as their ignitability characteristics. The various types of discharge, their characteristics, and prevention measures for ignition are reviewed in Table 3.3.

Note also that the dielectric breakdown electric field E_b of air becomes

$$E_b \approx 3 \text{ MV/m } (= 30 \text{ kV/cm}).$$

Therefore, the surface charge density (in other words, the maximum surface charge density of electrification) σ_{max} of the charged body at the inception of the discharge becomes

$$\sigma_{max} = \varepsilon_0 E_b \approx 27 \ \mu\text{C/m}^2. \tag{3.6}$$

3.3.2 Discharge energy

When the charged body is a conductor, the electrostatic energy W accumulated in that body becomes as follows:

$$W = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C} \tag{3.7}$$

Here, C is the capacitance of the body, Q and V are the charge and potential of the body, respectively. The inception of an electrostatic discharge causes most or part of this electrostatic energy to be released as discharge energy. This discharge energy will ignite the flammable substance, resulting in an explosion or fire. The key to preventing such electrostatic hazards is, therefore, preventing incendiary electrostatic discharges.

3.3.3 Ignition

Some kind of ignition source ignites a mixture of a flammable substance and air (more precisely, oxygen). Furthermore, the initiation of combustion due to the creation of a flame kernel, which makes the flame evolve, will cause an explosion or fire. The three elements for ignition leading to explosion or combustion are fuel (a flammable substance), oxygen , and an ignition source. More specifically, the following three requirements need to be met:

(1) The flammable substance has a concentration between the lower and the upper limits of explosion;

Table 3.3: Various types of electrostatic discharge, their characteristics, and prevention measures

Type	Cause/Example	Discharge energy[a]	Ignitability	Measures
Spark discharge	Discharge between an electrically insulated conductor and a grounded conductor	Up to ~ 1 J	Gas, vapour, and dust	Grounding and bonding (Chapter 5)
Corona discharge	When a grounded pointed conductor approaches a charged object or similar situations	Up to tens of μJ	Hydrogen, acetylene, and others.	Generally unnecessary measures
Brush discharge	When a grounded conductor having a relatively large radius of curvature approaches a charged nonconductor	Up to ~3 mJ	Gas and vapour	Measures for nonconductors (Chapter 7)
Propagating brush discharge	Charging on thin nonconductor with a grounded backing conductor	Up to ~ 10 J	Gas, vapour, and dust	Limitations of charging of thin nonconductors or use of materials with a breakdown of less than 4 kV (3.3.8)
Cone discharge	Continuous mass loading of high-resistivity charged powder with a size of 0.1–10 mm	About tens of mJ	Gas, vapour, and dust	Preventing the accumulation of charge in a container

[a] Discharge energies, except for sparks, are equivalent (see 2.22)

(2) The oxygen concentration is over the explosion limit (limit oxygen (oxidant) concentration);

(3) The energy of the ignition source is more than the minimum ignition energy.

Causing the environment to fail to satisfy any one of these prevents ignition. In other words, the key is to prevent the generation of a flammable atmosphere or to eliminate the sources of ignition.

Electrostatic discharge is another important source of ignition leading to a fire or explosion. Fire and explosion accidents due to electrostatic discharge occurred at an incidence of about 100 per yearaccording to the Fire Annual Reports by the Fire and Disaster Management Agency, Ministry of Internal Affairs and Communications from 1993 to 2004. The breakdown of causes of the fires due to static electricity indicates that the most important causes are electrification of workers or their clothes, electrification of powder, and electrification of liquid in that order, about 15% each, followed by electrostatic coating, eruption, and rolling processes, in that order.

3.3.4 Minimum ignition energy

In general, the ignition energy depends on the concentration of the flammable substance. The curve of the minimum ignition energy plotting whose concentration as the horizontal-axis is a U-shaped curve in which the value reaches its minimum near the concentration at which the flammable substance and oxygen reach the stoichiometric composition ratio. When this gas mixture is a mixture of a flammable substance and air, its minimum ignition energy is higher than that of oxygen by about 2 orders of magnitude. Moreover, it is well known that the minimum ignition energy depends on the temperature and pressure as well, decreases almost exponentially with the temperature rise, and decreases in proportion to almost the square of the pressure [6].

The minimum ignition energy provides important data when assessing the risk of static electricity and appropriate measures are taken on the basis of a comparison of the predictable discharge energy W_d and minimum ignition energy W_{mie}. In other words,

$$W_d \geq W_{mie} \tag{3.8}$$

is used to assess the risk of static electricity. The minimum ignition energy follows a rough range for gas, vapour, and dust, as shown in Figure 3.7, and the values of specific substances can experimentally determined.

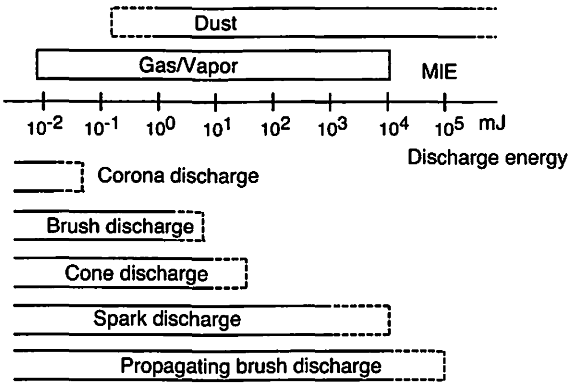

Figure 3.7: Discharge (or equivalent) and minimum ignition energies

Table 3.4: Capacitances of conductors and ignitability of a spark discharge (hazardous charge and potential [8]

Objects: examples	Capacitance (pF)	Charge (nC)		Potential (kV)	
		0.2 mJ	5 mJ	0.2 mJ	5 mJ
Small metals: flanges and small tools	10	63	320	6.3	32
Small containers: buckets	10–100	63–200	320–1000	6.3–2.0	32–10
Medium-size containers: drums (150–500 L)	50–300	140–350	710–1700	2.8–1.2	14–5.8
Persons	100–300	200–350	1000–1700	2.0–1.2	10–5.8
Large metal objects: tanks and road tankers	100–1000	200–630	1000–3200	2.0–0.63	10–3.2

3.3.5 Spark discharge

3.3.5.1 Occurrence of spark discharge

A spark discharge occurs between flat plates or between conductors having a radius of curvature larger than the gap creating a uniform electric field (Figure 3.8a). The spark is a discharge that occurs between conductors, and most of their charge disappears due to the discharge. Discharge energy can, therefore, be estimated by using Equation (3.7) of electrostatic energy. That energy is relatively high and can reach about 1 J.

A spark discharge resulting from static electricity is similar to a capacitive discharge. It occurs between an electrically insulated conductor which works as a capacitor and a grounded conductor. In industrial situations, examples of an insulated conductor include an electrically insulated metal container, a shovel, hopper plumbing, a pipe, a worker wearing insulated shoes, or other insulated objects. Table 3.4 shows the ignitability levels of spark discharges that can occur in industries. In this way, spark discharges generated in industrial processes have enough energy to ignite a mixture of flammable gas, vapour, or powder with air. Many of the dust explosions caused by an electrostatic discharge are said to result from these spark discharges.

As guidelines [7] indicate that a person-generated spark discharge can ignite a flammable atmosphere having a minimum ignition energy of 100 mJ or less, workers are also a possible source of ignition. Antistatic measures for workers are, therefore, an important element.

3.3.5.2 Risk assessment of a spark discharge

A spark discharge due to static electricity is a discharge between conductors when a conductor is charged and its distance from a grounded conductor becomes shorter. The possibility of a spark discharge can be evaluated by comparing the maximum potential V_{max} of the conductors with the minimum spark inception voltage in atmospheric-pressure air which is 330 V; in other words,

$$V_{max} \geq 330 \text{ V}. \tag{3.9}$$

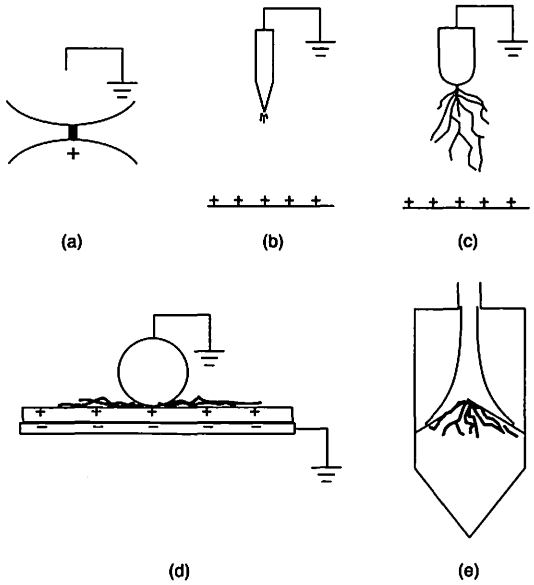

Figure 3.8: Various types of electrostatic discharge; (a) spark discharge, (b) corona discharge, (c) brush discharge, (d) propagating brush discharge, and (e) cone discharge.

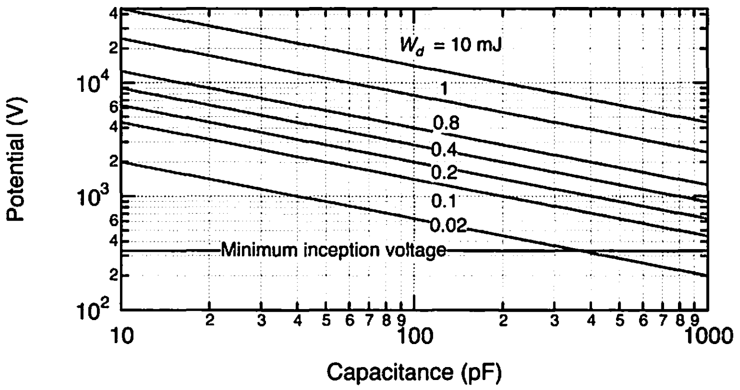

Figure 3.9: Risk assessment of a spark discharge (hazardous charging levels of conductors)

The ignition risk due to a spark discharge can be assessed by comparing its energy, W_d, with the minimum ignition energy W_{mie}.

$$W_d \approx W = \frac{1}{2}CV_{max}^2 \geq W_{mie}, \tag{3.10}$$

here, the discharge energy of a spark discharge is almost equal to the electrostatic energy W before the discharge. Figure 3.9 shows the risk evaluation of a spark discharge (the hazardous charging levels of conductors).

3.3.5.3 Prevention of a spark discharge

A spark discharge can be prevented by reducing the voltage of the conductive equipment, tool, or person to ground to 100 V or less [9]. This ordinary practical value of 100 V is employed as a margin of safety taking into account the minimum dielectric breakdown voltage (330 V) for a spark discharge in air. One specific conceivable measure is the grounding or bonding (chapter 5) of all conductors (including the workers). For this purpose, the following requirements should

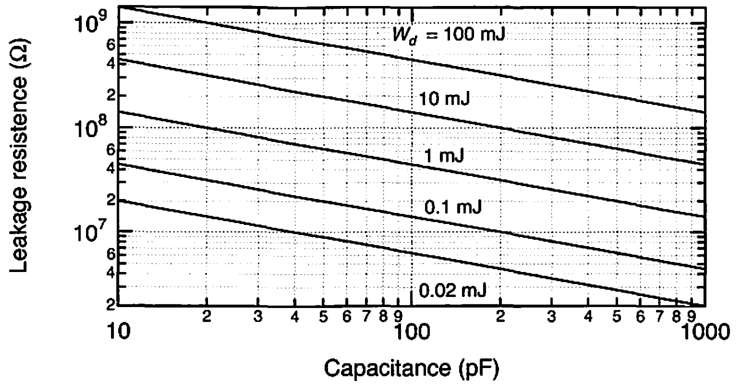

Figure 3.10: Risk assessment of a spark discharge due to the leakage resistance of a conductor. The threshold is calculated on the basis that $I_G = 100\ \mu\text{A}$. A spark discharge is possible in the region above each straight line.

be met:

(1) Leakage resistance of 10^6 Ω or less[9] for conductive bodies other than persons;

(2) For persons, the leakage resistance is 10^8 Ω or less[10].

In addition, from Equations (3.4) and (3.10), the leakage resistance of a conductor that causes the risk of spark discharge can be evaluated.

$$R = \sqrt{\frac{2W_d}{CI_G^2}} \tag{3.11}$$

In industrial processes, the generated current almost never exceeds 100 μA. Using this current level, the relationship between the leakage resistance and spark discharge energy of conductors of Equation (3.11) is shown in Figure 3.10. Note also that, from Equation (3.4), the leakage resistance satisfying a potential of less than 100 V for preventing a spark discharge becomes,

$$R \leq \frac{100}{I_G} \tag{3.12}$$

3.3.6 Corona discharge

A corona discharge is a discharge generated by a locally intensified electric field when a non-uniform electric field is created near an electrode having an extremely small radius of curvature, such as needles and thin wires (Figure 3.8b). This generally occurs when the radius of curvature is less than 5 mm [10].

The characteristics of a corona discharge depend largely on the polarity of the electrode, and coronas are referred to as 'negative corona' and 'positive corona' depending on the difference in

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[9] The leakage resistance of 10^6 Ω is a value obtained by substituting Equation (3.4) with $V = 100$ V (potential for preventing a spark discharge) and with the current ($I_G = 100\ \mu\text{A}$) generated by the largest charge possible in industrial processes.

[10] The generation of static electricity in a person is relatively low; thus, 10^8 Ω is a value obtained by setting the current generated in static electricity to 1 μA because the current by manual work by persons becomes a relatively small value with that value at most. Furthermore, since the capacitance of a person is about 100–300 pF, its relaxation time becomes about 10^{-2} s at a leakage resistance of 10^8 Ω. In consideration of the time for a person's action (such as walking), this relaxation time is enough. For these reasons, the leakage resistance is set to a level higher than that for conductors other than persons.

polarity. A corona discharge changes in form with increasing the voltage as well, and both of them eventually shift to a spark discharge. These changes in form due to polarity and voltage result from the differences in the space charge created by electrons and ions. The corona onset voltage depends on the curvature of the electrode and the electric field near the electrode increases as the curvature decreases, resulting in a decrease in the corona onset voltage. For example, when the radius of curvature is 1000 μm, corona onset voltage is about 6 kV but about 2 kV at 100 μm [6]. The value of the electrode potential is, therefore, not very important; this means that, in industrial situations, a corona discharge can occur even when the potential of charging is low.

In practical situations, when the surface of a charged body is approached by a grounded piece of metal having a small radius of curvature, and conversely, when the sharp edge of a grounded metal container is approached by a charged body, a corona discharge occurs.

This corona discharge can be prevented by eliminating sharp edges and protrusions. However, the energy released from a corona discharge is relatively low, and most of the flammable substances are not ignition-prone from this energy, except for hydrogen and other sensitive gases whose ignition energy levels are extremely low [9]. Rather, a corona discharge works as a function of neutralisation of a charged body. A corona discharge is, therefore, applied to neutralisers and antistatic measures for clothes, flexible intermediate bulk containers (FIBCs), and other textile products.

3.3.7 Brush discharge

3.3.7.1 Occurrence of a brush discharge

A brush discharge occurs when the potential for a positive corona discharge is high or when there is a protrusion or something similar that can be an electrode and has a radius of curvature between ~5 and 50 mm (Figure 3.8c). This occurs, in particular, when an insulator is charged and is approached by a metal ground with such curvature. This brush discharge is also known as a streamer corona discharge. A brush discharge is considered to occur when the surface charge density of the charged body is 3 μC/m^2 or more and the surface electric field is 0.5 MV/m (= 5 kV/cm) or more [10–13].

This brush discharge depends on the electrode polarity, just like a corona discharge. It is known that a positive-polarity discharge is more ignitable in cases such as those when a body is negatively charged and is approached by a grounding conductor with a radius of the curvature above. The brush discharge energy is up to between 1 and about 3 mJ [12, 14, 15] and never exceeds 4 mJ [16]. Therefore, it is a possible source of ignition for flammable gas and vapour. In addition, there is no evidence that even sensitive dusts can be iginited by brush discharges in the absence of any flammable gases and vapours.

Examples of a brush discharge in industrial situations are described below:

- Discharges that occur when an insulating pipe, plastic bag, or insulating conveyor belt through which powder or liquid is conveyed is approached by a grounded metal or human finger;
- Discharges that occur when a plastic bag is swung or otherwise moved to discharge the powder from within and the plastic bag thus approaches a grounded metal;
- Discharges generated near the edge at the inlet of a tank, a probe for measuring the fill level, or other internal protrusions when the tank is being filled with liquid or powder or when the charged liquid or powder is accumulated in the tank;
- Discharges generated through the contact of an FIBC for transporting and accumulating powder with a grounded conductor (including persons).

These discharges mainly occur when an insulator is charged and this charged body approaches a grounded metal tool, equipment edge, protrusion, or finger. When the protrusion or something similar has a radius of curvature of less 3.5 mm [2], a corona discharge is much more likely to occur than a brush discharge.

3.3.7.2 Risk evaluation of a brush discharge

The onset voltage of a brush discharge depends on the radius of curvature of the electrode, and the capacitance of nonconductors cannot be defined. It is, therefore, not easy to theoretically obtain the limit for the potential for the inception of brush discharge. Below are examples of the relationship between the ignitability and potential for the onset of a brush discharge.

- The liquid surface potential was 58 kV when in ignition experiments, a brush discharge (positive polarity) with a grounding electrode on a hydrocarbon liquid charged negatively with a 1 m^3 insulating tank [17] or a metal tank 1.6 m in diameter [18] ignited such a flammable atmosphere;

- The results led to the conclusion that a charging potential of at least about 40 kV is required for the occurrence of an incendiary brush discharge [18];

- In an experiment in laboratory scale, it required −25 kV [19];

- In an EU standard [4], the threshold is 58 kV.

It was stated earlier that the onset limit for a brush discharge concerning the charging potential was not easy to obtain in theory; however, the relationship between the average potential $\overline{V}$ of the nonconductor surface (equivalent to the potential measured with an electrostatic voltmeter) and the energy of a brush discharge, which can be expressed by

$$W_d = k\left(\overline{V}Q_{tm} - \frac{Q_{tm}^2}{2C_d}\right), \tag{3.13}$$

has been revealed by a theory and an experiment (an ignition experiment on hydrogen and propane with a brush discharge between a grounded sphere up to 25 mm in diameter and an a charged plastic sheet) [20]. Here, Q_{tm} is the maximum charge transferred and C_d is the apparent capacitance of the discharged portion. Q_{tm}, C_d and k have experimentally been determined as follows:

$$Q_{tm} = 1.4 \times 10^{-9} D^{1.7}, \tag{3.14}$$

where D is the diameter of the grounded sphere and its unit in mm. When $D > 20$, $D = 20$.

$$C_d = 9.8 \times 10^{-12},\ k = 0.08. \tag{3.15}$$

This can be used to estimate the discharge energy based on the potential measured with an electrostatic voltmeter. Conversely, the minimum ignition energy of an atmosphere can be used to estimate the permissible charging potential. In consideration of this, Figure 3.11 shows the relationship between the energy of the brush discharge and the potential of a nonconductive body. The analysis of this equation has also led to the conclusion that an incendiary discharge cannot be generated even in a hydrogen-air mixture of group IIC at $\overline{V} \leq 4$ kV or at $D = 2$ mm or less [20].

3.3.7.3 Prevention of a brush discharge

A surface charge density of less than 3 $\mu C/m^2$ of a nonconductor is required to prevent the conditions for generating brush discharge. However, it is difficult to suppress the charge of nonconductive materials. In general, therefore, a brush discharge is prevented by limiting the area and width (Table 7.1) with electrostatic shielding (see 7.5) or by using conductive/dissipative materials. Another method available is the use of a charge neutraliser (ioniser) (see 7.6), but such a neutraliser may serve as a source of ignition [11].

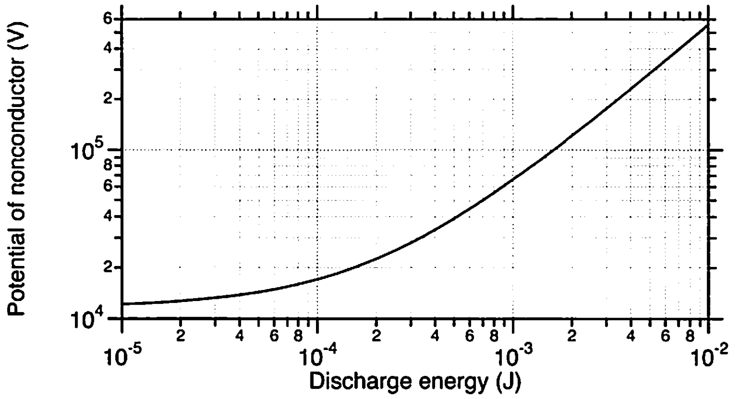

Figure 3.11: Relationship between the average potential (the potential measured with an electrostatic voltmeter) on nonconductor surface and the energy of a brush discharge at D = 20 mm in Equation (3.13).

3.3.8 Propagating brush discharge

3.3.8.1 Occurrence of a propagating brush discharge

The maximum surface charge density that can be held on an insulating body is 27 μC/m^2 from Equation (3.6). However, as this insulating body becomes thinner, a double layer charge of positive and negative polaroties will be formed at the front and the rear side of the thin insulator, which enables even higher surface charges to be held. This can be explained by the fact that each surface electric field is reduced by the electric field due to the surface charge of the other layer. A discharge generated along the surface of the insulator where such a double layer occurs when a grounded object approaches it (Figure 3.8d) is referred to as a propagating brush discharge. This discharge also depends on the polarity of the surface charge, which is similar to corona and brush discharges.

Propagating brush discharge is initiated by the approaching of a grounded sphere to this double layer or a closed circuit on the double layer due to a pinhole or other fault on the surface of this insulating layer. The space charge of this discharge generates an electric field in the radial direction on the layer; then, many discharge channels in the direction centering on the point of the onset of the discharge will spread on the insulating layer, and a propagating brush discharge will thus be observed. A propagating brush discharge has long been considered to require a backing grounded conductor. However, as seen on the surface of an insulating tank, pipe, flexible intermediate bulk container, or other object, the presence of the grounded conductor is not considered to be essential[11] [6, 10].

This propagating brush discharge occurs when the surface charge density is $\geq 2.5 \times 10^{-4}$ C/m^2 (this threshold of the surface charge density becomes about 10 times as high as that of the surface charge density of an ordinary charged body on which no double layer is formed) and is considered not to occur unless the insulating layer is $\leq$ 8 mm [21–23]. Moreover, as shown in Figure 3.12 [21], in which the limit for a propagating brush discharge has experimentally been determined, this discharge may not occur when the dielectric breakdown voltage of the insulating layer is less than 4 kV. The electrostatic energy accumulated in the insulating layer is several kJ/m^2, and the discharge energy may reach about 10 J. The propagating brush discharge can, therefore, become a source of ignition not only for flammable gas or vapour but also for flammable dust.

In practical situations, propagating brush discharges occur when

- an insulating pipe or a pipe coated on the inside with glass lining or other insulating coat

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[11] When an insulating tank is charged on the inside, charges generated by a corona or brush discharge outside of the charged tank induced lead to charging outside with opposite polarity, resulting in a double layer

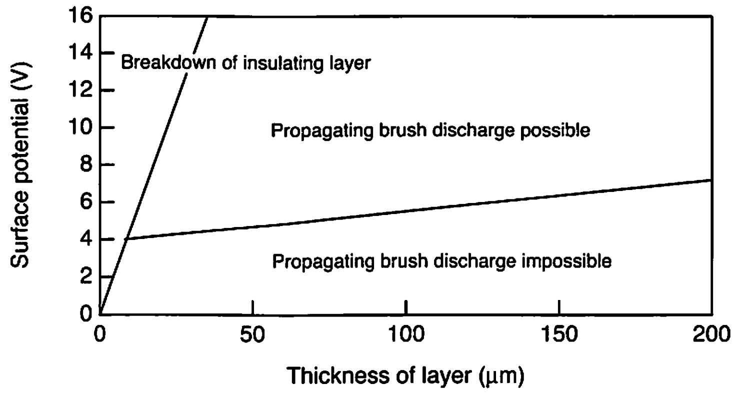

Figure 3.12: Inception limit of a propagating brush discharge [21]

is used to transport powder or liquid fast;

- liquid or powder is filled into an insulating container, an FIBC, or a grounded metal container with an insulating coat;
- powder or liquid is agitated in an insulating container, a container coated on the inside with insulation, or a container having a window made of glass or other material;
- powders collide continually with an insulating plate, such as a dust separator;
- a metal roller coated with insulating materials or an insulating film or tape rolled by a metal roller.

3.3.8.2 Prevention of a propagating brush discharge

A propagating brush discharge can be prevented by reducing the surface charge density of a thin insulator ≤ 8 mm thick to $< 2.5 \times 10^{-4}$ C/m^2 which is the generation limit for the discharge. Another method available is to reduce the dielectric breakdown voltage of the insulating layer to less than 4 kV.

3.3.9 Cone discharge

3.3.9.1 Occurrence of a cone discharge

When a silo or another relatively large container is filled with an insulating powder (mainly by pneumatic transport), the surface of the conical heap where the charged powder is accumulated will develop a discharge, as shown in Figure 3.8e [10, 14, 24]. This discharge is referred to as a cone discharge. At present, the conditions for the occurrence of a cone discharge have not been accurately determined, but such a discharge occurs frequently when the following conditions are met:

- The powder particle size is relatively large: discharge occurs frequently when the size is 1 mm or more;
- The powder resistivity is high: frequent when 10^{10} Ω·m or more;
- The charge-to-mass ratio is large: frequent at $\geq 1\mu$C/kg;
- There is a high flow rate: frequent when the filling is high (thousands of kg/h or more) continuously, for example, 2×10^3 kg/h or more for powder with a size greater than 1 to 2 mm, or 20–30 $\times 10^3$ or more for powder with a size of about 0.8 mm.

The discharge energy of the cone discharge is tens of mJ or less, and the cone discharge may become a source of ignition for gas, vapour, or dust. In the case of a dust explosion, powder with relatively large particle sizes under the conditions for a cone discharge described above cannot disperse in space; thus, it is difficult to create an explosive atmosphere. For ignition with this discharge, it must contain fine powder with sizes up to hundreds of μm.

When powder less than 10^{10} Ω·m is filled into a grounded container, a cone discharge is unlikely to occur. However, it will begin to occur at larger than 10^{10} Ω·m. At larger than 10^{12} Ω·m, such a discharge is difficult to avoid.

For the reader's information, for a silo of 0.5 to 3.0 m in diameter and powder having an average particle size (median diameter) of 0.1 to 3 mm, the maximum energy of a cone discharge can be estimated with the following equation obtained experimentally [25],

$$W = 5.22D^{3.36}d^{1.46}, \tag{3.16}$$

where W (mJ) is the maximum energy of a cone discharge, D (m) is the diameter of the grounded silo, and d (mm) is the median diameter of powder. A cone discharge is likely to occur with powder of relatively large particle sizes, but a cone discharge has been observed in fine powder of 0.1 to 0.2 mm as well, as shown in the condition above for this equation, while the frequency has relatively declined [25].

3.3.10 Lightning-like discharge

When powder is loaded or transported into a silo or jet-washing in a tank, charged powder or mist distributes in the gas-phase space, creating a space charge cloud (a charged cloud). This charged cloud is considered to be able to cause a discharge with regard to a grounded silo or tank wall. This discharge is referred to as a lightning-like discharge and becomes a possible source of ignition for flammable powders or liquid vapours as well as gasses; however, the results of experimental investigations of the possibility of a lightning-like discharge due to the space charge are as follows:

- It has not been observed in silos of 60 m^3 or with a diameter of up to 3 m [26];
- No lightning-like discharges due to an charged cloud of liquid mist have been observed during water jet-washing of a tanker of up to 3×10^4 m^3 [27].

British standards [7] go as far as to tolerate large-capacity tanks (with a grounded metal) of 3,000 m^3, one-tenth of the above mentioned in jet washing. In general, lightning up in the sky is considered to require charged clouds at least tens to hundreds in meter size. Moreover, the sustainment and evolution of a streamer requires an average electric field of 5 kV/cm [28], i.e., a potential difference of 500 kV per 1 m in a charged cloud. The above leads to the consideration that no lightning-like discharge occurs under the conditions of industrial processes. However, the presence of a protrusion grounded close to a charged cloud may cause a brush discharge. That issue will be described in B.3.4.

3.4 Mechanic phenomena due to electrostatic force

Mechanic phenomena of static electricity are phenomena in which a lightweight body close to an charged body is attracted to the charged body or repels and moves in relation to it due to a Coulomb force, which is the electrical action due to static electricity. Since it acts due to the surface charge of the body, such materials as paper, film, sheet cloth, fibre, powder, and fine powder having a higher percentage in surface area than in weight are more susceptible to mechanic phenomena, thus becoming a cause of various problems for fabrication.

Chapter 4

General concepts related to the risk evaluation of static electricity and protective measures

4.1 Assessment of electrostatic risk

The risk of static electricity can be determined by evaluating the matters listed below. This procedure corresponds to the identification of hazards for risk assessment.

(1) Is the atmosphere flammable (within a flammable limit)?

(2) Can charge be generated and, if so, can it accumulate?

(3) Can electrostatic discharge occur? If so, what type of discharge?

(4) Is that type of discharge incendiary? (Can that type of discharge ignite the target flammable atmosphere?)

4.2 Basic measures against electrostatic hazards

It is no exaggeration to say that measures for preventing electrostatic disasters (risk reduction measures) are those to prevent incendiary electrostatic discharges. When it becomes difficult to take measures to prevent electrostatic hazards, measures to prevent ignition by avoiding the generation of an explosive atmosphere must be taken. A disaster caused by electrostatic hazards occurs following the flow shown in Figure 4.1, and antistatic measures or measures to prevent the formation of an explosive atmosphere are then taken. The main measures for preventing electrostatic hazards can be summarised as follows:

(1) Grounding all conductors (Chapter 5)

   (a) Grounding equipment, machinery, or any other conducting structure

   (b) Eliminating electrically floating (insulated) metals: Grounding metals on nonconductors (such as plastic pipes, a container flange, or a metal drum on an insulating floor). Here, small metal objects with capacitance below 3 pF, such as screws, are excluded from grounding.

(2) Grounding the bodies of workers and making their clothes antistatic (chapter 6)

   (a) Grounding human bodies by using a combination of antistatic footwear and conductive/dissipative flooring

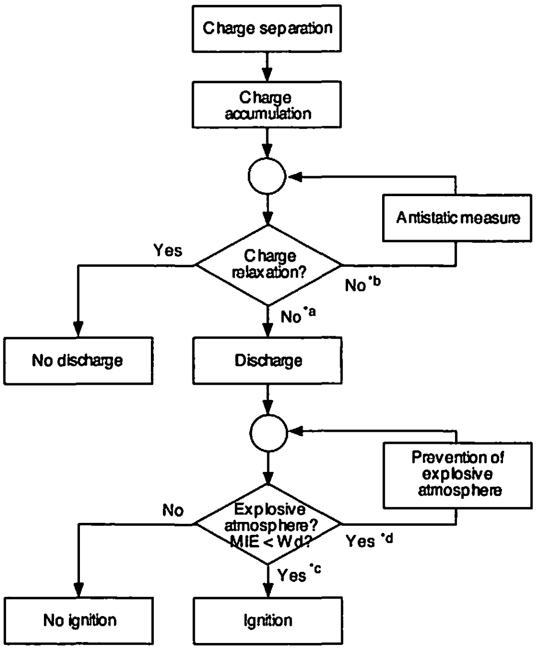

Figure 4.1: Flow of the occurrence of electrostatic hazards and preventive measures, *a: when there is hardly any charge relaxation, or when an inappropriate antistatic measure has resulted in the lack of charge relaxation, *b: when an antistatic measure is taken against the lack of charge relaxation, *c: when the discharge energy W_d is higher than the minimum ignition energy MIE, or when the measures to prevent the formation of explosive atmospheres is inappropriate and $W_d \geq$ MIE, *d: when there is a risk of ignition and a measure to prevent formation of explosive atmospheres is taken.

  (b) Wearing antistatic work clothes

(3) Eliminating nonconductors (chapter 7)

  (a) Using a container, pipe, filter, or something similar made of conductive/dissipative material and grounding it. (7.4)
  (b) Limiting the area of nonconductors (7.3)
  (c) Using electrostatic shielding (7.5)
  (d) Adding an antistatic agent or a conductive liquid to nonconductive liquid. (7.4)

(4) Suppressing charge generation (Chapter 7)

  (a) Limiting the operation speed at work and the flow velocity of liquid or powder being transported.
  (b) For chargeable liquids, avoiding turbulence, splashes, and eruptions.

(5) Preventing explosive atmospheres (Appendix A)

  (a) Ensuring proper ventilation
  (b) Eliminating flammable gas, vapour, and powder (using a local exhaust).
  (c) In operations using flammable liquid, reducing its temperature to a level at least 5°C lower than the flash point.
  (d) Inerting

(6) Establishing appropriate safety management systems

(a) Measures must be controlled and maintained under a safety management system at the workplace.

(b) Performing risk assessment.

As shown in (1)–(4) above, the essence of antistatic measures is to accelerate charge relaxation and suppress charge generation to prevent unwanted charges.

4.3 Control of static electricity

The accumulation of static charge can be suppressed to prevent electrostatic hazards by reducing the leakage resistance of the charged body or increasing the conductivity of the surroundings, thus accelerating the charge relaxation.

4.3.1 Grounding and bonding for conductors

A charged conductor may generate a spark discharge that can cause an electrostatic hazard. All conductors and conductive materials should, therefore, be grounded.

Grounding is a measure that is taken to prevent the electrification of conductors by connecting them to ground electrically. Bonding refers to connecting a conductor electrically with another grounded conductor and is used as a method for grounding when it is not easy to directly ground a conductor. Such bonding results in a potential difference between conductors bonded to zero.

Since the current due to static electricity is less than several tens of μA in industrial processes, grounding any conductive bodies with a leakage resistance of $\leq 10^6$ Ω can eliminate their hazardous potential (see Chapters 5 and 3.3.5.3)

4.3.2 Eliminating nonconductors and using conductive materials

Nonconductors undergo hardly any charge relaxation even when grounded; as a result, grounding does not work. A charge generated in a nonconductor will accumulate and become a cause of electrostatic hazards. Nonconductors should be replaced with something made of conductive/dissipative material, which should then be grounded. Alternatively, a nonconductor (such as an insulating liquid) may be given an antistatic additive or something similar to increase the conductivity, thus reducing the risk of brush discharges and propagating brush discharges (see Chapter 7).

4.3.3 Grounding and prevention of charging for workers

Workers can also be a source of electrostatic discharges. Therefore, the shoes they wear and the flooring walk on should be conductive or dissipative so that the workers (human bodies) are grounded. Furthermore, workers should wear antistatic work clothes to suppress charge accumulation on the clothes and to prevent an incendiary discharge occurs from clothes (Chapter 6).

4.3.4 Control of charge generation

In general, charge generation due to its separation rises with the contact area and the friction velocity. Such charge generation can be controlled by slowdown or other change in processes.

4.3.5 Charge neutralisation

Charge neutralisation is the elimination of charge using an ioniser. The ions generated by it are used to neutralise the charge on a charged body. Charge neutralisation is equivalent to increasing the conductivity of the medium surrounding a charged body (charge relaxation via the conductive path of those surroundings). It is effective in neutralising nonconductors. However, risk reduction measures on an ioniser should not be taken alone but in conjunction with other measures (7.6).

4.3.6 Electrostatic shielding

Covering a charged nonconductor with a grounded conductor can reduce the influence of its charge, thus suppressing the risk of brush discharges and propagating brush discharges. These include grounded conductors wound on an insulating hose in a spiral manner. (see 7.5.)

4.4 Prevention of a flammable atmosphere

Even in the presence of a source of ignition, an ignition never occurs in a nonflammable atmosphere; thus, measures for preventing the generation of flammable atmospheres are effective. Appropriate measures would be those making the atmosphere nonflammable, thus obviating the need for any antistatic measures for preventing ignition. (Appendix A.)

4.5 Safety management

Antistatic measures need periodic inspection and maintenance based on systematic management. Moreover, regardless of the measures taken, static electricity will be, to some extent, inevitable as long as there is matter. Furthermore, absolute safety is impossible in processes requiring the handling of flammable substances. To prevent disasters, therefore, it is important to establish a risk management system to effectively conduct risk assessment.

Chapter 5

Grounding and bonding

5.1 Purpose of grounding and bonding

Grounding is one of the most basic of all antistatic measures. Grounding[1] aims to build an electric leakage path to allow static charge generated in a conductive body to go to the earth in an attempt to prevent the body from accumulating static charge by charge relaxation. Grounding and bonding eliminate the potential difference between nearby conductive bodies grounded or bonded, thus preventing discharges occurring between them.

5.2 Application scope of grounding and bonding

Grounding a conductor, such as a body made of metal or conductive materials or a worker (a human body), as described in 4.3, prevents static charge accumulation on that body that can cause a spark discharge. Bodies that can be effectively grounded are made of a material having volume resistivity of less than 10^8 Ω·m and surface resistivity of less than 10^{10} Ω. In other words, they are made of something other than the nonconductive materials specified in Table 2.2.

5.3 Objects to be grounded or bonded

Objects to be grounded or bonded are conductors:

(1) Grounding of all metals regardless of their sizes as long as they are susceptible to electrostatic charging or induction. Here, metals with capacitance to ground of less than 3 pF can be excluded;

(2) Metals supported by a nonconductor or on a nonconductor should be grounded directly or via bonding;

(3) Bodies made of conductive/dissipative materials should be grounded via a metal adhering them;

(4) Grounding of workers (see Chapter 6).

If a metal conductor is already grounded as described below, or if it is bonded to the following grounded item, it is not necessary to establish another grounding:

(1) Protection grounding against lightning;

(2) Protection grounding for electrical equipment and appliances against electric leakage ;

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[1] Note that the resistance for grounding for antistatic measures is higher than that of electric equipment because the electrostatic current is much lower than that of the current.

(3) Protection grounding against induction of high voltage, electromagnetic waves, and other phenomena;

(4) When a part of a metal conductor is buried underground or bonded to a buried steel frame, reinforcing bar, or other metal structures.

5.4 Leakage resistance

For grounding of conductors except for workers, the leakage resistance should be less than 10^6 Ω. Toward this end, the grounding resistance of a grounding electrode must be set to less than 1000 Ω[2].

5.5 Bonding resistance

To ensure the necessary leakage resistance, the bonding resistance must be set to less than 1000 Ω. This requirement is generally satisfied because bonding is usually performed with sheathed conductive wires.

5.6 Methods of grounding and bonding

5.6.1 Grounding electrode

Grounding electrodes designed to establish antistatic grounding are as described below:

(1) Grounding electrodes and grounding bars used to ground general electrical appliances are available as electrodes;

(2) If a part of a structure made of a metal conductor or a part of a metal body is buried underground and if its grounding resistance is less than 1000 Ω, it may be used as a grounding electrode.

5.6.2 Grounding and bonding wires

Grounding and bonding wires must be made of a material that is unlikely to corrode and of a sheathed wire, cabtyre cable, metal plate, or other material having mechanical strength that is high enough to prevent easy wire breaks under normal operation conditions. Enough attention should be paid, in particular, to ensuring that the grounding and bonding for a conductor of a moving, portable, or vibrating body are strong.

5.6.3 Connection terminals

Below is a list of instructions for proper installation of connection terminals,

(1) Connect the grounding and bonding wires securely to prevent them from coming off easily.

(2) For connection terminals and terminal instruments with grounding and bonding wires, use those made of a material having high mechanical strength and resistance to corrosion.

(3) To connect a connection terminal with a grounding and bonding wires, use screwing with crimp terminals and bolts (Figure 5.1a) or large alligator clamp connectors having high pinching forces for moving and portable bodies[3] (Figure 5.1b) or a similar method that ensures connections that are electrically and mechanically secure.

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[2] The leakage resistance includes this grounding resistance. The grounding resistance of large tanks and other fixed equipment needs to be set to less than 10 Ω.

[3] Metal buckets on a grounded conductive floor, trolleys equipped with conductive rollers, and similar equip-

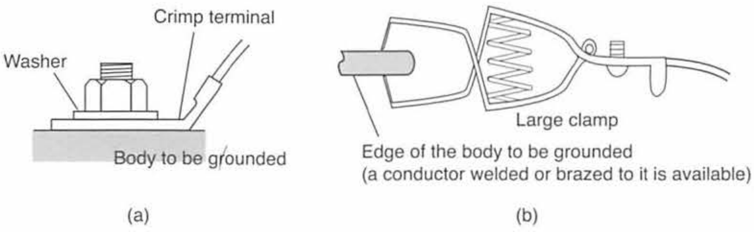

Figure 5.1: Grounding terminal: (a) terminal of fixed equipment; (b) terminal of a portable body

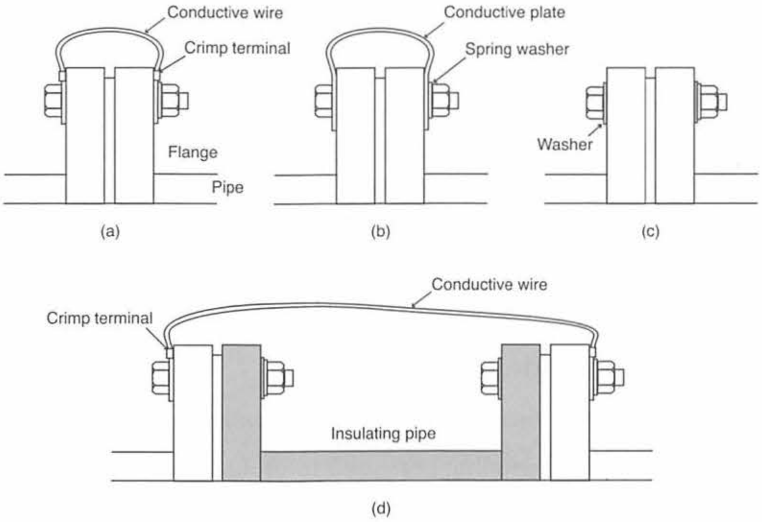

Figure 5.2: Examples of pipe bonding

5.6.4 Precautions for grounding and bonding

When using grounding as an antistatic measure, the current capacity of the grounding wire is not an issue. The key is to prevent wire breaks, coming off of wires, imperfect contact, and other mechanically and electrically imperfect contacts, and omissions of connection. When bonding metal pipes (Figure 5.2), each flange of which is used to make metal connections with a resistance of less than 1000 Ω with metal bolts and nuts (Figure 5.2c), it is not necessary to make connections with any conductor. Installing an insulating pipe or hose midway in the metal piping should be avoided because it would be equivalent to a break in bonding. Moreover, such a pipe or hose may cause a propagating brush discharge. If the use of such an insulating pipe, e.g., a window, is unavoidable, then bonding must be performed as shown in Figure 5.2d. At that time, the insulating pipe must be made as short as possible, and, in a hazardous area, it must be shielded electrostatically.

Grounding and bonding need to be constantly carried out. Temporary grounding or bonding may cause induction charging (see 3.2.2), thus being hazardous.

Putting a grounded conductor into contact with a nonconductive fluid as illustrated in Figure 5.3 may cause the generation of static charge. Therefore, a grounded conductor should not be put into a nonconductive fluid for antistatic purposes. See "Antistatic Grounding," in the separate volume, TR–85–3: *Supplement of Guidelines* of this document.

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ment are grounded through contact with that floor. However, dirt on the floor, a metal bottom on a bucket, or rollers will increase the leakage resistance, resulting in electrostatic disasters. Therefore, securely ground and bond these objects as well.

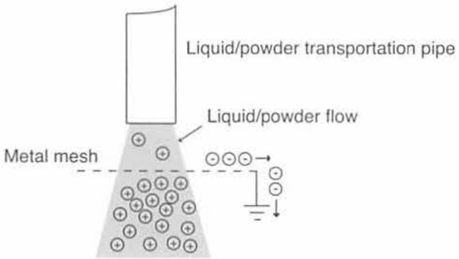

Figure 5.3: Example of incorrect grounding: charging of a liquid or powder due to charge separation at the contact with a grounded metal

5.7 Maintenance of grounding and bonding

A break in a grounding or bonding wire will cause an electrostatic hazard. Grounding and bonding, therefore, need periodic maintenance. For a method to measure their resistances, see C.9.6. In addition, see "Inspections for Avoidance of Electrostatic Hazards on Facilities for Manufacturing flammable Liquids, Powders, and Other Materials," in the separate volume, TR–85–3: *Supplement of Guidelines* of this document.

Chapter 6

Antistatic measures for workers

6.1 Risk of workers becoming charged

- Workers become charged mainly as a result of charge separation, such as that due to friction of workers' clothes with a seat or between footwear and floor during walking, and as a result of electrostatic induction when workers approach a high-voltage object.
- The human body is an electrostatic conductor. It may, therefore, cause spark, brush, or propagating brush discharges.
- Therefore, a discharge caused by a worker is a sufficiently possible source of ignition for flammable gases, vapours, and dusts.

6.2 Antistatic measures for workers

In hazardous areas susceptible to electric shocks, workers should be grounded and be prevented from becoming charged:

(1) Grounding human bodies
Making work floors and footwear conductive or dissipative.

(2) Antistatic measures for work clothes
Wearing antistatic work clothes[1].

6.2.1 Grounding a worker (human body)

To prevent electrostatic hazards caused by workers becoming charged, the leakage resistance of the workers (human bodies) must be reduced to less than 10^8 Ω[2] , thus reducing the potential of workers to be charged to less than 100 V (see 3.3.5.3). The leakage resistance of a human body is mainly the sum of the resistance of their footwear and the leakage resistance of the floor. To satisfy the conditions for the leakage resistance of a human body, the floor and footwear need to be made conductive or dissipative, as described below.

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[1] Needless to say, these include overalls, heavy winter work clothes, dust-free garments, and other work clothes.

[2] The leakage resistance of workers does not necessarily decrease to less than 10^8 Ω under the following conditions:

- The leakage resistance must be set to more than 10^5 Ω to prevent electric shocks due to a distribution wire of less than 400 V.
- The leakage resistance must be set to less than 10^6 Ω in hazardous areas of Zone 0 (IIC) and Zone 1 (IIC). Normally, people should not work in such areas.
- If electric shocks are frequent, they may be prevented by setting the leakage resistance to less than 10^9 Ω.

(1) Making the flooring conductive/dissipative
To prevent workers from being electrical insulated from the earth, ground them by using an appropriately grounded conductive or dissipative flooring or mat. The leakage resistance of the work floor should be set to less than 10^8 Ω to allow the static electricity from the human body to leak to the earth through it in a short time.

(2) Making footwear conductive/dissipative
Shoe resistance[3] must be 10^5–10^8 Ω (JIS T8103 [29] specifies that it should be 10^5–10^9 Ω[4]).

(3) If the range of action is limited, as in seated operations, another effective way for grounding human body is to use a wrist strap.

For guidelines for selecting antistatic clothes and footwear and measuring their antistatic properties, see "Antistatic Footwear, Work Clothes, and Gloves," in the separate volume, TR-85-3: *Supplement of Guidelines* of this document.

6.2.2 Prevention of charging of work clothes

To control charge accumulation in workers, workers should wear antistatic work clothes, and the following comprehensive antistatic measures should be taken:

(1) Regarding work clothes, workers should wear antistatic work clothes that are made of conductive fibre so that they do not become charged and are JIS-compliant (JIS T8118 [30]).

(2) Regarding gloves, helmets and hats, and other gear, workers should wear antistatic ones if necessary in consideration of the nature of their specific task and location.

(3) Regarding rubber gloves, workers should wear conductive/dissipative gloves.

(4) It must be ensured that workers do not put on or take off their work clothes in hazardous areas because this may cause charge generation and discharge.

(5) Regarding antistatic work clothes, they should be worn correctly with the buttons and should be correctly fastened. As long as this rule is followed (on the precondition that workers are grounded through antistatic footwear and conductive or dissipative flooring), there are no limitations regarding what material the clothes workers wear underneath their antistatic clothes are made of.

In hazardous areas of Zones 0, 1, 20, and 21, workers should preferably wear nonflammable or flame-retardant antistatic work clothes.

For the guidelines for selecting antistatic clothes and footwear and measuring their antistatic properties, see "Antistatic Footwear, Work Clothes, and Gloves," in the separate volume, TR-85-3: *Supplement of Guidelines* of this document.

6.2.3 Encouraging safe work

Workers should avoid as much as possible any behaviour that may cause them to become charged. Reasons that workers become charged include:

(1) Approaching or contacting a highly electrified body (a cause of induced charge which leads to a spark or brush discharge);

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[3] Workers should not take any action that could increase resistance, such as wearing two pairs of socks, heavy socks, or insulating liner.

[4] This upper limit of 10^9 Ω is a revised standard because the JIS testing method was revised according to IEC and there have been cases in which products which used to comply with JIS standards at less than 10^8 Ω ceased to be in compliance. Therefore, it suffices for work footwear to be the antistatic type, complying with JIS standards.

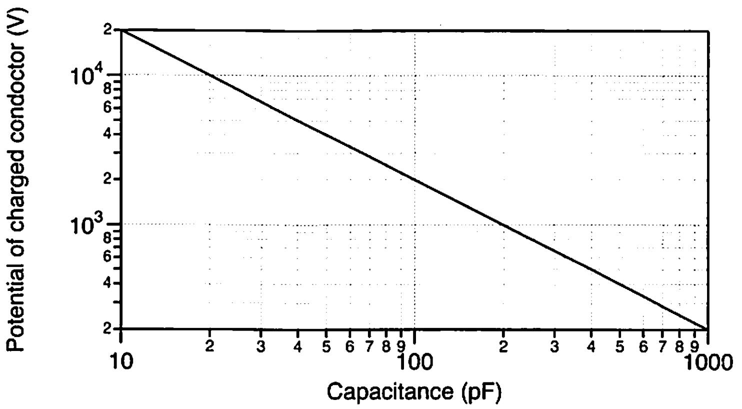

Figure 6.1: Limit of electric shocks by a charged conductor (calculations to be performed with the transferred charge set at 0.2 μC): An electric shock may occur in the region above the straight line.

(2) Operations in an environment where workers are insulated (a cause of charge accumulation which leads to a spark discharge);

(3) Workers putting on and taking off their clothes during work (charging by friction may lead to a discharge).

To avoid these incidents, it would be effective to write a work manual and have workers observe the procedures outlined there for safety. Simultaneously, safety training, including that regarding the risk of static electricity described above, is necessary.

6.3 Safety management

Work flooring, clothes, footwear, and other gear may change in resistance and antistatic performance due to dirt on their surface. The resistance and antistatic performance must then be periodically measured and managed. For the method of measurement, see the annex to this recommendations, TR-84-1: *Recommended Standards of Construction of Appliances used for Protection against Electrostatic Hazards.* Another effective method is to use a simple meter to test the leakage resistance of workers with their shoes on before work.

Regarding the work floor, its leakage resistance should be measured and managed at least once a year, including during the dry season. In addition, the floor must be periodically cleaned. For this task, insulating wax should not be used. Note that flooring with an antistatic agent[5] on it may become less antistatic when cleaned.

In addition, as workers' behaviour might be unpredictable, such behaviour needs to be identified, the potential hazard evaluated, and the necessary risk reduction measures defined.

6.4 Electric shocks

An electrostatic discharge from workers can cause electric shocks. Electric shocks can, through a shock-induced action, result in a fall or other secondary accidents. They are caused mainly by spark discharges due to charging potential of several kV to tens of kV. Electric shocks due to these spark discharges can be prevented by grounding and bonding the conductors and taking the antistatic measures for workers specified in this chapter.

The magnitude of an electric shock is correlated with the charge transferred by a discharge. An electric shock generally occurs when the transferred charge exceeds 2–3 $\times 10^{-7}$ (0.2–0.3 μC). The potential V of a charged worker receiving an electric shock due to a spark discharge that

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[5] Since the antistatic effects do not last long, frequent measurement and management are necessary.

Table 6.1: Potential of a charged human body and the intensity of electric shocks

Potential (kV)	Intensity	Remarks
1.0	Not felt at all	
2.0	Felt on the outside of the fingers, with no pain.	Slight discharge noises occurred.
2.5	Felt like a needle slightly piercing, but there was no pain.	
3.0	Felt like a needle piercing, and there was slight pain.	
4.0	Felt like a needle piercing deeply, with slight pain in the finger.	Discharge-induced light seen.
5.0	Felt pain from the palm to the forearm.	Discharge light extended from the fingertip.
6.0	Felt strong pain in the finger and heaviness in the upper arm.	
7.0	Felt intense pain in the fingers and palm with a feeling of numbness.	
8.0	Felt numbness from the palm to the forearm.	
9.0	Felt intense pain in the wrist and numbness and heaviness in the hand.	
10.0	Felt pain and electricity in the entire hand.	
11.0	Felt complete numbness in the fingers and an intense electrical shock in the entire hand.	
12.0	Felt as if the entire hand had been hit hard.	

Note: Capacitance of the human body: about 100 pF

occurs on a grounding conductor can be expressed as $V = Q_d/C$, where Q_d is the transferred charge. Moreover, since the capacitance C of a person is between 100 and 300 pF, minimum potential V_{min} of a worker that may receive a shock is within the following range:

$$667\ \mathrm{V} \leq V_{min} \leq 3\ \mathrm{kV}. \tag{6.1}$$

The severity of an electric shock depends on a person's threshold of pain. In general, however, when the potential exceeds 3 kV, any human being is supposed to feel an electric shock. Table 6.1 indicates the relationship between the potential of a charged human body and the intensity of an electric shock.

Conversely, the limit of electric shocks between a charged body (conductor) and a worker (considered as a grounded conductor) is

$$V_o \geq \frac{2 \times 10^{-7}}{C_o}. \tag{6.2}$$

Here, V_0 and C_0 are the electrification potential and the capacitance of an electrified body, respectively. Equation (6.2) is represented in Figure 6.1. Electric shocks may occur above the straight line.

When the charged body is a nonconductor, the discharge is either a brush discharge or a propagating brush discharge. In a brush discharge, the worker often receives an electric shock when its potential exceeds about 30 kV. To prevent electric shocks due to brush discharges, the potential of the nonconductor should be set to less than 10 kV. For preventing electric shocks due to propagating brush discharges, see 3.3.8.2.

Chapter 7

Antistatic measures for nonconductors

7.1 Electrostatic risk of nonconductors

Nonconductors can accumulate charge easily; thus, they have the potential to create brush discharges, propagating brush discharges, or cone discharges.

7.2 Resistivity and conductivity of nonconductors

Nonconductors are made of matter in which charge relaxation unlikely occurs and charge is accumulated. As shown in Table 2.2, they can be defined by their resistivity (conductivity). The matter has volume resistivity of more than 10^8 Ω·m (with conductivity of less than 10^{-8} S/m) and, in the case of solids, surface resistivity of more than 10^{10} Ω. The use of such matter can cause electrostatic hazards but the risk can be reduced if the measures described below are taken.

7.3 Nonconductor limitation

It is difficult to prevent the charging of nonconductors. The use of nonconductive materials should, therefore, be avoided whenever possible. The areas and widths of nonconductive materials should be restricted depending on hazardous areas, Zones 0, 1, and 2 (see Table 2.3) and ignition energy, gas/vapour groups IIA, IIB, and IIC (see Table 2.4). A guide as to hazardous areas and ignition energy is given in Table 7.1. This table is based on ignition experiments on various gases by the discharges from charged nonconductors having various areas [1,11,31]. Precautions regarding the limitations of these nonconductors are described in 7.4 and 7.5.

Table 7.1: Restriction of the area or width of nonconductive materials [4]

Zone	Group IIA		Group IIB		Group IIC	
	Max. area cm^2	Max. width cm	Max. area cm^2	Max. width cm	Max. area cm^2	Max. width cm
0	50	0.3	25	0.3	4	0.1
1	100	3.0	100	3.0	20	2.0
2	No limit	No limit	No limit	No limit	No limit	No limit

The width applies to thin pipes, cable sheaths, and other nonconductive materials having small widths (diameters).

7.4 Improving conductivity

This antistatic measure consists of increasing the conductivity of a nonconductive material and grounding it appropriately, thus accelerating the charge relaxation in an attempt to control charge accumulation.

7.4.1 Using metal materials

For the items listed below, the use of nonconductive materials should be avoided, instead, metal materials should be used whenever possible, and they should be grounded and/or bonded:

(1) Parts, devices, and equipment in which charge generation continues to occur due to friction or a similar phenomenon;

(2) Containers and other equipment that handle large quantities of charged substances, such as liquid and powders;

(3) Mobile devices and equipment.

7.4.2 Using conductive/dissipative materials

If no metal is available, items made of conductive or dissipative materials should be substituted, and the items should be appropriately grounded. At that time, the following requirements for preventing electrostatic hazards should be satisfied:

(1) The leakage resistance should be set to less than 10^6 Ω;

(2) For conductive/dissipative materials, use those having volume resistivity of less than 10^8 Ω·m or surface resistivity of less than 10^{10} Ω;

The performance of conductive/dissipative materials may be affected by the environment; as a result, their conductivity should be tested periodically under relative humidity of 50% or less (see the annex to this recommendations, TR–84–1: *Recommended Standards of Construction of Appliances used for Protection against Electrostatic Hazards.*). Even conductors have the potential to create propagating brush discharges when they are given an insulating paint or coat. If there is a risk of electrification, conductive or dissipative material must be used.

7.4.3 Using antistatic agents

An antistatic agent is a chemical based mainly on surfactants. Using it on a nonconductor will make the surface of the nonconductor hydrophilic, resulting in higher moisture absorptivity, or ionic, resulting in higher surface conductivity and thus making the nonconductor antistatic. The antistatic performance is affected by the humidity, and it declines when the relative humidity is less than 40–50%.

7.4.4 Using antistatic materials

Regarding cloth products, those containing conductive fibre to make them antistatic through electric conduction involving self-generated corona discharges[1] should be used. Such products include work clothes, bag filters, cloth chutes, and FIBCs. All antistatic materials must be appropriately grounded, except those related to workers, as workers' bodies should be grounded by their footwear and the flooring they walk on. Although antistatic materials using a corona

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[1] Corona discharges will occur if, in the vicinity of a charged body, there is a metallic or conductive thin-wire (thread) or a conductor having an extremely small tip (see 3.3.6). Ions generated by this corona discharge (such as negative ions if the charged body is positive) neutralise most or part of the charge of the charged body. Thus, since the electric field of the charged body itself generates a corona discharge, it is called a self-generated discharge (sometimes referred to as a passive ioniser) and is used as a precaution for nonconductive materials.

discharge are less affected by humidity, they do not function unless they produce a corona discharge. Such materials using a corona discharge, therefore, cannot reduce charge to levels below several kV.

7.4.5 Humidification

An absorbent nonconductive material can be humidified to reduce its surface resistance and accelerate its charge relaxation. For humidification, the following methods are useful to set the relative humidity to 50–65%:

(1) Using a heating or supersonic humidifier;

(2) Using steam at a pressure slightly higher than the atmospheric pressure;

(3) Using a water atomiser for humidification applicable to a relatively wide range;

(4) Sprinkling water on the floor. However, this method may not be as effective as the others and may entail the risk of a person slipping on a wet floor, depending of the flooring materials.

7.5 Electrostatic shielding

Electrostatic shielding is a method of suppressing the risk of static electricity by covering or by partitioning a nonconductor that has a risk of static electrification with a grounded conductor. Since the charged body is covered with a grounded conductor, the charge will have no effect outside the grounded conductor; therefore, the risk of electrostatic discharge outside it can be suppressed.

7.5.1 Shielding materials

Shielding material should preferably consist of a metal plate or a metal wire net having a mesh of less than several centimetres. The shielding may alternatively be of metallic or conductive tape, a conductive film or sheet, a cloth product containing conductive fibre, or something similar. Regardless of the material used, careful attention should be paid to grounding the shielding.

7.5.2 Methods of shielding

These instructions should be followed when installing shielding:

(1) Ensure that the shielding covers the charged body;

(2) If using metal wire, wind it at intervals of several centimetres;

(3) If using something other than metal, adhere a piece of metal sufficiently to the shielding and ground it securely;

(4) For sheets and similar items, the shielding on only one side should be avoided to prevent a propagating brush discharge on the opposite side (Figure 7.1).

7.5.3 Examples of shielding

(1) To shield a nonconductive hose or pipe, its surface should be shielded with a metal wire or metal tape, or a hose or pipe containing metal wire should be used; in either case, the metal wire should be securely grounded (Figure 7.2).

(2) To shield a powder-handling cloth chute or bag filter, shielding made with a conductive fibre or including metal thin wire should be used and properly grounded.

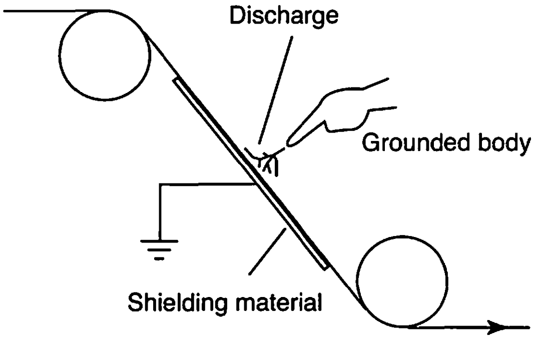

Figure 7.1: Example of incorrect shielding. A cause of a propagating brush discharge.

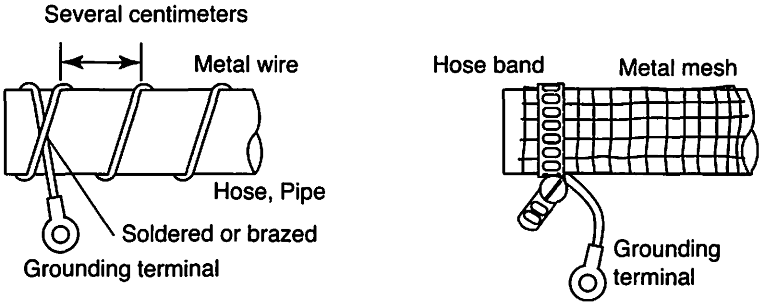

Figure 7.2: Example of shielding of a hose or pipe

7.6 Adding an ioniser

Ionisers are used for charge neutralisation of charged body, in which the charge of the body is neutralised by ions generated by ionizing air in a specific manner. The use of an ioniser should, as a rule, be combined with another measure. In an experiment [11] conducted to evaluate the safety of ionisers, it was confirmed that these instruments can be a source of ignition. When using an ioniser in a hazardous area, therefore, sufficient risk assessment is necessary. In such a case, it is necessary to either use an explosion-proof ioniser[2] or take precautions to prevent an explosive atmosphere by draft, ventilation, or another method. Moreover, it is advisable to obtain expert advice, including that on the effects of neutralisation and the maintenance of ionisers.

7.6.1 Passive ioniser

This method consists of arranging grounded electrodes for a self-generated corona discharge, such as metal needles and thin conductive wires (fibre or brush), to neutralise the charge of charged bodies. This ioniser is limited in scope of application, and its neutralisation performance needs to be investigated. Its use should be avoided in hazardous locations of Zone 0. In Zone 1 as well, it is desirable that not all safety measures rely on an ioniser alone[3].

7.6.2 Voltage-application ioniser

This device neutralises charged objects by using a DC (discharge needles, with separate positive and negative voltages) or an AC corona discharge generated by applying a DC or AC voltage of

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[2] At present there are no explosion-proof ionisers complying with Zones 0, 20, 21, or 22.

[3] A positive corona discharge (in this case, the charged body is negative) turns into a brush discharge when the voltage is tens of kV. It can, therefore, be a source of ignition for flammable atmospheres of gases or vapours.

about 5-10 kV to the discharge needle. The discharge circuit used should incorporate a series high resistor or capacitor (in the case of AC) to limit the current. In hazardous areas, its use should be avoided; alternatively, an explosion-proof neutraliser should be used to prevent it from becoming a source of ignition.

7.6.3 Radiation ioniser

This ioniser generates ions by the ionisation of radioisotopes mostly using α rays of Polonium-210. These ionisers do not become a source of ignition themselves, but they include a source of radiation. Therefore, they should be handled with care according to the law. Their neutralisation capacity is not very high, and their effects need investigation. In hazardous areas, safety measures should not depend on ionisers alone.

7.6.4 Soft X-ray ioniser

Among the various of the wavelengths of X-rays (0.001-10 nm), soft X-rays are those with relatively long wavelengths (0.1-10 nm) and lower penetrating power. When a photon of these soft X-rays collides with a molecule in air, an electron is emitted from the molecule, and the molecule becomes a positive ion. That electron attaches to another molecule, forming a negative ion. These ions are used for neutralisation. Since the ioniser has a source of soft X-rays, laws for their handling should be followed with care. The neutralisation effects need investigation. In hazardous areas, their use should be avoided; alternatively, explosion-proof ones should be used; thus preventing the ioniser from becoming a source of ignition.

Chapter 8

Antistatic measures for liquids

8.1 Ignition by electrification of liquid and mist

8.1.1 Formation of a flammable atmosphere

When a liquid handled is flammable, a flammable atmosphere is formed as a result of the presence of liquid vapour over the liquid.

8.1.2 Hazards of static electricity

Factors of ignition risk in the course of liquid handling operations include:

(1) Liquid flows in pipes, hoses, or filters;

(2) Loading operations;

(3) Phenomena in a process container, such as agitation and post-agitation sedimentation of a liquid containing powder or insoluble liquid;

(4) Gauging and sampling;

(5) Cleaning.

Many disasters have been attributed to these processes.

8.2 Conductivity of liquids

Electrostatic ignition is particularly likely in liquids having low conductivity (less than 50 pS/m), in which charge relaxation unlikely occurs. Liquid conductivity can be classified as shown in Table 8.1. The conductivity and relative permittivity of liquids are shown in Table D.6.

8.3 Classification of tank size

Tanks entail different electrostatic risk levels due to their sizes; thus, the required precautions vary with their size. Tanks are classified by size as shown in Table 8.2.

Table 8.1: Liquid conductivities classified electrostatically

Classification	Conductivity	Typical liquids
High conductivity	> 1000 pS/m	water, pure water, alcohol, ketone, etc.
Medium conductivity	50 – 1000 pS/m	gasoline (leaded), trichlorobenzene, etc.
Low conductivity	< 50 pS/m	gasoline (unleaded), kerosene, toluene, etc.

Table 8.2: Classification of tank size

Large	Diameter or diagonal length > 5 m, and volume > 50 m^3
Medium	Diameter or diagonal length ≤ 5 m, and volume of 1–50 m^3
Small	Container with a volume less than 1 m^3

8.4 Pipe transport

When liquid flows through a pipe or something similar, a double layer of charge (see 3.1.1) is formed at the interface between the liquid and the wall. The charge of one polarity will then flow with the liquid, while another charge will remain on the wall if not grounded. The charge will depend not only on the conductivities of the pipe and liquid but also on the flow velocity v, the pipe diameter d, and other factors. The electrical current of the liquid flow in the grounded metal pipe has a relationship [32], as expressed experimentally in

$$i = 3.7 \times 10^{-6} d^2 v^2 \left[1 - \exp\left(-\frac{l}{v\tau}\right)\right]. \tag{8.1}$$

This equation has also been demonstrated to be within the error range between 0.5 and 2 times [33]; therefore, it is handy as a guide for charging [1] in liquid transport. Here, l is the pipe length and τ is the charge relaxation time ε/σ of the liquid (ε, σ: liquid permittivity and conductivity). The term of the exponential function can be ignored when the liquid has low conductivity or the pipe is sufficiently long ($l/v\tau = \infty$). Then, this equation can be expressed by an equation in which the charge density q is proportional to the flow velocity,

$$q = 4.7 \times 10^{-6} v. \tag{8.2}$$

These equations are quoted in overseas standards [4, 16, 34] as well. Equation (8.2) reveals that flow velocities of 1–10 m/s used in actual antistatic measures are within the range between about 5 and 50 μC/m^3 at the charge density of the liquid. In addition, pipes with a length $l \geq 3v\tau$ are considered to be the same as pipes of infinite length.

8.4.1 Antistatic measures for liquid flows

The following instructions should be followed:

(1) Grounding and bonding.
  (a) Use a conductive pipe or hose to establish a ground.
  (b) Bond the pipe connections.

(2) Controlling charge generation by limiting the flow velocity [4, 7, 19, 27, 34, 35].
  (a) The maximum flow velocity for transporting liquids of medium and high conductivities is 10 m/s.
  (b) The maximum flow velocity for transporting liquids with low conductivity is 7 m/s or Equation (8.3), whichever is the lower velocity.
  (c) The initial maximum flow velocity for loading is 1 m/s.
  (d) The maximum flow velocity is 1 m/s for a two-phase liquid [2] , such as liquid mixture of water droplets, powder, or other insoluble matters.

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[1] However, if the electrification increases considerably as in pipes equipped with a microfilter, Equation (8.1) does not apply.

[2] An experiment in which xylene was provided with powdered silica gel or polycarbonate (with a measured charge density of 400 – 1500 μC/m^3) demonstrated that a two-phase liquid risks ignition when it exceeds 10 – 50 μC/m^3 [35]. From Equation (8.2), the charge density is 5 μC/m^3 at a flow velocity of 1 m/s and does not exceed the above risk limit.

   (e) The maximum flow velocity is 1 m/s when an insulating pipe or container (including its lining) is used. No insulating pipe and container are used for a low-conductivity liquid.

8.5 Loading

8.5.1 Electrostatic hazards in loading

When a tank is loaded with liquid, charged liquid will flow in as shown in 8.4, with the tank accumulating static charges. When a flammable atmosphere is being formed in the tank, there arises a risk of ignition. Possible incendiary discharges during loading are spark and brush discharges caused by charge generation during the pipe transport of liquid, charged mists generated by splash loading, sedimentation charging of liquid drops and powder particles[3], and/or a worker's charging. In other words, charge accumulates not only in the liquid itself but also in the insulated conductor, such as a worker wearing insulating footwear, an ungrounded metal pipe, container, tank, or something similar.

8.5.2 Antistatic measures when loading

8.5.2.1 Generals

Below are the general antistatic measures for tank loading with a liquid. To control charge accumulation during loading:

(1) Grounding and bonding: Appropriately ground and bond not only containers or tanks but also floating roofs, pipes, pumps, filters, hoses, and all other accompanying conductors;

   (a) Large tanks and other fixed equipment should desirably have a ground resistance of less than 10 Ω;

   (b) If a hose is involved, choose a conductive/dissipative one and ground it by bonding;

   (c) Remove a conductor floating on liquid (such as a gauge float or sample vessel), because it may cause spark discharge;

   (d) Ensure that buckets, pails and other portable metal containers are securely grounded or bonded. They have been responsible for many disasters.

(2) Antistatic measures for workers
Grounding workers (human bodies) and making their work clothes antistatic;

(3) Using bottom loading or dip (drop) pipes to avoid liquid splashing;

   (a) The top loading causes liquid splashing, the generation of mist and foam, and splashing from the liquid surface, thus accelerating electrification. Therefore, lower the pipe to a level as low as below the tank (dip pipe). Simultaneously, ensure that it does not contact the tank bottom. To protect against splashes, it is advisable to install a tip on the dip pipe at 45 degrees or install a tee pipe on the tip to make the liquid flow parallel with the tank bottom;

   (b) Alternatively, load the tank from the bottom (bottom loading). At that time, ensure that the liquid flows in the direction of the tank wall to avoid upward eruption and mist generation. To that end, the pipe may be tipped with a tee pipe or something similar;

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[3] Loading fire-extinguishing foam on the surface of oil may cause sedimentation charging. It is therefore necessary to perform loading with equipment having the appropriate flow rate and pipe diameter so that the foam covers the entire surface

   (c) Limit the flow velocity to 1 m/s or less until the tip of the dip pipe becomes 0.6 m below the liquid level or twice the pipe diameter;

(4) For safety, ensure that the maximum flow velocity in the piping does not exceed 10 m/s even in the case of medium- or high-conductivity liquid;

(5) For liquids containing solid foreign matter and water drops, limit the flow velocity to less than 1 m/s;

(6) Fill the tank without stirring the water or other sediment layer, which would generate charge;

(7) Install a grounded pillar-shaped conductor or metal mesh at the centre of the tank, covering from top to bottom, to suppress a potential rise in liquid level;

(8) Take antistatic measures for gauging and sampling (see 8.7, 8.10)

8.5.2.2 Loading low-conductivity liquid

Loading a tank with low-conductivity liquid (< 50 pS/m) requires the measures listed in 8.5.2.1, as well as the following:

(1) Making the liquid conductive by adding an antistatic agent or conductive liquid;

(2) Alternatively, taking either of the following measures to suppress the explosive atmosphere, thus taking measures to prevent ignition;

   (a) Making the inside of the tank inert by using nitrogen or other inert gases;

   (b) Using a floating roof or cover. These should be conductive and appropriately bonded;

(3) Limiting the loading velocity;

   (a) A tank inerting has no velocity limit;

   (b) If the tank has a floating roof or cover and is not made inert, set the flow velocity to less than 1 m/s until the roof or cover floats. After it floats, there may remain no particular velocity limit. For safety, however, it is recommended to limit the velocity to less than 7 m/s.

   (c) If the tank is large with a fixed roof and not inert, limit the velocity to less than 1 m/s;

   (d) Flow velocity limit: Below is the flow velocity limit for loading low-conductivity liquid (liquid in which there is no solid, water drops, or other matter that does not dissolve in liquid);

$$vd = \begin{cases} N \times 0.50\ \mathrm{m^2/s} & \text{(Conductivity} > 5\ \text{pS/m)} \\ N \times 0.38\ \mathrm{m^2/s} & \text{(Conductivity} \le 5\ \text{pS/m)} \end{cases} \tag{8.3}$$

Here, v is the flow velocity in the pipe, while d is the diameter of the upstream pipe. When there are different pipe diameters, use the smallest one. If this minimum diameter part is not more than 10 m long and if its cross section is at least 67% of the cross-sectional area of the next smallest diameter, then it would be advisable to use the second smallest diameter.

$$N = \begin{cases} 1 & (L < 2\ \mathrm{m}) \\ \sqrt{L/2} & (2 \le L \le 4.6) \\ 1.5 & (L > 4.6) \end{cases}$$

L is the length of the diagonal of the tank cross section. Here, if the inside of the tank is completely partitioned as in a road tanker, use the L of that partition. Even if this equation is satisfied, do not allow the v to exceed 7 m/s.

Due to lack of a grounded dip pipe, bottom loading entails a higher surface potential than top loading. Therefore, set the equation of the flow velocity limitation in bottom loading to 75% of Equation (8.3);

(4) For strong charge-generating elements such as microfilters, install them upstream and allow for an appropriate relaxation distance ($= 3v\varepsilon/\sigma$) before liquid enters the tank. If that length cannot be achieved, residence time in the piping of more than 30 seconds should be provided;

8.5.2.3 Road and rail tankers

There is a risk of static electricity when loading liquid into a road tanker ($\leq$50 m^3) or rail tanker ($\leq$100 m^3) or loading into another container from it. Therefore, antistatic measures should be taken, as described below:

(1) Grounding and bonding
Before loading, ground and bond (ground first and then bond) any road and rail tankers, accompanying hoses, other containers, and all other conductors. Then, release the connections (release the bonding first and then the ground) after the loading. It is desirable to use an interlock pump which cannot be activated unless it is grounded;

(2) Using conductive or dissipative hoses;

(3) Flow velocity limit
For low-conductivity liquids, the flow velocity should be set to Equation (8.3) or 7 m/s, whichever is the lower velocity. For medium- and high-conductivity liquids, the velocity should be set to less than 10 m/s;

(4) Grounding workers (human bodies) and making their work clothes and other gear antistatic (see Chapter 6);
Use antistatic wear (work clothes, footwear, and gloves);

(5) Time delay (Residence time): Before gauging and sampling, appropriate time after loading should be provided to sufficiently relax the charge of liquid in the tank (see 8.9);

   (a) After the loading, taking the dip pipe out should be delayed by at least 5 minutes;
   (b) Gauging and sampling should be delayed by at least 10 minutes (see 8.7)
   (c) No time delay is required before gauging or sampling with a gaugewell.

8.5.2.4 Tanker

For tanker loading and discharging with liquid, conform to the *International Safety Guide for Oil Tankers and Terminals* (a Japanese translation of this is published by the Japan Tanker Association, at present The Japanese Ship Owners' Association).

8.5.2.5 Hose

(1) Conductive or dissipative hoses with resistance $10^3 - 10^6$ Ω per metre of length should be used. At that time, they should be grounded by bonding;

(2) In handling low-conductivity liquid or flammable liquid, conductive or dissipative hoses should be used, not insulating ones;

(3) If any hose has metal wire (which may be covered with insulating hose material) around it for reinforcement, the metal wire should be securely bounded. However, such a hose should not be used for low-conductivity liquid or flammable liquid.

8.6 Pouring into another container

If a worker is supposed to pour liquid into another container by using a small container, there are electrostatic hazards due to liquid splashing or friction or collision with a pipe, hose, or tank. Therefore, antistatic measures as listed below should be taken:

(1) Ground the workers (human bodies) and make their work clothes and other gear antistatic (see chapter 6);

(2) The containers, funnel, pipe, hose nozzle, and other equipment should preferably be metal or conductive and otherwise dissipative;

(3) For a conductive or dissipative container, ground the destination container and ground or bond the source container;

(4) Ground and/or bond the funnel, pipe, hose nozzle, weighing scale, cart, pump, and other conductors.

(5) Grounding first, and then bonding before liquid pouring. After the work, de-bond the containers and wait for an appropriate amount of delay time (see 8.9) before de-grounding them;

(6) To prevent liquid splashes, a funnel or dip pipe to lower the tip down to the container bottom should be used;

(7) When pouring the liquid directly from the source container, it is preferable to use a funnel or dip pipe. An acceptable alternative is to pour the liquid slowly along the container wall so that the liquid does not splash;

(8) When using a pump, take care not to let air bubbles in.

8.7 Gauging and sampling

In liquid level gauging or sampling liquid by a liquid float or other part inside a tank, there is a risk of electrostatic ignition. It is, therefore, advisable to install a gaugewell. If that is not possible, avoid gauging and sampling whenever possible. Another effective method when gauging is to use an explosion-proof supersonic liquid level gauge. If gauging or sampling is absolutely necessary without using a gaugewell, allow for some still delay time (at least 10 minutes for a low conductivity liquid or more than 30 minutes for a low-conductivity liquid containing water drops; see 8.9). For a tank equipped with a gaugewell, no still delay time is necessary. All the metal parts for gauging and sampling should be bonded to the tank if it is grounded. For an ungrounded tank (such as a nonconductive container), all metal parts should be directly ground. At that time, a metal chain for grounding or bonding should not be used. In the case of manual gauging and sampling, it is important to ground the human bodies and make their work clothes and other gear antistatic (see Chapter 6).

8.8 Nonconductive containers, pipes, hoses, and valves

In liquid processes, static charge may accumulate in glass linings, plastic tanks, and other nonconductive containers, pipes, hoses, or ball valves made of a material having volume resistivity greater than 10^8 Ω·m or a surface resistivity greater than 10^{10} Ω. Such electrification will then cause induced charging or result in brush or propagating brush discharges due to the approach of a conductor. Therefore, the use of any such nonconductive equipment should be avoided whenever possible. If any flammable liquid is handled, a conductive/dissipative container, pipe, hose, and valve should be used, and it should be grounded or bonded. For large or medium tanks or for low-conductivity liquid, in particular, using nonconductive materials should be avoided. Moreover, in hazardous areas of Zone 0, it is advisable not to use nonconductive containers even if they are small. If the use of any such equipment is unavoidable, expert advice should be sought.

(1) For a non-metallic container, the container should be conductive/dissipative; a flange or something similar made of metal should be used and grounded.

(2) Even when liquid is highly conductive, its flow velocity should be to less than 1 m/s when using a nonconductive container or pipe (including metal containers and pipes with nonconductive liners).

(3) For loading with liquid, 8.5.2 should be followed.

(4) Any conductor (such as a flange or metal shielding) installed on/in a nonconductive container, pipe, or hose should be grounded.

(5) If possible, a metal grounding plate should be inserted into the nonconductive container to put it into contact with the liquid. At that time, the area of the metal plate should be more than $0.04V_t$ m^2 [7][4]. Here, V_t is the tank volume (m^3).

(6) Use of a portable nonconductive container which contains any metal part in hazardous areas should be avoided because it could cause a spark discharge.

(7) Use of a nonconductive container or pipe in hazardous areas of Zone 1 requires sufficient risk assessment.

(8) In hazardous areas of Zone 0, use of a nonconductive container or pipe should be avoided; otherwise, precautions to prevent ignition (preventing the formation of an explosive atmosphere) should be taken. If its use is necessary, expert advice should be sought.

(9) In hazardous areas of Zones 0 or 1, friction (such as wiping) of any nonconductive container or pipe surface, which would cause charge generation, should be avoided.

8.9 Delay time

This is an antistatic measure through charge relaxation; it relies on the fact that even a low-conductivity liquid stops generating static electricity after being loaded, and charge relaxation then gradually reduces the charge of the liquid.

When gauging and sampling are performed in a tank in which an explosive atmosphere is formed by a flammable liquid that is loaded, a gaugewell should be installed. If not, this operation should be performed at the end of a certain delay time after the loading to sufficiently reduce the liquid charge and thus avoid an incendiary electrostatic discharge. It must also be ensured that this measure is taken together with other measures to control the generation of static charge; this should not be taken as an isolated safety measure.

(1) The delay time should be either at least three times the charge relaxation time ($3\varepsilon/\sigma$, the time until it becomes $1/e^3$ (≈ 0.05) times the initial value) or, in general, in the case of a low-conductivity liquid (less than 50 pS/m), at least 10 minutes. For a low-conductivity liquid containing free water, powder, or something similar[5], it should be at least 30 minutes [7]. Alternatively, Table 8.3 may be used.

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[4] This measure has been experimentally demonstrated to be effective in tanks of up to 5 m^3. Tanks larger than those need investigation.

[5] For liquids containing water, powder, or other foreign matter, sedimentation will increase its charge after loading or agitation.

Table 8.3: Reference values (in minutes) of delay time

Conductivity	Volume of liquid in tank (m^3)			
(S/m)	≤ 10	10–50	50–5000	≥ 5000
$\geq 10^{-8}$	≥ 1	≥ 1	≥ 1	≥ 2
10^{-12}–10^{-8}	≥ 2	≥ 3	≥ 10	≥ 30
10^{-14}–10^{-12}	≥ 4	≥ 5	≥ 60	≥ 120
$\leq 10^{-14}$	≥ 10	≥ 10	≥ 120	≥ 240

(2) When using Table 8.3, and if the liquid contains free water or other foreign matter, the delay time should be set to 3 times the value indicated in Table 8.3.

(3) Although Table 8.3 may have been used for practical purposes, it is strictly for reference (experienced) values. If appropriate grounds are obtained, these values may be reduced.

(4) In tanks and other containers coated on the inside, and if the coat has lower conductivity than the liquid, it should be set to at least 3 times the charge relaxation time of the coat.

(5) If a tank or something similar is equipped with a gaugewell (see 8.10) and if gauging, sampling, measurement, or other operation is performed in it, there is no need for delay time. Moreover, for manual sampling or gauging (see 8.7) by workers, it is important that the bodies of the workers be grounded by wearing appropriate shoes as well (see Chapter 6) .

The delay time consists mainly of that obtained by experience. Below is some reference information for risk assessment:

(1) The relationship with the tank size is specified by experience as follows:

  (a) At least 10 minutes for tanks of up to about 50 m^3; at least 30 minutes for tanks greater than 100 m^3 [2];

  (b) One minute for tanks of up to 20 m^3; 5 minutes for those of 20–40 m^3; and 30 minutes of delay time for those greater than 40 m^3; for low conductivity liquid of less than 2 pS/m or liquid containing powder or something similar (0.5 wt% or more), an even longer delay time is required [34].

(2) From the container size, filling ratio, and liquid conductivity, the delay time (such as the time until it reaches 5% of the initial value) can be theoretically calculated [36].

8.10 Electrostatic shielding

The presence of a protrusion grounded in an electric field formed by a charged body may cause ignitable discharge. A grounded metal plate, mesh, or something similar can be used to partition the space into small segments, thus creating some electrostatically shielded spaces (see 7.5), to control the electric field for preventing electrostatic discharge at the protrusion. This example involves a grounded metal cylinder (gaugewell) of about 30 cm in inner diameter installed inside the tank for gauging or sampling (Figure 8.1). Road tankers are mandated by the Fire Service Law to be equipped with a device designed to prevent electrostatic disasters.

8.11 Mixing and agitation

(1) High-purity liquids do not increase to a hazardous level in charge quantity when mixed and agitated. When mixed with air, water, powder, or other foreign matter, however, these liquids become more charged.

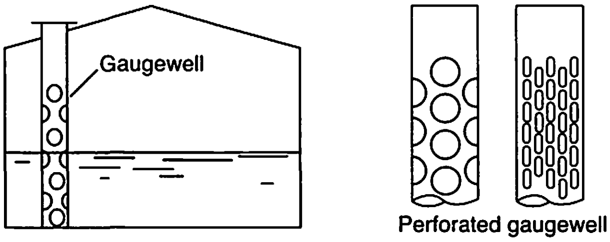

Figure 8.1: Gaugewell

(2) If possible, the conductivity of any low-conductivity liquid should be increased to more than 1,000 pS/m by adding an antistatic agent or high-conductivity liquid[6].

(3) Containers should be grounded, and all other metal equipment should be bounded.

(4) Liquid should be charged according to 8.5.2.

(5) Containers with nonconductive linings should not be used because they promote electrification and cause propagating brush discharges when the lining layer becomes highly resistive. In that case, it would be effective to replace it with a conductive/dissipative lining or insert a grounded metal plate (see 8.8) into the container. If this is inapplicable, expert advice should be sought.

(6) Antistatic measures should be taken to prevent workers from creating a risk of ignition (see Chapter 6).

(7) If an explosive atmosphere is formed by the vapour of flammable liquid,

  (a) A gas-based mixer, jet mixer, or fast propeller mixer should not be used;

  (b) An antistatic agent or high-conductivity liquid should be used to increase the conductivity to more than 1,000 pS/m or inerting.

8.11.1 Inline mixing

Inline mixing, in which the material is mixed in piping, is safe because it has no vapour space for efeectively generating flammable atmospheres. For the destination tank, take antistatic measures against charging (see 8.5).

8.11.2 Jet mixer

(1) For low-conductivity liquids, it is desirable not to use a jet mixer.

(2) For medium- and high-conductivity liquids (and for low-conductivity liquids whose conductivity can be increased to more than 50 pS/m by using an antistatic agent or something similar), and if a jet does not burst the liquid surface and all the metal parts are appropriately grounded, then a jet mixer can be used.

(3) If a space above the liquid constitutes a hazardous area of Zone 0 or 1, it would be necessary to either prevent the formation of an explosive atmosphere or avoid using a jet mixer.

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[6] High-conductivity liquids, such as alcohol and methylethylketone normally prove effective at a dose of about 20 vol%. Note that these liquids change the ignition risk of the target liquid. For example, adding ketone to xylene lowers its flash point. An antistatic agent generally shows a similar effect at a dose of 1-5 ppm.

8.12 Tank washing

Spraying liquid during washing may form a high charge density in space. Below are antistatic measures to be taken during high-pressure washing [4, 7, 34, 37]:

(1) Grounding and bonding containers, nozzles, pipes, hoses (insulating materials should not be used in a flammable atmosphere), and all other conductors;

(2) Taking precautions to prevent workers from creating an ignition risk (see 6);

(3) Opening the liquid drain outlet to prevent the cleaning liquid from accumulating in the tank;

(4) Jet washing with water[7]

  (a) The container to be jet-washed must be of metal and must not have a volume exceeding 30 m^3 or 3 m in diameter;
  (b) Maximum pressure: 50 MPa;
  (c) Maximum liquid flow rate: 5 L/s;

(5) High-pressure washing using flammable solvent;

  (a) The container to be cleaned must be of metal and have a volume of less than 5 m^3 or less than 3 m in diameter;
  (b) Maximum pressure: 5 MPa
  (c) Maximum liquid flow rate: L/s
  (d) High-purity solvent: The content of powder or other solid must not exceed 1 wt%;
  (e) If the above conditions are unsatisfied, inerting must be provided.

(6) Washing using steam should not be applied to tanks exceeding 100 m^3;

(7) If washing is impossible under the above conditions and if flammable gas or vapour is present or can be generated by washing, precautions to prevent formation of explosive atmospheres should be taken.

When washing insulating containers, inerting should be provided.

Tanker washing should conform to *International Safety Guide for Oil Tankers and Terminals* (a Japanese translation of this is published by the Japan Tanker Association, at present, The Japanese Ship Owners' Association).

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[7] Sea water and purified water should not be used.

Chapter 9

Antistatic measures for powder

9.1 Powder ignition due to charging

Many powders are nonconductive; as a result, the processes involved in their handling generate and accumulate static charge (Table 9.1) and may cause spark, brush, propagating brush, or cone discharges. The minimum ignition energy of powder (Table D.2) is larger than that of gas or vapour, but these discharges are sufficient to cause a dust explosion.

9.1.1 Formation of dust explosive atmospheres

Flammable powder involving metal powder (generally with a particle size of up to 0.5 mm) can form an explosive atmosphere (the explosion limit of many organic powders ranges from about 20 g/m^3 to several kg/m^3: the upper limit is difficult to determine experimentally) when a dust cloud is formed in air.

9.1.2 Electrostatic hazards and ignitability of powder

The characteristics of a specific type of powder (Table 9.2) allow a rough evaluation of its electrostatic hazards. In general, when powder reaches a resistivity of more than 10^{12} Ω·m, antistatic measures become extremely difficult. The minimum ignition energy of dust is higher than that of gas or vapour and ranges from several mJ to tens of mJ in many powders. The minimum ignition energy, explosion limit concentration, and other ignition characteristics depend largely on the particle size. In risk assessment, therefore, it is imperative to use data measured with the powder used. Note also that aluminium, zirconium, and other metals in powder form oxidise on the surface, thus often becoming insulating ($\sim 10^{12}$ Ω·m).

Table 9.1: Typical charging levels of powders in various processes

Processes	Charge (μC/kg)
Sieving	$10^{-5} - 10^{-3*}$
Pouring	$10^{-3} - 10^{-1*}$
Scroll-feeding	$10^{-2} - 10^{0*}$
Grinding	$10^{-1} - 10^{0*}$
Micronising	$10^{-1} - 10^{2*}$
Pneumatic transport	$10^{0} - 10^{2}$

* obtained for powders of medium resistivity, i.e., $\sim 10^{12}$ Ω·m

Table 9.2: Powder characteristics and electrostatic risk

Charge level μC/kg	Resistivity $\Omega\cdot$m	Relaxation time s	Risk level
$< 10^{-3}$	$< 10^{8}$	$< 10^{-3}$	Low
10^{-3}–10^{0}	10^{8}–10^{12}	10^{-3}–10^{2}	Medium
$> 10^{0}$	$> 10^{12}$	$> 10^{2}$	High

9.2 General antistatic measures in handling powder

(1) Antistatic measures for conductors (grounding and bonding, see Chapter 5).

  (a) Grounding or bonding all conductors

(2) Antistatic measures for nonconductive materials (see Chapter7)

  (a) Nonconductive pipes, hoses, containers, bags, sheets, coatings, liners, and other equipment readily accumulate static charge, resulting in brush and propagating brush discharges. Therefore, using nonconductive materials should be avoided.

  (b) If the minimum ignition energy of an explosive atmosphere exceeds 3 mJ, it will not catch on fire in a corona or brush discharge. Unless a propagating brush discharge occurs, therefore, a nonconductive material can be used. This corresponds to flexible intermediate bulk containers (FIBCs) protected against propagating brush discharges.

  (c) From the conditions for the generation of propagating brush discharges, a sheet-like insulator or insulating coating should not be used unless its dielectric breakdown voltage in the direction of the thickness is less than 4 kV.

  (d) Replace any material with a conductive/dissipative material in dust hazardous areas of Zone 20. In Zone 21, using nonconductive materials should be avoided if possible.

  (e) Using antistatic goods: For cloth bags, cloth chutes, bag filters, FIBCs, and similar items, antistatic ones should be selected and grounded appropriately if they require grounding.

(3) Antistatic measures for workers (see Chapter 6)

  (a) Ground the human bodies

  (b) Make the work clothes and other gear antistatic

(4) Controlling charge accumulation

  (a) It is difficult to suppress charge generation in powder; however, its generation may be reduced by controlling the handling velocity and preventing friction.

  (b) Charge relaxation is not large at the humidity between 50 and 60% controlled as a normal antistatic measure. However, at a relative humidity of 70% or more, it may be possible to reduce the surface resistance and increase the charge relaxation for many powders. This method can be used only for slow pneumatic transport at normal-temperature.

  (c) Using an ioniser: passive ioniser and voltage-application corona ioniser [38–41] (see 7.6).

(5) Safety management system based on risk assessment

(6) Preventing dust explosive atmospheres (see A.3)

  (a) Processes involved in handling powder with a minimum ignition energy of 3 mJ or less should be protected against ignition (inerting). (see 9.2.1.2(4) and (6))

For details, see A.3.1.

9.2.1 Antistatic measures and precautions for various processes

In addition, see "Antistatic measures for loading powders," in the separate volume, TR–85–3: *Supplement of Guidelines* of this document.

9.2.1.1 Pneumatic transport

Pneumatic transport entails contact (collision or friction) between powder and pipe walls, resulting in charging of the powder and pipes. Therefore, the following precautions should be taken:

(1) Using metal pipes and grounding or bonding them;

(2) Minimising pipe bends;

(3) Minimising the transport velocity as long as it does not allow powders to accumulate in the pipes.

9.2.1.2 loading and reloading

(1) Grounding workers' bodies and making their clothes antistatic: a discharge from a worker may generate a discharge energy of up to 100 mJ. Therefore, discharges must be prevented by grounding the workers' bodies and making their clothes antistatic.

(2) In loading a grounded powder tank or silo, it could be assumed that powder with a minimum ignition energy of 25 mJ or more will involve a cone discharge alone as an incendiary discharge [25, 42–45].

(3) Powder tanks or silos on an industrial level are unlikely to generate lightning-like discharges [26, 27] (see 3.3.10). However, cases in which the charge quantity is extremely high (such as tens of μC/kg or more) may require risk assessment, such as the size of charged clouds, space charge density, and ignition energy (see B.3.4).

(4) Ignition due to a brush discharge from a charged dust cloud will have a discharge energy of up to about 3 mJ. Therefore consider this risk for powders with a minimum ignition energy of up to 10 mJ.

(5) A possible effective method to prevent cone discharges in loading is to use an ioniser [38–41].

(6) Cone discharges occur during loading are difficult to prevent. Therefore, precautions to prevent the formation of an explosive atmosphere (inerting) should be taken. Powder with resistivity of more than 10^{12} Ω·m cannot be protected against cone discharges.

(7) To load powder in an open location, a precautionary measure that does not allow the formation of an explosive atmosphere should be taken.

(8) A metal or conductive/dissipative container and a chute[1] and/or a hopper must be used and they should be grounded and/or bonded to the earth.

(9) For bags of powder with a minimum ignition energy of less than 10 mJ, it is better not to use insulating bags. Moreover, dissipative paper bags should be put into contact with the chute or hopper to prevent potential differences between them (this corresponds to bonding).

(10) A bag containing residual powder should not be swung during pouring because the swinging may cause a discharge.

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[1] The chute should be separated from the loading inlet. However, it should be not more than 3 m long to prevent friction charging.

9.2.1.3 Loading powder into liquid

In container-related processes, loading powder into flammable liquid has most frequently caused disasters. Therefore, appropriate antistatic measures as described below should be taken. If there is any unavoidable situation that makes it difficult to take any of the following measures, expert advice should be sought.

(1) Ground and/or bond all conductors (see Chapter 5).

(2) Precautions to prevent workers from generating a risk of ignition should be taken (see Chapter 6)

(3) If there is a risk of ignition, it is necessary not only to take general antistatic measures (e.g., not using pneumatic transport or providing some delay time for liquids before loading powder) but also to prevent the generation of an explosive atmosphere.

(4) Even if the inside of a container is made inert, loading powder will allow air to enter the container. Therefore, the powder should not be loaded directly.

(5) A container, chute, and hopper made of nonconductive materials should be avoided. Instead, a metal or otherwise conductive/dissipative container and a chute (not more than 3 m long) or a hopper equipped with a rotary valve should be used and surely grounded and/or bonded.

(6) For flammable liquid, an insulating drum or bag for powder should not be used.

(7) Metal or otherwise conductive/dissipative drums and bags should be bonded. When bonding paper bags[2] (except for those containing a nonconductive inner bag[3]) are used, in particular, the paper bag should be in contact with the above chute or hopper for bonding to prevent a potential difference.

(8) Too much powder should not be loaded at a time, as it would cause a discharge from charged powder floating in the space on the liquid.

(9) When workers have to load powder, they must slowly put 25 kg or less of it at a time into the chute or hopper (with a rotary valve or a damper). Furthermore, swinging a bag containing residual powder should be avoided.

(10) Loading a large amount of powder from a flexible intermediate bulk container should be done through a hopper or a rotary valve. Since a significant amount of air will enter the container together with the powder, this hopper must be prevented from generating an explosive atmosphere in its own.

(11) When using a metal container with a coat (a liner) on the inside, a conductive/dissipative coating should be used.

In addition, see "Antistatic measures for loading powders," in the separate volume, TR–85–3: *Supplement of Guidelines* of this document.

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[2] Paper bags with an inner PE coat usually present no risk of static electricity [6]. It is advisable to measure and to assess the risk of, the resistance of the paper bag and the chargeability of the powder and bag during discharge in advance.

[3] A disaster once took place in which an inner bag slipped out during discharge, resulting in a discharge leading to a fire.

9.2.1.4 Discharging powder from a container or bag

(1) Workers' bodies should be grounded, and their clothes should be made antistatic (see Chapter 6)

(2) For containers and bags, those made of metal, paper (not insulating), or conductive / dissipative material should be used and maintained grounded or bonded to the earth throughout the process of discharge.

(3) In a hazardous location of a flammable atmosphere or in a location that may become hazardous after powder discharge, discharge from an insulating container or bag should be avoided.

(4) Swinging a bag containing residual powder should be avoided because it might cause a discharge.

9.2.1.5 Precautions for cloth products

(1) For bag filters, cloth bags, cloth chutes, and other cloth products, those that have been made antistatic by the use of conductive fibre should be used, and they should be grounded and/or bonded to the earth.

(2) Corona discharges from conductive fibre cannot become a source of ignition for flammable powder and they may not only make the cloth antistatic but also reduce the powder charge. Furthermore, conductive fiber grounded is also expected to work as a shielding conductor, thus preventing hazardous charging and discharge outside the shielding.

(3) It is advisable to use bag filters that can swing powder away automatically in order to prevent the deposit of powder deposit from increasing excessively.

9.3 Nonconductive containers

The use of containers made of nonconductive materials having volume resistivity greater than 10^8 Ω·m or surface resistivity greater than 10^{10} Ω and the use of metal containers coated with an insulator on the inside should be minimised. Since nonconductive containers do not entail charge relaxation even if electrically connected to the earth, they may cause electrostatic hazards. Such containers should not be used for powders having a minimum ignition energy of less than 3 mJ. The use of nonconductive containers should be limited to those with capacities of up to 5 m^3 and to powders with a minimum ignition energy of 10 mJ or more; even then, precautions to prevent ignition should also be taken.

Antistatic measures to prevent workers from generating a risk of ignition should be taken (see Chapter 6). It is very important to protect the workers from electric shocks.

9.4 Flexible intermediate bulk container

Flexible intermediate bulk containers (FIBCs) are bags made of flexible cloth and widely used when storing and transporting powder, flakes, and granules. However, loading and discharge generate static charge, and flexible containers with no protection at all quickly accumulate high levels of charge. In such a case, spark, brush, cone, or propagating brush discharges are unavoidable. These will, therefore, not only cause electric shocks but also, when used in a flammable atmosphere, risk causing ignition that could lead to an explosion. A flammable atmosphere also occurs when a dust cloud or a thin dust layer is formed when powder is handled; such an atmosphere may catch on fire due to electrostatic discharge.

Similarly to other industrial equipment, every time an FIBC is to be used in a potentially hazardous situation, complete risk assessment should be conducted in advance. The following sections present the minimum precautions to be considered at that time.

9.4.1 Types of FIBC

IEC 61340-4-4 [46] classifies FIBCs as follows[4]:

(1) Non-static control type
Products made of an un-antistatic insulating cloth which is neither of the propagating brush discharge control type nor of the static control type.

(2) Propagating brush discharge control type
Those made of a nonconductive cloth and whose thickness-wise dielectric breakdown voltage (including that of an insulating laminate layer if any) is less than 6 kV.

(3) Static control type
Those satisfying either of the following conditions:

  (a) Those having a dielectric breakdown voltage similar to that of the propagating brush discharge control type and which do not ignite a test gas with a minimum ignition energy of 0.14 mJ under specified test conditions;

  (b) Those whose discharge is prevented by grounding, which have a resistance of 10^8 Ω or less between the grounding terminal and conductive part installed on the FIBC, and which have either of the following structures:

    (i) Those based on an insulating cloth into which mutually electrically connected conductive threads or pieces of tape are woven or sewn at intervals of not more than 20 mm in a striped manner or not more than 50 mm in a lattice-like manner;

    (ii) Products made of a conductive/dissipative cloth made of equal material;

    (iii) For products based on a multilayer structure cloth, those having a conductive layer on at least one of its sides and with a conductive layer used for the inside of the bag.

9.4.2 Selecting FIBCs

Selections should be made as described below according to the type of flammable atmosphere and the ignitability of the powder. However, risk assessment is also necessary to prevent the possibility of discharge and ignition due to powder peel-off and the generation of cone discharges.

(1) In the presence of a flammable mixture of gas or vapour with a minimum ignition energy of 0.14 mJ or less, no FIBC of any kind is applicable. The operation of an FIBC in such an environment should be strictly restricted.

(2) In a location with a flammable mixture of gas or vapour with a minimum ignition energy of 0.14 mJ or when a flammable powder with a minimum ignition energy of 3 mJ or less is handled, the static control type alone is applicable.

(3) If no flammable mixture of gas or vapour is present and if a flammable powder exceeding a minimum ignition energy of more than 3 mJ is handled, either a static control type or a propagating brush discharge control type is applicable.

(4) There are no limitations for FIBCs if there is no flammable mixture of gas or vapour and a non-flammable powder is handled.

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[4] CENELEC-compliant FIBCs can also be used. In that case, type A is of the non-static control type, type B the propagating brush discharge control type, and type C (to be grounded) and type D (grounding unneeded) the static control types.

9.4.3 General operating instructions

(1) In the presence of a flammable mixture of gas or vapour having a minimum ignition energy of more than 0.14 mJ or in cases in which a flammable powder with a minimum ignition energy of 3 mJ or less is handled, even the static control type should preferably be handled with a chute, hopper, or something similar rather than being loaded directly.

(2) Even the static control type may become slightly charged and, even if it does not generate an ignitable discharge by itself, a nearby ungrounded conductor may cause a spark discharge due to electrostatic induction. It is therefore imperative to ground conductors (including human bodies) present within a range of 1 m from any FIBC.

(3) If a propagating brush discharge control type or a static control type is combined with an insulating inner bag (such as one of polyvinyl chloride or polyethylene), the specific discharge control functions may not work. If either is used for an unavoidable reason to protect the powder from dirt or for any other purpose, it must be ensured in advance that the conditions stated in 9.4.1 are met in combination with these. Moreover, conductive inner bags should not be combined with a non-static control type or a propagating brush discharge type. This is because the FIBC is charged when the inner bag and FIBC are peeled off.

(4) To prevent workers from experiencing electric shocks due to a charged FIBC in the presence of a flammable atmosphere, a static control type should be used. At the highest charge level, the surface potential will exceed 100 kV which may give a strong electric shock.

Chapter 10

Antistatic measures for nonconductive solid materials

10.1 General precautions for handling nonconductive solids

Antistatic measures for nonconductive materials are outlined in Chapter 7. Below are some general measures:

(1) Grounding and/or bonding conductors (see Chapter 5);

(2) Changing materials if possible: using conductive or dissipative materials or antistatic agents (see Chapter 7);

(3) Antistatic measures for nonconductors: selecting low-chargeable materials, proper humidification, ionisers, electrostatic shielding (limiting the effective area of the charged surface) (see Chapter 7);

(4) Making workers antistatic and grounding them (work clothes, shoes, and flooring) (see Chapter 6);

(5) Preventing explosive atmospheres (see Appendix A)
If the risk of an explosive atmosphere exists, ventilate the area or take some other measure to prevent the formation of an explosive atmosphere;

(6) Safety management system based on risk assessment.

10.2 Electrostatic hazards in various processes involved in handling nonconductive solids

Processes having a potential risk of electrostatic ignition when handling solid materials include the transportation, packing, moulding, kneading, rolling, peeling, polishing, cutting off, and cleaning of plastics, paper, cloth, and other nonconductive materials and products. The risk is caused by spark, brush, or propagating brush discharges when the materials become charged.

10.2.1 Kneading, peeling, and polishing plastics

The processes listed below generate hazardous static charge and this is difficult to prevent. Therefore, measures to prevent the formation of explosive atmospheres should be taken.

(1) Kneading rubber, plastics, and other nonconductive materials.

(2) Peeling and attaching moulded products, film, and other nonconductive products.

(3) Releasing the moulds from moulded products.

(4) Cutting off, polishing, and dry-wiping moulded products, film, and other nonconductive products.

10.2.2 Belt drives and conveyors

Belt drives, conveyors, and rolling processes generate continuous charge separation, thus entailing an electrostatic risk. The charge increases with the velocity, tension, and contact area of the belts or rollers.

10.2.2.1 Belt drive

(1) Dissipative belts should be used to control charge accumulation. At that time, the belts should be grounded via pulleys.

(2) In hazardous areas of Zone 0, Zone 1 (IIC), and Zone 20 (with a minimum dust ignition energy of less than 10 mJ), even if the belts are dissipative, a belt drive should not be used. A direct drive should be used instead.

(3) In hazardous areas of Zone 1 (IIA, IIB), Zone 20 (with a minimum dust ignition energy of more than 10 mJ), and Zone 21, the following measures should be taken:

  (a) The belt velocity should be set to less than 30 m/s;
  (b) Dissipative belts[1] should be used;
  (c) Grounding the belts via pulleys.

10.2.2.2 Conveyor belts

(1) Use dissipative conveyor belts[2].

(2) In Zone 0 and Zone 1 (IIC), the belt velocity should be set to less than 0.5 m/s.

(3) In Zone I (IIA, IIB), Zone 20, and Zone 21, the conveyor belt velocity should be kept at not more than 5 m/s.

10.2.3 Rolling process

In rolling processes of paper, plastic film, cloth, and other materials, such as for winding, rewinding, printing, and coating, the following measures should be taken to prevent static charge generation:

(1) Use rollers that are of metal or otherwise dissipative and ground them through a shaft;

(2) Select an unchargeable material for products if possible;

(3) Lower the travel velocity and avoid abrupt velocity changes;

(4) Keep the roll pressure and tension low and homogenous;

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[1] When $RB \leq 10^5$ Ω·m, the belt is defined as dissipative, where R is the resistance between the belt and ground (pulley) at the centre between the pulleys on both sides with the belts installed and B is the width of the flat belt or twice the width of the sides of the V belt.

[2] If the belt has surface resistances on both sides that are below 3×10^8 Ω or in case that the belt consists of a layer of different materials, if the resistance through it does not exceed 10^9 Ω, the belt is considered to be dissipative.

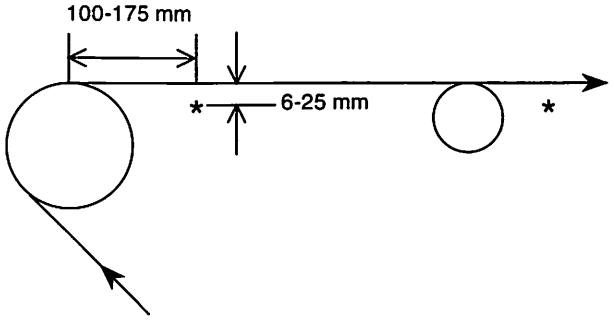

Figure 10.1: Typical location for installing an ioniser: $*$ represents the location of the ioniser.

(5) Use a humidifier or ioniser to protect against static charging. The ioniser will prove effective if installed 100–175 mm from the rollers and 6–25 mm from the products rolled (Figure 10.1). It must also be note that, when using an ioniser in a hazardous area, it is necessary to use an explosion-proof type to prevent the ioniser from becoming a source of ignition; risk assessment is required whether or not the ioniser is effective to perform neutralisation.

If a risk of flammable atmosphere exists, ventilation should also be available to prevent the formation of a flammable atmosphere.

10.2.4 Handling explosive devices

Even sensitive explosive devices (with minimum ignition energy of less than 1 mJ) can be sufficiently protected with the antistatic measures specified in these recommendations. In addition, below are the precautions to be taken to prevent an electrostatic discharge exceeding the ignition energy of explosive devices:

(1) Ground properly portable and mobile conductors and any other conductors;

(2) Surely eliminate nonconductors;

(3) Use conductive or dissipative flooring and footwear to ground all personnel;

(4) Inspect the performance of the antistatic footwear before work;

(5) Do not wear work clothes made of insulating cloth. Do not put on or take off the work clothes at the site;

(6) Conductive tools, wires, and other small metal bodies may cause spark discharges. Therefore, properly bond and/or ground them;

(7) Set the relative humidity to more than 65% (at normal temperature).

Chapter 11

Antistatic measures for gases

Gases free of foreign matter are not charged. However, if the gases contain mist, condensate, powder, or other liquid or solid particles, they will undergo friction on the surface of an object, resulting in electrification. Such gases include, for example, carbon dioxide hydrants, steam cleaning products, spray paints (including powder paints), and vacuum cleaners. This chapter describes antistatic measures for cases where there is a risk of electrostatic ignition due to processes involving gases.

11.1 General antistatic measures for gases

Common antistatic measures for handling flammable gases are as follows:

(1) Preventing the formation and spread of explosive atmospheres;

(2) Grounding and bonding (see Chapter 5);

(3) Antistatic measures for nonconductive materials (see Chapter 7);

(4) Antistatic measures for workers: grounding human bodies and making their work clothes and other gear antistatic (see Chapter 6);

(5) Safety management system based on risk assessment.

In addition, the following measures to handle flammable gases should be taken:

(1) Removing foreign matter
Charging of gases is caused by the charge of liquid or solid particles from mist, condensate, powder, or other matter contained in the gas. Therefore, pipes, containers, nozzles, flanges, and other equipment should be cleaned to remove any foreign matter containing in gasses;

(2) Exhaust and eruption of gases

  (a) Exhaust pipes for gases should be equipped with a filter, dust collection net, or something similar to trap any dust, mist, or other foreign matter;

  (b) The exhaust velocity should be minimised;

  (c) Flammable gases should be collected with a scrubber;

  (d) The eruption of high-pressure gases or liquefied gases results in adiabatic expansion and subsequent cooling. This leads to the generation of mist (which often turns solid, similar to dry ice, when carbon dioxide has erupted), resulting in static charging on the mist. Subsequent discharge by charging may lead to the ignition of their flammable gases or vapours. Therefore, the eruption of such gases should be prevented;

(e) When gas is to be exhausted out into the atmosphere, it should be exhausted outdoor, where there is good draft, to prevent the risk of ignition. The gas exhausted out of a safety valve and similar parts should also be exhausted into the atmosphere by leading it outdoors through a pipe. Gases should be exhausted in a direction in which there are no obstacles to prevent the charging by adhesion or collisions of mists;

(f) If flammable gas leaks and erupts from a container, pipe, or flange, an inert gas or steam should be used with an eruption pressure of less than 1.0 MPa to disperse the gas. It should be ensured, however, that the inert gas or steam does not contain mists and/or solid.

11.1.1 Transport of gases

Antistatic measures for transporting flammable gas are as follows:

(1) Storage and transportation of steam, or flammable liquid vapour may entail the generation of mist when the temperature of the steam or vapour decreases. Therefore, its generation and electrification should be prevented;

(2) Since the transport of a flammable gas may result in the formation of an explosive atmosphere when mixed with air, the ingress of air should be prevented as much as possible. In particular, if there is a high risk of ignition, such as when a waste gas duct is passed through, inerting should be used;

(3) For containers and pipes used to transport ethylene oxide, acetylene, or other gases having an upper explosive limit concentration close to 100% or gases that form an explosive atmosphere, their volumes and diameters should be minimised to prevent the formation of a hazardous charged cloud inside them.

11.1.2 Liquid/powder painting

Liquid and powder painting may form a charged cloud in space. This may charge the surrounding bodies as well. Then, if liquid drops or a dust cloud creates an explosive atmosphere, there might be a risk of ignition. It is necessary to make the work clothes and other gear antistatic and to ground the workers (human bodies) using dissipative footwear and flooring as well as all the conductors attached to spray devices (cans and other paint containers and nozzles). Ordinary spray painting (except for airless painting) has a low risk of static electricity, but electrostatic painting presents a higher risk due to the higher charges of liquid drops or powder. When using electrostatic paint, a measure to prevent formation of flammable atmospheres should be taken. Reference should also be made to EU standards concerning electrostatic paint[1]. In addition, it is necessary to guard against electric shocks caused by a high voltage used in the electrostatic paint.

11.1.3 Vacuum cleaners

Installed and portable vacuum cleaners present a risk of spark and brush discharges. Therefore, the following precautions should be taken:

(1) When a flammable matter is to be sucked, the metal parts of the cleaner should be grounded and/or bonded;

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[1] (1) EN 50050, Electrical apparatus for potentially explosive atmospheres. Electrostatic hand-held spraying equipment, 2001. (2) EN 50059, Specification for electrostatic hand-held spraying equipment for non-flammable material for painting and finishing, 1991. (3) EN 50176, Automatic electrostatic spraying installations for flammable liquid spraying material, 1997. (4) EN 50177, Automatic electrostatic spraying installations for flammable coating powder, 1997. (5) EN 50223, Automatic electrostatic application equipment for flammable flock material, 2001.

(2) A conductive or dissipative hose, nozzle, and filter should be used, and they should be grounded and/or bonded;

(3) Portable cleaners that cannot be grounded or bonded should not be used in hazardous areas;

(4) Explosion-proof equipment should be used with appropriate provisions in hazardous areas where there are flammable gases, vapour, or powders;

(5) Any powders that have a minimum ignition energy of less than 3 mJ or include deflagrable metal powders should not be sucked with a vacuum cleaner.

Appendix A

Prevention of the formation of an explosive atmosphere

A.1 Hazardous areas

The classification of hazardous areas [3–5] has been described in 2.23. This section contains examples of such classifications to identify hazardous areas.

A.1.1 Hazardous areas of gases and vapours

Areas that are at risk of becoming explosive atmospheres due to gases or vapours include:

(1) Areas where flammable gases or liquids are handled in an open space;

(2) Areas where flammable gases or liquids are in an enclosed space from which they may leak.

The following are examples of such areas:

(1) Zone 0: Areas listed below that are exposed to a gas/vapour explosive atmosphere either constantly, or over a long period, or frequently:
   (a) Areas where flammable gas or liquid is handled in an open space;
   (b) Areas where flammable gas, vapour, or liquid flows out;
   (c) Areas on, over, and around the surface of a flammable liquid.

(2) Zone 1: Areas listed below where a gas/vapour explosive atmosphere may sometimes occur in a normal process:
   (a) Areas prone to leakage of flammable gas, vapour, or liquid;
   (b) Areas around tank openings that are often left open;
   (c) Indoor or other areas where ventilation is blocked and flammable gas or vapour may stagnate.

(3) Zone 2: Areas listed below where a gas/vapour explosive atmosphere is normally unlikely or, even if one does occur, it occurs only for a short time:
   (a) Areas around tanks, pipes, and similar equipment provided with a flange, valve, meter, or similar device;
   (b) Areas equipped with a forceful ventilator to prevent gas/vapour stagnation;
   (c) Areas inside and around tanks where inerting is performed.

A.1.2 Hazardous areas with dusts

Areas that may form an explosive atmosphere due to flammable dusts include:

(1) Areas where flammable powder is handled in an open space or where dusts are accumulated;

(2) Areas where flammable powder is handled in an enclosed space from which it may leak;

(3) Areas where flammable powder is handled together with a trace quantity of flammable gas, vapour, or liquid.

Examples of such areas include:

(1) Areas where flammable powder is loaded into a container or moved from container to container in an open space;

(2) Areas where flammable dust is collected;

(3) Areas where flammable dust or a dust containing flammable gas or liquid is floating or accumulated;

(4) Areas inside and around enclosed structures; examples in which flammable powder is handled are listed below:

  (a) Storage silos, tanks, containers, FIBCs, pipes, or other equipment;
  (b) Dry dust collectors;
  (c) Mixer/agitators.

A.2 Controlling gas/vapour explosive atmospheres

A.2.1 Removing unneeded residues of flammable gas or liquid

(1) Put unneeded flammable liquid into a specified container as soon as possible.

(2) Remove all of any volatile liquid remaining in a container before putting any other liquid into that container.

(3) Remove any flammable liquid remaining in a container, pipe, or other equipment that is no longer in use as soon as possible.

(4) Discharge as soon as possible any unneeded gas or vapour remaining in a container, pipe, or something similar. In such a case, it is advisable to use air, nitrogen, or something similar as a discharge gas and avoid using compressed steam. No such discharge should be performed in the case of a liquid of Class I[1] with a flash point of 37.8°C or less and a vapour pressure that does not exceed 0.276 MPa (2,068.6 mmHg) as measured with the Reid method[2] or in the case of an environment equal to or more than the flash point of the residual liquid. If a liquid of Class I must be discharged, nitrogen should be used to prevent explosive atmospheres.

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[1] NFPA 30, "Flammable and combustible liquids code" classifies the degree of flammability according to its flash point and vapour pressure.

[2] JIS K2258: "Testing Method for Vapor Pressure of Crude Oil and Products (Reid Method)" provides related regulations. Measurements are taken at 37.8°C.

A.2.2 Preventing leakage of flammable gas or liquid

(1) Daily inspections should be performed on the joints of any pipe, valve, meter, and other equipment or pump bearing that is likely to leak flammable gas or liquid. If any anomaly is detected, immediate measures should be taken to prevent leakage.

(2) When periodically inspecting facilities, equipment, or devices that handle flammable gas or liquid, care should be taken to check for cracks, corrosion, and other anomalies that may lead to leakage.

(3) When operating a valve, care should be taken not to apply an overstraining force.

(4) When loading flammable liquid into a container or pouring it from container to container, the liquid surface should be monitored .

(5) When leaving open any facility or equipment that handles flammable gas or liquid for maintenance, a check should be made in advance for residual gas or liquid. If there is any residue, it should be removed.

(6) Facilities prone to the leakage of flammable liquid should be equipped with a liquid pan, pit, or something similar to prevent far-reaching leakage.

(7) Facilities and other equipment that are prone to the leakage of flammable gas or liquid should be equipped with a leak detector or the amount of such fluid handled or consumed should be controlled in an attempt to detect leakage early.

(8) Facilities, devices, and other equipment prone to disasters stemming from the leakage of flammable gas or liquid should be equipped with a leak detector to activate a valve to shut off any leakage as an emergency measure.

A.2.3 Controlling the exhaust of flammable gas or vapour

(1) Piping should be used to ventilate the hazardous location to an outdoor location, thereby discharging it. If the fluid is to be discharged indoors for an unavoidable reason, forced ventilation or some other measure should be performed. The electric equipment for the forced ventilator must be explosion-proof.

(2) For the exhaust, an appropriate method and exhaust rate should be assessed in advance to prevent the formation of an explosive atmosphere.

A.2.4 Preventing the stagnation of flammable gas or vapour by natural ventilation

(1) When handling flammable gas or liquid outdoors, operations should be conducted in a location where gas and vapour are unlikely to stagnate.

(2) When handling flammable gas or liquid indoors, windows and doors should be opened to ensure natural drafts and ventilation.

A.2.5 Preventing stagnation of flammable gas/vapour by forced ventilation

In processes in which flammable gas or liquid is handled (such as painting, transferring such fluids from container to container, loading, washing, or exhausting gas or vapour) in any poorly ventilated location, such as (1) a building or room with a small window or door opening, (2) enclosed or nearly enclosed facility or equipment, (3) areas surrounded with facilities, equipment, walls, or something similar, or (4) liquid waste ditch or pit, a forced ventilator should be used with an appropriate air flow and pressure and an explosion-proof structure. When using such a forced ventilator, its operation status should be constantly monitored. If any anomaly occurs, the necessary emergency actions should be taken immediately.

A.3 Controlling dust explosive atmospheres

A.3.1 General precautions for handling powder

The following are general measures for handling flammable powder:

(1) Selection of the particle size of powder
The smaller the particle size of powder is, the more likely static charging will be, and the more likely electrostatic discharge will cause ignition and a dust explosion. Flammable powder should, therefore, be handled with as large a particle size as possible.

(2) Preventing powder destruction
When powder is destroyed and pulverised, much static charging is likely to occur. This also makes it likely for ignition to occur due to electrostatic discharge, resulting in the possibility of a dust explosion. Therefore, flammable powder should be handled as follows whenever possible:

  (a) A powder with indestructible material and shape should be selected;
  (b) A kind of equipment that is not prone to powder destruction should not be used;
  (c) The scale and velocity for handling powder should be limited.

(3) Preventing powder stagnation and accumulation
When powder stagnates and accumulates on a conveyance route, static charge may generate during powder collision , friction or peeling on equipment walls. Dust explosions are also possible as a result of electrostatic discharge by the charge accumulation on such powder. Therefore, the measures listed below should be taken whenever possible to prevent the stagnation and accumulation of flammable powder:

  (a) Equipment should be designed to resist powder stagnation and accumulation;
  (b) Powder should be handled under conditions in which it is unlikely to stagnate or accumulate;
  (c) Any powder that has stagnated or accumulated on equipment walls, floors or similar items should be periodically cleaned and removed to prevent significant accumulation.
  (d) Before a vacuum electric cleaner is used to remove stagnate and accumulated powder, as much of the powder as possible should be removed with a broom. A suction nozzle made of metal (grounded or bonded) and not plastics should be used. However, for metal powder and other kinds of powder that are highly ignitable, cleaning with such suction should not be performed (see 11.1.3.);
  (e) To remove powder deposits from cloth, film, sheeting, or other material, strong swinging or striking should be avoided.

(4) Scale limitation
The more flammable powder that is handled, the more static charge will be generated. In addition, a large amount of dust and its cloud will form an explosive atmosphere, resulting in electrostatic discharge, which increases the possibility of a dust explosion. Therefore, the amount of use should be limited as much as possible.

(5) Equipment partitioning
If the equipment for flammable powder has an opening or is connected to other equipment by piping or other means so that the powder is free to move in between, a dust explosive

atmosphere is likely to occur, and disasters are likely to take place. To prevent these outcomes, the powder outlet/inlet should be equipped with a rotary valve and a choke midway in the piping or ducting.

(6) Removing protrusions
Any edge or other metal structure inside a silo or other container makes it likely for electrostatic discharge (brush discharge) to occur from a charged cloud onto these protrusions. Therefore, all unnecessary protrusions should be removed whenever possible.

A.3.2 Preventing leakage of flammable powder

(1) For cloth parts and joints that are likely to leak flammable powder, daily inspections should be performed. If any anomaly is found, leak-preventive measures should be implemented immediately.

(2) In periodically inspecting facilities, devices, and equipment in which flammable powder is handled, cracks, corrosions, and other anomalies that may lead to leakage should be carefully investigated.

(3) In facilities, devices, and equipment in which flammable powder is handled, their internal pressure should be reduced to a level lower than the atmospheric pressure if possible, to prevent dust leakage.

(4) For containers, devices, and equipment that supply flammable powder or receive the supply of such powder, a bag-filter-type dust collector or similar device should be mounted in which breathing occurs as powder is loaded and discharged.

(5) When loading flammable powder into a bag, container, or FIBC, the opening area should be minimised, and a hopper and/or chute should be used.

(6) When pouring and loading flammable powder into another container by using a bag, container, FIBC or something similar, powder deposits on the bag or container should not removed forcibly.

(7) For machinery and equipment for transporting and loading flammable powder, an alarm system that monitors the amount handled should be used. Should a leak occur, a measure that makes the machinery or equipment stop automatically should be implemented.

(8) When a facility, device, or equipment for handling flammable powder is to be left open for repair or maintenance, residual powder should be checked in advance. If there is any residue, it should be removed.

A.3.3 Preventing flammable powder from splashing and accumulating

Prevent flammable powder from splashing and accumulating in the following manner:

(1) A local exhaust with appropriate functions should be used in the following areas:
  (a) Areas in which a bag, container, or something similar containing flammable powder is opened;
  (b) Areas in which flammable powder is handled in an open space;
  (c) Areas in which flammable powder leaks frequently;
  (d) Areas in which dust is generated from processes such as polishing and grinding.

(2) A portable local exhaust should be used as necessary in the following areas:
  (a) Areas in which flammable powder, which is easy to be suspended, is temporarily handled;

(b) Areas in which flammable powder deposited on bags, containers, workers, and other objects is removed;

(c) Areas in which facilities, devices, and equipment that are used in the handling of flammable powder are inspected, repaired, and cleaned;

(3) Flammable powder deposited and accumulated on facilities, devices, or other equipment should be periodically cleaned.

A.4 Inerting

A.4.1 Significance of inerting

The partial or complete substitution of the air or flammable atmosphere by an inert gas is a very effective method for preventing explosion. Inerting consists of the following: (1) When an ignition source is difficult to remove or prevent, an inert gas is added to a flammable gas mixture. (2) In so doing, the oxygen concentration of the gas mixture is reduced to a level that is lower than the oxygen concentration as the flammable limit (LOC) necessary for the continuation of combustion in an attempt to prevent ignition. Moreover, this is also performed even when the oxygen concentration of the gas mixture cannot be reduced to a level that is lower than the LOC. The aim here is to increase the ignition energy of the flammable mixture in an attempt to reduce the ignition risk due to static electricity.

A.4.2 Inert gases

Gases[3] The materials that could be used for inerting include nitrogen, carbon dioxide, steam or flue gases. Although the effect of inerting rises in the order of nitrogen, steam, and carbon dioxide gas, in general nitrogen is often used because it is ease to use.

A.4.3 Controlling oxygen concentration

A.4.3.1 Controlling oxygen concentration

The oxygen concentration should be controlled as described below according to the limiting oxidant concentration (LOC) of flammable substances [47].

(1) Oxygen concentration to be continuously monitored
If the LOC is more than 5 vol%, a safety margin of at least 2 vol% lower than the LOC should be allowed. If the LOC is not more than 5 vol%, the level should not exceed 60% of the LOC.

(2) Oxygen concentration not to be continuously monitored
If the LOC is more than 5 vol%, the level should be maintained at not more than 60% of the LOC. If the LOC is not more than 5 vol%, it is important that the level not exceed 40% of the LOC.

A.4.3.2 Other estimations of the concentration

If a flammable substance with an LOC of 5 vol% or more is handled and inerting is to be performed for a reaction tank or something similar with a volume of 20 m^3 or less, then the

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[3] Users of inert gas should take sufficient care by means, such as installing signs, to prevent workers from inadvertently inhaling the inert gas. In case of inhalation, workers should be instructed in how to reach to emergencies.

oxygen concentration in the tank after the onset of substitution may be estimated from the following formula:

$$C_t = C_o \exp\left(-\frac{Qt}{V}\right) \tag{A.1}$$

where t (h) is the time elapsed from the onset of substitution, C_t (vol%), the intra-tank oxygen concentration after time t, C_o (vol%), the oxygen concentration of the air (20.95 vol%), Q (Nm^3/h), the feed of the inert gas, and V (m^3), the intra-tank space volume.

A.4.4 Method of inerting

Substitution should be performed in a batch or continuous method depending on the type of target equipment or operation.

A.4.4.1 Batch-type inerting

Batch-type inerting, which refers to supplying inert gas in every task or operation for the substitution, should be chosen in the following areas:

(1) when loading a highly flammable liquid into a tank ;

(2) when drawing liquid from an enclosed tank containing a highly flammable liquid without using a pressure equaliser;

(3) when loading a highly flammable solvent or something similar into a batch-type reaction tank opened to the atmosphere;

(4) when discharging gas, steam, or stagnant on equipment or in a tank or something similar that handles flammable gas or matter and performing an open inspection, repair, or other operation;

(5) when discharging flammable gas or highly flammable solvent vapour from a vent stack or when an explosive atmosphere may form in the vent stack or around its discharge outlet;

(6) when temporarily leaving a manhole open for an enclosed tank filled with flammable solvent and loading powder through such a manhole or when an explosive atmosphere may develop in or outside the opening.

A.4.4.2 Continuous inerting

Continuous inerting (which refers to supplying inert gas continuously for inerting) should be chosen in the following cases:

(1) when handling equipment and flammable matter with a wide explosion range at normal pressure and normal temperature and when supplying inert gas to prevent explosion and fire, thereby preventing air ingress through a gas exhaust pipe;

(2) when handling a compressor of the dry-seal shaft-seal type used for flammable gas and when supplying inert gas into the first-stage stuffing box in an attempt to prevent explosion and fire;

(3) when loading a flammable solvent or something similar into a batch-type reaction tank opened to the atmosphere;

(4) when inactivating the vapour phase of the liquid-phase reaction system of a substance with a considerably low LOC (such as silanes) in an attempt to increase the safety of the entire process;

(5) when flammable powder may form a large dust cloud in a silo or other equipment in an attempt to prevent an explosion or fire.

A.4.5 Equipment for inert gas

Equipment for inert gas for inerting should be handled as follows.

A.4.5.1 Determining where to install

When determining where to install supply equipment, the following should be considered:

(1) Installing equipment in a safe location protected from damage stemming from an explosion or fire from other equipment.

(2) If any equipment is to be installed near equipment likely to undergo an explosion or fire, the equipment should be protected from damage by installing an explosion-proof wall.

(3) For equipment provided with an air separator, its air intake must be installed upstream of the wind.

A.4.5.2 Amount of inert gas held

The amount of inert gas held in equipment should be determined as follows:

(1) When using shared equipment, the sum of the following two items should be determined as the amount held.

  (a) The total of the steady-state consumption of all the facilities.

  (b) The amount of inert gas for an intra-system substitute required for each facility to make the plant safe in an emergency. Here, the amount of inert gas for a substitute should be calculated by considering the following matters and coordinating efforts between facilities.

    (i) the piping system of the supply equipment
    (ii) the substitution method in an emergency (such as complete and partial substitution)
    (iii) the stoppage procedure of the plant
    (iv) time-series changes in the pressure of the inert gas holder

(2) When using equipment in isolation, the amount held should match the inerting for the entirety of the space volume of the facilities. Furthermore, the amount held may be as much as that in the process in which the consumption of inert gas is the maximum among those in processes.

A.4.5.3 Securing an appropriate inert gas pressure

An appropriate gas pressure in equipment for inert gas should be secured by doing the following:

(1) Keeping equipment at a sufficiently high gas pressure to protect other equipment from experiencing problems at the end of the process even if a significant amount of inert gas is consumed during the process.

(2) Piping for supplying inert gas should be classified by their consumption pressure.

(3) If consumption is low and an inert gas of a considerably high pressure is needed, a gas cylinder or a small storage tank equipped with a compressor should be used.

A.4.5.4 Emergency power supply

Equipment for inert gas should come with an emergency power supply to enable a continued supply of inert gas if commercial power fails.

A.4.6 Control by using the upper flammable limit

This control method uses a system that sets an atmosphere to over the upper flammable limit (UFL). The method ensures that the following conditions are met to set the level at least to a concentration higher than the upper flammable limit by supplying at least 25 vol% of natural gas or methane [47].

(1) The vent heders are operated near atmospheric pressure.

(2) Vapour with a UFL exceeding that of hydrogen air (75 vol%) is not included.

(3) A supply of oxygen with a concentration higher than that in air is not allowed.

A.4.7 Localising disasters

It is effective to use such equipment as flame arrestors, pressure dischargers, and explosion vents (see Technical Recommendations of the National Institute of Industrial Safety, TR-No. 38, *Guide for Explosion Venting (Revised Edition)*, 2005) designed to minimise disasters in the case of fire or explosion.

Appendix B

Electrostatic risk assessment

B.1 Electrostatic risk assessment

Below are points to be considered in risk assessment to prevent electrostatic explosions and fires. The items listed below are important in investigating processes and risk sources.

(1) Points concerning static electricity

  (a) Grounding and bonding (leakage resistance and bonding resistance)
  (b) Presence or absence of a nonconductor and its chargeability
  (c) Discharge possibility and its ignitability
  (d) Risk factors concerning static electricity in workers.

(2) Points concerning flammable matter handled

  (a) Boiling point, flash point, ignition point, and other factors
  (b) Relationship between handling conditions and flammable limits
  (c) Conductivity
  (d) Permittivity
  (e) Charge and potential levels
  (f) Ignition energy
  (g) Relationship between temperature and vapour pressure
  (h) Liquid contains an immiscible component or a suspended solid, or not
  (i) Hydrophilic or hydrophobic materials.

(3) Points concerning processes

  (a) Ranges and changes in conditions of operation and handling (such as velocity, temperature, pressure, and amount handled)
  (b) Changes in charge during processing
  (c) Ripple effects of urgent shutdowns and emergency stops
  (d) Risk factors in an anomaly
  (e) Human error

(4) Points concerning equipment

  (a) Risk factors concerning equipment arrangement, and position

- (b) Effects of high-risk equipment on other equipment
- (c) Risk factors of corridors and spaces for operating equipment
- (d) Risk factors generated during inspection, investigation, and tests
- (e) Risk factors generated by a trouble, damage, or breakdown.

The risk of all the hazardous sources identified should be assessed, and the antistatic measures specified in this document should be taken as necessary.

B.2 Considering case history

(1) The following electrifications have been identified as the cause of previous accidents or disasters. Therefore, their risks should sufficiently be assessed:

- (a) Electrification of fast-travelling film, paper, cloth, or other material;
- (b) Electrification of insulated metal containers and parts that contain liquid or powder;
- (c) Electrification of metal bodies mounted on a part of insulated pipes or hoses;
- (d) Electrification of bag filters, chutes, or other fibre products;
- (e) Electrification of nonconductive liquid splashing out of a nozzle, hose, or pipe;
- (f) Electrification of workers insulated by nonconductive footwear or nonconductive flooring;
- (g) Electrification of nonconductive liquid loaded into a tank or large container;
- (h) Electrification of liquid loaded into nonconductive containers;
- (i) Electrification of liquid being mixed or agitated.

(2) The following processes have been deemed responsible for previous accidents or disasters. Therefore, their risks should be sufficiently assessed:

- (a) Processes for loading powder into a container with flammable liquid inside;
- (b) Processes for applying or printing adhesive, paint, ink, solvent, or other material;
- (c) Processes for fluidising and drying powder containing solvent;
- (d) Processes for spraying solvent, paint, or other material;
- (e) Processes for cleaning with solvent;
- (f) Processes for gauging and sampling flammable liquid;
- (g) Processes for removing moulded plastics from their moulds;
- (h) Processes for winding up and back film, paper, cloth, and other materials using rollers;
- (i) Processes for bagging and fluidising significant amounts of powder;
- (j) Processes for attaching and adhering objects with adhesive;
- (k) Processes for loading and reloading flammable liquid into a tank or container;
- (l) Processes in which fine dust is generated by the pneumatic transport, collector, or other handling of powder;
- (m) Processes for foaming and moulding resin.

(3) The following discharges have been deemed responsible for previous accidents or disasters. Therefore, their risks should be sufficiently assessed:

- (a) Discharge from a charged metal body;
- (b) Discharge generated by peeling off an adhered object;

- (c) Discharge generated when powder adheres to a bag filter or a chute is peeled off;
- (d) Discharge generated by removing moulded plastics from their mould;
- (e) Discharge from a charged worker;
- (f) Discharge generated when working clothes are being taken off;
- (g) Discharge from a metal container for sampling;
- (h) Discharge from a metal part installed on an insulator;
- (i) Discharge generated due to an ioniser malfunction or its mishandling;

(4) The following cases have been identified as responsible for previous accidents or disasters. Therefore, their risks should be sufficiently assessed:

- (a) A first-time run of a facility, device, or other equipment or the resumption of operations following repairs;
- (b) A change in operational conditions;
- (c) An extreme decrease in relative humidity;
- (d) A problem with a facility, device, or equipment, resulting in an abrupt change in its operational state;
- (e) When foreign matter is mixed with a material;
- (f) When there is an inappropriate change in the work manual or standards;
- (g) When there is insufficient maintenance of an ioniser;
- (h) When a device or equipment is mishandled;
- (i) In the course of operations different from dairy processes, such as cleaning.

B.3 Control indicators

Control indicators for safety may be useful to assess electrostatic hazards and to control static electricity. Therefore, such indicators are collectively described here, although some of them have already been specified in Chapter 3. Use of this information is encouraged for identifying the hazards and estimating and evaluating risks.

B.3.1 Control indicators for conductors

B.3.1.1 Prevention of spark discharges

To prevent spark discharges (to reduce a charged potential of up to 100 V for conductors), the leakage resistance of conductors (made of metal or other conductive material) should be set to less than 10^6 Ω. In addition, the leakage resistance of workers should be set to less than 10^8 Ω. The grounds of these values are described in 3.3.5.3. In addition, the leakage resistance of workers must be set to 10^5 Ω or more to prevent electric shock due to low-voltage power lines (100-400 V). In hazardous areas of Zone 0 (IIC) and Zone 1 (IIC), the leakage resistance of workers should be set to less than 10^6 Ω. If not, the hazardous areas should be off limits to workers.

For risk indicators of spark discharges, see 3.3.5.3 and Figure 3.9 in that clause.

Table B.1: Control indicators for the leakage resistance of conductors

Leakage resistance (Ω)	Degree of electrification	Typical potential (kV)*
$< 10^6$	Almost nil	< 0.01
$10^6 - 10^8$	Low	0.01 – 1
$10^8 - 10^{10}$	High	1 – 100
$> 10^{10}$	Very high	> 100

* Potential determined from Equation (3.4) with a generated current $I_G = 10\ \mu A$.

Table B.2: Guideline for chargeability

Chargeability	Volume resistivity (Ω·m)	Surface resistivity (Ω)
Unchangeable	$< 10^8$	$< 10^{10}$
Low	$10^8 - 10^{10}$	$10^{10} - 10^{12}$
Chargeable	$10^{10} - 10^{12}$	$10^{12} - 10^{14}$
High	$> 10^{12}$	$> 10^{14}$

B.3.1.2 Maximum potential and maximum charge

The potential of a charged conductor depends on the leakage resistance as shown in Equation (3.4), $V = I_G R$. Moreover, the charge depends on the relaxation time (the product of the leakage resistance and capacitance), as shown in Equation (3.5), $Q = I_G CR$. As the current I_G generated in static electricity on an industrial level almost never exceeds 100 μA, this current can be used to estimate the possible maximum potential V_{max} and maximum charge Q_{max} of the conductor by using the following equations:

$$V_{max} = 1 \times 10^{-4} R, \tag{B.1}$$

$$Q_{max} = 1 \times 10^{-4} CR. \tag{B.2}$$

B.3.1.3 Leakage resistance

From Equation (B.1), a guideline for the leakage resistance of a conductor can be expressed as shown in Table B.1. For the maximum leakage resistances related to the ignition energy, see 3.3.5.3 and Figure 3.10 in that clause.

B.3.2 Guideline for chargeability

The chargeability of materials depends on the volume and surface resistivities as shown in Table B.2

B.3.3 Control indicators for nonconductors

B.3.3.1 Control indicators by nonconductor area and width

The charging of nonconductor electrification is difficult to control. Therefore, a method of control by limiting area or width with an electrostatic shielding is recommended as shown in Table 7.1.

B.3.3.2 Control indicator for the potential of a nonconductor

The potential of a charged nonconductor must be below the curve shown in Figure 3.11, which indicates the relationship between the potential of a charged body and the discharge energy of a brush discharge in Equation (3.13) in 3.4.7. Based on the minimum ignition energy of the atmosphere of a workplace, the nonconductor potential should not be more than curve "a" shown in Figure B.1 which has a safety margin of 1/10 of the relationship. Alternatively, a step-like straight line "b" matched to curve "a" (1 kV (MIE < 0.1 mJ), 5 kV (0.1 mJ $\leq$ MIE < 1 mJ), and 10 kV (MIE > 1 mJ) is available.

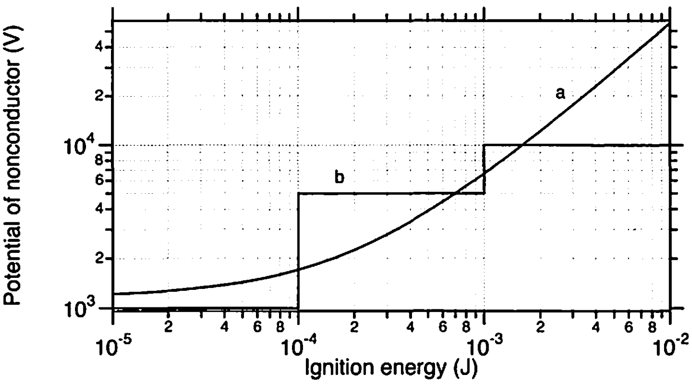

Figure B.1: Control indicator for the potential of a charged nonconductor (below curve a or a stair-like straight line b)

B.3.3.3 Control indicator for the surface charge density of a nonconductor

The maximum surface charge density of a nonconductor should be controlled to less than 1 $\mu C/m^2$ (IIC), 3 $\mu C/m^2$ (IIB), 5 $\mu C/m^2$ (IIA), 7 $\mu C/m^2$ ($1 \leq$ MIE < 10 mJ), and 10 $\mu C/m^2$ (MIE ≥ 10 mJ)[1].

B.3.4 Control indicator for charged cloud

If a charge cloud in a tank includes a flammable substance and has a low ignition energy, preventing an explosive atmosphere is more desirable than controlling the charged clouds. If, therefore, the control indicator for a charged cloud reported here is used in hazardous areas of Zone 0 or Zone 20, sufficient risk assessment is necessary. As described in 3.3.10, a lightning-like discharge is very unlikely to occur under industrial process conditions. Even if one does occur, the conditions for its initiation will require a considerably higher space charge density than that for a brush discharge generated from a grounded protrusion. Therefore, it is sufficient to give consideration to preventing this brush discharge as the control indicator for a charged cloud. From the result of a calculation with wide ranges in tank volume and protrusion sizes [48], the control indicator for the discharge due to charged cloud in a grounded tank can be expressed as shown below. It is noteworthy that the conditions specified allow for a safety margin of less than 1/2 of the conditions for initiating a brush discharge, the energy of which is greater than 0.1, 0.2 or 1mJ.

Charged clouds should be controlled so as to meet the following equations:

$$\begin{cases} \rho \leq 1.5 \times 10^{-6} R^{-1} & (MIE \geq 0.1 \text{ mJ}) \\ \rho \leq 2.3 \times 10^{-6} R^{-1} & (MIE \geq 0.2 \text{ mJ}) \\ \rho \leq 4.0 \times 10^{-6} R^{-1} & (MIE \geq 1 \text{ mJ}) \end{cases} \tag{B.3}$$

for charge density ρ of clouds, and

$$\begin{cases} E \leq 0.85 \times 10^5 \text{ V/m} & (MIE \geq 0.1 \text{ mJ}) \\ E \leq 1.1 \times 10^5 \text{ V/m} & (MIE \geq 0.2 \text{ mJ}) \\ E \leq 1.6 \times 10^5 \text{ V/m} & (MIE \geq 1 \text{ mJ}) \end{cases} \tag{B.4}$$

for the wall electric field E at the half height of tanks. Here, R is the tank radius and MIE is the minimum ignition energy of the flammable atmosphere inside the tanks.

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[1] In ignition experiments with hydrogen and propane due to a discharge from a charged nonconductor, a charge density up to -3.8 $\mu C/m^2$ for a negatively charged nonconductor, and up to $+17$ $\mu C/m^2$ for a positively charged one could not ignite hydrogen. Propane, on the other hand, reaches -7.4 $\mu C/m^2$ for negative charging and stays non-ignited in any positive charging. The maximum safe surface charge density with no ignitable discharge is therefore set to -3 $\mu C/m^2$ and $+5$ $\mu C/m^2$ [11].

Note that the control indicator below from the former guidelines,TR-87-1 (1998) may be available. However, if the average electric field inside the charged cloud is difficult to measure, the value may be replaced with the electric field on the container side wall. In addition, if risk assessment proves that such a method is appropriate, the electric field value may be changed.

(1) To prevent a lightning-like discharge, the charged cloud should be kept within 1.5 m in diameter, or the average electric field should be kept in the charged cloud within 3 kV/cm.

(2) To prevent a brush discharge from a charged cloud, the charged cloud should be kept within 0.7 m in diameter, or the average electric field should be kept in the charged cloud within 1 kV/cm.

Appendix C

Measurements for electrostatics

C.1 Analysis and monitoring of risks by measurement

Disaster prevention requires the quantitative analysis and monitoring of electrostatic risks and quantitative investigation and periodic inspection of antistatic precautions on the basis of risk assessment. For these purpose, measurements are necessary.

C.2 Cautions on measurement

When taking measurements in the workplaces, the risk of inducing a disaster, such as a fire, due to the measurement itself, should be assessed. If there is any hazard, it should be eliminated before the measurements are taken. In hazardous areas with an explosive atmosphere, explosion-proof measuring equipment should be used. Fire-fighting and emergency manuals should be provided in advance to prepare for the possibility of fires during measurement.

The measurement of static electricity is affected by humidity; therefore, the environmental conditions (relative humidity and temperature) should be stated with the results.

C.3 Measurements of potential and electric field

C.3.1 Measurement of potential with contact

This method consists of using a voltmeter, such as an electrometer and high-voltage meter with a high input impedance ($> 10^{12}\ \Omega$), and connecting it directly to a charged object (conductor) to be measured via a lead wire, thereby measuring the potential. This method is, therefore, applicable to the measurement of the potential of conductors. At that time, care should be taken not to let the level exceed the maximum input voltage of the voltmeter, and a voltage divider for high voltage should be used if necessary. If the voltmeter is placed into contact, as shown in Figure C.1, the input impedance (parallel with input resistance R_{in} and input capacitance C_{in}) will reduce the potential. At the same time, the potential will be reduced with time t as well. The result is an error in potential measurements. This can be expressed as the following equation:

$$V = \frac{C_0 V_0}{C_0 + C_{in}} \exp\left[-\frac{t}{(C_0 + C_{in})R_{in}}\right] \tag{C.1}$$

where V_0 and C_0 are the potential and capacitance to ground of the conductor to be measured before a voltmeter is connected. It should also be noted that, at time $t = 0$, a voltmeter is connected to the conductor.

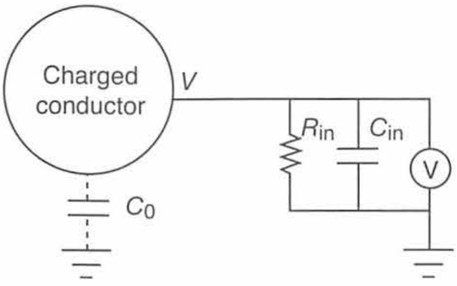


Figure C.1: Equivalent circuit for the measurement potential with a voltmeter connected

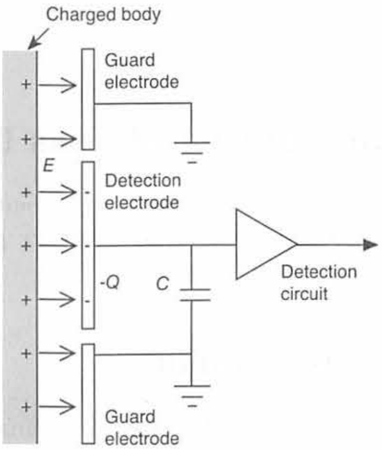


Figure C.2: Principle for measuring the electric field based on electrostatic induction

C.3.2 Measurements of the potential and electric field without contact

A noncontact electrostatic voltmeter can be used to measure the potential and electric field. The principle of measurement is electrostatic induction. This method consists of: (1) detecting the charge (potential) induced into the detection electrode by a charged body to be measured and, (2) in view of the fact that this is proportional to the electric field and potential, converting it to an electric field or potential of a charged body. Assuming that charge Q is induced onto the detection electrode (area A) by electric field E as shown in Figure C.2, the Gauss' theorem leads to the following relationship:

$$\varepsilon_0 E A = Q. \tag{C.2}$$

At that time, the induction potential V of the detection electrode becomes

$$V = \frac{Q}{C} = \frac{\varepsilon_0 E A}{C}. \tag{C.3}$$

From this equation, electric field E can be measured. Here, C is the capacitance of the detection electrode (including the capacitor connected to the detection electrode and the input capacitance of the circuit connected to it). To apply this to the voltmeter, with the application of voltage V_m to a relatively large metal plate as shown in Figure C.3, it is necessary to obtain in advance the proportional relationship between induction potential V and V_m at a specified distance of about a few centimetres. Commercially available electrostatic voltmeters use this relationship to convert the value to the potential and display the result.

To improve the sensitivity for measuring this induction potential, some equipment vibrates the detection electrode or provides a rotation sector, thereby setting the detection signal to AC

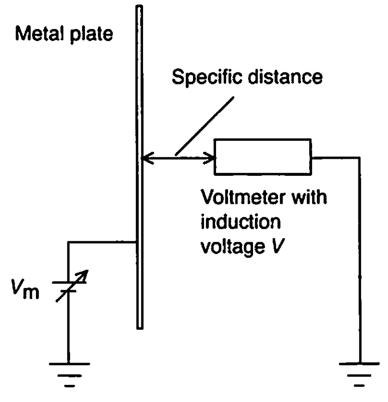


Figure C.3: Calibration of an electrostatic voltmeter. For zero adjustment, the metal plate is grounded.

and detecting it phase-synchronously. Such equipment corresponds to a vibration capacitance-type electrostatic voltmeter and rotation sector-type fieldmeter, both of which are commercially available. These meters can measure the potential or electric field of both conductors and nonconductors. Accurate measurement requires grounding of the measuring equipment. Voltmeters with a specified measuring distance cannot measure the potential accurately unless they take measurements at that specified distance. Moreover, since the nonconductor potential is not equal on the surface, the meter measures the average potential around it.

Attaching a fieldmeter on the side wall of the tank or large pipe is an effective way to monitor and evaluate the electrostatic risk of the inside of it (see B.3.4).

C.4 Charge measurement

C.4.1 Faraday pail

Surrounding a charged body with an insulated closed metal will induce a charge of the same amount with the opposite polarity of the charged body inside the closed metal and a charge of the same amount with the same polarity outside. The outside charge can be measured to enable measurement of the charge of the charged body, such as the charge density of a liquid and the charge-to-mass ratio of powder.

The Faraday pail is a container of two metal pieces, large and small (which may be replaced with metal meshes when measuring a space charge), as shown in Figure C.4. The internal and external containers are electrically insulated with PTFE (polytetrafluoroethylene) , acrylic, or other insulating materials. The external container is grounded to eliminate the effects of the charge exterior to it.

This charge Q can be determined by: (1) measuring the charge directly with a Coulomb-meter or (2) measuring potential V with a voltmeter with a high input impedance, such as an electrometer, by connecting, in parallel, capacitor C_m with a capacitance sufficiently larger than capacitance C_f between the inside and the outside the Faraday pail as shown in Figure C.4 and by using the following equation,

$$Q = (C_f + C_m)V \approx C_m V. \tag{C.4}$$

Here, for capacitor C_m, one having a high insulation resistance should be selected, such as a polystyrene capacitor. Moreover, the capacitor value should meet the following conditions: (1) $C_m \gg C_f$, which is the measurement condition indicated above, (2) C_m sufficiently larger than the input capacitance of the electrometer, and (3) the measured voltage V $(= Q/C_m)$ smaller than the maximum input voltage of the electrometer. It should be noted, however, that an excessively large C_m would reduce the measurement sensitivity and an excessively small charge would then not be measured.

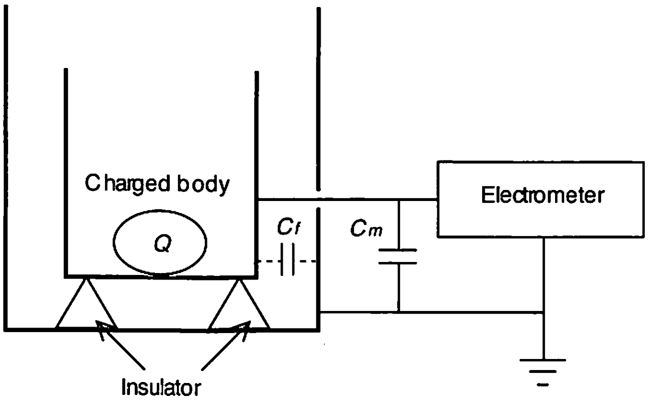


Figure C.4: Charge measurement with a Faraday pail

C.4.2 Surface charge measurement with an electrostatic voltmeter or fieldmeter

A fieldmeter or electrostatic voltmeter based on the measurement principle of electrostatic induction shown in Figure C.2 can be used to measure the surface charge density σ on a charged body by a conversion of the following equation,

$$\sigma = \varepsilon_0 E = \varepsilon_0 \frac{V}{\delta}, \tag{C.5}$$

where E is the measured value measured with the fieldmeter, V, the value measured with the electrostatic voltmeter, and δ, the distance between the voltmeter and the body to be measured. In view of the measurement precision, the measurement distance should be set to about 1 cm or less to form a uniform electric field. For this purpose, a voltmeter having a shorter specific distance should be selected. In addition, care should be taken not to let discharges occur because the grounded case of the devise approaches the charged body.

C.4.3 Space charge measurement with a fieldmeter or Faraday cage

Installing a fieldmeter on a grounded cage having the desired shape enables the measurement of the space charge density inside the cage from the measured electric field E. Assuming that the charge density of the space inside the cage is uniform, space charge density ρ is obtained as follows in the case of a spherical cage with radius a (Figure C.5a),

$$\rho = \frac{3\varepsilon_0 E}{a}$$

and in the case of a cylindrical cage with radius a (Figure C.5) ,

$$\rho = \frac{2\varepsilon_0 E}{a}.$$

Alternatively, a Faraday cage consisting of two cages can also be used to measure the space charge density.

C.4.4 Space charge measurement with a suction Faraday tube

The Faraday tube consists of a coaxial tube that can be equipped with suction capability to collect powder and mist floating in space, and their charge amount and the volume of air sucked can be used to measure the space charge density. For example, it would be convenient to use an

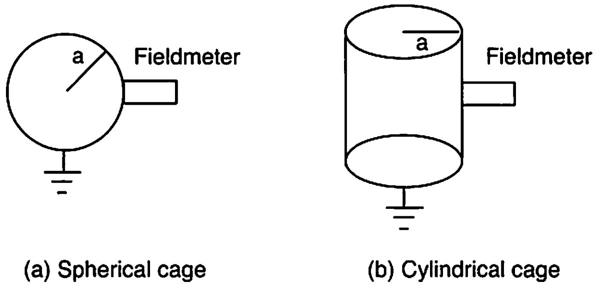


Figure C.5: Measurement of the space charge density with a fieldmeter

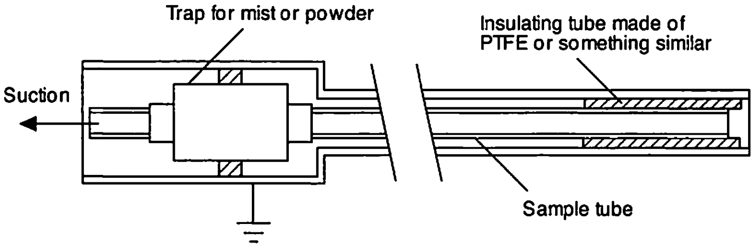


Figure C.6: Suction Faraday tube

apparatus combining a Faraday tube with a liquid or powder trap as shown in Figure C.6. For the tube and trap, those made of metal for gas piping may be used. The insulating pipe at the tip of the tube should be used for not only electrical insulation but also sealing for suction.

C.5 Measurement of the generated charge

A charge generated per unit time due to charge separation between liquid or powder and any conductor, such as a metal nozzle and pipe, can be measured by inserting a low-current meter capable of measuring a current in the range of about 10^{-11} – 10^{-6} A in series between the conductor and the earth. For a precise measurement, the cable furnished with the measuring equipment should be used. If such cables are not available, a shielded wire should be used.

For example, setting up the apparatus as shown in Figure C.7a enables the measurement of current I of flow in the metal piping. On the other hand, setting up the apparatus as shown in Figure C.7b enables measuring the nozzle current I to determine the current by a mist or something similar that is sprayed. The nozzle current I has opposite polarity with the same quantity as the spray current I_m; thus, it can be converted to the volume charge density of the bulk of mist or something similar that is sprayed by using the flow rate. Setting up the apparatus as shown in Figure C.7c enables measurement of the generated charge between a roller and a roll.

Other methods for the measurement of the generated charge include connecting a capacitor to a pipe, nozzle, roller, or something similar and grounding the other end of the capacitor and measuring the charge accumulated with time to this capacitor as the potential (Figure C.7d). At that time, the relationship between the generated current I and measuring voltage V can be expressed as $I = C\frac{dV}{dt}$ with capacitance C of the measurement-use capacitor. The generated current can, therefore, be determined on the basis of the voltage change for a very short period.

When the instantaneous value of the generated current is measured as illustrated in Figure C.7e, resistance R must be sufficiently lower than the input resistance of the oscilloscope. In practice, this current is small; thus, it would be required to use either a voltage amplifier with a high input impedance or an I–V converter with a resistor inserted into the negative feedback of the operational amplifier instead of resistor R. In the latter case, the measured voltage has the

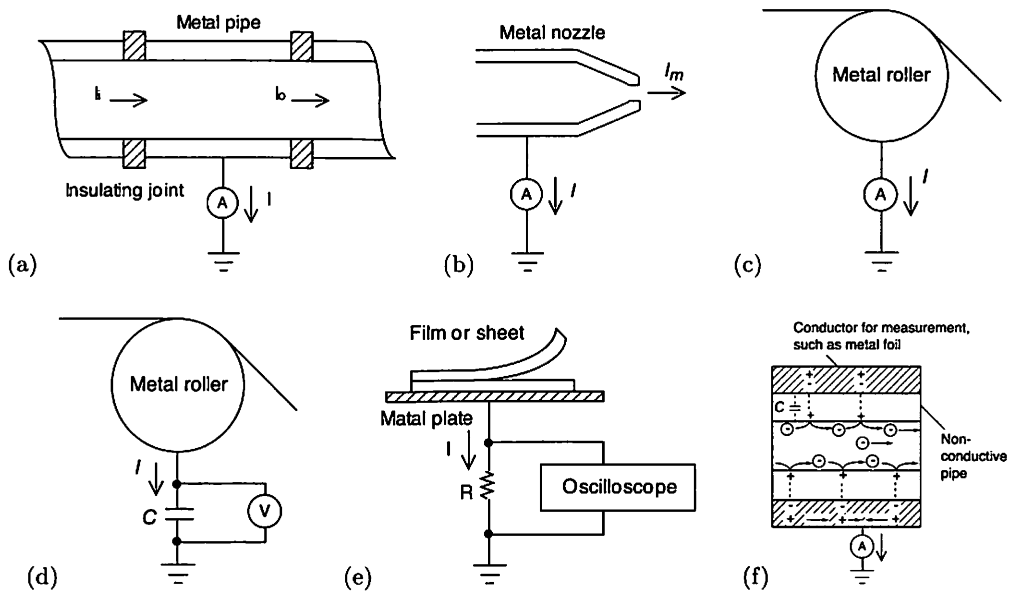


Figure C.7: Examples of the measurement of the generated charge: (a) example of the measurement of charge generation in a metal pipe due to a liquid or powder stream; (b) example of the measurement of charge generation during spraying by a nozzle current; (c), (d) example of the measurement of a charge generated due to friction electrification between a roller and a roll; (e) example of the measurement of charge generation due to peeling; (f) example of the measurement of the charge generation in an insulating pipe.

opposite polarity of the real current.

The charge generated in a nonconductor can be measured indirectly by winding metal foil or something similar around as illustrated in Figure C.7f and by inserting a low-current meter between it and the earth.

If charge generation occurs at several points in the movement route of a body, it is desirable to measure simultaneously the charge generated at each point and the final charge of the body (if necessary, the initial charge as well) as shown in Figure C.8. It would be advisable for the final charge to be measured with a Faraday cage or pail. In an ideal measurement system, the algebraic sum of the measured currents at different points becomes zero from the continuity of the current, i.e., in the example of Figure C.8, $I_1 + I_2 + I_3 + I_f = 0$. In a noisy environment, shielding the entire measurement system with a grounded metal net or something similar reduces the noise.

C.6 Dust figure method

The surface charge distribution of a charged body in which charges of both positive and negative polarities are complexly mixed is often difficult to measure with a method for detecting the external electric field. However, using the electrostatic attraction acting on powder allows such a charge distribution to be easily observed. This method is called the dust figure method. For example, this method can consist of mixing well a powder mixture of about 90% dry (yellow) sulphur and about 10% lead oxide (trilead tetroxide: red lead, Pb_3O_4) in a mortar, wrapping the mixture in a dry piece of linen or bleached cotton cloth, and sprinkling it over the charged body. Here, the negatively charged sulphur powder adheres to the positive charge on the surface of the charged body, and the positively charged lead oxide powder adheres to the negative charge on the surface. Consequently, the distribution with positive and negative charges can be observed by the naked eye.

The dust figure method is for observing the surface charge distribution qualitatively and has

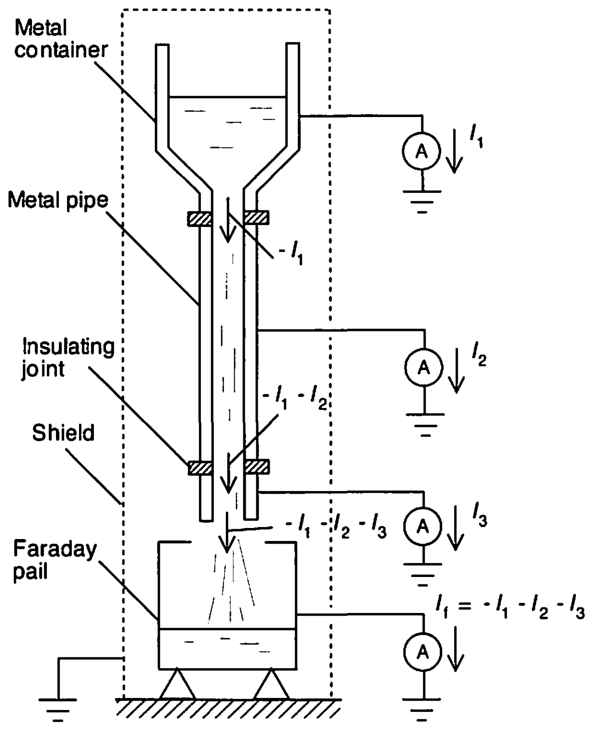


Figure C.8: Example of the systematic measurement of generated charge

various uses, such as observing discharge traces (static marks) and testing the charging property of plastic products.

C.7 Measurement of electrostatic discharge

Electrostatic discharge between a charged body and a grounded conductor located close to it can be evaluated in terms of risk by measuring its discharge current, transferred charge, and potential of the charged body before its discharge (see C.3.2).

(1) For the characteristics of the corona discharge which occurs continuously, its average discharge current can be measured by using a DC current meter capable of measuring currents in the range between 10^{-8}–10^{-3} A (Figure C.9a). At that time, to protect the meter from spark discharges, a protective resistor of about 1 MΩ should be connected between the discharge electrode and the meter.

(2) For spark discharges and other intermittent discharges, their charge transferred ($Q = CV$) can be measured by accumulating the charge Q into capacitor C and measuring the potential V of the capacitor with a voltmeter with a high input impedance (Figure C.9b). The value of the capacitor should be selected for a measured potential V not exceeding the maximum input voltage of the voltmeter and its sensitivity.

(3) Converting the discharge current to a voltage through a resistor and observing it with an oscilloscope having a wide frequency bandwidth (which should preferably be more than 100 MHz in analogue band) enable an instantaneous waveform of the discharge current to be measured (Figure C.9c). At that time, the resistor R used must be sufficiently smaller than the input resistance of the oscilloscope. Here, it should be tens of kilo-ohms at most. The resistor may be replaced with a current probe.

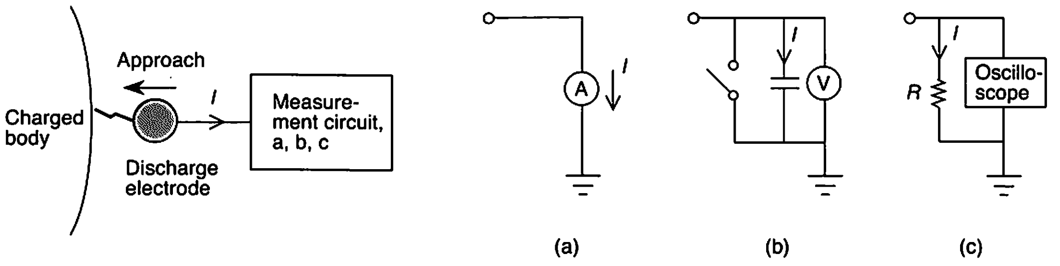


Figure C.9: Examples of the measurement of an electrostatic discharge: (a) measurement circuit of the average discharge current, (b) measurement circuit of the transferred charge, (c) measurement circuit for the discharge current waveform

Since the type of discharge depends on the size and sharpness of the electrode (see 3.3), a metal conductor should be determined according to the target discharge. In general, a needle or a metal sphere of up to 30 mm in diameter is used.

C.8 Pretreatment and environment for measuring material properties

When measuring the resistance, capacitance, resistivity, conductivity, permittivity, and other material properties, the measurement environment must be controlled because the measurement may be affected by the dirt on the specimen and the environmental temperature and humidity.

(1) Dirt and other foreign matter should be removed from the electrodes and specimens with solvent. If any such matter is in a liquid state, after the foreign matter in an electrode cells is removed, the cell should be washed together with the specimens.

(2) When measuring a solid, the specimen should be dried if necessary.

(3) The measurement environment should be about 20°C in temperature and not more than 50% in relative humidity.

C.8.1 Solid

(1) The surface of each solid specimen should be wiped with a dry, clean piece of gauze, dust-free paper, or something similar that contains alcohol; it should then be thoroughly dried. If the surface is very dirty, the specimen should be washed with a neutral detergent, rinsed well with water, and thoroughly dried.

(2) If thermal strain is to be removed, the specimen should be kept in a drier vessel at a specific temperature for a specific amount of time (typically at a temperature of 80° for an hour).

(3) During pretreatment for adjusting the temperature and humidity, the specimen should be maintained under the same conditions as those of the measuring environment (C.8.4) for a specific time. The standard time is 24 hours.

(4) To adjust the temperature and humidity for the measurement environment and for pretreatment, a thermo-hygrostat or a humidity-regulated desiccator may be used.

(5) If the measurement electrode is dirty, it should be wiped clean with a piece of gauze or dust-free paper containing alcohol.

C.8.2 Liquid

A liquid specimen should pretreated by being kept at a specific temperature for a specific amount of time. The standard time is one hour.

C.8.2.1 Cleaning electrodes

An electrode cell and other parts in contact with liquid specimens should be sufficiently cleaned. For example, they should be cleaned as follows:

(1) A solvent that does not dissolve the insulating material of the electrodes, such as acetone or alcohol, should be used. After being cleaned a few times, the electrode should then be washed with the specimens.

(2) If the inside of the electrode cell is very dirty, it should be cleaned as follows before it is cleaned as specified in (1) above. A neutral detergent should be used for cleaning it with water. The electrode cell should then be boiled in pure water for 30 minutes, dried in a drier vessel at 120°C for one hour, and then left to cool down in a desiccator. For maintenance, it would be desirable to clean the electrodes when they are disassembled.

C.8.3 Powder

To pretreat a powder specimen, the specimen should be left at a specific temperature and humidity for a specific amount of time. The standard time is 24 hours. The electrodes should be cleaned in a manner similarly to that described inC.8.2.1 .

C.8.4 Measurement environment

The standard measurement environment is 20±2°C in temperature and 50±5% in relative humidity. In general, however, the environment may be indoors at a low humidity (50% or less). For measuring the effects of the temperature and humidity, the environmental conditions must include constant temperature and humidity.

It is noteworthy that, for the risk assessment of a process using liquids, the temperature should be the same as the liquid temperature used in the process because of the temperature dependency of liquid properties.

C.9 Resistance measurement

C.9.1 Method of resistance measurement

For resistance measurement, on the basis of Ohm's law, a DC voltage V should be applied to the specimen to be measured, and the current I should be determined at that time to obtain resistance R ($= V/I$). Other applicable equipment includes a general circuit meter (tester), a portable insulation resistance meter, and high-resistance meter incorporating a voltage source and a current meter, which converts resistance to a reading. The choice of a meter depends on the resistance to be measured, and a general circuit meter is sufficient for applications with up to about 10^6 Ω. At about 10^6–10^9 Ω, an insulation resistance meter should be used. For measuring resistances exceeding 10^9 Ω, a high-resistance meter should be used. If the current is not more than 1 nA, it is recommended that a guard ring be used for the measurement electrode for shielding .

It is noteworthy that the measured resistance, R, contains the insulation resistance R_i (the resistance of the material for insulation between the main electrode and the opposite one) of the electrode itself in parallel to the specimen resistance, R_s, to be measured. In other words, $R = R_sR_i/(R_s + R_i)$, and R_s cannot be correctly measured when $R_i \ll R_s$. It is, therefore, necessary to measure the insulation resistance of R_i in advance.

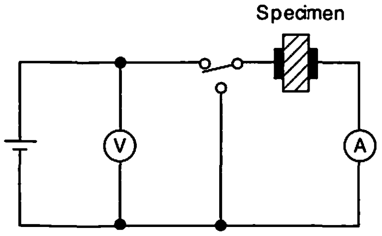


Figure C.10: Resistance measurement with the I–V method

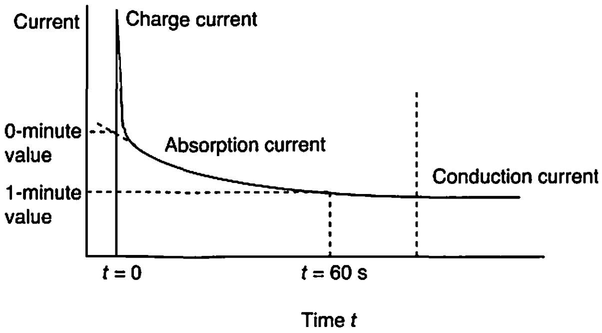


Figure C.11: Current of a high-resistance material

Measurements can also be performed by applying AC voltage. Such measuring equipment includes an LCR meter, which can measure the capacitance at the same time.

C.9.2 Current of high-resistance materials

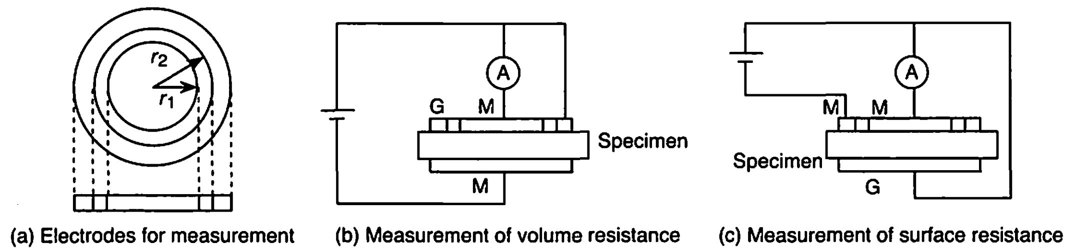
The current generated when voltage is applied to an insulator or other high-resistance material does not stay constant. A current will instead flow as shown in Figure C.11. The initial quick surge of a current is one that charges the capacitance constituted by the measuring system. After that, the absorption current flows, declining exponentially. Then, the steady-state conductive current (leakage current) of the specimen flows. This conductive current can also be used to determine the resistance. In practice, however, this may take a long time or a space charge of reverse polarity will be formed in each electrode at the interface between the electrode and the specimen. This may result in a decrease in the voltage actually applied to the specimen. In consequence, a common practice is to determine a resistance based on the current generated one minute after voltage is applied (a 1-minute value) or a steady-state value. For liquid, this effect of a space charge will be more active. Normally, therefore, the resistance is determined by the 0-minute value obtained by extrapolation.

C.9.3 Applied voltage

The voltage to be applied, up to 1,000 V, is generally used at 100 V or 500 V. For measuring a resistance of less than $10^6\ \Omega$, it should be set to not more than 50 V (1, 5, 10, or 50 V, for example). Guide values include 10 V (less than $10^6\ \Omega$), 100 V (10^6–$10^{11}\ \Omega$), and 500 V (more than $10^{11}\ \Omega$).

C.9.4 Volume resistance and surface resistance

The resistance of an insulator (nonconductive material) is generally measured with an electrode equipped with a guard electrode (Figure C.12a). Thin specimens are suitable. Measurement



(a) Electrodes for measurement (b) Measurement of volume resistance (c) Measurement of surface resistance

Figure C.12: Electrode and circuit for volume and surface resistance measurements; M: measurement electrodes, G: guard electrode

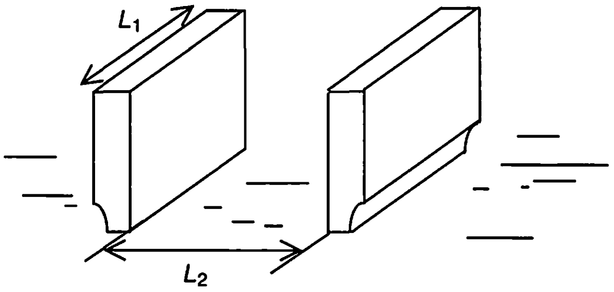


Figure C.13: Simple measurement of the surface resistivity (see Equation (2.8))

circuits for volume resistance and for surface resistance are as shown in Figure C.12b and c respectively.

C.9.5 Volume resistivity and surface resistivity

The volume resistivity ρ_v and surface resistivity ρ_s can be determined using

$$\rho_v = \pi r^2 R_v / \delta \tag{C.6}$$

$$\rho_s = 2\pi r R_s / d \tag{C.7}$$

on the basis of the measurements of the volume resistance R_v and surface resistance R_s using electrodes as shown in Figure C.12a. Here, r is the effective electrode radius $(r_1 + r_2)/2$, δ the specimen thickness, and d $(= r_2 - r_1)$ the distance between the main electrode and the guard electrode.

The surface resistivity of a body with some thickness can also be measured by arranging electrodes as shown in Figure C.13 (see Equation (2.8)).

C.9.6 Measurement of the leakage and bonding resistances

For safety, a quantitative investigation of antistatic precautions of grounding and bonding is required. The requirements that the leakage resistance be not more than 10^6 Ω and the bonding resistance not more than 1,000 Ω should be evaluated with an insulation resistance meter (megger) or circuit meter (multi-meter or tester). If the samples are dirty, rusty, or otherwise dusty, it is possible that they cannot be measured with a circuit meter, in which case an insulation resistance meter should be used. As a guide, a resistance of up to about 10^6 Ω can be accurately measured with a circuit meter, and an insulation resistance meter should be used for a resistance of about 10^6 to 10^9 Ω.

It would be convenient to use commercially available equipment that can easily be used to measure the leakage resistance of workers wearing work footwear before they start work.

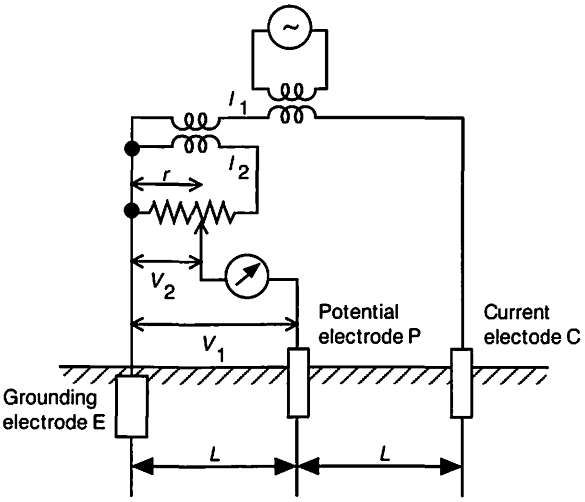


Figure C.14: Principle of the measurement of the grounding resistance with the voltage-drop method

C.9.7 Measurement of the grounding resistance of equipment

Soil has the nature of an electrolyte. To avoid polarisation, therefore, an AC voltage application should be used for measuring the grounding resistance. Commercially available equipment generally relies on the voltage-drop method and is used for taking measurements with two auxiliary electrodes (grounding rods) driven into the ground. When using commercially available equipment, measurements should be taken according to the manufacturer's manual.

The principle of the measurement of grounding resistance with the voltage-drop method is shown in Figure C.14. At a point about $L \approx 10$ m each from ground electrode E to be measured in an almost straight line, a voltage-use auxiliary grounding rod P and a current-use auxiliary grounding rod C should be driven. On the assumption that the current transformer has a relationship $I_2 = kI_1$, the skid resistor should be adjusted. When a balance is established and $V_1 = V_2$ is met, the voltage drop by I_1 equals the voltage drop of the skid resistance, i.e., $I_1 R = I_2 r = krI_1$. The grounding resistance R can then be determined from $R = kr$.

C.9.8 Measurement of the leakage resistance of the working floor

There is a standardised method for measuring the leakage resistance of working floors [49]. The electrode has a total weight of 2.5 ± 0.25 or 5 ± 0.25 kg, with 65 ± 5 mm in diameter, and the surface in contact with the floor is covered with conductive rubber. This electrode, which is placed on floor to ensure that the centre of the electrodes does not come within 100 mm of the edge of the floor, is used to measure the resistance to ground. First, a voltage of 10 V for 15 ± 2 s should be applied; then, the resistance should be measured. If the measurement exceeds 10^6 Ω, the measurement should be taken in a manner similar to that with an applied voltage of 100 V. In addition, if the second measurement exceeds 10^{11} Ω, the measurement should be made with the applied voltage of 500 V.

C.9.9 Measurement of the powder resistivity

When measuring the powder resistivity, an electrode unit as illustrated in Figure C.15 should be used. For the unit, an insulating container made of PTFE, acrylic, or other high-insulation synthetic resin should be used. The applied voltage is 100 or 500 V in general. For resistances up to 10^6 Ω, the voltage should be set not to exceed 50 V (1, 5, 10, or 50 V, for example). As a current for obtaining the resistance, a 1-minute value,10-minute value, or steady-state value

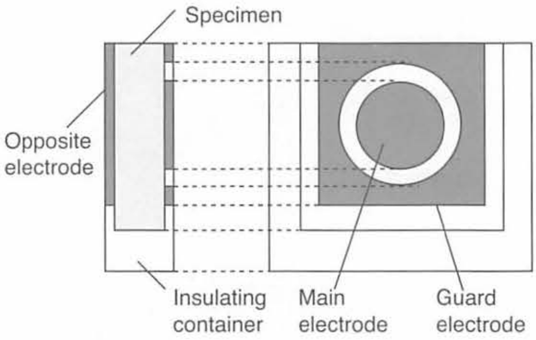


Figure C.15: Electrode with a guard electrode for powder

should be employed. The resistivity ρ of powder is obtained from

$$\rho = R\frac{A}{d}, \tag{C.8}$$

where R is the resistance obtained from a measuring circuit as illustrated in Figure C.12b, A, the area of the circular electrode (or the average area of the circular electrode and opposite electrode) , and d, the distance from the opposite electrode.

Note that the bulk density of powder affects the measurements. Therefore, loading with tapping may be required.

C.9.10 Measurement of the liquid conductivity

For the measurement of the liquid conductivity, an electrode unit as illustrated in Figure C.16 should be used. The electrodes ideally should be made of stainless steel, platinum, or gold-plated metal, but they may be made of aluminium, brass, or a similar metal. Suitable insulators include insulating synthetic resin designed to ward off liquid contamination, such as PTFE. Before the measurement, the electrodes should be sufficiently cleaned with acetone or another solvent; if they are very dirty, they should be washed with neutral detergent and dried thoroughly beforehand. They should then be washed together with the liquid to be measured at least three times (see C.8.2.1).

The applied voltage should be within the voltage range in which the resistance remains stable despite voltage changes when varying the voltage between 1 and 1,000 V for the preliminary measurement. In general, the voltage is 1, 5, 10, 50, or 100 V. Here, high-conductivity liquids may be better measured with an AC application. In the case of a DC application, however, it is appropriate to apply a voltage of 50 V or less, and, in general, the appropriate range is usually between 1 and 10 V. Liquid conductivity (the reciprocal of the resistivity) is obtained from the 0-minute current by extrapolating it as shown in Figure C.11. For measurement electrodes designed with an electrode factor of 1 m, the reciprocal of the measured resistance R corresponds to the conductivity. If not, it is determined by the following equation,

$$R = \int_{r_1}^{r_2} \frac{1}{\sigma}\frac{dr}{2\pi r L} = \frac{1}{2\pi\sigma L}\ln\frac{r_2}{r_1}$$

Then, the conductivity, σ can be obtained from

$$\sigma = \frac{1}{2\pi L}\ln\frac{r_2}{r_1} \times \frac{1}{R} = \frac{k^{-1}}{R}. \tag{C.9}$$

The electrode factor corresponds to k $(= 2\pi L/\ln(r_2/r_1))$ of Equation (C.9). To set the electrode factor k to 1 m, the following parameters are typically set to the following values:

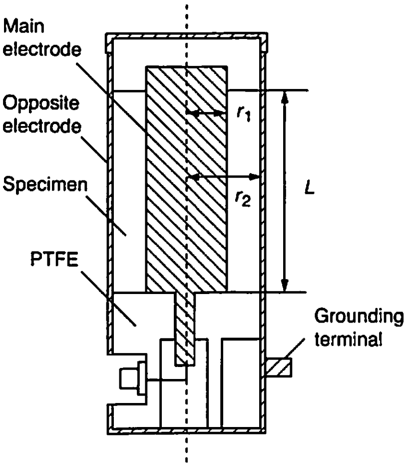


Figure C.16: Liquid-use electrode

$2r_1 = 30.7$ mm, $2r_2 = 50.5$ mm, and $L = 79.2$ mm (specimen 100 mL). If the measurement is performed with a parallel flat plate electrode, $k = A/d$, where A is the electrode area and d the electrode distance.

C.10 Measurement of capacitance

The capacitance can be measured using AC or DC. The AC methods include the I-V, resonance, and bridge methods when commercially measuring equipment is used.

When conducting measurements, the lead wire should be as short as possible. If the capacitance of the lead wire is at issue, a correction to remove it from the measurement should be conducted. When using commercially available equipment, a cable equipped with measuring equipment should be used. In general, commercially available measuring equipment has a function of this correction capability.

When an insulator is used to support and insulate the main electrode, it is noteworthy that the measurement includes the capacitance of that portion as well. If the capacitance of that portion is not sufficiently smaller than the capacitance of the specimen, then it will constitute an error. Therefore, this should be determined in advance.

C.10.1 AC method

When the AC method is used to measure the capacitance of something with one of its sides grounded, the capacitance cannot be measured using the bridge method and the resonance method. If these methods must be used, the power supply of the measuring equipment should be insulated with a transformer and measured with a relatively low frequency; however, this is not recommended. Instead, appropriate equipment that permits the measurement of capacitance grounded should be used.

C.10.1.1 I–V method

The I–V method uses the principle that, when a specified AC voltage is applied to a specimen, the current phase component of 90 degrees in advance of the voltage is proportional to the capacitance of the specimen. In general, the frequency of the AC voltage applied ranges from tens of hertz to hundreds of kilohertz, depending on the capacitance to be measured. The I–V method is also applicable to measuring the capacitance of something with one of its sides grounded. Measuring equipment based on that principle includes a C meter and an LCR meter.

C.10.1.2 Resonance method

The resonance method uses the principle that, when a specified high-frequency voltage is applied to an LC series circuit and thereby resonated (which is conducted by using a variable capacitor), the ratio of the terminal voltage of the capacitor to the applied voltage reaches level Q. This method relies on a Q meter.

C.10.1.3 Bridge method

There are several bridge methods, for example, the parallel resistance bridge, the series resistance bridge, and the Schering bridge method. A variable resistor, a variable capacitor, and the capacitor to be measured are combined to constitute a bridge circuit, and a variable resistor and a variable capacitor are adjusted to balance the bridge (the zero method) to determine the capacitance to be measured.

Other measuring equipment includes an LCR meter based on an automatic balance bridge circuit. In principle, such equipment has a circuit based on the I–V converter, which, in turn, is based on an operational amplifier, in practice, such equipment does not form a bridge circuit as described above. This I–V converter grounds the non-inverting terminal of the operational amplifier so that the non-inverting terminal constitutes a virtual ground. This method, therefore, becomes a zero method in principle.

C.10.2 DC method

Methods of DC measurement are in two types: the charge division method, which is based on the charge division of capacitances in parallel, and the charge relaxation method, which is based on the charge relaxation of the RC parallel circuit. Also available is a C meter that measures capacitance based on the charge/discharge characteristics.

C.10.2.1 Charge division method

A measurement circuit based on the charge division method consists, as illustrated in Figure C.17, of a DC power supply, a voltmeter of high-input resistance for potential measurements, the capacitance to be measured, a capacitor C for capacitance division, and switches. For the capacitor, an air capacitor, polystyrene (styrol), mica, a ceramic capacitor, or any other high-insulation capacitor should be used. Its capacitance should be comparable to the capacitance to be measured. The measurement procedure is as described below. Here, the manual switching is unsuitable for measuring a low capacitance; this is because the charge relaxation time of the specimen, C_sR_s, becomes much shorter than the period during manual switching. This method is also unsuitable for the measurement of a capacitance with low-resistance specimens for the same reason.

(1) Open S2, close S1, charge capacitor C with a DC power supply, and take a reading of charge voltage V_0 with a voltmeter. At that time, the capacitor may be charged to the supply voltage.

(2) Close S3, thereby short-circuiting the specimen, and relax the specimen charge; then, open S3 again.

(3) Open S1 and cut off the DC power supply from the circuit.

(4) Close S2 for an instant, thereby dividing the charge of C into the specimen, immediately open S2, and take a reading of the terminal voltage V_1 of capacitor C.

(5) The capacitance C_s of the specimen to be measured can be calculated from the following equation:

$$C_s = \frac{(C + C_{in})(V_0 - V_1)}{V_1} \tag{C.10}$$

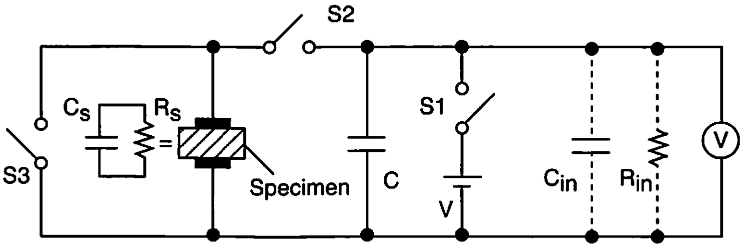


Figure C.17: Capacitance measurement using the charge division method

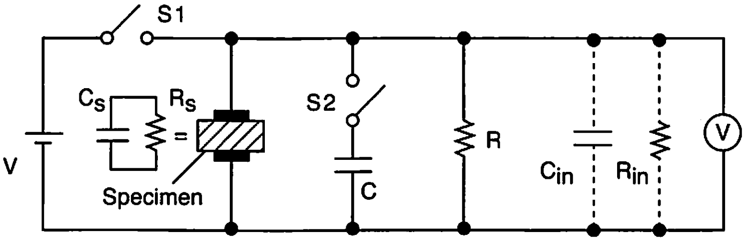


Figure C.18: Capacitance measurement using the charge relaxation method

where C_{in} is the input capacitance of the voltmeter.

C.10.2.2 Charge relaxation method

A typical measurement circuit for the charge relaxation method is as shown in Figure C.18. The procedure for measurement is as described below.

(1) Open switch S2, close S1, and charge the specimen to be measured.

(2) Open S1, discharge the charge from the specimen through high resistor R for measurement, and measure the time t_1 required for the terminal voltage of the specimen to attenuate from its initial value V_0 to the specified value V_1 (for example, $V_0/2$).

(3) Next, close S2 to connect capacitor C, operate the system similarly to (1) and (2), and measure the time t_2 required for the terminal voltage of the specimen to attenuate from V_0 to V_1.

(4) The capacitance of C_s of the specimen to be measured can be determined using the following equation:

$$C_s = \frac{t_1 C}{t_2 - t_1} - C_{in} \tag{C.11}$$

where C_{in} is the input capacitance of the voltmeter.

C.10.3 Capacitance measurement to ground for a worker

Assuming that a worker, with footwear on, works on a floor (with a potential almost equal to that of the earth) or on the ground and that the worker has become charged, at that time, most of the electric lines of force go toward the floor unless there is a grounded conductor around. We will, therefore, describe a method for measuring the capacitance to ground that simulates such a situation. An overview is as illustrated in Figure C.19, with the measurement procedure as follows:

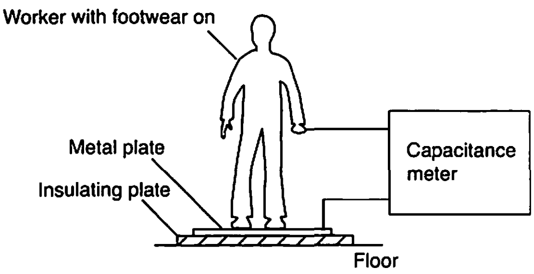


Figure C.19: Measurement of the capacitance of a human body

(1) For electrical insulation, lay an insulating plate or something similar on the floor and a metal plate (about 1 m by 1 m) on top of it. The capacitance of the worker (have them stand on this metal plate with working shoes on) is measured to the metal plate.

(2) For the measurement terminal, equip the terminal of a metal ball or bar of such a size that can be contained in a human hand and then grasp it.

(3) The capacitance of a human body varies according to the position it takes. It is therefore desirable to measure the capacitance with a human body changed into different positions, such as standing upright with both legs, standing with one leg, and half-sitting.

(4) The capacitance measurement should be done as described in C.10.1. It would be simple and easy to use a C meter or an LCR meter.

C.10.4 Measurement of the relative permittivity

The relative permittivity of solid, powder, and liquid can be determined by measuring the capacitance using an electrode unit suited for each. A simple and easy method for measuring capacitance is to use a C meter or an LCR meter.

Relative permittivity ε_r can be determined by the ratio of the measured capacitance C when the specimen is between electrodes to the measured capacitance C_0 of electrodes alone (the capacitance is based on the use of air with permittivity ε_0 as a dielectric),

$$\varepsilon_r = \frac{C}{C_0}. \tag{C.12}$$

The capacitance to be measured includes the capacitance C_i for insulation between electrodes, such as a PTFE insulator used to insulate and support the main electrode and the opposite electrode. If Equation (C.12) is used, therefore, the electrode must be designed with this C_i sufficiently lower than the capacitance between electrodes in the air portion with no specimen put into it. If not, C_i should be determined, and then the relative permittivity is obtained from

$$\varepsilon_r = \frac{C - C_i}{C_0 - C_i} \tag{C.13}$$

If the electrode structure is simple, the capacitance of the specimen to be measured can also be calculated by using the following equation. This may be used to determine the relative permittivity.

(1) Parallel plate electrode

$$C - C_i = \varepsilon_0 \varepsilon_r \frac{A}{d} \rightarrow \varepsilon_r = 1.129 \times 10^{11} \frac{(C - C_i)d}{A}, \tag{C.14}$$

where A and d are the area and distance of the electrode, respectively. For discs (with the main electrode diameter D), the equation is

$$C - C_i = \varepsilon_0\varepsilon_r\frac{\pi D^2}{4d} \rightarrow \varepsilon_r = 1.438 \times 10^{11}\frac{(C - C_i)d}{D^2}. \qquad \text{(C.15)}$$

(2) Coaxial cylindrical electrode (internal electrode diameter D_1, external electrode diameter D_2, and main electrode length L)

$$C - C_i = \frac{2\pi\varepsilon_0\varepsilon_r L}{\ln\frac{D_2}{D_1}} \rightarrow \varepsilon_r = 1.798 \times 10^{10}\frac{(C - C_i)\ln\frac{D_2}{D_1}}{L}. \qquad \text{(C.16)}$$

For liquid-use electrodes with an electrode factor k as shown in Figure C.16 (see C.9.10)

$$C - C_i = \varepsilon_0\varepsilon_r k \rightarrow \varepsilon_r = 1.129 \times 10^{11}\frac{C - C_i}{k}. \qquad \text{(C.17)}$$

Here, since liquid-use electrode units in general are not filled with liquid, the capacitance of the air portion is included. For liquids with a particularly low relative permittivity, units having such an electrode structure that makes the capacitance of the air portion sufficiently smaller than the capacitance of the specimen liquid should be used.

Appendix D

Material data

In this Appendix, the physical characteristics of materials, ignitability of gases, vapours, and dusts, limiting oxidant concentrations of gases, vapours and dusts, and electrical properties of liquids and solids are listed in Tables D.1, D.2, D.1, D.3, D.4, D.5, D.6, and D.7. In addition, databases on the Internet listed in D.7 may be useful.

The data in these tables are obtained under specific conditions (mainly at normal ambient temperature and atmospheric pressure). Therefore, a measurement may be required when the conditions do not match those of a process to be assessed. In addition, since dust ignitability may depend on the particle size of dust, a measurement with powder used is required to assess its risk.

D.1 Ignitability of gases and vapours

(1) The data are based on references [2,34,50].

(2) The boiling point of each liquid is given at a pressure of 0.1 MPa. When an accurate boiling point is not available for a specific entry or a specific entry does not have a constant boiling point, the boiling point given is the 10 percent distillation point as determined by ASTM D86, *Standard method of test for distillation of petroleum products.*

(3) The flash points given are for the most part closed cup flash points. The data based on open cup tests are specified as "oc."

(4) Ignition temperatures were obtained by one of two methods: ASTM D286 and ASTM D2155. At present ASTM D2155 has been replaced by ASTM E659.

(5) Minimum ignition energy (MIE) and flammable limits (LFL and UFL) were obtained at normal ambient temperature (mainly 25°C) except when otherwise specified. "*" indicates MIEs obtained by the Technical Institution of Industrial Safety, which are lower than those in the literature. The unit, %, of values after "@" is vol%.

(6) The MIE given is the lowest minimum ignition energy (LMIE) except when otherwise specified.

(7) The data of the maximum explosion pressure, P_{max}, and maximum rate of pressure rise, K_g, are those obtained at normal ambient temperature and atmospheric pressure except when otherwise specified.

(8) The vapour density of a substance is the weight ratio of the weight of a volume of dry air at the same temperature and pressure. It is calculated as the ratio of the molecular weight of the substance to that of air, 29. A vapour density of less than 1 indicates that the substance is lighter than air and will tend to rise in a relatively calm atmosphere. A

vapour density greater than 1 indicates that a substance heavier than air may travel along the grade level for a considerable distance to a source of ignition and flash back, assuming that the gas or vapour is flammable.

(9) The CAS number is a code for specifying a chemical substance registered in the system of Chemical Abstracts Service (CAS). This may be useful for searching MSDS information on the Internet.

Table D.1: Ignitability of gases and vapours [2,27,34,50–53]

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Acetaldehyde	44.05	–123.5	21	–39	175	0.37	4.0	57	0.65	14.5	1.52	75-07-0
(Acetic acid aldehyde)									@10-12%	@10%		
CH_3CHO												
Acetic acid	60.05	16.635	118	39	463		4.0	19.9			2.07	64-19-7
CH_3COOH								@93.4°C				
Acetic anhydride	102.1	–68	140	49	316		2.7	10.3			3.52	108-24-7
$(CH_3CO)_2O$												
Acetone	58.08	–94.82	56	–20	465	0.74*	2.6	12.8	0.57	13.8	2.00	67-64-1
CH_3COCH_3						@5.1%			@6%	@6%		
Acetone (in oxygen)						0.0024	2.5	60				
Acetonitrile	41.05	–45.72	82	6	524	6.0	3.0	16.0			1.42	75-05-8
(Methyl cyanide)				oc		@7.02%						
CH_3CN												
Acetophenone	120.2	19.65	202	77	570		1.1				4.14	98-86-2
$(C_6H_5)COCH_3$												
Acetylene	26.04	–81.8	–83		305	0.017	2.5	100	1.03	82.8	0.90	74-86-2
CHCH						@8.5%			@13%	@12-13%		
Acetylene (in oxygen)						0.0002						
						@40%						
Acrolein	56.06	–86.95	52	–26	220	0.13	2.8	31			1.93	107-02-8
(Acrylaldehyde)					unstable							
$CH_2{=}CHCHO$												
Acrylic acid nitrile	53.06	–83.55	77	0	481	0.16	3.0	17	0.76	19.3	1.83	107-13-1
(Acrylonitrile)				co		@9.0%			@8.0%	@8.0%		
$CH_2{=}CHCN$												
Allyl chloride	76.5		45	–32	485	0.77	2.9	11.1			2.64	107-05-1
$CH_2{=}CHCH_2Cl$												
Ammonia	17.03	–77.7	–33		651	680	15	28			0.59	7664-41-7
NH_3												
Amyl formate	116.2	–73.5	131	26	265						4.01	638-49-3
$HCOO(CH_2)_4CH_3$												
Benzene	78.12	5.533	80	–11	498	0.2	1.3	8.0	0.67	15.9	2.69	71-43-2
(C_6H_6)						@4.7%			@4%	@3-4%		
Benzoic acid ethyl	150.2	–34.7	212	88	490		1.0				5.18	93-89-0
$(C_6H_5)COOC_2H_5$												
Benzoic acid methyl	136.2	–12.21	150	83	510						4.70	93-58-3
$(C_6H_5)COOCH_3$												

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Benzyl alcohol $C_6H_5CH_2OH$	108.1	–15.5	206	93	436						3.73	100-51-6
Benzyl benzoate $(C_6H_5)COOCH_2(C_6H_5)$	212.3	20	323	148	480		0.7				7.32	120-51-4
Biphenyl $(C_6H_5)(C_6H_5)$	154.2	71	254	113	540		0.6 @111°C	5.8 @155°C			5.32	92-52-4
Bromobenzene (Phenyl bromide) $(C_6H_5)Br$	157.0	–30.6	156	51	565		1.6				5.41	108-86-1
Butane C_4H_{10}	58.12	–138.3	–1	–60	287	0.25 @4.7%	1.6	8.4	0.67 @4-5%	15.9 @5%	2.00	106-97-8
Butane (in oxygen)						0.009	1.6	49				
1,3-Butadiene $CH_2{=}(CH)_2{=}CH_2$	54.09	–108.915	-4		420	0.13 @5.2%	2.0	12			1.87	106-99-0
1-Butanol $CH_3(CH_2)_3OH$	74.12	–89.53	117	37	343		1.4	11.2	0.72 @6%	18.6 @6%	2.56	71-36-3
1-Butene $CH_3CH_2CH{=}CH_2$	56.11	–185.35	–6		385		1.6	10.0			1.93	106-98-9
Butyl acetate $CH_3COO(CH_2)_3CH_3$	116.2	–73.5	127	22	425		1.7	7.6			4.01	123-86-4
t-Butyl alcohol $(CH_3)_3COH$	74.12	25.6	83	11	478		2.4	8.0			2.56	75-65-0
Butylbenzene $CH_3(CH_2)_3(C_6H_5)$	134.2	–87.54	180	71 oc	410		0.8	5.8			4.63	104-51-8
Butyl chloride (1-Chlorobutane) $CH_3(CH_2)_3Cl$	92.16	–123.1	77	–9	240	1.24	1.8	10.1			3.18	109-69-3
Butylamine $CH_3(CH_2)_3NH_2$	73.14	–50.5	78	–12	312		1.7	9.8			2.52	109-73-9
Butyl formate $HCOO(CH_2)_3CH_3$	102.1	–91.9	107	18	322		1.7	8.2			3.52	592-84-7
t-Butyl peroxide (di-t-Butyl peroxide) $(CH_3)_3COOC(CH_3)_3$	146.23	–40		18 oc		0.41					5.03	110-05-4
n-Butyraldehyde $CH_3CH_2CH_2CHO$	72.11	–99	76	–22	218		1.9	12.5			2.49	123-72-8

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Carbon disulfide CS_2	76.14	–111.99	46	-30	90	0.009 @7.8%	1.0	50.0			2.63	75-15-0
Carbon monoxide CO	28.01	–205.0	–192		609	<0.3	12.5	74			0.97	630-08-0
Chlorobenzene $(C_6H_5)Cl$	112.6	–45	132	28	593		1.3	9.6			3.88	108-90-7
m-Cresol $OH(C_6H_4)CH_3$	108.1	11.9	201	86	558		1.1 @150°C				3.73	108-39-4
o-Cresol $OH(C_6H_4)CH_3$	108.1	31	191	81	599		1.4 @149°C				3.73	95-48-7
p-Cresol $OH(C_6H_4)CH_3$	108.1	34.7	201	86	558		1.1 @150°C				3.73	106-44-5
Crotonaldehyde $CH_3CH{=}CHCHO$	70.09	–76.6	102	13	232		2.1	15.5			2.42	4170-30-3
Cumene (Isopropyl benzene) $(C_6H_5)CH(CH_3)_2$	120.2	–96.02	152	36	424		0.9	6.5			4.14	98-82-8
Cyclohexane C_6H_{12}	84.16	6.47	82	-20	245	0.22 @3.8%	1.3	7.8	0.72 @3%	15.2 @3%	2.90	110-82-7
Cyclohexanone $C_6H_{10}O$	98.15	-32	156	44	420		1.1 @100°C	9.4			3.38	108-94-1
Cyclohexene C_6H_{10}	82.15	–103.51	83	<-7	244	0.52	1.2				2.83	110-83-8
Cyclopentadiene C_5H_{10}	66.1	-85	42	25	640	0.67					2.28	542-92-7
Cyclopentane C_5H_{10}	70.14	-93.46	49	<-7	361	0.54	1.5				2.42	287-92-3
Cyclopropane $(CH_2)_3$	42.08	–127.53	-34		498	0.17 @6.3%	2.4	10.4			1.45	75-19-4
Cyclopropane (in oxygen)						0.001 @17%	2.5	60				
Dibutyl ether $(CH_3(CH_2)_3)_2O$	130.2	–95.35	141	25	194		1.5	7.6			4.49	142-96-1
Dibutyl phthalate $(C_6H_4)(COO(CH_2)_3CH_3)_2$	278.3	-35	340	157	402		0.5 @235°C				9.60	84-74-2
Dibutyl sebacate $CH_3(CH_2)_3O_2C(CH_2)_8CO_2(CH_2)_3CH_3$	314.5	1	343	178 oc	365		0.44 @243°C				10.84	109-43-3

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
1,1-Dichloroethane (1,1-Ethylidene dichloride) $CHCl_2CH_3$	98.96	−96.7	57–59	−17	458		5.4	11.4			3.41	75-34-3
1,2-Dichloroethane CH_2ClCH_2Cl	98.96	−35.3	84	13	413		6.2	16			3.41	107-06-2
Dichloromethane (Methylene chloride) CH_2Cl_2	84.93	−96.8	40	none	556	>1000	14	22			2.93	75-09-2
Dichloromethane (in oxygen)						0.137	11.7	68				
cis-1,2-Dichloroethylene $ClCH{=}CHCl$	96.94	−80.5	61	2	460		9.7	12.8			3.34	156-59-2
1,2-Dichloropropane $CH_2ClCHClCH_3$	113.0	−100.42	96	16	557		3.4	14.5			3.90	78-87-5
Dichlorosilane SiH_2Cl_2	101.01		8.4	−28	36	0.015	4.7	96			3.48	4109-96-0
1,4-Diethyl benzene (p-Diethyl benzene) $(C_6H_4)(C_2H_5)_2$	134.2	−42.85	181	55	430		0.7	6.0			4.63	105-05-5
Diethyl carbonate $(C_2H_5O)_2CO$	118.1	−43.0	126	25							4.07	105-58-8
Diethyl oxalate (Ethyl oxalate) $C_2H_5OOCCOOC_2H_5$	146.1	−38.5	186	76							5.04	95-92-1
Diethylamine $(C_2H_5)_2NH$	73.14	−48	57	−23	312		1.8	10.1			2.52	109-89-7
Dihydropyran $CH_2CH_2CH_2{=}CHCHO$	84.12		39	−18		0.36					2.9	110-87-2
Dimethoxymethane (Methylal) $(CH_3O)_2CH_2$	76.10	−104.8	44	−32 oc	237	0.20* @6.8%	2.2	13.8			2.62	109-87-5
2,2-Dimethylbutane $CH_3CH_2C(CH_3)_2CH_3$	86.18	−99.870	50	−48	405	0.25 @3.4%	1.2	7.0			2.97	75-83-2
Dimethyl ether (Methyl ether) $(CH_3)_2O$	46.07	−141.50	−24	−41	350	0.17* @6.6%	3.4	27.0			1.59	115-10-6

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
2,6-Dimethyl-4-heptanone (Diisobutyl ketone) $(CH_3)_2CHCH_2COCH_2CH(CH_3)_2$	142.2	-46.04	168	49	396		0.8 @93°C	7.1 @93°C			4.90	108-83-8
2,2-Dimethyl-1-propanol $(CH_3)_3CCH_2OH$	88.15	55	114	37	420		1.2	8			3.04	75-84-3
Dimethyl sulfide $(CH_3)_2S$	62.13	-98.25	37	<-18	206	0.48	2.2	19.7			2.14	75-18-3
Dimethyl sulfoxide $(CH_3)_2S{=}O$	78.13	18.42	189	95 oc	215	0.48	2.6	42			2.69	67-68-5
Dimethylamine $(CH_3)_2NH$	45.09	-93.0	7	-50	400		2.8	14.4			1.55	124-40-3
Diphenyl ether $(C_6H_5)O(C_6H_5)$	170.2	26.90	258	115	618		0.7	6.0			5.87	101-84-8
Dipropyl ether $(CH_3CH_2CH_2)_2O$	102.2	-122	90	21	188	1.14	1.4	7.9			3.52	111-43-3
Divinyl ether $CH_2{=}CHOCH{=}CH_2$	70.09	-101.1	39	<-30	360		1.7	27			2.42	109-93-3
Ethane CH_3CH_3	30.07	-183.6	-89.0	-130	472	0.24 @6.5%	3.0	12.5	0.68 @7%	17.3 @7%	1.04	74-84-0
Ethane (in oxygen)						0.0019	3.0	66				
Ethanol CH_3CH_2OH	46.07	-114.5	78	13	363		3.3	19	0.69 @12%	17.3 @10%	1.59	64-17-5
Ethyl acetate $CH_3COOC_2H_5$	88.11	-83.6	77	-4	426	0.46 @5.2%	2.0	11.5			3.04	141-78-6
Ethyl acrylate $CH_2{=}CHCOO_2H_5$	100.12		99	10	372		1.4	14			3.49	140-88-5
Ethylamine $C_2H_5NH_2$	45.09	-81.0	17	<-18	385	2.4	3.5	14.0			1.55	75-04-7
Ethylbenzene $(C_6H_5)C_2H_5$	106.2	-94.98	136	21	432		0.8	6.7			3.66	100-41-4
Ethyl bromide CH_3CH_2Br	109.0	-118.9	38.402	none	511		6.8	8.0			3.76	74-96-4
Ethyl chloride CH_3CH_2Cl	64.52	-136.4	12	-50	519		3.8	15.4			2.22	75-00-3
Ethyl ether $(C_2H_5)_2O$	72.12	-116.3	35	-45	180	0.19 @5.1%	1.85	36.5	0.72 @5%	20.7 @5%	2.56	60-29-7
Ethyl ether (in oxygen)						0.0012	2.0	82				

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Ethyl formate $HCOOC_2H_5$	74.08	-79	54	-20	455		2.8	16.0			2.55	109-94-4
Ethyl methyl ether (Methyl ethyl ether) $C_2H_5OCH_3$	60.10	10.8	11	-37	190		2.0	10.1			2.07	540-67-0
Ethyl methyl ketone (2-Butanone,Methyl ethyl ketone) $CH_3COCH_2CH_3$	72.11	-87.3	80	-9	404	0.53 @5.3%	1.4 @93°C	11.4 @93°C			2.49	78-93-3
Ethyl propionate $C_2H_5OOCCH_2CH_3$	102.1	-73.9	99	12	440		1.9	11			3.52	105-37-3
Ethyl propyl ether $CH_3CH_2CH_2OC_2H_5$	88.15		64	<-20			1.7	9.0			3.04	628-32-0
Ethyl vinyl ether (Vinyl ethyl ether) $C_2H_5OCH{=}CH_2$	72.11	-115.8	36	<-46	202		1.7	28			2.49	109-92-2
Ethylene glycol monobutyl ether (2-Butoxyethanol) $CH_3(CH_2)_2CH_2OCH_2CH_2OH$	118.2		171	62	238		1.1 @93°C	12.7 @135°C			4.08	111-76-2
Ethylene glycol monomethyl ether (2-Methoxyethanol) $(CH_3O)CH_2CH_2OH$	76.10	-85.1	124	39	285		1.8	14			2.62	109-86-4
Ethylene glycol (1,2-Ethanediol) $HOCH_2CH_2OH$	62.07	-12.6	197	111	398		3.2				2.14	107-21-1
Ethylene oxide $(CH_2)_2O$	44.05	-112	11	-29	570 No air	0.065 @10.8%	3.0	100			1.52	75-21-8
Ethylene $CH_2{=}CH_2$	28.05	-169.2	-104		450	0.07	2.7	36.0	0.82 @8%	58.6 @8%	0.97	74-85-1
Ethylene (in oxygen)						0.0009	3.0	80				
Ethylenimine $(CH_2)_2NH$	43.07	-71.5	56	-11	320	0.48	3.6	46			1.48	151-56-4
Formaldehyde $HCHO$	30.03	-118	-19	85	424		7.0	73			1.04	50-00-0
Formic acid $HCOOH$	46.03	8.4	101	69	539						1.59	64-18-6

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Furan	68.08	-85.68	31	<0		0.22	2.3	14.3			2.35	110-00-9
C_4H_4O												
Furfural	96.09	-38.7	161	60	316		2.1	19.3			3.31	98-01-1
(2-Furaldehyde)												
$C_5H_4O_2$												
Heptane	100.2	-90.610	98	-4	204	0.24	1.05	6.7			3.46	142-82-5
$CH_3(CH_2)_5CH_3$						@3.4%						
1-Heptanol	116.2	-34.03	177	77	275						4.01	111-70-6
$H_3C(CH_2)_5CH_2OH$												
Hexane	86.18	-95.348	69	-22	225	0.24	1.1	7.5	0.64	17.3	2.97	110-54-3
$CH_3(CH_2)_4CH_3$						@3.8%			@2.5%	@2.5%		
Hexane (in oxygen)						0.006	1.2	52				
3-Hexanon	100.2		123	35	575		∼1	∼8			3.46	589-38-8
(Ethyl propyl ketone)				oc								
$CH_3CH_2CO(CH_2)_2CH_3$												
2-Hexanone	100.2	-56.9	128	25	423		1.2	8.0			3.46	591-78-6
(Methyl butyl ketone)												
$CH_3CO(CH_2)_3CH_3$												
Hydrazine	32.05	1.4	113	38			2.9	98			1.11	302-01-2
N_2H_4												
Hydrogen cyanide	27.03	-13.3	26	-18	538		5.6	40.0			0.93	74-90-8
HCN												
Hydrogen sulfide	34.08	-82.9	-60		260	0.068	4.0	44.0			1.18	7783-06-4
H_2S												
Hydrogen	2.016	-259.14	-252		500	0.016	4.0	75	0.70	75.8	0.07	1333-74-0
H_2						@28%			@35%	@35%		
Hydrogen (in oxygen)						0.0012	4.0	94				
Hydrogen (in nitric oxide)						8.7						
Isoamyl acetate	130.2	-78.5	143	25	360		1.0	7.5			4.49	123-92-2
(Acetic acid isopentyl)							@100°C					
$CH_3COO(CH_2)_2CH(CH_3)_2$												
Isobutane	58.12	-159.60	-12	-81	460	0.52	1.8	8.4			2.00	75-28-5
(2-Methylpropane)						@3.12%						
$(CH_3)_2CHCH_3$												
Isobutyl acetate	116.2	-98.9	118	18	421		1.3	10.5			4.01	110-19-0
$CH_3COOCH_2CH(CH_3)_2$												

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Isobutyl alcohol (2-Methyl-1-Propanol) $(CH_3)_2CHCH_2OH$	74.12	−108	107	28	415		1.7 @51°C	10.6 @94°C			2.56	78-83-1
Isobutyl formate $HCOOCH_2CH(CH_3)_2$	102.1	−95.8	98	<21	320		~1.7	~8.9			3.52	542-55-2
Isobutyraldehyde $(CH_3)_2CHCHO$	72.11	−65.9	61	−18	196		1.6	10.6			2.49	78-84-2
Isopentane (Ethyl dimethyl methane, 2-Methylbutane) $(CH_3)_2CHCH_2CH_3$	72.15	−159.200	28	<−51	420	0.21 @3.8%	1.4	7.6			2.49	78-78-4
Isopentyl alcohol (3-Methyl-1-Butanol, Isoamyl alcohol) $HOCH_2CH_2CH(CH_3)_2$	88.15	−117.2	132	43	350		1.2	9.0 @100°C			3.04	123-51-3
Isopropyl acetate $CH_3COOCH(CH_3)_2$	102.1	−73.4	90	2	460		1.8 @38°C	8			3.52	108-21-4
Isopropyl chloride (2-Chloropropane) $CH_3CHClCH_3$	78.54	−117.0	35	−32	593	1.08	2.8	10.7			2.71	75-29-6
Isopropyl ether (Diisopropyl ether) $((CH_3)_2CH)_2O$	102.2	−87.8	69	−28	443	1.14	1.4	7.9	0.71 @3%	11.6 @3%	3.52	108-20-3
Isopropyl mercaptan (2-Mercaptopropane, 2-propane thiol) C_3H_8S	76.17	−131	57	−34		0.53					2.6	75-33-2
Isopropylamine $(CH_3)_2CHNH_2$	59.11	−101.2	32	−37 oc	402	2.0 @3.82%	2.0	10.4			2.04	75-31-0
Methane CH_4	16.04	−182.76	−162	−187	537	0.21 @8.5%	5.0	15.0			0.55	74-82-8
Methane (in oxygen)						0.0027	5.1	61				
Methane (in nitric oxide)						8.7						
Methanol CH_3OH	32.04	−97.78	64	11	464	0.14 @14.7%	6.0	36.0	0.62 @15%	20.9 @15%	1.10	67-56-1
Methyl acetate CH_3COOCH_3	74.08	−98.05	60	−10	454		3.1	16			2.55	79-20-9
Methyl acrylate $CH_2{=}CHCOOCH_3$	86.09	−76.5	80.3	−3 oc	468		2.8	25			2.97	96-33-3

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Methyl chloride CH_3Cl	50.49	-97.72	-24	-50	632		8.1	17.4			1.74	74-87-3
Methyl formate $HCOOCH_3$	60.05	-99	32	-19	449	0.4	4.5	23			2.07	107-31-3
Methylamine CH_3NH_2	31.06	-93.46	-6		430		4.9	20.7			1.07	74-89-5
Methylcyclohexane $C_6H_{11}CH_3$	98.19	-126.34	101	-4	250	0.27 @3.5%	1.2	6.7			3.39	108-87-2
2-Methylpentane (Isohexane) $CH_3(CH_2)_2CH(CH_3)CH_3$	86.18	-153.670	57-61	<-29	264		1.0	7.0			2.97	107-83-5
4-Methyl-2-pentanone (Methyl isobutyl ketone) $CH_3C(=O)CH_2CH(CH_3)_2$	100.2	-83.5	118	18	448		1.2 @93°C	8.0 @93°C			3.46	108-10-1
2-Methylpentene $CH_2=C(CH_3)CH_2CH_2CH_3$	84.16		62	<-7	300	0.18 @4.4%					2.91	27236-46-0
2-Methylpropene (Isobutylene) $(CH_3)_2C=CH_2$	56.11	-140.35	-7		465		1.8	9.6			1.93	115-11-7
Neopentane (2,2-Dimethylpropane) $CH_3C(CH_3)_2CH_3$	72.15	-16.55	9		450	1.57	1.4	7.5			2.49	463-82-1
Nitrobenzene $(C_6H_5)NO_2$	123.1	5.85	211	88	482		1.8 @93°C				4.24	98-95-3
Nitroethane $CH_3CH_2NO_2$	75.07	-90	114	28	414		3.4				2.59	79-24-3
Nitromethane CH_3NO_2	61.04	-28.37	101	35	418		7.3				2.10	75-52-5
1-Nitropropane $CH_3(CH_2)_2NO_2$	89.10	-108	131	36	421		2.2				3.07	108-03-2
2-Nitropropane $CH_3CH(NO_2)CH_3$	89.10	-93	120	24	428		2.6	11.0			3.07	79-46-9
Octane $CH_3(CH_2)_6CH_3$	114.2	-56.8	126	13	206		1.0	6.5			3.94	111-65-9
Octyl alcohol (1-Octanol) $CH_3(CH_2)_6CH_2OH$	130.2	-15	194	81	260						4.49	111-87-5

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Pentane $CH_3(CH_2)_3CH_3$	72.15	-129.7	36	<-40	260	0.28 @3.3%	1.5	7.8			2.49	109-66-0
1-Pentanol $CH_3(CH_2)_4OH$	88.15	-78.85	138	33	300		1.2	10.0 @100°C			3.04	71-41-0
2-Pentanone (Methyl propyl ketone) $CH_3COCH_2CH_2CH_3$	86.14	-77.75	102	7	452		1.5	8.2			2.97	107-87-9
3-Pentanone (Diethyl ketone) $CH_3CH_2COCH_2CH_3$	86.14	-39.8	103	13 oc	450		1.6				2.97	96-22-0
1-Pentene $CH_3(CH_2)_2CH{=}CH_2$	70.14	-165.22	30	-18 oc	275		1.5	8.7			2.42	109-67-1
cis-2-Pentene $H_3CCH_2CH{=}CHCH_3$	70.14	-151.39	37	<-20	275	0.18 @4.4%	1.4	8.7			2.42	627-20-3
Pentyl acetate (Amyl acetate) $CH_3COO(CH_2)_4CH_3$	130.2	-70.8	149	16	360		1.1	7.5			4.49	628-63-7
Phenetole $C_6H_5OC_2H_5$	122.2	-29.5	172	63							4.21	103-73-1
1,2-Propanediol (Propylene glycol) $CH_3CH(OH)CH_2OH$	76.10	-59.5	188	99	371		2.6	12.5			2.62	57-55-6
Phenol C_6H_5OH	94.11	40.95	181	79	715		1.8	8.6			3.25	108-95-2
Propane $CH_3CH_2CH_3$	44.10	-187.69	-42	-104	450	0.25 @5.2%	2.1	9.5	0.66 @5%	17.3 @5%	1.52	74-98-6
Propane (in oxygen)						0.0021						
1-Propanol (Propyl alcohol) $CH_3(CH_2)_2OH$	60.10	-126.5	97	23	412		2.2	13.7			2.07	71-23-8
2-Propanol (Isopropyl alcohol) $(CH_3)_2CHOH$	60.10	-89.5	83	12	399	0.51	2.0	12.7 @93°C	0.64 @6%	13.2 @6%	2.07	67-63-0
Propionaldehyde (Propanal) CH_3CH_2CHO	58.08	-80.05	49	-30	207	0.32	2.6	17			2.00	123-38-6

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Propionic acid CH_3CH_2COOH	74.08	-20.83	147	52	465		2.9	12.1			2.55	79-09-4
Propyl acetate $CH_3COOCH_2CH_2CH_3$	102.1	-95.0	102	13	450		1.7 @38°C	8			3.52	109-60-4
Propyl chloride $CH_3CH_2CH_2Cl$	78.54	-122.3	47	<-18	520	1.08	2.6	11.1			2.71	540-54-5
Propyl formate $HCOOCH_2CH_2CH_3$	88.11	-92.9	82	-3	455						3.04	110-74-7
Propylamine $CH_3CH_2CH_2NH_2$	59.11	-83.0	49	-37	318		2.0	10.4			2.04	107-10-8
Propylbenzene $(C_6H_5)(CH_2)_2CH_3$	120.2	-99.56	159	30	450		0.8	6.0			4.14	103-65-1
Propylene oxide CH_3CHCH_2O	58.08	-111.8	35	-37	449	0.13 @7.5%	2.3	36.0			2.00	75-56-9
Propylene $CH_3CH=CH_2$	42.08	-185.25	-47		455	0.28	2.0	11.0			1.45	115-07-1
Propyne (Methylacetylene) CH_3CCH	40.07	-104	-23			0.11	1.7				1.40	74-99-7
Pyridine (C_5H_5N)	79.10	-41.8	115	20	482		1.8	12.4			2.73	110-86-1
Pyrrole C_4H_5N	67.09	-24	130	39		3.4 @3.83%					2.31	109-97-7
Styrene $CH_2=CH(C_6H_5)$	104.2	-30.69	146	31	490		0.9	6.8			3.59	100-42-5
Tetrahydrofuran C_4H_8O	72.11	-108.5	66	-14	321	0.54	2.0	11.8			2.49	109-99-9
Tetrahydropyran $SCH=CHCH=CH$	86.13	-49.2	81	-20		0.22 @4.7%					2.97	142-68-7
Thiophene $C_5H_{10}O$	84.14	-38.3	84	-1		0.39					2.9	110-02-1
Toluene $(C_6H_5CH_3)$	92.14	-94.99	111	4	480	0.24	1.27	7.0	0.64	16.6	3.18	108-88-3
1,1,1-Trichloroethane CH_3CCl_3	133.4	-32.8	74	none			7.5	12.5			4.6	71-55-6
1,1,1-Trichloroethane (in oxygen)						0.092	5.5	57				

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Ignitability of gases and vapours (cont.)

Gas or vapour	Molecular weight	Melting point °C	Boiling point °C	Flash point °C	Ignition temp. °C	MIE mJ	LFL vol%	UFL vol%	P_{max} MPa	K_g MPa/s	Vapour density	CAS No.
Trichloroethylene $CCl_2{=}CHCl$	131.4	-88.0	87	none	420		8 @25°C	10.5 @25°C			4.53	79-01-6
Trichlorosilane $SiHCl_3$	135.45	-134	32	-14 oc	93	0.017					4.6	10025-78-2
Triethlene glycol (2,2-Ethylenedioxydiedhanol) $HOCH_2CH_2OCH_2CH_2OCH_2CH_2OH$	150.2	-9.4	288	177 oc	371		0.9	9.2			5.18	112-27-6
Triethylamine $(C_2H_5)_3N$	101.2	-114.5	89	-7 oc	249	0.75	1.2	8.0			3.49	121-44-8
Trimethylamine $(CH_3)_3N$	59.11	-117.2	3	-13	190		2.0	11.6			2.04	75-50-3
2,2,4-Trimethylpentane (iso-Octane) $(CH_3)_3CCH_2CH(CH_3)_2$	114.2	-107.380	99	-12	415	1.35	0.95	6.0			3.93	540-84-1
2,4,4-Trimethyl-2-Pentene (Diisobutylene) $CH_3CH{=}C(CH_3)C(CH_3)_3$	112.2		105	2 oc	305	0.96	1.1	6.0			3.9	107-40-4
Vinyl acetate $CH_3COOCH{=}CH_2$	86.09	-93.2	72	-8	402	0.7	2.6	13.4			2.97	108-05-4
Vinyl acetylene (1-Buten-3-yne) $HCCCH{=}CH_2$	52.08		5			0.082	1.7	100			1.80	689-97-4
Vinyl chloride $CH_2{=}CHCl$	62.50	-159.7	-14	-78 oc	472		3.6	33.0			2.16	75-01-4
Vinyl methyl ether $CH_2{=}CHOCH_3$	58.08	-122	6		287		2.6	39			2.00	107-25-5
m-Xylene $(CH_3)_2(C_6H_4)$	106.2	-47.89	139.10	27	527	0.2	1.1	7.0			3.66	108-38-3
o-Xylene $(CH_3)_2(C_6H_4)$	106.2	-25.18	144.41	32	463	0.2	0.9	6.7			3.66	95-47-6
p-Xylene $(CH_3)_2(C_6H_4)$	106.2	13.26	138.35	27	528	0.2	1.1	7.0			3.66	106-42-3

D.2 Ignitabilty of dusts

Ignitability of dusts is greatly influenced by the particle size of dusts, and the data given here is to be used as a reference only. Tests with powder that is the same as that practically processed should be used to assess risks. In addition, the database [54] of dust ignitability and exposivility, which is well maintained by BIA on the Internet (D.7(2) and on which the data given here is based, should be applied for the risk assessment.

(1) Test conditions: Use of a standard closed 1 m^3 ISO vessel or a closed 20 litre Siwek sphere; Atmospheric pressure from -0.2 to +0.2 bar (gauge pressure); Oxygen concentration from 18 to 22 vol%; Normal ambient temperature from 0 to 40°C.

(2) The median diameter of a particle size distribution is the mass median diameter.

(3) The values of the lower explosive limit (minimum explosible dust concentration) within brackets were determined in a 1.2 litre Hartmann apparatus.

(4) Ignition temperature of dust clouds was obtained using the Godbert-Greenwald furnace or BAM furnace (indicator "(B)").

(5) The glow temperature was obtained with a 5 mm-thick layer and a 6 cm diameter of dust resting on a hot plate with controllable temperature. "melts" indicates that dust melts during a test and, as a result, the glow temperature of dust cannot be measured.

(6) Flammability: dusts are classified according to their ability to propagate a combustion wave when deposited in a layer. Ignition is accomplished using either a gas flame or a glowing platinum wire at 1000°C. The test sample is a 2 cm-wide and 4 cm-long dust ridge resting on a ceramic plate. The ignition is performed at one end. The definitions of the classification are as follows:

1: No self-sustained combustion
2: Local combustion of short duration
3: Local sustained combustion but no propagation
4: Propagating smouldering combustion
5: Propagating open flame
6: Explosive combustion

The numbers in brackets refer to a modified test procedure according to which 20 wt% diatomaceous earth is mixed with the powder or dust to be tested. By this means, some materials that would otherwise not propagate a flame because they melt may show sustained flame propagation.

Table D.2: Ignitability of dusts [54, 55]

Dust	Median μm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flammability
Cotton, Wood, Peat								
Cellulose	51	60	9.3	66	500	380	250	5
Cotton	44	(100)	7.2	24	560	350		3
Lignin dust	18	15	8.7	208	470	>450		5
Paper (phenolresin treated)	23	30	9.8	190	490	310		
Paper dust	<10		5.7	18	580	360		
Paper pulp	29		9.8	168				
Paper tissue dust	54	30	8.6	52	540	300		4
Peat (15% moisture)	58	60	10.9	157	480	320		4
Peat (22% moisture)	46	125	8.4	69	470	320		4
Peat (31% moisture)	38	125	8.1	64	500	320		
Peat (41% moisture)	39	no ignition	–	–	500	315		
Peat (dust deposit)	49	60	9.2	144	(360)	295		
Peat (from bottom of sieve)	74	125	8.3	51	490	310		4
Wood dust	33				500	320	100	
Wood dust	80				480	310	7	
Wood dust(chip board)	43	60	9.5	102	490	320		3
Wood/cardboard/jute/resin		30	8.4	67	520	350	3	5
Wood/cardbord/jute		30	5.8	26	610	360	245	5
Coal,Coal products								
Activated carbon	18	60	8.8	44	790	>450		
Activated carbon	22	no ignition	–	–	670	335		
Activated carbon(16% moisture)	46	125	8.4	67	(630)			
Anthracite (dust from filter)	<10	no ignition	–	–	>850	360		
Asphalt	29	15	8.4	117	550	melts		
Bituminous coal (high volat.)	4	60	9.1	59	510	260		
Bituminous coal (Petchora)	38	125	8.6	86	610	360		
Bituminous coal	<10		9	55	590	270		
Brown coal (dust from grinding)	60		8.9	107	420	230	230	3
Brown coal (from electrostatic filter)	55	60	9	143	450	240		4
Brown coal (graphitized)	28	no ignition	–	–	>850	>450		

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Ignitabilty of dusts (cont.)

Dust	Median µm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flammability
Brown coal coke	290	250	8.4	115	560	>450		3
Brown coal	41		9.1	123	420	230	160	4
Brown coal/anthracite (20:80)	<10		0.4	1	590	280		
Brown coal/anthracite (80:20)	40	60	8.6	108	440	230	>4000	
Char coal	14	60	9	10	520	320		4
Char coal	19	60	8.5	117	540	270		
Char coal	>500	no ignition	–	–	>850	>450		
Other natural organic products								
Blood flour	57	60	9.4	85	610	>450		1
Cotton seed expellers	245	125	7.7	35	(480)	350		3
Dextrin	55		8.8	109	490	>450		2
Grass dust	200	125	8	47	470	310		
Hops, malted	490		8.2	90	420	270		
Leather dust (from collector)		(100)						5
Linen (containing oil))	300		6	17	(440)	230		
Lycopodium					410(B)	280		
Oil shale dust	20	125	5.2	35	520	290		2
Oil shale dust	32	no ignition	–	–	610	>450		
Walnut shell powder		(100)						4
Wheat gluten (after mill)	48	30	8.7	105	540	melts		
Food, Feed								
Barley grain dust		125	7.7	83	400(B)			
Barley grain dust	240						100	4
Citrus pelets		60	7.7	39	460(B)		250	
Cocoa bean shell dust		125	8.1	68			>250	4
Cocoa/sugar mixture	500	125	7.4	43	580	460		2
Coffee (from filter)	<10	60	9	90	470	>450		
Coffee (refined)			6.8	11	460(B)		>500	4
Dextrose	80	60	4.3	18	500	570		3
Dextrose, ground)	22							2
Fat powder (48% fat)	92	30	6.4	20				2
Fat powder					430(B)		>100	
Fat/whey mixture	330		7	23	450	410	180	5

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Ignitabilty of dusts (cont.)

Dust	Median µm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flammability
Fish meal	320	125	7	35	530			
Fructose (from filter)	150	60	9	102	430	melts	<1	
Fructose	200	60	7	28	440	440	180	
Fructose	400	125	6.4	27	530	melts	>4000	
Gravy powder (21% starch)			5.1	12	500(B)		>1000	
Lactose (from cyclone)	23	60	7.7	81	520	>450		3
Lactose(from filter)	22	125	6.9	29	450	>450	80	
Maize seed waste (9% moisture)	165	30	8.7	117	440(B)		>10	
Maize starch	<10		10.2	128	520	>450	300	2
Maize starch	16	60	9.7	158	520	440		2
Meat flour	62	60	8.5	106	540	>450		2
Milk powder (full fat, spray dried)	88	60	8.6	83	520	330		2
Milk powder (low fat, spray dried)	46	30	7.5	109			>100	
Milk powder	165	60	8.1	90	460	330	75	
Milk powder	235	60	8.2	75	450	320	80	
Milk sugar	10	60	8.3	75	440	melts	14	5
Milk sugar	27	60	8.3	82	490	460		2
Oats grain dust	295	750	6	14		350		3
Olive pellets		125	10.4	74	470(B)		>1000	
Potatoe flour	65	125	9.1	69	480	>450		
Potatoe granulate			6.4	21	440(B)		>250	3
Potatoe starch		30	7.8	43	420(B)		>1000	
Potatoe starch	32		(9.4)	(89)	520	>450	>3200	2
Rice flour		60	7.4	57	360(B)		>100	
Rice starch (hydrolyzed)	120	60	9.3	190	480	555		5
Rice starch	18		10	190	530	420		3
Rice starch	18				470	390	90	3
Rye flour	29		8.9	79	490	>450		
Soy bean flour	20	(200)	9.2	110	620	280		2
Suger (Icing-)	19				470	>450		
Tapioca pellets	44	125	9	53	(450)	290		4
Tea (6% moisture)		30	8.1	68	510(B)			≥3
Tea (black, from dust collector)	76	125	8.2	59	510	300		4

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Ignitabilty of dusts (cont.)

Dust	Median μm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flammability
Tobacco	49		4.8	12	470	280		
Wheat flour 550	56	60	7.4	42	470	>450	400	
Wheat flour	50				500	>450	540	
Wheat flour	57	60	8.3	87	430	>450		
Wheat flour					400(B)		>100	
Wheat grain dust	80	60	9.3	112		290		3
Wheat grain dust	125							3
Wheat starch	20	60	9.8	132	500	535		3
Whey fat emulgator	400		7.2	38	450	420	90	5
Plastics, Resins, Rubber								
Acrylnitrile-butadiene-syrene-copolymer	200	60	9.2	147	480	>450		5
Caoutchouc	95	30	9.5	192	450	230		
Cellulose-2,5-Acetate	19	30	9.8	180	520	>450		
El.stat. coating powder (Epoxy)	29	30	8.9	100	540	melts		2(3)
El.stat. coating powder (Polyurethane)	29	30	7.8	89	490	melts		2(2)
Epoxy resin (for powder coating)	55	(100)						2
Epoxy resin with Al	34		8.9	208	570	melts		
Epoxy resin	26	30	7.9	129	510	melts		2
Epoxy resin (60% resin+36% TiO_2)	23		7.8	155				
Melamin resin	18	125	10.2	110	840	>450		2
Melamin resin	57	60	10.5	172	470	>450		2
Melamine-formaldehyde (mold.-form.)	14	60	10.2	189	800	>440		2
Methylmethacrylate-butadiene-styrene	135	30	8.6	120	470	melts	11	5
Methylmethacrylate-butadiene-styrene	150	30	8.4	114	480	melts	30	5
Phenol formaldehyde resin	60	(100)						4
Phenol resin	<10	15	9.3	129	610	>450		2
Polyacrylamide (from filter)	10	250	5.9	12	780	410		2
Polyacrylate (from filter)	62	125	6.9	38	460	420	>1800	5
Polyacrylnitrile (32% H_2O)	63	60	7.4	41				
Polyamid resin	15	30	8.9	105	450	melts		
Polyamide flock (3.3 dtex 0.5 mm)	37	30	9.8	93	520	melts		2(3)
Polyester resin with glass	14	(100)						5
Polyester	<10		10.1	194	570	melts		

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Ignitabilty of dusts (cont.)

Dust	Median	LEL	P_{max}	K_{St}	Ignition temp.	Glow temp.	MIE	Flammability
	µm	g/m^3	bar	bar·m/s	°C	°C	mJ	
Polyethylene (high-pressure)	26		8.7	104	490	>450		
Polyethylene (low-pressure)	<10	(30)	8	156	420	melts		2(5)
Polyethylene (low-pressure)	150	125	7.4	54	480	melts		3(5)
Polyethylene (low-pressure)	245	125	7.5	46	460	melts		3(5)
Polyethylene	72		7.5	67	440	melts		
Polyethylenes	280		6.2	20	470	melts		
Polymethacrylate (from filter)	21	30	9.4	269	550	melts		5
Polymethacrylate		15	8	199				(2)
Polymethacrylimide	105	30	9.6	125	530	melts		5
Polypropylene	25	(30)	8.4	101	410	melts		3(5)
Polypropylene	162	(200)	7.7	38	440	melts		2(5)
Polystyrene (Copolymer)	155	30	8.4	110	450	melts		
Polystyrene (Hard-foam)	760		8.4	23				
Polyurethane	3	<30	(7.8)	(156)				5
Polyvinylacetate (Copolymer)	20	60	8.7	86	660	melts		2
Polyvinylalcohol	26	60	8.9	128	460	melts		5
Polyvinylalcohol	56	60	8.3	83	460	melts		5
Polyvinylchloride (Em.,97.5% PVC)	25	125	8.2	42	750	>450	>2000	
Polyvinylchloride (Em.,97.5% PVC)	51	125	8.5	63	790	350	>2000	
Polyvinylchloride (Susp.)	105	125	7.7	45	510	>450		2
Polyvinylchloride (Susp.)	137	no ignition	–	–	>800	>450		
Polyvinylchloride	<10	30	8.4	168				
Polyvinylchloride	125	30	7.7	68	530	340		
Resin (from filter)	40	30	8.7	108	460	melts		
Rubber (dust from grinding)	80	30	8.5	138	500	230	13	5
Rubber	34	(100)	7.4	106				5
Shellac		15	7.6	144				
Sillicon resin	100	60	7.2	80	480	melts		
Synthetical caoutchouc)	80	15	8.6	145	450	240		5
Urea-formaldehyde (mold.-form.)	13	60	10.2	136	700	390		2
Wax (N,N ethylene distearamide)	10	15	8.7	269				2(2)
Pharmaceuticals, Cosmetics, Pesticides								
Acetyl salicylic acid		15	7.9	217	550(B)			2(5)

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Ignitabilty of dusts (cont.)

Dust	Median µm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flam-mability
Amino phenazone	<10		10.3	238	330	>450		
Ascorbic acid	39	60	9	111	460	melts		2(5)
L(+)-Ascorbic acid	14	60	6.6	48	490	melts		2(5)
Coffein		30	8.2	165	>550(B)	melts		2(5)
Cystein hydrate	<10	125	7.4	40	420	melts	>2000	
L-Cystin	15	60	8.5	142	400	melts	40	
Digitalis leaves	46	250	8.5	73				
Dimethylaminophenazone	<10		10	337				
2-Ethoxybenzamide		15	8.6	214	490(B)	melts		2(5)
Fungicide (Captan)	5	(500)						5
Fungicide (Org. zinc comp.)	<10	60	9	154	480	300		
Fungicide (Maneb)	<10				380	200	>2500	
Methionine	<10	30	9.4	143	390	melts	9	5
Methionine	<10	30	8.7	128	390	melts	100	5
Paracetamole		15	7.9	156		melts		2(5)
Pesticide	<10	60	8.6	151	410	320		
Sodium-L(+) ascorbate	23	60	8.4	119	380	380		2
L(+)- Ascorbic acid	14	60	6.6	48	490	melts		2(5)
Intermediate products, Auxiliary materials								
Anthracene	235	15	8.7	231	600	>450		
Anthrachinone	<10		10.6	364				
Anthrachinone	12	30	9.1	91				
Azodicarbonamide	<10		12.3	176				
Benzoic acid		(30)						2(5)
Betaine hydrochloride	<10	60	9.8	114	400	>450		3
Betaine monohydrate	710	60	8.2	63	510	>450		5
Calcium acetate	92	500	5.2	9	730	>460		2
Calcium stearate	<10				520	melts	9	
Calcium stearate	<10	30	9.2	99	580	>450	16	
Calcium stearate	145	30	9.2	155	550	>450	12	
Carboxy methyl cellulose	<15		9.2	184				
Carboxy methyl cellulose	71	125	8.9	127	390	320		3
Casein	24	30	8.5	115	560	>450		

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Ignitabilty of dusts (cont.)

Dust	Median	LEL	P_{max}	K_{St}	Ignition temp.	Glow temp.	MIE	Flammability
	µm	g/m^3	bar	bar·m/s	°C	°C	mJ	
Cellulose ion exchange resin	<10	60	10.0	91	410	>450		5
Cellulose ion exchange resin	112	30	9.4	112	(350)	>465		
Chloroacetamide	170	(200)						2(2)
Cyanoacrylicacid methylester	260	30	10.1	269	500	>450		5
Dicyandiamide	<10		3.7	9	>850	>450		
1,3-Diethyldiphenyl urea	<10	15	8.8	163	530	melts		2(5)
1.3-Diethyldiphenyl urea	1300	30	8.7	116	600	melts		2(5)
Dimethyl terephtalate	27	30	9.7	247	460	>450		2
Diphenol ketylene	15		9.0	270				
Diphenyl urethane	128	30	8.9	218	660	melts		2
Diphenyl urethane	1100	30	7.6	51	660	melts		2
Emulgator (50% CH, 30% fat)	71	30	9.6	167	430	390	17	
Epoxy resin hardener	17	60	10.0	64	>850	melts		2
Ethyl cellulose	40		8.1	162	(330)	275		
Ferrocene	95	15	8.3	267	500	>450	5	5
Fumaric acid	215	(100)						5
Hexamethylene teramine	27	30	10.5	286				
Hexamethylene teramine	155		10.0	224	530	melts		
Lead stearate	<10				480	melts	<1	
Lead stearate	12	30	9.2	152	630	melts		5
Magnesium searate		(100)						2(2)
D(–)-Mannite	67	60	7.6	54	460	melts		2
Melamine peroxide	24	250	12.2	73	>850	380		2
Melamine phosphate	22							2
Melamine phtalate	16	125	8.1	52	910	melts		2
Melamine	<10	1000	0.5	1	>850	>450		2
Metal soap (Ba/Pb-stearate)		15	8.1	180				2(2)
Metal soap (Zn-behenate)		15	8.1	119				2(3)
Methacrylamide	580		8.5	113	530	>450	180	
Methyl cellulose	22		10.0	157	400	380	12	
Methyl cellulose	29	60	10.0	152	400	>450	105	5
Methyl cellulose	37	30	10.1	209	410	450	29	5
Naphtalene	95	15	8.5	178	660	>450	<1	(5)

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Ignitabilty of dusts (cont.)

Dust	Median μm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flammability
Naphtalic acid anhydride	16	60	9.0	90	690	melts	3	
2-Naphtol	<10		8.4	137	430	>450	5	
Oil absorber (hydrophobic cellulose)	65	60	7.2	42	540	>450		
Paraformaldehyde	23	60	9.9	178	460	>480		5
Paraformaldehyde	27	60	10.7	222	460	>450		
Pectin	59	60	9.5	162	460	300		
Pectinase	34	60	10.6	177	510	>450	180	3
Pentaerythrite (from filter)	85	30	9.1	188	490	melts	6	5
Pentaerythrite	<10	30	9.6	120	460	melts	<1	2(5)
Pentaerythrite	135	30	9.0	158		melts	27	5
Phenol (Condensation product)	20	15	8.2	171	560	melts		2(5)
Phtalic acid anhydride		(100)						5
Polyethylene oxide	115	(30)						3(5)
Polysaccharide	23	(500)						4
Propyleneglycol alginate	115	125	8.8	82	440	450		
Salicylic acid		(30)						2(5)
Saponin	13		9.4	150	440	>450		3
Sodium amide		(200)						2
Sodium caseinate (from filter)	17	60	8.8	117	560	>450	740	
Sodium cyclamate	260							5
Sodium hydrogen cyanamide	40	125	7.0	47	460	melts		
Sodium ligno sulphonate	58	(200)						2
Sodium stearate	22	30	8.8	123	670	melts		2
Stearic acid	1300	8	7.2	34	500	melts		1(1)
Stearin/Calcium	16	30	9.3	133	620	>450	25	
Stearin/Lead	15	60	9.1	111	600	>450	3	
Tartaric acid	480							2
Terephthalic acid dinitrile		<30	8.8	260				5
Thio urea	460	250	3.5	8	440	melts		2(2)
2.2-Thiodiacetic acid	75	30	6.5	72	350	410		2
Trimellitic anhydride	1250	30	6.8	33	740	melts	>2500	2(5)
Trisodium citrate	800							2
Tyrosine (final product)	10							5

Continued on next page

Ignitabilty of dusts (cont.)

Dust	Median μm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flammability
Tyrosine (raw product)	15							5
Urea	2900							1(2)
Viscose flock	13	(100)						4
Zinc cyanamide	<10	no ignition	–	–	>850	>450		3
Zinc cyanamide	600		(4.8)	(53)				2
Zinc pyridine thione		(500)						2(5)
Zinc stearate		(100)						2(5)
Zinc stearate	13				520	melts	5	
Other technical/chemical products								
Bituminous hydrocarbon	260	30	7.6	63	500	melts		2
Fuchsin base	36		8.4	115	640	melts		
Light protection agent	<10		8.9	214	530	>450		
Light protection agent	<15		10.0	310				
Organic dyestuff (Azo, yellow)	<10	60	11.0	288	480	melts		2(5)
Organic dyestuff (blue)	<10		9.0	73	710	360		
Organic dyestuff (brown)		(200)						4
Organic dyestuff (Disp., brilliant pink)	46				610	450	>4000	
Organic dyestuff (khaki)	44				690	450		
Organic dyestuff (Phthalocyanine)	<10	(200)	8.8	73	770	355		4
Organic dyestuff (red)	<10	50	11.2	249	520	melts		
Organic dyestuff (red)	52	60	9.8	237	470	>450		5
Soap	65	30	9.1	111	580	melts		
Surfacer (Epoxy based)	24	(200)						2
Surfacer (Polyester based)	19	(500)						2
Washing agent (Na-sulph)	275	30	9.0	267	330	melts		5
Wax raw material (Alkylaryl sulphonate)								5
Wax raw material (Olefin sulphonate)	105	30	8.6	115	390	>590		
Metals, Alloys								
Aluminium grit	41	60	10.2	100	>850	>450		
Aluminium grit	170	no ignition	–	–	>850	>450		1
Aluminium grit	23	30	11.0	320	850	>450		
Aluminium powder	<10	60	11.2	515	560	430		
Aluminium powder	22		12.5	400	650	270		

Continued on next page

Ignitabilty of dusts (cont.)

Dust	Median µm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flammability
Aluminium powder	22	30	11.5	1100	500	>450		
Aluminium powder	29	30	12.4	415	710	>450		4
Aluminium shavings	190				620	>450	>1800	
Aluminium shavings	240	no ignition	–	–	>850	>450		
Aluminium/Iron (50:50)	21	250	9.4	230	760	>450		
Aluminium/Magnesium	130		10.4	52	>850	>450		2
Aluminium/Nickel (50:50)	90	no ignition	–	–	>850	>450		
Aluminium/Nickel	<10		11.4	300				
Bronze powder	18	750	4.1	31	390	260		4
Calcium/Aluminium (30:70)	22		11.2	420	600	>450		6
Calcium/Silicon (from cyclone)	21	60	9.8	200	770	>450	145	1
Calcium/Silicon	28				770	>450		
Co-Al-Ti (62:18:20)	25	500	7.4	134	730	>450		
Fe/Si/Mg (22:45:26)	17		9.4	169	670	>450	210	
Fe/Si/Mg (24:47:17)	21		9.9	267	560	>450	35	
Ferrochromium	<10	500	6.4	86	>850	>450		
Ferromanganese	<10		6.8	84	730	>450		
Ferrosilicon (22:78)	21	125	9.2	87	>850	>450		
Hard metal (TiC, TiN, WC, VC, Mo)	43	(200)						4
Iron (from dry filter)	12	500	5.2	50	580	>450		
Iron carbonyl	<10	125	6.1	111	310	300		3
Magnanese (electrolyt.)	16		6.3	157	(330)	285		
Magnanese (electrolyt.)	33		6.6	69				
Magnesium	28	30	17.5	508				
Magnesium	240	500	7.0	12	760	>450		5
Molybodenum	<10	no ignition	–	–	>850	390		
Niobium (6% Al)	250	(200)						2
Silicon	<10	125	10.2	126	>850	>450	54	3
Silicon(from dust extr.)	16	60	9.4	100	800	>450		
Silicon(from filter)	<10	60	9.5	116	>850	>450	250	1
Steel (100% Cr-6) dust		(30)	(4.0)	(83)				2
Tantalum/Niobium	<10		6.6	37	700	450		
Ti/TiO_2 (dust deposit)	310	(100)						5

Continued on next page

Ignitabilty of dusts (cont.)

Dust	Median μm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flammability
Titanium (pre-oxidized)	35				380	400		
Titanium	30				450	>450		
Zinc (dust from collector)	<10	250	6.7	125	570	440		3
Zinc (dust from collector)	10	125	7.3	176				2
Zinc (from zinc coating)	21	250	6.8	93	790	>450		
Zinc (from zinc coating)	19		6.0	85	800	>450		2
Other inorganic products								
Carbon fibres (99% C)		(100)						2
Graphite (99.5% C)	7	<30	5.9	71	>600(B)	680		1
Molybodenum disulphide	19	250	5.6	37	520	320		4
NH_4NO_3/Dicyanamide(66:34)	50	250	7.0	21	390	>450		
Petroleum coke	15	125	7.6	47	690	280		4
Petroleum coke	71	125	3.8	3	750	>450		3
Petroleum coke(calcinated)	22	250	6.8	14	>850	>450		3
Phorsphorus (red)	18		7.9	526	400	340		5
Soot (from filter)	<10	30	8.8	88	840	570		
Soot	5	60	9.2	85	760	590		
Sulphur	12				240	250	<1	
Sulphur	20	30	6.8	151	280			5
Sulphur	40				330	270	3	
Sulphur	120				370	270	5	
Titanium carbide		(100)						4
Titanium hydride		(200)						2
Titanium monoxide		(200)						4
Other materials								
Ash concentrate	21	60	8.6	91	580	260		
Bentonite der.+org. comp	35	60	7.4	123	430	>450		3
Bentonite/Asphalt/Coal/Org. (15:45:35:5)	54	(100)						2
Bentonite/Coal (50:50)	42	(100)						2
Blasting dust (light metals)		15	7.6	242	370(B)	280		4
Break liner (grinding dust)	<10	250	6.9	71	530	310		
Brush dust (Al-brushes)	25	30	11.4	360	590	450	<1	
CaC/Diamide lime/Mg (72:18:10)	8	125	5.8	30				4

Continued on next page

Ignitabilty of dusts (cont.)

Dust	Median µm	LEL g/m^3	P_{max} bar	K_{St} bar·m/s	Ignition temp. °C	Glow temp. °C	MIE mJ	Flammability
Dust from grinding (Al)		(30)	(5.7)	(214)	480(B)			4
Dust from grinding (cardbord)	160	(100)						5
Dust from grinding (polyester)	<10	30	9.5	153	500	>450		5
Dust from grinding (polyester))	25		9.4	237	550	>450		5
Dust from grinding (Ti)	170	(100)						2
Dust from grinding (Zn)		(500)	(2.3)	(24)				1
Dust from grinding + polish. (polyester)	<10				530	>450	<1	
Dust from polishing (Al)	150		5.0	18	440	320		5
Dust from polishing (brass)		(100)						4
Dust from polishing (Zn)	190	(200)			400(B)	350		2
Flyash (from electrofilter)	6	125	1.9	35				1
Immersion polishing agent	600	(30)	6.2	11	580	340		2
Mud from setting chamber	23	60	7.7	96	430	260		5
Pb and Ca stearate mixture	35	(100)		116				2(2)
Textile fibres (nat.+synth.)		(30)						5
Toner resin	18				580(B)	>450	<1	(5)
Toner	<10	60	8.9	196	520(B)	melts	4	
Toner	<10	30	8.7	137	530(B)	melts	<1	5
Toner	21	60	8.8	134	530(B)	melts	<1	(3)
Toner	23	60	8.8	145	530(B)	melts	8	(3)
Toner/iron powder	60	60	8.2	169	570(B)	>450		
Zinc stearate/Bentonite (20:80)								2
Zinc stearate/Bentonite (90:10)		(100)						3

D.3 Limiting oxidant concentration for gases and vapours

(1) The reference is NFPA 69 [47].

(2) The data were obtained using a test by a spark or pilot flame at normal ambient temperature and atmospheric pressure.

(3) LOC N_2 and LOC CO_2 indicate the limiting oxidant concentrations for nitrogen and carbon dioxide used for inerting, respectively.

Table D.3: Limiting oxidant concentaration for gases and vapours [47]

Gas or vapour	LOC N_2 vol%	LOC CO_2 vol%
Acetone	11.5	14
Benzene	11.4	14
Butadiene (1,3-Butadiene)	10.5	13
n-Butane	12	14.5
n-Butanol	NA	16.5 (150°C)
1-Butene	11.5	14
n-Butyl chloride	14, 12 (100°C)	—
Carbon disulfide	5	7.5
Carbon monoxide	5.5	5.5
Cyclopropane	11.5	14
1,2-Dichloro ethane	13,11.5 (100°C)	—
Diethylbenzene	8.5	—
Divinylbenzene	8.5	—
Ethane	11	13.5
Ethanol	10.5	13
2-Ethyl butanol	9.5 (150°C)	—
Ethyl ether	10.5	13
Ethylbenzene	9.0	—
Ethylene	10	11.5
Gasoline (100/130)	12	15
Gasoline (115/145)	12	14.5
Gasoline (73/100)	12	15
n-Heptane	11.5	14.5
n-Hexane	12	14.5
Hydrogen sulfide	7.5	11.5
Hydrogen	5	5.2
Isobutane	12	15
Isobutyl formate	12.5	15
Isobutylene	12	15
Isopentane	12	14.5
JP-1 fuel	10.5 (150°C)	14 (150°C)
JP-3 fuel	12	14.5
JP-4 fuel	11.5	14.5
Kerosene	10 (150°C)	13 (150°C)
Methane	12	14.5
Methanol	10	12
Methyl acetate	11	13.5
Methyl ether	10.5	13
Methyl ethyl ketone	10	12.5
Methyl formate	11	13.5
3-Methyl-1-Butene	11.5	14
Methylene chloride	19 (30°C)17 (100°C)	—
Natural gas (Pittsburgh)	12	14.5

Continued on next page

Limiting oxidant concentration for gases and vapours (cont.)

Gas or vapour	LOC N_2 vol%	LOC CO_2 vol%
n-Pentane	12	14.5
Propane	11.5	14.5
Propylene oxide	7.8	-
Propylene	11.5	14
Styrene	9.0	—
Toluene	9.5	—
1,1,1-Trichloroethane (Methyl chloroform)	14	—
Trichloroethylene	9 (100°C)	—
UDMH (1,1-Dimethylhydrazine)	7	—
Vinyl chloride	13.4	—
Vinylidiene chloride	15	—
Vinyltoluene	9.0	—

D.4 Limiting oxidant concentration for dusts

D.4.1 Limiting oxidant concentration for dusts –1

(1) The reference is NFPA 69 [47].

(2) Data given in this table were obtained by tests at room temperature and pressure using a 24-watt continuous-spark ignition source and are reported in U.S. Bureau of Mines, Report of Investiagetion 6543.

(3) LOC N_2 and LOC CO_2 are the limiting oxidant concentrations for nitrogen and carbon dioxide used for inerting, respectively.

(4) When nitrogen is used as the inert gas and no data are listed in the table, the following equation should be used to calculate the oxygen value for carbonaceous dusts:

$$O_n = 1.3(O_c - 6.3)$$

where O_n is the limiting oxygen concentration for inerting by nitrogen and O_c that for inerting by carbon dioxide.

(5) The values in this table can differ from those in Table D.5 because of differences in test methods and dust characteristics, such as particle size and other factors.

(6) The LOC of dust should also be measured with dust practically processed.

Table D.4: Limiting oxidant concentration for dusts -1 [47]

Dust	LOC N_2 (vol%)	LOC CO_2 (vol%)
Agricultural		
Coffee		17
Cornstarch		11
Dextrin	11	14
Soy Flour		15
Starch		12
Sucrose	10	14
Chemical		
Ethylene diamine tetra-acetic acid		13
Isatoic anhydride		13
Methionine		15

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Limiting oxidant concentration for dusts -1 (cont.)

Dust	LOC N_2 (vol%)	LOC CO_2 (vol%)
Ortazol		19
Phenothiazine		17
Phosphorous pentasulfide		12
Salicylic acid	15	17
Sodium lignosulfate		17
Stearic acid & Metal stearates	10.6	13
Carbonaceous		
Charcoal		17
Coal, Bituminous		17
Coal, Sub-bituminous		15
Lignite		15
Metal		
Aluminum	5	2
Antimony		16
Chromium		14
Iron		10
Uranium	1	0
Magnesium	0	0
Manganese		14
Silicon	11	12
Thorium	2	0
Titanium	4	0
Vanadium	14	
Zinc	9	10
Zirconium	0	0
Plastics ingredients		
Azelaic Acid		14
Bisphenol A		12
Casein, rennet		17
Hexamethylene tetramine	13	14
Isophthalic Acid		14
Paraformaldehyde	8	12
Pentaerythritol	13	14
Phthalic Anhydride		14
Terephtalic acid		15
Plastics–special resins		
Coumarone-indene resin		14
Lignin		17
Phenol, Chlorinated		16
Pinewood residue		13
Rosin,DK		14
Rubber, hard		15
Shellac		14
Sodium resinate	13	14
Plastics–thermoplastic resins		
Acetal		11
Acrylonitrile		13
Butadiene-styrene		13
Carboxymethyl cellulose		16
Cellulose acetate	9	11
Cellulose acetate butyrate		14
Cellulose triacetate		12
Ethyl cellulose		11
Methyl cellulose		13
Methyl methacrylate		11

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Limiting oxidant concentration for dusts –1 (cont.)

Dust	LOC N_2 (vol%)	LOC CO_2 (vol%)
Nylon		13
Polycarbonate		15
Polyethylene		12
Polystyrene		14
Polyvinyl acetate		17
Polyvinyl butyrate		14
Plastics–thermosetting resins		
Allyl Alcohol		13
Dimethyl isophthalate		13
Dimethyl terephthalate		12
Epoxy		12
Melamine formaldehyde		15
Polyethylene terephthalate		13
Urea formaldehyde		16
Miscellaneous		
Cellulose		13
Paper		13
Pitch		11
Sulfur		12
Wood Flour		16

D.4.2 Limiting oxidant concentration for dusts –2

(1) The dada are from references [47, 55] originated from [54].

(2) The data were obtained using 1 m^3 or 20 L chamber.

(3) The data in Table D.5 can differ from those in Table D.4 because of differences in test methods and dust characteristics.

Table D.5: Limiting oxidant concentration for dusts –2 [47, 54, 55]

Dust	Median diameter (μm)	LOC N_2 (vol%)
Cellulosic materials		
Cellulose	22	9
Cellulose	51	11
Wood Flour	27	10
Food and Feed		
Waste from malted barley	25	11
Corn starch	17	9
Pea flour	25	15
Rye flour	29	13
Starch derivative	24	14
Wheat flour	60	11
Coals		
Brown coal	42	12
Brown coal	63	12
Brown coal	66	12
Brown coal briquette dust	51	15
Bituminous coal	17	14
Plastics, Resins, Rubber		
Resin	<63	10
Rubber powder	95	11
Polyacrylonitrile	26	10
Polyethylene, h.p.	26	10

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Limiting oxidant concentration for dusts -2 (cont.)

Dust	Median diameter (μm)	LOC N_2 (vol%)
Pharmaceuticals, Pesticides		
Aminophenazone	<10	9
Methionine	<10	12
Intermediate products, Additives		
Barium stearate	<63	13
Benzoyl peroxide	59	10
Bisphenol A	34	9
Bistrimethylsilyl-urea	65	9
Cadmium laurate	<63	14
Cadmium stearate	<63	12
Calcium stearate	<63	12
Dimethl terephthalate	27	9
Ferrocene	95	7
Methyl cellulose	70	10
Naphthalic acid anhydride	16	12
2-Naphthol	<30	9
Paraformaldehyde	23	6
Pentaerythritol	<10	11
Metals, Alloys		
Aluminum	22	5
Calcium/aluminium alloy	22	6
Ferrosilicon alloy	21	12
Ferrosilicon magnesium alloy	17	7
Magnesium alloy	21	3
Other inorganic products		
Soot	<10	12
Soot	13	12
Soot	16	12
Others		
Bentonite derivative	43	12

D.5 Electrical properties of liquids

(1) The main references are [2,34].

(2) Symbols C, S1, S2, and NC of the classification of conductivity are as follows:

C: conductive liquid (> 10^4 pS/m)
S1: semiconductive liquid (1000–10000 pS/m)
S2: semiconductive liquid (100–1000 pS/m)
NC: nonconductive liquid (< 100 pS/m)

Table D.6: Electrical properties of liquids [2,27,34,51–53,56,57]

Liquid	Conductivity class	Conductivity (pS/m)	Relative permittivity	Relaxation time (s)
Acetaldehyde (15°C)	C	1.7×10^8	21.1	1.1×10^{-6}
Acetamide	C	8.8×10^7	59	5.9×10^{-6}
Acetic acid (0°C)	C	5×10^5	6.15	1.1×10^{-4}
Acetic acid (25°C)	C	1.12×10^6	6.15	4.9×10^{-5}
Acetic anhydride (25°C)	C	4.8×10^7		
Acetone (25°C)	C	6×10^6	20.7	3×10^{-5}

Continued on next page

Electrical properties of liquids (cont.)

Liquid	Conductivity		Relative	Relaxation
	class	(pS/m)	permittivity	time (s)
Acetonitrile (20°C)	C	7×10^8	37.5	5×10^{-7}
Acetophenone (25°C)	C	3.1×10^5	17.39	5.0×10^{-4}
Acetyl bromide (25°C)	C	2.4×10^8		
Acetyl chloride (25°C)	C	4×10^7		
Acrolein	C	1.55×10^7		
Acrylonitrile	C	7×10^5	38	4.8×10^{-4}
Allyl alcohol	C	7×10^8		
n-Aminoethyl piperazine	C	2.4×10^5		
Aminoethylethanolamine	C	$> 1 \times 10^6$		
Ammonia (−79°C)	C	1.3×10^7		
iso-Amyl alcohol	C	1.4×10^5	14.7	9.3×10^{-4}
Aniline (25°C)	C	2.4×10^6	6.89	2.5×10^{-5}
Anisole (Methyl phennyl ether)	NC	10	4.33	3.8
Anthracene (230°C)	C	3×10^4		
Armeen	S2	470		
Arsenic tribromide (25°C)	C	1.5×10^8		
Arsenic trichloride (25°C)	C	1.2×10^8		
Benzaldehyde (25°C)	C	1.5×10^7		
Benzene (purified)	NC	5×10^{-3}	2.3	~100
Benzoic acid (125°C)	C	3×10^5		
Benzonitrile (25°C)	C	5×10^6	25.2	4.5×10^{-5}
Benzyl benzoate (25°C)	C	$< 1 \times 10^5$	4.9	
Benzyl cyanide	C	$< 5 \times 10^6$	18.7	$> 3.3 \times 10^{-5}$
Benzylamine (25°C)	C	$< 1.7 \times 10^6$		
Biphenyl (liquid @69–120°C)	S1	2500–10000		
Biphenyl (liquid: above 120°C)	C	$> 1 \times 10^4$		
Biphenyl (solid:less than 69oC)	NC	0.17		
Blenzyl alcohol (25°C)	C	1.8×10^8		
Bromine (17.2°C)	NC	13		
Bromobenzene	S1	1200	5.4	0.04
Bromoform (Tribromomethane) (25°C)	C	$< 2 \times 10^6$	4.39	$> 1.9 \times 10^{-5}$
1-Bromonaphthalene	S1	3660	4.83	0.011
iso-Butyl acetate (4°C)	S1	2650	5.3	0.018
iso-Butyl acetate (23°C)	S1	4320	5.3	0.011
n-Butyl acetate (23°C)	S1	4700	5	0.0094
n-Butyl acetate (4°C)	S1	2170	5	0.02
Butyl acrylate	S1	3580		
iso-Butyl alcohol	C	9.12×10^5	17.51	1.7×10^{-4}
n-Butyl alcohol (23°C)	C	2.0×10^7		
sec-Butyl alcohol	C	$< 1 \times 10^7$	16.56	$> 1.5 \times 10^{-5}$
tert-Butyl alcohol	C	2.66×10^6	27.47	4.2×10^{-5}
Butyl Carbitol	C	$> 1 \times 10^6$		
iso-Butyl chloride	C	1×10^4	6.49	5.7×10^{-3}
sec-Butyl chloride	C	1×10^4	7.09	6.3×10^{-3}
n-Butyl propionate (24°C)	S1	2300		
Butyl stearate	NC	21	3.111	1.3
Capronitrile (25°C)	C	3.7×10^8		
Caprylic acid (Octanoic acid)	NC	< 37	2.45	> 0.58
Carbon disulfide (1°C))	NC	7.8×10^{-4}	2.6	~100
Carbon tetrachloride	NC	4×10^{-4}	2.238	~100
Chlorine (-70°C)	NC	< 0.01		
m-Chloroaniline (25°C)	C	5×10^6		
Chlorobenzene	S1	7000	5.621	0.0071
Chloroform	S1	< 10000	4.806	> 0.0043

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Electrical properties of liquids (cont.)

Liquid	Conductivity		Relative permittivity	Relaxation time (s)
	class	(pS/m)		
Chlorohydrin (25°C)	C	5×10^7		
o-Cresol	C	1.27×10^5	11.5	8.0×10^{-4}
m-Cresol	C	1.397×10^6	11.8	7.5×10^{-5}
p-Cresol	C	1.378×10^6	9.91	6.4×10^{-5}
Cyclohexane	NC	< 2	2	> 8.8
Cyclohexanone	C	5×10^5		
Cymene (25°C)	C	$< 2 \times 10^6$		
Decalin	NC	6	2.18	3.2
Dibutyl-o-phthalate	C	1.8×10^5	6.436	3.2×10^{-4}
Dibutyl sebacate	S1	1700	4.54	0.024
Dichloroacetic acid (25°C)	C	7×10^6		
o-Dichlorobenzene	S1	3000	9.93	0.0029
cis-Dichloroethylene	C	8.5×10^5	9.2	9.6×10^{-5}
Dichlorohydrin (25°C)	C	1.2×10^9		
Dichlorosilane	NC			
Diehyl sulfate (25°C)	C	2.6×10^7		
Diesel oil (purified)	NC	~ 0.1	~ 2	~ 100
Diethanolamine (20°C)	C	4.6×10^7		
Diethyl carbonate (25°C)	C	1.7×10^6	2.82	1.5×10^{-5}
Diethyl ether	NC	30	4.6	1.4
Diethyl ketone	C	5.2×10^7		
Diethyl oxalate (25°C)	C	7.6×10^7		
Diethylamine (−33.5°C)	C	2.2×10^5		
Diethylene glycol	C	5.86×10^7	31.69	4.8×10^{-6}
Diethylenetriamine	C	$> 1 \times 10^6$		
Dimethyl acetamide	C	1.1×10^7		
Dimethyl formamide	C	6×10^6	36.71	5.4×10^{-5}
Dimethyl sulfate (0°C)	C	1.6×10^7		
Dimethyl sulfoxide	C	2×10^5	46.68	2.1×10^{-3}
1,4-Dioxane (Diethylene oxide)	NC	0.1	2.2	~ 100
Diphenyl oxide	C	$< 1.7 \times 10^6$	4.22	$> 2.2 \times 10^{-5}$
Epichlorohydrin (25°C)	C	3.4×10^6	22.6	5.9×10^{-5}
Ethanolamine	C	1.1×10^9	37.72	3.0×10^{-7}
Ethyl acetate (23°C)	C	4.6×10^4	6.02	1.16×10^{-3}
Ethyl acetate (4°C)	C	2.9×10^4	6.02	1.84×10^{-3}
Ethyl acetoacetate (25°C)	C	4×10^6	15.7	3.5×10^{-5}
Ethyl acrylate	C	3.35×10^5		
Ethyl alcohol (25°C)	C	1.35×10^5	24.55	1.6×10^{-3}
Ethyl benzene	NC	30	2.3	0.68
Ethyl bromide (25°C)	C	$< 2 \times 10^6$	9.39	$> 4.2 \times 10^{-5}$
Ethyl chloride	C	$< 3 \times 10^5$	9.45	$> 2.8 \times 10^{-4}$
Ethyl cyanoacetate	C	6.9×10^7	26.7	3.4×10^{-6}
Ethyl formate	C	1.45×10^5	7.16	4.4×10^{-4}
2-Ethyl hexanol	S1	7900		
Ethyl isothiocyanate (25°C)	C	1.26×10^7		
Ethyl lactate	C	1.0×10^8	13.1	1.2×10^{-6}
Ethyl nitrate (25°C)	C	5.3×10^7		
Ethyl oxalate	C	7.12×10^7	1.8	2.2×10^{-7}
Ethyl propionate	C	8.33×10^{10}	5.65	6×10^{-10}
Ethyl thiocyanate (25°C)	C	1.2×10^8		
Ethylamine (0°C)	C	4×10^7		
Ethyle benzoate (25°C)	C	$< 1 \times 10^5$	6.02	$> 5.3 \times 10^{-4}$
Ethylene carbonate	C	$< 1 \times 10^7$	89.6	$> 7.9 \times 10^{-5}$
Ethylene dibromide	S1	< 10000	4.78	> 0.0042

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Electrical properties of liquids (cont.)

Liquid	Conductivity class	Conductivity (pS/m)	Relative permittivity	Relaxation time (s)
Ethylene dichloride	S1	4000	10.36	0.022
Ethylene glycol	C	1.16×10^{8}	37.7	2.9×10^{-6}
Ethylene glycol monobutyl ether	C	4.32×10^{7}	9.3	1.9×10^{-6}
Ethylene glycol monoethyl ether	C	9.3×10^{6}	29.6	2.8×10^{-5}
Ethylene glycol monomethyl ether	C	1.09×10^{8}	16.93	1.4×10^{-6}
Ethylene oxide	C	4×10^{6}	12.7	2.8×10^{-5}
Ethylenediamine	C	9×10^{6}	12.9	1.3×10^{-5}
Ethyleneimine	C	8×10^{8}	18.3	2.0×10^{-7}
2-Ethylhexyl acrylate	S2	610		
Ethylidene chloride	C	2.0×10^{5}	10	4.4×10^{-4}
Eugenol (25°C)	C	$< 1.7 \times 10^{6}$		
Formamide (25°C)	C	4×10^{8}	111	2×10^{-6}
Formic acid (25°C)	C	6.4×10^{9}	58.5	8.1×10^{-8}
Furfural (25°C)	C	1.5×10^{8}		
Gasoline (leaded)	S2	∼100	2.3	∼0.41
Gasoline (straight run)	NC	∼0.1	∼2	∼100
Gasoline (unleaded)	NC	< 50		
Glycerol (25°C)	C	6.4×10^{6}	42.5	5.9×10^{-5}
Guaiacol (25°C)	C	2.8×10^{7}		
Heptane (purified)	NC	3×10^{-2}	2	∼100
Hexamethyldisilazane	NC	29		
Hexane (purified)	NC	1×10^{-5}	1.9	∼100
Hydrogen bromide (−80°C)	C	8×10^{5}		
Hydrogen chloride (−96°C)	C	1×10^{6}		
Hydrogen cyanide (0°C)	C	3.3×10^{8}		
Hydrogen iodide (@B.P.)	C	2×10^{7}		
Hydrogen sulfide (@ B.P.)	S2	1000		
Iodine (110°C)	C	1.3×10^{4}		
Isopropyl ether	S2	500		
Jet fuel A and A-1	NC	0.01-50	2.2	0.39-100
Jet fuel B	NC	0.01-50	2.2	0.39-100
Kerosene	NC	1-50	2.2	0.39-19
Mercury (0°C)	C	1.063×10^{18}		
Methoxy triglycol	C	$> 1 \times 10^{6}$		
Methyl acetamide	C	2×10^{7}	191.3	8.5×10^{-5}
Methyl acetate (25°C)	C	3.4×10^{8}	6.68	1.7×10^{-7}
Methyl alcohol (18°C)	C	4.4×10^{7}	32.7	6.6×10^{-6}
Methyl benzoate (20°C)	C	1.37×10^{9}	6.63	
Methyl cyanoacetate	C	4.49×10^{7}	29.3	5.8×10^{-6}
Methyl ethyl keton (25°C)	C	1×10^{7}	18.51	1.6×10^{-5}
Methyl formamide	C	8×10^{7}	182.4	2.0×10^{-5}
Methyl formate	C	1.92×10^{8}	8.5	3.9×10^{-7}
Methyl iodide (25°C)	C	$< 2 \times 10^{6}$		
Methyl isobutyl ketone	C	$< 5.2 \times 10^{6}$	13.11	$> 2.2 \times 10^{-5}$
Methyl methacrylate	NC			
Methyl nitrate (25°C)	C	4.5×10^{8}		
n-Methyl-2-pyrrolidone	C	2×10^{6}	32	1.4×10^{-4}
Methyl tertiary butyl ether (MTBE)	NC			
Methyl thiocyanate (25°C)	C	1.5×10^{8}		
Methylene chloride	S1	4300	8.93	0.018
Monoethanolamine (20°C)	C	1.2×10^{9}		
Naphtalene (82°C)	C	4×10^{4}		
Naphtas	NC		∼2	∼100
Nitrobenzene (0°C)	C	5×10^{5}	34.82	6.2×10^{-4}

Continued on next page

Electrical properties of liquids (cont.)

Liquid	Conductivity		Relative	Relaxation
	class	(pS/m)	permittivity	time (s)
Nitroethane	C	5×10^7	28.06	5.0×10^{-6}
Nitromethane (18°C)	C	6×10^7	35.87	5.3×10^{-6}
1-Nitropropane	C	3.3×10^7	23.24	6.2×10^{-6}
2-Nitropropane	C	5×10^7	25.52	4.5×10^{-6}
o- or m- Nitrotoluene (25°C)	C	$< 2 \times 10^7$		
Octyl alcohol	C	1.39×10^7	10.34	6.9×10^{-6}
Pentachorodiphenyl	NC	0.8	5.06	~ 100
Pentachoroethane	NC	< 100	3.83	> 0.3
2,4-Pentanedione	C	8.82×10^8		
Pentyl acetate (23°C)	S1	3400		
Phenetole (25°C)	C	$< 1.7 \times 10^6$		
Phenol	C	1×10^6	9.78	8.7×10^{-5}
Phenyl isothiocyanate (25°C)	C	1.4×10^8		
Phosgene (25°C)	C	7×10^5		
Phosphorus (25°C)	C	4×10^8		
Phosphorus oxychloride (25°C)	C	2.2×10^8		
Pinene (23°C)	C	$< 2 \times 10^4$		
Piperidine (25°C)	C	$< 2 \times 10^7$		
Polyalkylene oxide (Y-6132)	C	$> 1 \times 10^7$		
Polyalkylene oxide (Y-6854)	C	5.4×10^5		
Primary amyl acetate (23°C) (23°C)	S1	2160	4.75	0.02
Primary amyl acetate (4°C)(4°C)	S1	1250	4.75	0.034
Propionaldehyde (25°C)	C	8.5×10^7	18.5	1.9×10^{-6}
Propionic acid (25°C)	S1	8500	3.44	0.0036
Propionitrile	C	8.51×10^6	27.2	2.8×10^{-5}
iso-Propyl acetate (23°C)	C	6.5×10^4		
iso-Propyl acetate (4°C)	C	1.3×10^4		
n-Propyl acetate (23°C)	C	1.12×10^4		
n-Propyl acetate (4°C)	S1	8460	8.1	0.0085
n-Propyl alcohol (25°C)	C	2×10^6	20.33	9×10^{-5}
iso-Propyl alcohol (25°C)	C	3.5×10^8	19.92	5×10^{-7}
Propyl formate	C	5.5×10^9	7.72	1.54×10^{-8}
Propyl Propasol	C	$> 1 \times 10^6$		
Pyridine (18°C)	C	5.3×10^6	12.4	2.1×10^{-5}
Quinoline (25°C)	C	2.2×10^6	9	3.6×10^{-5}
Salicyaldehyde (25°C)	C	1.6×10^7	13.9	7.5×10^{-6}
Silicon tetrachloride	NC			
Stearic acid (80°C)	NC	< 40		
Styrene monomer	NC	10	2.43	2.2
Succinonitrile	C	5.64×10^{10}	56.5	8.9×10^{-9}
Sulfolane (Teramethylene sulfone)	C	$< 2 \times 10^6$	43.3	$> 1.9 \times 10^{-4}$
Sulfonyl chloride (25°C)	C	2×10^8		
Sulfur (115°C)	S2	100		
Sulfur (130°C)	S1	5000		
Sulfuric acid (25°C)	C	1×10^{12}		
1,1,2,2-Tetrachloroethane (20°C)	C	4.5×10^5	8	
Tetrachloroethylene (25°C)	C	5.55×10^{10}	2.3	
Tetraethylenepentamine	C	$> 1 \times 10^6$		
Tetrahydrofuran	C	3.3×10^5		
Tetramethylurea	C	$< 6 \times 10^6$	23.06	$> 3.44 \times 10^{-5}$
Toluene	NC	< 1	2.38	~ 100
m-Toluidine	C	5.5×10^4	9.91	1.64×10^{-3}
o-Toluidine	C	3.79×10^7	6.34	1.54×10^{-6}
p-Toluidine (100°C)	C	6.2×10^6	4.98	7.1×10^{-6}

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Electrical properties of liquids (cont.)

Liquid	Conductivity		Relative permittivity	Relaxation time (s)
	class	(pS/m)		
1,2,4-Trichlorobenzene	S2	200	4.08	0.18
1,1,1-Trichloroethane	C	7.3×10^5	7.53	9.1×10^{-5}
Trichlorosilane	NC			
Trichoroacetic acid (25°C)	C	3×10^5		
Triethanolamine	C	2.2×10^7		
Triethylene glycol	C	8.4×10^6	23.69	2.54×10^{-5}
Triethylenetetramine	C	$> 1 \times 10^6$		
Trimethylamine (−33.5°C)	C	2.2×10^4		
Turpentine	NC	22		
iso-Valeric acid	NC	< 40	2.64	> 0.58
Vinyl acetate (23°C)	C	2.6×10^4		
Vinyl acetate (4°C)	C	2.0×10^4		
Vinyltrichlorosilane	C	5×10^4		
Vinyltrimethoxysilane (<2% CH_3OH)	S1	5900		
Water (air distilled)	C	$\sim 1 \times 10^9$	80.4	7.1×10^{-7}
Water (extremely pure))	C	4.3×10^6	80.4	1.7×10^{-4}
Xylene	NC	0.1	2.38	~100

D.6 Electrical properties of dielectric solid materials

(1) The main references are [2,56,57].

(2) The data of the breakdown field may be useful for selecting materials to prevent propagating brush discharges (see 3.3.8).

Table D.7: Electrical properties of dielectric solid materials [2,27,51–53,56–58]

Solid	Resistivity (Ω·m)	Relative permittivity	Breakdown field (kV/mm)
Ceramics			
Aluminum nitride (AlN)	2×10^9–10^{11}		
Aluminum oxide (Al_2O_3)	$> 10^{13}$	9	13.4
Beryllium oxide (BeO)	$> 10^{15}$	6.5–7.5	13.8
Boron nitride (BN)	1.7×10^{11}	3.5–4.0	30–40
Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)	$> 10^{12}$	5–5.5	7–10
Forsterite	$> 10^{12}$	6–7	9.1–15.4
Magnesium oxide (MgO)	1.3×10^{13}		
Steatite ($MgO\ SiO_2$)	$> 10^{12}$	~6	8–16
Glass			
Borosilicate glass ($SiO_2\ B_2O_3\ Na_2O\ K_2O$)	$> 10^{12}$	4.5–5	20–35
Lead glass ($SiO_2\ Na_2O\ K_2O\ PbO\ CaO\ MgO$)	$> 10^{11}$	6–9	5–20
Mica	10^{11}–10^{13}	5–8	80–120
Quartz (SiO_2)	$> 10^{17}$	3.8–4.1	470–670
Soda-lime glass ($SiO_2\ Na_2O\ CaO\ MgO$)	$> 10^9$	6–8	5–20
Rubber			
Butyl rubber	10^{13}–10^{16}	2–3	20–30
Chlorobutyl rubber	10^8–10^{10}	6–10	10–20
Ethylene propylene rubbe	10^{13}–10^{14}	3–4	30–60
Fluorine rubber	10^8–10^{12}	2–3	10–30
Natural rubber	10^8–10^{13}	3–4	20–30
Nitrile rubber	10^8–10^9	20	20

Continued on next page

Electrical properties of dielectric solid materials (cont.)

Solid	Resistivity (Ω·m)	Relative permittivity	Breakdown field (kV/mm)
Silicone rubber	10^{9}–10^{14}	3–4	20–30
Styrene butadiene rubber SBR	10^{12}–10^{13}	2	20–40
Polymers			
Acrylics	$> 10^{13}$	3.5–4.5	16–21
Acrylonitrile-butadiene-stylene (ABS)	$1\text{-}5 \times 10^{13}$	2.5–3.5	12–17
Alkyds	10^{12}–10^{13}	5.2–7.4	
Cellulose acetate butyrate	10^{9}–10^{12}	3.5–6.4	10–16
Cellulose acetate propionate	10^{9}–10^{12}	3.7–4.0	12–18
Cellulose acetate	10^{8}–10^{11}	3.5–7.5	10–14
Epoxies	10^{10}–10^{12}	4.0–5.7	13
Fluorinated ethylene propylene (FEP)	$> 2 \times 10^{16}$	2.1	83
Melamines	10^{10}–10^{11}	7.9–11	12–16
Phenlen oxides	10^{14}–10^{15}	2.7	16–20
Phenolics	10^{7}–10^{11}	4–7	10–16
Polyacetals	10^{12}–10^{13}	3.7	20
Polyamide resin: 6 Nylon	10^{11}–10^{13}	4.0–5.3	15
Polyamide resin: 6/6 Nylon	10^{12}–10^{13}	4	15
Polycarbonates	10^{13}–10^{14}	3.17	16
Polyester	10^{8}–10^{15}	3.1–3.3	12–21
Polyethylenes (PE)	10^{13}–10^{17}	2.3	39
Polyimide	10^{8}–10^{15}	4.1	12
Polymethyl methacrylate	$> 10^{12}$	3.5–4.5	15
Polyolefin: Ethylene ethyl acrylate (EEA)	2.4×10^{13}	2.8	22
Polyolefin: Polyallomer	$> 10^{14}$	2.3	20–26
Polyolefin: Ethylene vinyl acetate	1.5×10^{12}	3.16	22
Polyolefin: Ionomer	10^{14}	2.4	39
polyphenylene sulfide (PPS)	10^{14}	3.17	18–23
Polypropylene (PP)	10^{14}–10^{15}	2.2–2.3	18–26
Polystyrenes (PS)	$> 10^{16}$	2.45–2.65	20–28
polytetrafluoroethylene (PTFE)	$> 10^{16}$	2.1	40–80
polytetrifluoro chloroethylen (PTFCE)	10^{16}	2.3–2.7	21–24
Polyvinyl chloride (PVC)	10^{13}–10^{14}	3.08	16
Polyvinylidene-fluoride PVDF	5×10^{12}	10	10
Thermoset carbonate	4×10^{12}	4.4	8–17
Urea	10^{8}–10^{9}	7–9	12–16
Vinylidene chloride	10^{12}–10^{14}	3–5	16

D.7 Databases

The following databases on the Internet may be useful.

(1) International Chemical Safety Card (ICSC), Japanese version is provided by National Institute of Health Sciences (NIHS), Japan:
http://www.nihs.go.jp/ICSC/

(2) GESTIS-DUST-EX, Database combustion and explosion characteristics of dusts of Berufsgenossenschaftliches Institut für Arbeitsschutz–BGIA:
http://www.hvbg.de/e/bia/fac/expl/index.html

(3) WebKis-Plus, National Institute for Environmental Studies:
http://w-chemdb.nies.go.jp/

(4) Kis-net, Kanagawa Environmental Research Center:
http://www.k-erc.pref.kanagawa.jp/kisnet/index.htm

(5) MSDS information, Japan Advanced Information Center of Safety and Health: http://www.jaish.gr.jp/user/anzen/kag/kag_main01.html

(6) Vermont SIRI Material Safety Data Sheet (MSDS): http://hazard.com/msds/

(7) MSDS, Japan Petrochemical Industry Association: http://www.jpca.or.jp/61_f.htm

Appendix E

Glossary

Air A mixture of various gases constituting the atmosphere that surrounds the Earth. The molecular weight is 28.98. The composition (volume ratio) is nitrogen (78.08%), oxygen (20.95%), argon (0.93%), carbon dioxide (0.038%), neon (0.0018%), helium (0.0005%), krypton (0.0001%), hydrogen (0.00005%), and xenon (8.7×10^{-6}%). Water vapour is included in the range of 0 to 6% depending on the environment.

Antistatic agents A chemical added to a nonconductive material to make it antistatic.

Antistatic goods Products consisting of a static-proofed or fabricated material.

Antistatic measures/precautions Generically, measures in the wide sense designed to prevent electrostatic explosions and fires by controlling charge generation and preventing its accumulation.

Antistatic work clothes Work clothes that are static-proofed and fabricated with conductive fibre.

Bonding The process of electrically connecting one or more conductors to a grounded conductor, thereby establishing a grounding.

Brush discharge A local electrostatic discharge that occurs mainly between a charged nonconductive body and grounded conductor with a relatively large radius of curvature in which a non-uniform electric field creates. The discharge is accompanied by a tree-branch-like illumination.

Charge neutralisation The process in which a charge recombines with a charge (ion) of opposite polarity and, thereby, becomes neutralised.

Charge relaxation The process whereby a charge accumulated in a body is lost through electrical conduction.

Charge relaxation time A time constant of charge relaxation that applies when the charge relaxation of a charged body occurs exponentially; the time required for it to reach $1/e$ (36.8%) of the initial value.

Chargeability The ease with which a body becomes electrified, which is almost determined by the resistivity.

Charged cloud A cloud of charges formed in space by means of a large number of charged particles, such as mist, fume, liquid drops, and dust.

Conductive/dissipative floor An antistatic floor, such as antistatic coated flooring, an antistatic mat, and an antistatic carpet; conductive or dissipative floor installed to make workers and other conductors on it antistatic.

Conductive/dissipative footwear Footwear designed to prevent charge accumulation on the human body. Its electrical resistance is reduced by using conductive or dissipative soles.

Conductivity Ease with which a body performs electrical conduction, which is almost determined by the conductivity.

Conductor A body considered to be electrostatically equal in potential. Conductors include bodies made of metal or conductive material, along with human bodies.

Cone discharge An electrostatic discharge that occurs on the heap of bulked powder inside a silo or large container during filling with highly charged nonconductive powder.

Corona discharge A local electrostatic discharge in which ionisation occurs close to a sharp point as a discharge electrode due to a non-uniform electric field in which only the field near the electrode is locally strong.

Delay time Time during which flammable liquid stands before sampling or gauging after loading for the purpose of relaxing the charge of the liquid.

Dip/drop pipe A vertical pipe that reaches a point close to the bottom of a tank and is used to prevent the liquid from splashing when flammable liquid is top-loaded.

Discharge energy Energy to create a discharge, which involves the energy that is consumed in a discharge space. In an electrostatic discharge, it corresponds to a whole or a part of the electrostatic energy due to a charged body.

Dust cloud Dust that is floating in space and spreads like a cloud.

Dust hazardous area A hazardous area with a flammable atmosphere of dust.

Dust → flammable dust

Electric field A fundamental field causing a charged body to be attracted to or repelled by other charged bodies; specifically, the electric force per unit charge.

Electric shock A shock that a human undergoes due to electrostatic discharge or touching a voltage.

Electrification/charging A phenomenon in which generated static charge accumulates in or on a body; the process of establishing a charge in an object.

Electrostatic discharge An ionisation phenomenon generated when an electric field due to a charged object reaches the dielectric breakdown electric field strength of the medium. It usually takes the form of a gas discharge in which air undergoes dielectric breakdown.

Electrostatic induction A phenomenon in which the surface charge on a conductor is redistributed by the electric field generated by a charged body near the conductor. At the time, the conductor has a potential but no true charge transferred from the charged body.

Electrostatic shielding Surrounding with a grounded conductor a whole or a part of a charged object to reduce electrostatic interaction.

Excessive charge A charge in which either the positive or the negative charge is higher than the other throughout the body or locally.

Faraday cap/cage/pail/tube A device to measure charge; it consists of an insulated conductive container and a shielding conductor surrounding the container and is used to measure the charge of an object inside the inner container by using an electrostatic induction.

Flammable dust Flammable powder that is scattered and floating in air or is adhered to or accumulated on a wall, floor, or other surface within a facility, on equipment, or at another location.

Flammable gas or vapour Generically, flammable gas and flammable liquid vapour.

Flammable matter (substance) Generically, flammable gas, flammable liquid, and flammable powder.

Flammable mixture A mixture of flammable matter and combustion-susceptible gas (such as air or oxygen) which is within the range of the flammable limit concentration.

Flammable/explosive atmosphere An atmosphere in which the concentration of a flammable mixture is within a flammable limit.

Flammable/explosive limit The limit of the mixture concentration at which a mixture of an explosive (flammable) substance and air or something similar can explode or burn by an ignition source.

Gas Generically, in this document, gas, liquid vapour, and a gas containing small quantities of liquid drops or solid particles.

Gaugewell Equipment made of metal pipes used for specimen collection, the measurement of filling level, and other purposes and so installed as to reach from the ceiling surface to a point close to the bottom of the flammable liquid storage tank.

Grounding In this document, electrically connecting a conductive body with the earth to prevent the electrification of the conductor.

Hazardous areas with gas or vapour Locations that have a risk of ignition due to flammable gas or vapour.

Humidification The process of increasing the relative humidity of the atmosphere to prevent the electrification of the nonconductor.

Ignition The process of initiating the burning of a flammable mixture.

Induced potential A potential induced to an insulated conductor due to electrostatic induction; the potential of an insulated conductor induced by a charged body.

Induction charging The process of charging a conductive body near another charged object and then touching it to ground.

Inert gas A non-flammable, non-reactive gas which makes a flammable atmosphere in a system outside its flammable limit. Typical inert gases are nitrogen, carbon dioxide, steam, and flue gases.

Inerting The process to prevent the formation of an explosive atmosphere in a tank or other sealed or closed-in tanks containing flammable material by pumping nitrogen, steam, carbon dioxide, or some other inert gas into its air space in order to substitute oxygen.

Ion An atom or molecule which, by loss or gain of one or more electrons, has acquired a net charge. An atom or molecule that is ionised or one to which an electron is attached.

Ionisation The process whereby a neutral atom or molecule losses electrons, thereby acquiring a net charge and becoming an ion; it occurs as a result of the dissociation of the atoms of a molecule in solution or of a gas in an electric field.

Ioniser Equipment designed to eliminate the charge from a charged object through charge neutralisation by ions generated by ionising the air.

Leakage resistance The electric resistance between a conductive body and the earth.

Lightning-like discharge An electrostatic discharge considered to occur in conjunction with illumination, such as a flash of lightning in a large charged cloud.

Limiting oxidant concentration The concentration of an oxidant below which deflagration cannot occur in a specified mixture.

Liquid An intermediate state of matter between the crystallised state and the gaseous state. In this document, "liquid" refers generically to liquid and to colloid, emulsion, sol, and other liquid-state substances consisting of liquid with gas bubbles, powder, or other fine particles that are mixed or dispersed in it.

Minimum ignition energy A minimum level of energy required to ignite a mixture of air or oxygen and flammable substance in general.

Mist A group of fine liquid drops dispersed in a gaseous medium.

Nonconductor A body made of nonconductive materials and considered not to be equal in potential on the surface when charged.

Passive ioniser A non-power-supply ioniser designed to neutralise charged objects through a corona discharge generated by a locally enhanced electric field due to a sharp electrode of the ioniser and the charged object. In general, conductive fibre and a grounded needle are used.

Powder Generically, dust and powder; in this document, general powder except for powder materials used in explosives.

Propagating brush discharge An electrostatic discharge generated along the surface of a thin body, each side of which is charged with different polarity, when its charge density rises to a very high level.

Shielding → Electrostatic shielding

Solid In this document, generically, general solids except for powder.

Space charge cloud → A charged cloud.

Spark discharge An electrostatic discharge due to the sudden breakdown of air, accompanied by a momentary flash of light. It occurs in general between a charged conductive body and a grounded conductor in which a uniform electric field is created.

Splash loading The method of loading liquid into a tank by dropping it through the opening or the pipe on the top.

Static electricity An electrical charge that is significant only for the effects of the electric field but not for the effects of the magnetic field.

Switch loading The method for loading a low-volatility liquid into a tank containing a high-volatility flammable liquid vapour.

Triboelectric series A list of materials that produces a static charge when rubbed together in such an order that the material has a positive or a negative charge.

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