

Static Electricity

Guidance for Plant Engineers.

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Static electricity is one of the most insidious sources of fire and explosion encountered in modern industry. It is by nature unpredictable and therefore difficult to detect. In some industry sectors it is viewed almost as a black art.

Uncontrolled static electricity is a problem in many sectors of manufacturing industry but is of particular concern in operations where sensitive flammable materials are present. Fires and explosions attributable to static may actually be increasing in frequency due increased product purity and faster process speeds.

With the right approach electrostatic ignition hazards can be identified and controlled. This fact sheet looks at the steps taken in a hazard assessment and the key parameters that need to be determined.

Analysis

There are five general conditions necessary for an electrostatic ignition hazard to be present:

1. Sensitive flammable atmosphere
2. Generation of electrostatic charge
3. Accumulation of charge
4. Electrostatic discharge (ESD)
5. Sufficient discharge energy

If all of the above conditions exist, an ignition hazard will be present, if any of the conditions are removed, the hazard is obviated. As a belt and braces approach attempts are often made to remove more than one of these conditions, however the extent to which any mitigating measures can be applied in practice often involve other considerations which may include cost and practicality.

Are Sensitive Flammable Materials Present?

In any investigation, it is usually straightforward to identify the presence of flammable media.

From the point of view of electrostatic ignition hazard it is only necessary to restrict the

investigation of flammable atmospheres to those sensitive enough to be ignited by an electrostatic discharge. In most industrial situations these are flammable gases, solvent vapours, aerosols and fine combustible dusts. Many pyrotechnic materials are also very sensitive to electrostatic ignition.

Gases and vapours

Many common industrial hydrocarbon gases and solvents are flammable in air over the range 1 - 12% by volume. This is referred to as the flammable or explosive range existing between the lower explosive limit (LEL) and the upper explosive limit (UEL). The electrostatic discharge energy required for ignition varies significantly over this range but the minimum ignition energy value is likely to be of the order of 0.2 - 2.0 millijoules (mJ). This energy level is very low and indicates that ignition may result easily.

From Lewis and von Elbe [1] the relationship between the minimum ignition energy of the solvent vapours and their concentration will be similar to that shown by the red U-shaped curve in Figure 2. Note that the solvent is most sensitive to ignition approximately midway between the lower and upper flammable limits and that the spark energy required to ignite the vapour increases rapidly as it approaches these limits.

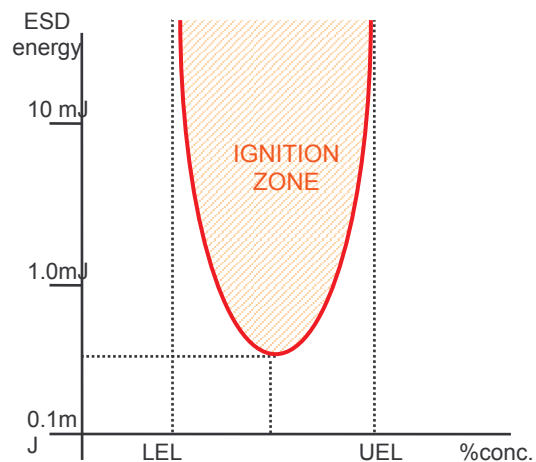


Figure 1. Typical relationship between ignition sensitivity and concentration of fuel vapour in air.

If the atmosphere is oxygen-rich (in excess of normal air), the sensitivity to ignition is significantly increased. This will be in terms of both an extended flammable range and a greatly

reduced minimum ignition energy (MIE). Reduction in pressure below atmospheric may also influence the flammable range and reduce the MIE.

Aerosols and foams

Flammable liquids in the form of a dense mist or aerosol may be ignited easily at temperatures below the liquid flashpoint. Kerosene for example may have a flashpoint in excess of 70C but can be ignited at room temperature with a low-energy spark [2]. In combustion, mists comprising small droplets below 10 μ m tend to behave like a vapour whereas those with droplet diameters above around 40 μ m propagate combustion in a similar way to flammable dust clouds[3]. Typical minimum flammable concentrations for aerosols vary from 15 to 50 g.m⁻³.



Figure 2. Electrostatic ignition of kerosene foam at 25C - fifty degrees below its flashpoint.

The presence of foam, for example on the surface of an agitated solvent, can also result in ignition below the liquid flashpoint (figure 2). Foaming liquid surfaces of non-volatile solvents allow fuel and oxygen to mix more effectively enabling ignition to occur at lower temperatures.

Dust clouds

Most natural and synthetic materials, if subdivided into a fine dust, will easily ignite and burn vigorously. In general, dust clouds are less sensitive to ignition than flammable gases or solvent vapours. They can however produce violent explosions and are more likely to be associated with electrostatic ignition due to their propensity over gases and liquids to generate electrostatic charge through handling.

For a flammable dust to be at risk from electrostatic ignition it must be dispersed to form a cloud. This cloud then exhibits upper and lower explosion limits similar to a flammable gas or vapour. Typical lower and upper explosive limits for a dust cloud are 50 and 1000 g.m⁻³, respectively. The sensitivity to ignition varies with dust concentration also in a similar way to gases and vapours. Even at the lowest extreme of the flammable range the concentration represents an extremely dense dust cloud and is unlikely to be encountered in a normal working environment other than within process equipment (driers, cyclones, silos, etc) or as the result of the temporary disturbance or dispersion of an accumulated dust layer. An innocuous 1mm thick layer of dust on the floor of a room, if partially or totally dispersed throughout the volume of the room, can easily produce a sensitive flammable dust cloud. The physical and chemical nature of the material, its particle size and moisture content, will all influence the ease at which the dust cloud is ignited. Fine dry dusts tend to have a lower ignition energy and are more explosive.

Hybrid vapour- dust mixtures

In many industrial situations, a dispersed flammable dust may coexist with traces of flammable hydrocarbon vapour. In such cases vapour concentrations well below the LEL may significantly reduce the minimum ignition energy of the dust cloud. The presence of propane in the concentration of 1% by volume with air for example can reduce the minimum ignition energy of the dust by 2 orders of magnitude [4].

Hazardous area classification (zoning)

Hazardous area classification is a method often used when undertaking risk management. The classification is based on identifying areas or zones within a plant according to the likelihood of sensitive flammable gas or vapour concentrations being present. For solvents or gases there are generally 3 classifications as follows.

- Zone 0 - in which an explosive gas/air mixture is continuously present, or present for long periods.
- Zone 1 - where an explosive gas/air mixture is likely to occur in normal operation.

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

An example of such zones would be a process vessel in which flammable solvents are being mixed within a building located at an industrial site. The inside of the reaction vessel can be classified as Zone 0. The building containing the vessel may be classified as Zone 1 (as the vessel may be opened from time to time and drums of solvent or solvent pipes may be present). The area outside the building would normally be classified as Zone 2 providing sensitive flammable atmospheres could not be generated from other sources.

Hazardous area classification is similarly applied to the presence of flammable dusts, in this case zones 0, 1 and 2 become zones 20, 21 and 22 respectively. Similar limitations apply to equipment and materials used in these areas.

The application of hazardous area classification has advantages from the point of view of general safety standards, in particular, the use of electrical equipment and other potential ignition sources which must be safety certified to the appropriate level before they can be used in certain zones. From the point of view of static electricity, highly insulating surfaces such as plastics are prohibited from use in Zones 0 and 1 if the exposed area exceeds certain limits. (This is interpreted in some detail later in this paper).

Is Static Electricity Generated?

The generation of electrostatic charge is intrinsic to many industrial operations. The rate of charge generation is notoriously difficult to predict, however, operations involving rapid and energetic movement and the contact and separation of surfaces will produce increased charging. Milling of powder, for example, will generate more charge than pouring. In industry charge generation mechanisms are as follows:

- The contact and separation of solid surfaces such as moving webs over rollers.
- The movement of personnel.
- The flow/movement of liquids.
- The production of mist or aerosols.
- The flow or movement of powders.
- Charging by induction in an electric field.

Powder handling

A powder has a large total surface area per unit mass and since electrostatics is a surface phenomenon there is a propensity to generate and store high levels of static. All powder handling operations are likely to generate electrostatic charge.

Studies at the University of Southampton [5,6] and elsewhere [7] have shown that electrostatic charge is generated when particles are transported through pipelines and ducts. The charging process arises from the physical interaction of the particles and the duct wall and occurs whether the pipe is constructed from plastic or metal. Industrial processes such as pneumatic conveying can often suffer from static electricity related problems and occasionally very high levels of potential and energetic sparks can be generated.

Parameters influencing the levels of electrostatic potential generated are:

- The nature of the material comprising the particulate.
- Flow velocity.
- Mass flow rate/density (kg/m^3)
- Particle size
- Composition of duct walls.
- Turbulence due to bends, constrictions etc.
- Temperature and humidity.

General observations are that the charge-to-mass ratio in Coulombs per kilogram (C.kg^{-1}) of particulate matter pneumatically conveyed through a duct increases with increased flow velocity and decreases with increased mass flow density and increased particle size. This can be explained in terms of the collision frequency of particles with the wall. The number of particle-wall collisions per unit mass is increased as mass flow density is decreased. The charge transfer efficiency increases with velocity of impact and separation and hence with flow velocity. Smaller particles can sustain a larger charge-to-mass ratio before leakage to the surrounding gas occurs. It follows that the largest charge-to-mass ratios are observed with small particles conveyed at high velocity and low mass flow density. The presence of electrostatic charge on powders or particles does not normally constitute an ignition hazard until a significant mass of the particles are bulked together.

It is envisaged that a charge generation mechanism will only occur when solid particles or liquid droplets are carried in the gas stream. The movement of gases alone creates little, if any, static electricity [8]. Since it is primarily the number of collisions and the force of each collision between particles and the duct wall, which influence the level of electrostatic charge generation, it follows that an increase in transport velocity will result in higher levels of charge generation. The relationship between the two, however, is complicated due to the influence of the duct geometry and turbulence. This makes it very difficult to set maximum velocity limits as a mitigating measure without performing an empirical study. Naturally, it is better to limit the velocity such that the gas flow is laminar rather than turbulent and this should be considered. It is known, however, that the maximum level of surface charge density for well-dispersed particles cannot exceed a value of approximately $10 \mu\text{C}\cdot\text{m}^{-2}$ [9]. This value can be used to estimate maximum levels of charging developed on objects or surfaces onto which the particles impinge and from this determine electrostatic ignition hazard at these points.

Charge generation in liquids

Unlike industrial powders most liquids are in electrostatic terms relatively electrically conductive. For this reason it is non-polar liquids such as paraffin, gasoline, purified aromatics (toluene, xylene, etc), diesel and light oils, which exhibit significant charge generation. This is actually more to do with their charge retention properties but it is appropriate to mention it in this section as electrostatic problems are confined to low conductivity liquids.

It is known that high levels of electrostatic charging occur as the result of high velocity flow in pipelines and agitation in tanks. Pouring, gravity fill and splashing are also charge generators but to a much lesser extent.

Charging of liquids in a pipeline, normally takes place because the moving liquid carries with it a loosely bound layer of charge leaving the other layer attached to the solid surface i.e. the pipe wall. The potential in the fluid at the plain of slip is called the zeta potential.

As the liquid flows through a pipe it carries with it charge from the diffuse layer. If the charging

process is to continue, the charge must be replenished by charge moving through the walls of the pipe. This movement of charge creates an electrical current measured between the pipe wall and ground called the streaming current and is generally in the order of 10^{-14} to 10^{-8} A. With electrically insulating pipe work material such as plastic, the current is reduced. As a consequence, there are large differences in the charging behaviour of liquids in metal and plastic pipes[10].

The amount of charge generated on a liquid flowing in a straight pipe is generally limited by three factors:

- The conductivity of the liquid
- The flow velocity
- The nature of the pipe wall

The rate at which charge on a liquid flows to earth depends on its conductivity. It follows, therefore, that a highly conductive liquid cannot store charge. A perfectly pure insulating liquid will not generate charge because there are insufficient disassociated ions present. It is generally found that the electrostatic activity associated with a liquid flow builds up as the conductivity increases, reaches a maximum when the liquid conductivity is in the range $10\text{-}50 \text{ pS}\cdot\text{m}^{-1}$, then decreases with further increasing conductivity as the generated charge flows rapidly to earth.

Volume charge densities in liquids can range from between 10^{-6} to 10^{-2} Coulombs. m^{-3} which infers that tanks receiving hydrocarbon fuels or solvents from pipeline systems can also store a relatively high level of electrical energy.

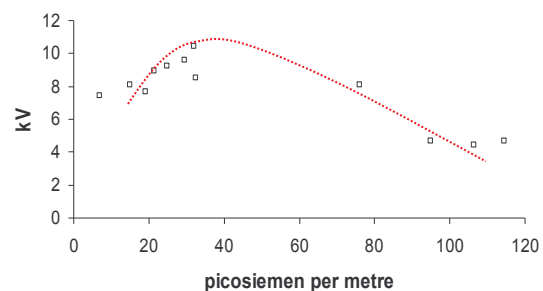


Figure 3. Electrostatic potential in kilovolts developed on an isolated metal valve during solvent flow through a pipeline as a function of solvent conductivity [11].

Although many people associate electrostatic problems with plastics and other insulators, it is metal pipes that give the highest charging rates (with very little difference between different metals)[12]. Naturally, charging also occurs in glass, rubber and plastic pipes. Turbulent flow produces more charge than laminar flow and pipes with rough internal surfaces tend to produce more charge than smooth surfaces, even when the roughness is on too small a scale to affect the state of turbulence.

Can Electrostatic Charge Accumulate?

As electrostatic charge is generated, by the means indicated above, it will either accumulate or dissipate depending of the conductivity of the materials involved and the possible conduction path to earth. Wood, concrete, natural fabrics, water, alcohols and of course metals can be considered conductive in electrostatic terms. Most polymers, on the other hand may retain electrostatic charge for many minutes or even hours. Glass can exhibit wide variations in conductivity.

Electrostatic charge can accumulate on insulating surfaces such as plastics and also on ungrounded conductors. Both of these situations can be potentially hazardous. An example of an ungrounded conductor is a metal solvent drum on an epoxy floor.

Capacitance

Any object or surface that can accumulate electrical charge can be thought of as a capacitor. In most industrial situations, the value of capacitance can be determined either by direct measurement or calculation. Capacitance is often expressed in picofarads (10^{-12} Farads) and in the example above, the ungrounded metal drum could be around 500pF. British Standard BS5958 gives typical capacitance values for various industrial objects including the human body.

It is important to note that objects or surfaces will only acquire and accumulate electrostatic charge if they are subjected to a charging mechanism. Furthermore, the accumulation of low levels of charge does not guarantee the presence of an ignition hazard. It is the magnitude of electrical energy that is stored and then released in a discharge which ultimately influences the degree of ignition hazard present.

Many powders used in industry are electrically insulating. A powder also has a large total surface area per unit volume and consequently, high levels of static electricity can be accumulated. Industrial liquids on the other hand tend to be relatively conductive. Exceptions include fuel oils, petroleum spirit, kerosene and non-polar solvents including toluene, xylene, heptane etc.

Resistivity and charge relaxation

If conductive materials are used, there can be no charge build up on their surface if they are sufficiently conductive and grounded. Standards usually recommend a maximum resistance to ground of between 10^6 and 10^8 ohms. In practice resistance paths of up to 10^{10} ohms may be sufficient for all but the most extreme situations.

Since electrical charge can be conducted across the surface or through the volume of a material, a resistivity value can be assigned to each. Surface and volume resistivity are usually related but have different units. It is often important to measure these parameters during hazard analysis.



Figure 4. Liquid Conductivity Meter

Surface resistivity (Δ_S) is expressed in ohms per square of surface i.e. The electrical resistance between two parallel 'bar' electrodes separated by a distance equal to their length. (This encompasses a square of surface the size of which is unimportant because the resistance value will remain the same. 1 cm^2 will exhibit the same resistance as 1 m^2 provided that the surface is homogeneous). In some standard test methods, the electrode geometry is two concentric rings with the resistance measured between the inner and the outer ring.

Volume resistivity (ρ_v) is the reciprocal of conductivity and is expressed in ohm.metres. It is defined as the resistance through a volume of material of cross-section 1m^2 and thickness 1m . Special metering cells are available which enable this parameter to be quantified for both liquids and powders. Figure 4 shows a commercially available instrument for measuring liquid conductivity.

Charge relaxation time (T) and resistivity (ρ_v) are related by the formula $T = \epsilon_0 \epsilon_r \rho_v$. Where ϵ_0 and ϵ_r are the permittivity of free space and the relative permittivity of the material. Like resistivity, charge relaxation time can be measured directly. This is normally achieved by applying charge to the surface under test using an ion source, grounding the sample and measuring the rate of decay of surface potential.

Charge on personnel

It is possible for a person to generate charge on his or her body by movement, particularly walking. In many industrial situations however charge is transferred to personnel by proximity to a process. Irrespective of the method of charge generation, the problem is one of accumulation. Electrostatic charge developed on the human body can be a particular problem (a) because a person is mobile and may carry dangerous potentials into hazardous areas and (b) because human skin is conductive in electrostatic terms and can give rise to energetic spark discharges.

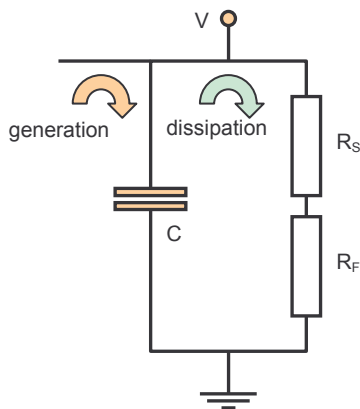


Figure 5. Electrostatic model of the human body. The charge generation mechanism could be walking, movement, powder handling etc.

A person standing can be modelled as a capacitor in parallel with two resistors (Figure 5). The capacitance (C) of the human body is usually in the range $100\text{-}300\text{pF}$. R_S and R_F respectively represent the footwear and flooring resistance to ground. The time taken for charge on the body to decay is given by the product $(R_S+R_F)C$. If either the footwear or flooring resistance is high, charge will be retained on the body.

Standards recommend a maximum resistance for footwear and flooring of 10^8 ohms. This gives a charge relaxation time of 0.06 seconds or less.

Can Electrostatic Discharges Occur?

There are four common types of electrostatic discharge (ESD) that need be considered from the point of view of ignition hazard. These are sparks, brush discharge propagating brush discharge and cone discharge. (Corona discharges may occur but are considered non-hazardous and are therefore not discussed here).

Sparks

Spark discharges are responsible for the majority of industrial fires and explosions caused by static electricity. Spark discharges will occur from conductive objects, surfaces and personnel, which are ungrounded and have become charged to an electrostatic potential. The energy (E) in a spark is expressed in Joules or more commonly millijoules (mJ) and can be calculated from the formula $E = \frac{1}{2}CV^2$ where C is the capacitance of the object and V is its potential. With the correct equipment both C and V can be measured and E can be calculated.

Flammable hydrocarbon vapours are extremely sensitive to spark ignition. A number of hydrocarbons have minimum ignition energies of 0.2 millijoules. A spark of this energy is often below human perception in terms of sight and sound.

In a plant, sources of spark energy will comprise ungrounded metal fixtures and fittings. They may also include personnel if their footwear and flooring are insulating, mobile and non-fixed items such as trolleys, metal drums, ancillary equipment, gauging equipment and hand tools. Once identified, this hazard can usually be simply remedied by providing a permanent conduction path to ground.

Brush Discharges

Electrostatic brush discharges occur from charged non-conductive surfaces such as plastics and may even occur from highly charged non-conductive liquids such as hydrocarbon solvents and fuels. The incendivity (igniting power) of a brush discharge depends on a number of factors but energy content is limited to a theoretical maximum of 4 millijoules. Furthermore, since the theoretical limit of 4mJ applies to brush discharges they only represent an ignition hazard with flammable gases and solvents over part of their flammable range (refer to fig.1).

Generally for brush discharges to present an ignition hazard, the following conditions must apply:

- the charged surface has a potential of 20kV or greater
- the polarity of charge on the surface is negative
- a flammable atmosphere exists at the point of discharge
- the energy content of the brush is greater than the minimum ignition energy of the flammable atmosphere.

The energy content of the brush will be dependant not only on the surface potential but also on the area of surface contributing to the discharge. Normally, since there is a maximum charge density that can be established on any surface, an area in excess of 100 cm² [13] is required to produce an ESD with sufficient energy to ignite a flammable hydrocarbon vapour (with some exceptions). It is doubtful that brush discharges can ignite flammable dusts and no such incidents have been observed..

Important differences exist between brush discharges and sparks. The first is that since only part of a charged insulator contributes to the brush it is possible to obtain many discharges from a single large charged surface. Secondly, because of the low mobility of charge carriers, in an insulator, it is impossible to remove the charge by simply connecting to ground. The discharges themselves also vary significantly in the way the energy is released with brushes producing lower currents and consequently lower temperatures[14].

Propagating Brush Discharges

Propagating brush discharges (PBD's) can occur when an insulating material of up to around 8mm thickness has become highly polarised with electrostatic charge, i.e. positive charge on one face and negative charge on the opposite face. In industry PBD's may occur where large areas of insulating sheets are subjected to high levels of electrostatic charge generation (*note that both of these conditions are necessary*). More often than not these insulating sheets are in the form of a lining or layer, with an earthed metal backing. An example of this situation is a Teflon or glass-lined reactor vessel.

A photograph of a propagating brush discharge is shown in figure 6. In this case the discharge has occurred during high velocity fuel flow through a plastic pipe. Partial ignition of the fuel can be observed. This type of discharge event is high in energy and dangerous.



Figure 6. Propagating brush discharge from a plastic pipe conveying diesel fuel (photo courtesy J. F. Hughes, University of Southampton).

Cone discharge

Cone discharges are sometimes referred to as 'bulking brush discharges' and occur across the surface of bulked powder in storage silos, containers and hoppers. They can also occur deep within the powder heap.

Conditions for cone discharges are a charged powder of resistivity exceeding 10¹⁰ ohms. In grounded metal silos the discharges travel radially towards the silo wall across the surface of the powder cone during filling and may have an effective energy of up to 20mJ.

Particle size and charge density will both affect the resultant ESD energy. Large vessels produce higher energies and cone discharges are not normally observed in volumes below 1m³[15]. In some cases this type of electrostatic discharge has been initiated by adding solvent to a vessel containing charged dry granular product. This practice is clearly dangerous and should not be undertaken unless it is certain that the product is uncharged.

Is The Discharge Energy Sufficient To Cause Ignition?

It is possible for a sensitive flammable atmosphere and electrostatic discharges to coexist without ignition. If the discharge energy is increased, a threshold energy is eventually obtained, at which the discharge becomes incendiary, either partially or wholly through the volume of the flammable medium. This threshold energy is known as a minimum ignition energy (MIE) and is usually expressed in milliJoules (mJ). Typical values for flammable media are given below.

- Hydrogen 0.02mJ.
- Hydrocarbon vapours 0.2-2.0mJ.
- Fine flammable dusts 1-50mJ.
- Coarse flammable dusts 40-1000mJ.

Published MIE values should be used as a guide when undertaking an electrostatic hazard analysis and a margin of safety should always be included. Many flammable hydrocarbons in air have a minimum ignition energy below 1 milliJoule. This is so low that in practice no electrostatic discharges at all can be tolerated in such atmospheres. Hydrogen, carbon disulphide and oxygen-rich hydrocarbon mixtures are particularly sensitive to electrostatic ignition and require special precautions.

Brush discharges, which are limited in energy, will present an ignition hazard in the presence of hydrocarbon gases and vapours and possibly hybrids but are unlikely to ignite dust clouds. Ignition of an industrial dust by an electrostatic brush discharge has yet to be demonstrated despite the fact that some fine dry powders may have a minimum ignition energy as low as 1 mJ.

Due to their higher energy content, propagating brush discharges and cone discharges can ignite dust clouds. Sparks from ungrounded conductors

however remain the most common source of electrostatic ignition in industry[16].

Figure 7 shows propane gas from a test probe being ignited by a brush discharge from a flexible intermediate bulk container (FIBC). The charging mechanism in this case is the FIBC being emptied of charged polystyrene pellets.

The ignition probe test has been developed to evaluate antistatic FIBC designs (often denoted as 'Type C or D') for use in potential flammable atmospheres. Since it is impossible to eliminate ESD's completely with these items, emphasis is placed upon limiting the igniting power of the discharge to a safe level.



Figure 7. Propane ignition by brush discharge from an FIBC.

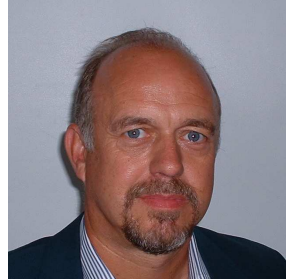
Concluding remarks

Most manufacturing processes which involve sensitive flammable materials will contain some of the elements necessary for an electrostatic ignition hazard to exist. More often than not the process runs trouble free - the generation and accumulation of electrostatic energy is unseen and discharges if they occur may be low in energy and remain unnoticed. A simple change in the properties of the materials, process or operating procedures however may be all that is necessary to complete the chain between charge generation and ignition. The consequences of an ignition are of course often catastrophic.

History has demonstrated that a plant may run trouble free for decades and then for no immediately apparent reason experience a series of fires. In the battle against static electricity it is important to be vigilant and to carefully consider the consequences of any changes to material, plant and process.

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