2-1. What Is Static Electricity?

As the name implies, the term originally referred to physical phenomena associated with charges at rest, such as on charged, isolated conductors. However, as used in this book, “static” charges may either be at rest or moving. The elementary unit of negative charge is the electron, which carries \(-1.6 \times 10^{-19}\) Coulombs of charge. A positive charge is equivalent to the absence of electrons. In semiconductor theory a group of covalent bonds deficient of one electron is treated as a mobile positively charged entity, or “hole.” This concept is used to describe the properties of semiconductive crystals used in transistors. However in the context of this book it is best to think of the flow of positive charge as a flow of positively charged particles or ions.

Static electricity hazards or nuisances arise when charge separation occurs leading to an accumulation of one sign of charge within some defined boundary, such as inside a container. The work performed in separating the charges results in differences of potential within or across the defined boundary and the accompanying generation of electric fields. If an electric field locally exceeds some threshold value, electrical breakdown of the intervening medium occurs in the form of a static discharge. This might come as a shock.

The “tingling” effects of static are caused by mutual repulsion between strands of hair carrying the same sign of charge, which tends to make them...
stand up. The phenomena occur either as the result of polarization (2-2.1) or a net charge on the body. When the body is polarized by a strong electric field, the charged strands of hair are both repelled from one another and attracted in the direction of the electric field. This can be especially hair-raising.

2-1.1. Charge Separation

This occurs in a variety of ways. When solid surfaces are placed in contact, an electronic rearrangement occurs to minimize the energy at the interface. Since this process is generally not reversible, charge separation occurs when contact between the surfaces is lost. If the interface is disrupted at a rate faster than equilibrium conditions can be established, additional charge separation occurs. However, the maximum surface charge density is limited by electrical breakdown in the gap between the separating surfaces. During separation of nonconductive plastic sheets, one sheet gains a net positive charge and the other gains an equal quantity of negative charge. If this process occurs in air, corona discharges in the gap formed between the sheets limit the maximum surface charge density to \( \leq 2.65 \times 10^{-5} \text{ C/m}^2 \) (6-2.1.1). As a stream of water breaks up, ions associated with aligned water dipoles at the water–air interface separate into the fine mist created as the surface layer shears away, while ions of predominantly opposite sign separate into the coarser droplets formed from the body of the water stream. This results in a charged water mist after the coarser droplets settle out (5-6.1). Ionic charge-carrying species in liquids are adsorbed nonuniformly at the wall of a pipe such that one sign of charge predominates in a tightly held “fixed layer” while the countercharge is situated farther from the wall in a less tightly held “diffuse layer.” When the liquid is pumped through the pipe the diffuse layer shears away and is convected downstream. The flow of charge is equivalent to a charging current or “streaming” current (5-2.1 and 5-3.1.1).

2-1.2. Magnitude of Current and Potential

Static electricity hazards and nuisances are typified by the generation of large potentials (0.1–100 kV) by small charging currents (0.01–100 \( \mu \text{A} \)) flowing in high resistance circuits \( (10^8–10^{15} \text{ } \Omega) \). This in part differentiates static electricity from other electrical phenomena. For example, stray currents in low resistance circuits are typically of the order 1 A for potential differences of the order 1 volt (A-4-1.3). The electric field at any point in relation to a conductor is proportional to its potential, while magnetic field is proportional to
the current flowing through the conductor. Since static electricity involves high potentials and very low currents, it can be differentiated from “current electricity” phenomena by its associated electric field but the absence of any significant magnetic field.

2-1.3. Concentration of Charged Species

The occurrence of static electricity is highly dependent on the presence of charged chemical species at extremely small concentrations. This is because only a minuscule fraction of an electrostatically charged substance carries a net charge. One Coulomb represents the same charge as $6.25 \times 10^{18}$ electrons, or an equal number of ionic species each carrying one elementary unit of charge. A mole of substance contains the Avogadro number, $6.023 \times 10^{23}$ molecules. Hence a charge density of one Coulomb per mole is equivalent to 1 molecule in 96,400 (~10 ppm) carrying an elementary charge. One Coulomb per mole is an extremely large charge density. The volumetric charge densities found in charged liquids typically range from 1 to 5000 μC/m$^3$. For a typical maximum charge density of 1000 μC/m$^3$, assuming a liquid with specific gravity 1.0 and molecular weight 100, the involvement of molecules in the net charge carrying process is one part per trillion.

Similarly, 1 m$^3$ of this substance contains $6.023 \times 10^{27}$ molecules. The maximum surface charge density of $\leq 2.65 \times 10^{-5}$ C/m$^2$ (2.1.1) corresponds to $1.6 \times 10^{14}$ electrons. If the surface charge is assumed to reside in a slice of the substance 10 Angstroms thick, containing $6.023 \times 10^{18}$ molecules, approximately 27 ppm of these molecules carry an elementary charge. A similar concentration (about 7 ppm) is found for the more realistic case of a plastic with molecular weight 20,000 and specific gravity 0.8, where the charge is trapped in a surface layer ~1 μm thick.

2-1.4. Importance of Trace Contaminants

The electrostatic behavior of intrinsically nonconductive substances, such as most pure thermoplastics and saturated hydrocarbons, is generally governed by chemical species regarded as “trace contaminants.” These are components that are not deliberately added and which may be present at less than detectable concentrations. Since charge separation occurs at interfaces, both the magnitude and polarity of charge transfer can be determined by contaminants that are surface active. This is particularly important for nonconductive liquids, where the electrostatic behavior can be governed by contaminants present at much less than 1 ppm (2-1.3).
An unpredictable charge density increase or polarity reversal caused by a “pro-static agent” (5-3.1.2) may lead to static ignition after years of uneventful operation under ostensibly identical conditions. For example, a change from positive to negative charging of a liquid may lead to formation of an incendive “positive brush” discharge (2-6.2). Such situations may be exacerbated by a coincidental decrease of ignition energy. An example is a temperature change that affects both charging of the condensed phase and flammability of the surrounding space. Many surface active trace contaminants increase the magnitude of charging in liquids. However, at higher concentrations they can have a beneficial effect by increasing the liquid conductivity to the extent that significant charge no longer accumulates in grounded containers. Special formulations are known as “antistatic additives” (5-2.6).

Trace contaminants are also significant at charged solid surfaces, affecting both the charging process and the surface conductivity. In ambient air atmospheres their effect is often determined by interaction with adsorbed water vapor, whose dominant concentration may be sufficiently large to form a monolayer. Topical antistatic agents for solids typically rely on interaction with adsorbed water and can lose effectiveness at low relative humidity (4-2.1).

2-1.5. Hazard Evaluation

The ignition hazard analysis in 2-5 begins with evaluating whether static electricity can accumulate, with the assumption that flammability has already been addressed. However, as reflected in Chapters 3, 5, and 6, a practical safety analysis should begin by evaluating whether a flammable mixture may be present, since this determines whether or not any ignition hazard exists in the first place. The usefulness of a hazard evaluation is determined largely by the evaluation of flammability, since this governs the ignition hazard with respect to any ignition source. Order-of-magnitude estimates may in some cases be sufficient to rule out ignition via static discharges. Conversely, if a large risk exists, or in the aftermath of an explosion, order-of-magnitude estimates may be inadequate. In such situations the coverage given in this book should be especially helpful.

2-1.6. Statistics

Static ignition statistics must be used with prudence not only because of possible misdiagnosis of the cause of ignition but also because of the way the losses are often grouped together. As discussed in Chapters 5 and 6 the likeli-
hood of ignition is related most strongly to the ignition energy of the flammable atmosphere involved. In road tanker operations, although switch loading is sometimes considered separately, accident statistics usually fail to identify fires involving pure liquids which can represent the most hazardous case (5-1.4.1). The sheer bulk of some operations having a small likelihood of ignition, such as gasoline trucking, can lead to misinterpretation of incident rate by incorporating and hiding those products with a much greater likelihood of ignition, such as toluene. Other grouping errors may involve the use of antistatic additives in certain products (5-2.6). Powder ignition is similarly much more likely for certain products, especially where a substantial mass fraction comprises fine powder or the process by its nature tends to accumulate easily ignitable dust. The methods outlined in this book should help identify those products and operations most at risk.

2.2. Charge Generation

The principal mechanisms are

a. contact and separation of solids (including frictional charging or tribocharging),

b. fragmentation of solids having nonuniform surface charge densities,

c. shear at liquid–solid, liquid–gas and two-phase liquid interfaces,

d. gravitational separation of suspended material having nonuniform size and charge,

e. induction charging, and

f. ionic charging.

Mechanisms (a) through (d) are process-specific as discussed in Chapters 5 and 6. The latter mechanisms require the presence of large electric fields and represent processes whereby charge can be transferred between systems that are electrically isolated from each other. Charge generation may be a discrete process, in which case it is associated with a transferred charge (Coulombs) resulting in a net charge density (Coulombs per unit area, volume or mass), or can continue indefinitely, in which case the rate of production of charge (Coulombs/second) is equivalent to a charging current (Amperes). An example of a discrete charging process is the electrophorus induction charging apparatus (see “Glossary”) while examples of continuous charging processes include flow of liquid or powder through pipelines.
2-2.1. **Induction Charging**

This is the process of momentarily grounding a conductor which has been polarized by an electric field, then removing the conductor from the electric field so that it gains a net charge. Polarization is the movement of charges to new locations by the action of an electric field acting on an ungrounded conductor, or the movement of an ungrounded conductor into an existing electric field. The electric field causes electron redistribution in the conductor and the performance of work, which raises its potential. An important feature of induction charging is that an ungrounded conductive object in an electric field can achieve a high potential and become a spark hazard without any contact or charge exchange with other objects. Once a spark occurs, the conductor gains a net charge and has become “inductively charged.”

2-2.1.1. **Production of Two Sparks via Induction**

Consider an ungrounded conductive object whose potential has been raised by an external electric field to the extent that it sparks to a neighboring grounded object. When this process occurs the potential of the ungrounded conductor is reduced approximately to ground potential by the spark, which can be considered as a conductive channel. When the spark occurs, a net charge flows to ground so as to minimize the potential energy of the ungrounded conductor in the electric field. Should the electric field be removed, the net charge now existing on the ungrounded conductor results in an elevated potential relative to ground and a second spark may occur to a grounded object.

2-2.1.2. **Practical Examples**

1. An uncharged person wearing nonconductive shoes is influenced by the electric field from a plastic tote bin containing charged resin. Since human bodies are conductive, charges move in the electric field leading to polarization and an increase in body potential even though no charge is transferred. If the person touches the grounded metal frame of the tote bin, a spark (static shock) occurs owing to the potential difference between the person and ground. The spark causes a net transfer of charge to the person, who may carry this net “induced charge” out of the influence of the electric field and suffer a second shock when again touching grounded metal, since once out of the influence of the electric field the charged body gains a potential difference with respect to ground.
Conductive liquid is transferred into a nonconductive plastic container whose external walls have been externally charged by rubbing. The electric field due to the charged plastic walls polarizes the liquid and raises its potential. The charged liquid surface may now spark to a grounded metal object inserted into the container, such as a metal dip tube. After the charge is lost from the external plastic walls the net “induced charge” now existing on the liquid may produce a second spark as the liquid is poured out. If the conductive liquid is flammable, such as a lower alcohol or ketone, ignition might occur due to either of the two sparks.

### 2-2. Ionic Charging

This includes any of a number of processes whereby charge is transferred via corona discharge. Contact ion transfer between solids is discussed separately in 6-2. Examples of deliberate ionic charging include the electrostatic precipitator, charge neutralizers such as ionizing blowers, and electrostatic crop and paint sprayers. Hazards may be produced where ungrounded conductors are charged by ionization in strong electric fields. This often involves corona discharge to conductive edges and other surfaces having a small radius of curvature.

### 2-3. Charge Dissipation

This is the process by which excess charge is neutralized. It occurs principally via conduction through bulk materials, determined by volume resistivity, and over their surfaces, determined by surface resistivity. However, where charging currents and resistivities are very high, such as during silo filling with nonconductive powder, an additional important charge dissipation mechanism is the electrostatic discharge. Charge loss via conduction can be evaluated using the concept of relaxation time \( \tau \) which is a time constant depending on the volume resistivity \( \rho \) and dielectric constant \( \varepsilon_r \) according to

\[
\tau = \varepsilon_r \varepsilon_0 \rho 
\]  

where \( \varepsilon_0 = \) permittivity of vacuum \( (8.854 \times 10^{-12} \text{ F/m}) \)

Since conductivity \( \kappa \) is the reciprocal of resistivity \( \rho \), this equation can alternatively be written

\[
\tau = \varepsilon_r \varepsilon_0 / \kappa
\]
Knowing \( \varepsilon_r \) and \( \rho \) (or \( \kappa \)), the relaxation time \( (\tau) \) can be estimated. The determination of relaxation time allows the rate of charge dissipation to be calculated for any process obeying Ohm’s law.

Consider the leaky parallel plate capacitor shown in Figure A-4-1.3. If the capacitor is momentarily charged and allowed to discharge through resistor \( R_L \) so that the charging current \( I_C = 0 \), the leakage current \( I_L \)

\[
I_L = -\frac{dQ}{dt} = \frac{V}{R_L} \quad (2-3.3)
\]

By definition, the resistivity and conductivity of a conductor of length \( d \) and cross-sectional area \( A \)

\[
R_L = \frac{\rho d}{A} = \frac{d}{\kappa A} \quad (2-3.4)
\]

From C-1.1 the equation for capacitance of a parallel plate capacitor (plate area \( A \), separation \( d \)) is

\[
C = \frac{Q}{V} = \frac{A \varepsilon_r \varepsilon_0}{d}
\]

or

\[
\frac{A}{d} = \frac{Q}{\varepsilon_r \varepsilon_0 V} \quad (2-3.5)
\]

From (2-3.3) through (2-3.5)

\[
\frac{dQ}{dt} = -\frac{Q}{\tau} \quad (2-3.6)
\]

where

\[
\tau = \frac{\varepsilon_r \varepsilon_0}{\kappa}
\]

Integrating (2-3.6)

\[
Q_t = Q_0 \exp(-t/\tau) \quad (2-3.7)
\]

Ohmic charge decay processes obey a first order rate law from which the charge \( Q_t \) remaining at any time \( t \) can be expressed in terms of the initial charge \( Q_0 \) and relaxation time constant \( \tau \). Using Eqs. (2-3.4) through (2-3.5) the time constant \( \tau \) can alternatively be expressed as

\[
\tau = R_L C \quad (2-3.8)
\]

From Eq. (2-3.6) the rate of charge loss to ground is proportional only to the quantity of charge remaining and is independent of the shape of the grounded boundary. The form of the rate law is the same as that governing radioactive decay. Just as plutonium’s decay rate is independent of the surrounding geometry, charge cannot be made to decay faster by packing a relaxation tank with conductive steel mesh (5-3.5). By measuring the time taken for charge to decay to \( e^{-1} \) (36.79%) of its initial value, \( \tau \) (hence \( \rho \) or \( \kappa \))
can be found using Eqs. (2-3.2) and (2-3.7). Alternatively, the “half-value”
time \( t_{0.5} \) taken for charge to fall to one-half its initial value is related to \( \tau \) by
the equation \( \tau = t_{0.5} / \ln 2 \). Half-value time is distinguished from radioactive
half-life since, unlike the latter, it can readily be modified (4-2).

Equations (2-3.7) for \( Q_t \) and Eqs. (2-3.1), (2-3.2), and (2-3.8) for \( \tau \) are used
extensively in static hazard analysis. Examples include selection and use of
instrumentation (3-5.3) and residence time provisions for charged liquids
(5-2.4).

2-3.1. Variability of Conductivity

When a voltage is applied to a dielectric (insulator), a current passes that
decays with time owing to various polarization mechanisms [133]. Conductivity is always time-dependent. This general time dependency affects con-
ductivity measurement for nonconductive liquids, where the peak initial
current is used to calculate conductivity. Test methods are given in 3-5.5 and
3-5.6. Nonohmic behavior is pronounced for nonconductive liquids in plastic
tanks, whose dielectric walls further complicate the charge decay rate [206].

The conductivity of solid dielectrics is roughly independent of tempera-
ture below about 20°C but increases according to an Arrhenius function at
higher temperatures as processes with different activation energies domi-
nate [133]. In the case of liquids, the conductivity continues to fall at temper-
atures less than 20°C and at low ambient temperatures the conductivity is
only a fraction of the value measured in the laboratory (3-5.5). The conduc-
tivity of liquids can decrease by orders of magnitude if they solidify (5-2.5.5).

The surface conductivity of solids is dependent on surface conditioning,
varying with the state of oxidation, ambient humidity and contamination.
The volume conductivity may depend on small concentrations of impurities
or additives. This effect is especially pronounced for nonconductive liquids,
where orders of magnitude increases in conductivity can be observed for
part-per-million concentrations of some antistatic additives (5-2.6). Non-
conductive liquids such as aliphatic hydrocarbons are intrinsically nonionic
and the measured conductivity is due to minor components that act as
charge carriers. Fuels such as gasoline and kerosene consist of mixtures of
up to about 200 different “bulk components” comprising aliphatic, naph-
thenic, aromatic, and unsaturated hydrocarbons whose composition is
nonspecified except in terms of fuel performance, which may include up to
about 11 parametric tests for gasoline and 26 in the case of aviation fuels
[147]. A change in specification, such as a low sulfur requirement, is likely to
lower a variety of other components that act as charge carriers, resulting in a
reduction in conductivity. However, the use of conductive bulk components, such as ethanol in gasohol, might not increase the conductivity to the extent expected owing to compensating factors in the new formulation. Depending on use, fuels may contain a variety of additives (lubricity, antioxidant, anti-knock, corrosion inhibitor, detergent, biocide, defoamer, dye, etc.), any of which can impact conductivity. Following formulation, the conductivity is impacted by handling which may introduce water and other “heavies” from tank bottoms, or might involve preferential removal of certain components in clay filters, filter coalescers or water layers.

2-4. Charge Accumulation

This occurs whenever the rate of charge generation exceeds that of charge dissipation. One of two results may occur for a leaky capacitor system with constant charging current: either a steady state is attained in which the rate of current dissipation balances the charging current, or a static discharge occurs before such a condition can be reached (Figure A-4-1.3). In practice, charging currents may be nonconstant and the system considered may be significantly changed during the charging process. Examples include tank filling with liquid and powder loading to a hopper, in which the effect of rising level inside the container must be included in any analysis.

The hazard of charge accumulation usually increases with increased container volume. This follows from the relations given in C-1.4. For example, if a tall, cylindrical container is filled with uniformly charged, non-conductive powder, the maximum electric field appears at the wall and is proportional to the radius of the container while the maximum potential appears on the axis and is proportional to the square of the radius. It follows that for any assumed powder charge density, the electric field eventually exceeds the breakdown field of air as container radius increases. In cases where charge dissipation occurs at a significant rate, such as liquid tank filling operations, it becomes impractical to fill very large tanks fast enough to offset the rate of charge dissipation (5-4.1). Therefore, hazardous charge accumulation is typically not seen in very large storage tanks but instead the hazard maximizes at an intermediate tank size, depending primarily on flow rate, inlet pipe diameter and liquid conductivity.

Owing to the competitive processes of charge generation and dissipation, the rate at which a container is filled is an important factor whenever significant current leakage can occur. Effects can be additive. For example, during drum filling with a nonconductive liquid, higher charge densities
result from higher velocities and rates of shear at the pipe wall (5-3.1.1) while there is less time for charge inside the drum to dissipate to the walls. If the drum is poorly grounded the high flow rate and charging current are likely to result in hazardous charge accumulation on the drum. If charging currents are very high the limiting charge dissipation rate becomes due to conduction through the liquid itself, and static discharges may occur inside a properly grounded drum (5-8.1).

2-5. Ignition

In order for static electricity to be a source of ignition, four conditions must be fulfilled

- The rate of charge generation must exceed the rate of dissipation, so charge can accumulate.
- A static discharge must coincide in time and space with a flammable atmosphere.
- The effective energy of the static discharge must exceed the ignition energy of the local mixture.
- A locally ignited flame must propagate into a surrounding flammable atmosphere.

Although charge accumulation and static discharges are commonplace in some systems, such as pneumatic silo filling with powders, ignition may be prevented or delayed for many years by failure to meet all four conditions. For example, a nonuniform dust cloud’s ignition energy varies by orders of magnitude with time and position, while a large range of effective energies may be manifested by static discharges, also varying with time and position. For flame propagation to result, these two random events must coincide in time and place such that a local ignition occurs, then the small flame kernel so formed must propagate into a surrounding flammable mixture without being quenched. Ignition is discussed further in Sections 3-5.4, 5-1.4, 6-1.2, and 6-5.

2-5.1. Effective Energy

Also known as “equivalent energy,” this is the spark ignition energy of the least easily ignitable mixture that can be ignited by a particular ignition source, such as a brush discharge under defined geometrical conditions.

The maximum effective energy is the largest effective energy exhibited by a particular category of ignition source, such as the entire category of
brush discharges. Figure 2-5 illustrates the maximum effective energies of various ignition sources including types of static discharge [10,157]. For example, bulking brush discharges are believed responsible for ignition of dusts having spark ignition energies less than that of Lycopodium (<20 mJ). Optimum hydrogen–air mixtures can be ignited by all types of static discharge, whereas coarse dusts (ignition energy >100 mJ) in air can be ignited only by relatively energetic sparks and propagating brush discharges. The important concept here is that static discharges such as the brush and bulking brush dissipate energy over a large volume, whereas minimal ignition corresponding to the minimum spark ignition energy takes place in a very small volume having a typical diameter of 2 mm for gases such as propane and 2–3 times this for fine dusts in air. Even optimized sparks are not 100% efficient since they lose heat to the electrodes and energy in the form of shock waves, and measured MIE values are larger than theoretical values [142].

FIGURE 2-5. Ignition energies (mJ) of various materials and types of ignition source that may ignite them.
A static discharge that is much larger in extent than the minimal ignition diameter dissipates much of its energy wastefully, and only the energy released within a local “hotspot” within the discharge contributes to ignition. Such hotspots have been observed to occur close to the metal electrode for both brush and bulking brush discharges [8,12]. The total energy dissipated in these discharges is irrelevant, although there is an apparent correlation of effective energy with the total charge transferred. This is to be expected from the $W = \frac{QV}{2}$ proportionality between energy $W$ and charge $Q$ (C-1.2).

If ignition is assumed to occur in a hotspot formed at the electrode, the local release of potential energy $W = \frac{QV}{2}$ is directly proportional to charge while independent of electric field except in the immediate vicinity of the electrode, since this determines the local change in potential. The electric field near the electrode becomes increasingly uniform as electrode radius increases and eventually, uniform field breakdown conditions are approached (C-2.5.3). These concepts allow first approximations for effective energy to be made. First it is assumed that air breakdown occurs at 30 kV/cm and that the electric field is approximately uniform between about 2–5 mm from the electrode (C-2.5.2). Second, it is assumed that minimal ignition occurs in a 3 mm diameter hotspot formed sufficiently far from the electrode to minimize heat losses. This distance is assumed to be about 2 mm.

A typical value of charge transferred in a positive brush discharge at a large electrode is 0.2 $\mu$C (2-6.2). The loss in $\frac{QV}{2}$ potential energy as this charge falls through the 3 mm distance is 0.9 mJ. The maximum energy might achieve about 10 mJ assuming a charge transfer of $\leq 1$ $\mu$C, a hotspot diameter $\leq 10$ mm and an average field of about 20 kV/cm. These rough estimates correctly predict the spark ignition energies of gas mixtures that have been ignited by positive brush discharges (2-6.2.1).

Similarly, a typical value of charge transferred in a bulking brush discharge is 10 $\mu$C (2-6.3) and the loss in $\frac{QV}{2}$ potential energy is 45 mJ. The maximum energy is 112–225 mJ for charge transfers in the range 25–50 $\mu$C. These estimates are significantly greater than the accepted maximum effective energy of about 20 mJ relative to dust ignition (2-6.3). The disparity can be explained if bulking brushes are less effective in igniting dust clouds than gas mixtures of equal spark ignition energy. Many dusts have MIEs much less than the 5–10 mJ maximum effective energy of positive brush discharges established by gas ignition tests. However, attempts to ignite sensitive dust clouds by positive brush discharges have failed (2-6.2.1). Relative to gas mixtures having the same spark ignition energies, it appears that the efficiency...
of dust cloud ignition by nonspark discharges is only about 10%. It is therefore possible that the maximum effective energy of the bulking brush would be closer to the estimated values if it were based on gas ignition rather than dust ignition. This implies that flammable gas in a large container should be at risk of ignition over most of its flammable range. This is consistent with the high frequency of ignition when unpurged resins are conveyed into silos containing air (6-5).

Since effective energy is an equivalent spark ignition energy, an important consideration is the maximum power density that a nonspark discharge can exert. Qualitatively, a high power density corresponds to the channeling of energy into a short-duration (50–500 ns) spark-like hotspot while a low power density corresponds to a long duration (10–250 μs) spatially diffuse discharge. These tendencies vary according to the type and polarity of the discharge. Hotspot formation close to an electrode should be encouraged by local field intensification (C-2.5.3). For nonspark discharges, local field intensification is greatest in the case of brush discharge to a small diameter electrode and smallest in the case of bulking brush discharge to a silo wall.

Even if all variables are maintained as constant as possible, nonspark discharges exhibit a distribution of maximum power densities and this introduces a probabilistic factor. The maximum effective energy attributed to any nonspark discharge category is based on a large number of repetitive ignition tests under conditions regarded as extreme. For example, in the case of the positive brush, a large area of charged surface and large diameter electrode are used. Since this might represent the top few percentiles of possible effective energies it provides a large margin of safety when applied to less severe conditions or where the discharge is a relatively isolated event.

2-6. Static Discharges

Spark, corona and brush discharge phenomena are described in detail in [137,138]. A more recent introduction is given in [139]. The inception voltage and characteristics of static discharges generally depend on the gas composition and pressure/temperature conditions. If the discharge gap is asymmetrical, the characteristics of the discharge also depend on electrode polarity. Two gas composition variables affecting electrical breakdown are ionization potential and electron affinity. For breakdown in ambient air, approximate breakdown conditions are that the average electric field in the discharge gap should exceed about 5 kV/cm and at some point the uniform breakdown field of air, about 30 kV/cm (2-6.4.1), must also be exceeded.
Discharges may be initiated by a sudden change in gas composition in an electrically stressed region. Conversely they are usually suppressed by increased gas density above atmospheric pressure (2-6.4). The effects of environmental variables on static discharge initiation are not well understood, particularly in the case of large-scale phenomena such as the bulking brush discharge, where effects due to charged powder suspensions above the bed are an added complication.

Several disparate categories of static discharge can be identified for the purposes of describing ignition and shock hazards. The most familiar (spark discharge) has an almost unlimited effective energy range. In roughly ascending order the maximum effective energies of the others are

1. Corona (positive) \( \approx 0.1 \) mJ
2. Brush (negative) \( \approx 1.0 \) mJ
3. Brush (positive) \( \approx 10 \) mJ
4. Transitional Brush (author’s term for energetic non-PBD discharge from nonconductive layer) \( \approx 10–100 \) mJ
5. Bulking Brush (also known as “cone discharge”) \( \approx 20 \) mJ
6. Propagating Brush Discharge (PBD) \( \approx 100–1000 \) mJ

The maximum effective energies given for discharge types (1–3) are based on gas ignition tests. In the case of the bulking brush the 20 mJ value reflects the ability to ignite dust clouds in air and is based on industrial loss experience. Gas mixtures of greater spark MIE might be ignited by bulking brushes as discussed in 2-5.1.1. The maximum effective energies of discharge types (4) and (6) vary widely with conditions as discussed later in this chapter. An additional type dubbed by the author a “surface streamer” (2-6.6) has frequently been mentioned in US literature under various other names but has not been subject to significant study. Another additional type is the “lightning-like” discharge which is a possibility where very large charged clouds are involved. Since lightning-like discharges have not been reported for any industrial situation they are discussed further only in the “Glossary”.

2.6.1. Corona Discharge

This term includes a number of glow discharge phenomena usually occurring in highly nonuniform electric fields, either in gaps or at high voltage conductors, below the spark breakdown value (Plate 1). Coronas are often produced in the divergent field between a charged surface, such as nonconductive oil, plastic sheet or powder, and a conductor having a radius of curvature less than about 3 mm. Typical arrangements are “point–plane”
and “rod–plane” geometries comprising needle or wire electrodes. The inception voltage for corona is reduced with reduced pressure and reduced radius of curvature of the electrode. Fine wires typically produce significant corona currents at about 1 kV in atmospheric air. While increased gas density usually increases the inception voltage of corona, Paschen’s law (2-6.4.1) is only obeyed if changes in gap length are accompanied by changes in all other gap dimensions. Two distinct types are negative and positive point–plane coronas, where the polarity is ascribed to the electrode rather than the plane surface. With negative point the corona flows in regular “Trichel” pulses whose frequency increases with current. With positive point the current increases steadily with voltage up to about 0.1 μA after which avalanches of electrons give rise to ~1 kHz “burst corona.” Pre-breakdown streamers accompanying the bursts at higher voltages may become observable as filamentary discharges more typical of brush discharges. The inception voltage for both types of corona varies with the gas composition.

Corona is usually a safe means of dissipating charge. Only very sensitive flammable mixtures such as hydrogen–air, carbon disulfide–air or fuels in oxygen enriched atmospheres (see 5-9.6) are at risk of ignition. Common fuel vapors in air can be ignited only if corona discharges have an average current in excess of 200 μA (5-9.6). This exceeds the charging currents possi-
ble in most systems. Exceptions include atmospheric electricity and some electrostatic process operations. Ignition currents for ignition sensitive gases such as acetylene in air have not been determined but might be less than 100 μA.

2.6.1.1. Positive Coronas from Active DC Neutralizers

The approach of a conductor to an active neutralizer using positive DC corona (i.e., positive needle electrode) can cause “pulsive” discharges whose peak currents attain several amperes (4-2.2.1). These have been shown to ignite stoichiometric (6.5%) ethylene in air. The discharges could be controlled by increasing the resistive coupling of the needle above 10 MΩ at 5 kV and 50 MΩ at 17 kV [39]. The phenomenon is only relevant to situations where a high voltage power supply is used.

2.6.2. Brush Discharge

Brush discharges are formed in the divergent field between a charged surface and a conductor having a radius of curvature more than about 3 mm and are a special case of point–plane coronas, requiring greater initiation voltages owing to the larger electrode radius and breakdown field. Under atmospheric conditions, brush discharges are observed at point–plane potential differences above 20–25 kV [8].

“Negative brush” discharges from positively charged surfaces appear as discrete bursts whose frequency increases with increased charging current flowing to the system. An example is liquid in a tank charged by a positive streaming current from a pipeline. Photographs show that the light-emitting region is found close to the electrode and is relatively featureless, lacking the
streamers typical of positive brushes \[8,71,227\]. The maximum effective energy is less than 1 mJ \[8,58\]. The only available report of gas ignition required an unusually large (89 mm diameter) spherical electrode \[35\]. If the surface is instead charged negatively, “positive brush” discharges are produced. For identical geometry and charging current these occur about an order of magnitude less frequently than negative brushes while the charge transfer is about an order of magnitude greater. Typical charge transfers are 0.05–0.2 \( \mu \text{C} \) and maximum charge transfers are less than 1 \( \mu \text{C} \). The discharges appear as a “brush” composed of streamers which converge into a single radiant channel close to the electrode (Plate 2). This channel has the highest power density within the discharge and it is here that ignition takes place \[8\]. Brush discharge energy increases with increased electrode diameter since the surface charge density must be greater before breakdown occurs at the electrode. Smaller electrodes are more likely to produce brush discharges but the charge transfer and effective energy are less (C-2.5.3). In work reviewed by Cross \[110\] the maximum charge transfer \( Q \) was found to increase with electrode diameter \( d \) according to \( Q \propto d^{1.7} \). As discussed in 2-5.1.1 the effective energy of a positive brush should be roughly proportional to \( Q \). Figure 2-6.2.1 lends some support to a power law dependence of effective energy on electrode diameter, but the curve intersections on the fuel lean side of Figure 2-6.2.1 are highly sensitive to concentration errors. Experimental errors were no doubt compounded by compiling the figure from two disparate sets of data. The result for the 15-mm electrode is least prone to error since the 0.6 mJ effective energy intercept corresponds to a less steep part of the spark MIE curve. If effective energy increases with \( d^{1.7} \), predicted results are 1.4 mJ for the 25-mm and 6.3 mJ for the 60-mm electrodes, compared with 4 mJ and 8–9 mJ observed.

2-6.2.1. Effective Energy of Brush Discharge

This section addresses positive brushes from negatively charged, nonconductive surfaces. It does not apply to discharges from plastic surfaces having a grounded metal substrate, which are discussed in Section 2-6.2.2. Ignitions of aliphatic hydrocarbons in air have been reported for charge transfers above 0.08 \( \mu \text{C} \). The tests used spherical discharge electrodes with diameters above about 7 mm \[8,26\]. Owing to charge conduction through the conductive flame plasma, charge transfers were deduced from previous discharges under identical conditions that did not lead to ignition. Mixtures of hexane in air were ignited by brush discharges from spherical electrodes of different diameters (15, 18, 20, 25, 35, and 60 mm) suspended above charged plastic sheet with no metal substrate \[36\]. The relative frequency of ignition was determined for each electrode with respect to hexane concentration. The
range of concentrations susceptible to ignition was determined by extrapolating the ignition frequency to zero. It was found that the range of concentrations that could be ignited widened with increased electrode diameter. For the 15-mm electrode, hexane was ignitable between 2.4 and 3.9% in air. The ignitable range increased to 1.6–4.4% with the 25-mm electrode and 1.4–5.2% with the 60-mm electrode.

The partial results are shown in Figure 2-6.2.1. The ranges of ignitable concentrations are superimposed on a spark ignition energy curve for hexane in air calculated from data in [56]. Both data sets are assumed to be characteristic of \( n \)-hexane, unbiased by the presence of methylcyclopentane or hexane isomers (dimethylbutanes and methylpentanes).

Figure 2-6.2.1 shows two interesting phenomena that have not previously been recognized. First, for a given electrode the effective energy is much greater at the lean end of the ignitable concentration range than at the rich end. Second, the concentration most susceptible to ignition by brush discharges is lean compared with the lowest minimum ignition energy (LMIE) composition most easily ignited by spark. The spark LMIE concentration of hexane is 3.8% in air (Appendix B). However, 3.8% hexane is close to where the ignition frequency for the 15-mm electrode falls to zero. The composition most frequently ignited by positive brushes was 3.2% hexane in air. No ignitions were observed above 5.2% which is considerably below the upper flammable limit (UFL) of 7.5%. Conversely, ignitions using large electrodes were
observed down to about 1.4% which is not far above the lower flammable limit (LFL) of 1.1%.

Consider a tank being filled with a liquid such as gasoline whose equilibrium vapor concentration exceeds the UFL. Close to the liquid surface where small brush discharges occur, the UFL will be approached or exceeded even during the early stages of filling. Ignition via small brush discharges is only probable if the vapor concentration near the surface is much less than the UFL. Hence, gasoline vapor ignition via brush discharge is improbable even if most of the vapor space is inside the flammable range. Consider now a single-component liquid such as toluene. The vapor concentration near the surface is typically close to optimum throughout tank filling and never approaches the UFL. Hence toluene vapor ignition via brush discharge is a far more probable event (5-1.4.1).

Propane–air–nitrogen ignition tests were conducted using a 70-mm-diameter spherical electrode suspended above a negatively charged plastic sheet [57]. Since gas mixtures with ignition energies up to 3.6 mJ were ignited at an ignition frequency of 40%, positive brush discharges were attributed a maximum effective energy of about 4 mJ. This work has been widely cited without reference to ignition frequency.

Figure 2-6.2.1 shows that electrodes of diameter ≤15 mm produce brush discharges with effective energies less than 1 mJ. This is partly offset by the greater likelihood of producing brush discharges with smaller diameter electrodes. As discussed in C-2.5.3 the surface charge density for breakdown in fixed geometry decreases with decreased electrode diameter and gap, so it is to be expected that smaller diameter electrodes produce discharges with smaller effective energies. Effective energies above 1 mJ are only observed for electrodes having a diameter above 15–20 mm. At small ignition frequency, the effective energy observed in lean mixtures using large electrodes exceeds 4 mJ and attains roughly 8–9 mJ at electrode diameters of 60–70 mm.

Ignition of fine sulfur dust was demonstrated by collecting the charge from brush discharges and discharging it to ground through the spark gap in a Hartmann tube [34]. Ignitions were obtained for charge transfers above about 0.25 μC, implying that brush discharges might ignite dusts in air. However, the test technique was unrealistic. By channeling the energy through a small spark gap, the power density of the original brush discharge was radically increased in the same way a focusing lens increases the power density of a light beam. No conclusion can be drawn from these tests regarding whether a thermally stable dust can be ignited in air by a brush discharge. All other dust ignition experiments have given negative results [10,12].
Brush discharges from isolated nonconductors have not been shown to ignite combustible dusts in air. Ignition of some fine dust suspensions may be possible in the presence of flammable gas below the gas LFL (6-1.3). Thus, hybrid mixtures containing flammable gas at a concentration below the LFL may be at risk. This may include powders that contain sorbed solvents above 0.2–0.5 wt% or which slowly decompose or react in storage evolving flammable gas, such as propanol evolution from aluminum propoxide in moist air (6-1.3.2). If the nonconductor has a grounded substrate, such as plastic-coated metal, more energetic discharges can be produced that might ignite dusts in air. In this book, these are described as having a continuum of effective energies beginning with the brush, then the transitional brush, and finally the propagating brush (PBD).

2.6.2.2. Effect of Grounded Substrate
The effective energy of a brush discharge varies with the charge transferred to the electrode (2-5.1.1) which in turn depends on the area and charge density of the nonconductive surface when the discharge occurs. For isolated nonconductors the charge density is limited by air breakdown as discussed in 6-2.1.1. However, if the charged nonconductor is in direct contact with a conductive surface, much larger charge densities can be accumulated. This is because the electric field is primarily exerted through the nonconductor to the countercharge produced in the conductor. In other words a capacitor is formed. A common example is a metal surface coated with plastic. Charge can accumulate on the exposed plastic surface until electrical breakdown occurs spontaneously through the plastic layer to ground. Where breakdown of the layer occurs a propagating brush discharge (PBD) might be produced (2-6.5).

If the surface charge density is insufficient for a spontaneous PBD to occur, the event can be initiated by the approach of a grounded metal electrode to the surface. Tests were conducted with plastic layers from 0.15 to 8.0 mm charged by corona at source voltages from 2.5 to 75 kV [37]. Using a 20-mm spherical electrode, PBDs were obtained at surface charge densities ≥250 μC/m², becoming fully developed at 800 μC/m² (2-6.2.3). Brush discharges were obtained at all smaller charge densities provided the charging voltage was at least 5 kV.

Rubbing the plastic with felt cloth produced 1–30 μC/m², the largest charge densities being obtained with the thinnest layers. This is only about one tenth the surface charge density required for a PBD. Charge accumulation was limited by corona discharge in the gap between the charged layer
and the oppositely charged cloth. Brush discharges from negatively charged layers less than 2 mm thick could not ignite hexane in air while layers less than 0.2 mm thick could not ignite hydrogen in air [37]. The former observation has yielded the rule of thumb that layers less than 2 mm thick, charged by simple rubbing, will not produce discharges capable of igniting common solvent vapors in air. The criterion should be conservative if applied to positively charged layers. However the criterion does not apply to surfaces which are intermittently charged by ions or by particle impact, since charge accumulation via these processes is not limited by the close proximity of a countercharged cloth. Instead, large surface charge densities can accumulate over an extended period, possibly resulting in PBDs.

2-6.2.3. Transitional Brush Discharges

The literature commonly states that PBDs have an effective energy of the order 1000 mJ and brush discharges have effective energies less than 4 mJ. No intermediate cases are described. Industrial experience does not support such a quantum change in effective energy. If all PBDs had effective energies of the order 1000 mJ, ignition should be commonplace under all conditions that PBDs occur. Although previously unrecognized, the concept of a more gradual transition is supported by several published studies. As layer thickness and breakdown voltage are increased, a transition region should first be reached within which PBDs (2-6.5) are not fully developed and cannot readily be distinguished from brush discharges. The author has coined the term “transitional brush” to describe discharges in this proposed transition region, which can be thought of as a discharge with effective energy between that of the brush (<10 mJ) and the fully developed PBD (>100 mJ).

Full PBD development has been described in terms of the appearance of luminous, branched channels over the entire charged surface as the initial surface charge density increases from 250–800 \( \mu \text{C/m}^2 \) [37]. This increase in surface charge density produces a corresponding increase in potential difference across the charged layer prior to electrical breakdown. Increased charge collection by the highly branched surface discharge results in a corresponding increase of charge transfer. Fully developed PBDs typically transfer 100–500 \( \mu \text{C} \) of charge [29,160] although this depends both on the area of the charged surface and the extent of lateral discharge (2-6.5.3).

Tests were conducted using an approximately 30-cm-diameter, 80-\( \mu \text{m} \)-thick polycarbonate film with brass backing plate. A 50-mm-diameter spherical discharge electrode was used to initiate discharge of the charged film.
Adapted test results are shown schematically in Figure 2-6.2.3. No discharges were observed where the potential difference across the film was less than 4 kV, consistent with the earlier finding that brush discharges started to be produced at a corona charging voltage of 5 kV (2-6.2.2). Between 4 and 8 kV across the film, charge transfers were less than 1 \( \mu \)C which is consistent with large brush discharges rather than PBDs. Between 8–12 kV the charge transfer increased rapidly to 100 \( \mu \)C while at greater voltages the charge transfer increased at a smaller rate. This suggests that in the 8–12 kV “transition region” there was a sudden increase in charge collection efficiency from the 80-\( \mu \)m film as surface flashover conditions typical of PBDs were developed. The threshold for a PBD might be tentatively defined by a charge transfer of at least 10 \( \mu \)C. This threshold occurred at a voltage of 10 kV across the 80-\( \mu \)m polycarbonate film. The significance of these results is discussed further in 2-6.5.

When breakdown of the layer occurs a large voltage gradient is created over the surface to the puncture point, which becomes an effective ground, and this initiates lateral discharge to the puncture point. However, this does not explain why PBDs can propagate over much larger distances than can be achieved in air gaps at the same voltages. A proposed step-by-step mechanism is discussed in A-2-6.5. The charged double layer is conceptually modeled as a system of capacitors between and among (1) arbitrary charges on the surface and (2) their countercharges in the underlying metal. On a
microscopic scale the layer surface is neither flat nor uniformly charged, so capacitance may exist between discrete charged areas of the surface. These charged areas also have some capacitance with the general surroundings. As layer thickness is increased the capacitance through the charged layer decreases, causing the electric field component across the surface to increase. Figure A-2-6.5 draws an analogy with a variable system of capacitors through the layer and across the surface; such arrangements of capacitors create a very steep gradient at the stepped discharge wavefront which allows extensive propagation for relatively small source voltages [176]. Surface flashover, which is accompanied by efficient collection of surface charge, requires a minimum surface voltage gradient of the order 4 kV/cm [176]. Transitional PBDs might be sensitive to effects that influence the proposed step-by-step propagation process, especially for thicker layers. Examples include surface topography or curvature, uniformity of surface charge density and external geometry.

2-6.2.4. Breakdown Strength of Layers
Also known as dielectric strength, this is the voltage per unit thickness at which a solid layer breaks down electrically under uniform field conditions. For a given material it depends on test parameters such as sample thickness and temperature, plus the frequency and waveform of the testing voltage. Measured values are found not to be linear with respect to thickness and higher values are found for thinner layers. Comparisons between different materials should preferably be made on samples of equal thickness under identical test conditions. Some data developed for use in capacitor design are given in Appendix B. These data indicate that a “typical” breakdown strength for cast resins such as phenol-formaldehyde is 400 volts/mil (16 volts/µm or 16 kV/mm). For polyolefins such as polyethylene a “typical” value is 1000 volts/mil (39 volts/µm or 39 kV/mm). The highest listed values correspond to polyethylene terephthalate film, averaging 4500 volts/mil (177 volts/µm or 177 kV/mm), and chloro-fluoro polymer films. The average value for PTFE film was 1500 volts/mil (59 volts/µm or 59 kV/mm) and for PCTFE film 4000 volts/mil (157 volts/µm or 157 kV/mm). A common interpretation of Figure 2-6.5 and its description in [29] is that the breakdown strength of plastic films is relatively constant at 400 volts/µm and independent of layer material, grade or thickness. This breakdown strength is 10 times the value given for polyethylene in [183] and approximately equal to the breakdown strength of many plastics when expressed in volts/mil (Appendix B). The breakdown voltages shown in Figure 2-6.5 corresponded to very thin layers
less than 50 μm (2 mil). Since thinner layers of high integrity plastic typically have greater measured breakdown strengths, this could result in an overestimate of breakdown voltage where test results are applied to greater layer thicknesses. An overestimate of breakdown voltage leads to an overestimate of PBD hazards (2-6.5).

Breakdown strength is lowered by pores, pinholes, or other spaces such as between the fibers in fabrics and composites. The corresponding reduction of breakdown voltage can in many cases prevent the occurrence of PBDs (2-6.5). In any case, breakdown strength and breakdown voltage should be determined by test rather than estimated. For electrostatic applications, breakdown strength should be measured using direct current (DC) methods rather than the high frequency AC typically used. DC breakdown strengths may exceed the 'typical' values compiled in Appendix B.

2-6.2.5. Dust Ignition via Transitional Brushes
Transitional brush discharges have little significance in gas ignition since it can be assumed that ignition requirements are exceeded at the brush discharge stage. However, the situation is different for dusts since it is often assumed that PBDs have an effective energy of the order 1000 mJ and can therefore ignite almost any ignitable dust. PBD ignition tests of anthraquinone dust having a MIE of 2–10 mJ were carried out using a circular, 17.8-cm (7 in.) diameter, 150-μm-thick PVC layer. The surface charge density of ~5000 μC/m² corresponded to about 125 μC of stored charge [181]. It was found that some tests did not give ignitions and subsequent investigation showed that the PVC layer had failed to completely discharge during these tests. This suggests that poor dispersion of the dust was not entirely responsible for the lack of ignitions and that transitional brush discharges having a large range of effective energies were probably involved.

While all available evidence indicates that brush discharges from isolated nonconductors are incapable of igniting combustible dusts in air, Figure 2-6.2.3 shows that nonconductive layers represent a different case. Any dust whose MIE is exceeded by a PBD will also be susceptible to ignition by a transitional brush discharge occurring at some smaller layer voltage. If a fully developed PBD is not generated, the effective energy may be anywhere above the 5–10 mJ maximum for brush discharges from isolated nonconductors. As a consequence, only easily ignitable dusts might be at risk of ignition. Since this behavior is difficult to quantify it is appropriate in some cases to consider transitional brushes and PBDs as a single phenomenon as shown in Figure 2-6.5. In any case, it is necessary for large surface charge densities to be accumulated such as via an extended period of powder impact on the layer.
2-6.3. Bulking Brush Discharge

See 6-3.1.1 and 6-4.2. This is a large discharge resulting when a dispersed, charged powder “bulks” when settling in a container, causing a very large increase in its volumetric charge density. Infrequent surface flashes up to several feet long are observed in large containers being filled with powder having a resistivity above $10^{10}$ Ω·m, both during, and occasionally for a short time after, the transfer of powder. The discharges originate at the container wall and propagate across the bed surface. For axial powder feed the discharges appear between the edge of the powder cone and the surrounding walls (Plate 3) while for off-axis powder feed the discharges appear on the side opposite the powder cone [121]. An accompanying crackling sound has been heard from the top of a silo over the noise of the powder transfer. Transferred charge channeled to the wall may attain 25–50 μC [50,160] and are accompanied by large peak currents (6-4.1.1). Bulking brushes have an apparent maximum effective energy of 10–20 mJ (with respect to dust ignition) and are believed to be responsible for dust explosions in grounded silos. This is inferred from analyses of silo explosions where ungrounded objects and other ignition sources could be confidently eliminated. Hybrid mixtures (6-1.3) and dusts whose ignition energies are less than *Lycopodium* (see “Glossary”) should be considered at risk from these discharges.

![Multiple bulking brush discharges on powder bed (time exposure).](image)

*PLATE 3. Multiple bulking brush discharges on powder bed (time exposure). (From Bartknecht in "Industrial Dust Explosions," ASTM STP 958, p. 175)*
2-6.3.1. Effect of Particle Size
It was initially thought that these discharges only occur during bulking of coarse powders with diameter 1–10 mm, such as pellets [25]. Later work demonstrated that this is not the case although the phenomenon is more frequently observed with coarse powders (6-3.1.1 and 6-4.2.1).

2-6.3.2. Effect of Container Size
Tests using vertical cylindrical silos have shown that the charge transferred by these discharges increases with silo diameter [161]. The maximum observed charge transfer $Q$ varied with silo diameter $D$ according to

$$Q = 2.3D^{2.8} \mu C$$ (2-6.3.2)

A wide distribution of charge transfers was observed with the maximum values roughly twice the average values. From Eq. (2-6.3.2) the maximum predicted charge transfer is about 40 $\mu C$ in a 3-m-diameter silo and about 2 $\mu C$ in a 1-m-diameter bin. The effective energy of discharges having comparable power densities is roughly proportional to charge transfer (2-5.1.1). If the maximum effective energy with respect to dust cloud ignition is assumed to be about 20 mJ (2-6.3) it follows that in small containers less than 1 m diameter the effective energy should be only about 1 mJ. This implies that the ignition hazard in small containers should be similar to that of a brush discharge, hence dusts in air should not be at risk of ignition. This result is consistent with the lack of reported ignitions when loading FIBCs (6-7).

The minimum size of container for bulking brush discharges has not been established, but is probably about 1 m$^3$. Their occurrence in such small containers might require coarse particles such as pellets and therefore represent a hazard only where flammable gas or hybrid mixtures are present. Assuming that the effective energy of the discharges is at the low end of the proposed 1–20 mJ range, the only significant feature vis-à-vis brush discharges is that no field-intensifying electrode is required to initiate the discharge.

2-6.3.3. Occurrence Inside Powder Heap
Bulking brush discharges occur not just on the powder surface but also deep within powder heaps, as demonstrated by large-scale tests [161]. This is one reason the author prefers the term “bulking brush” over “cone discharge” as used in some European texts; the other reason is that the discharges tend not to occur on the powder cone itself (2-6.3). Bulking brush discharges within the powder heap are usually nonhazardous because powders cannot combust in bulk. However, some unstable powders may be at risk since propagating decomposition is facilitated in the bulk state; this potential
hazard with respect to bulking brush discharges has not previously been recognized (6-1.4).

2-6.3.4. Effective Energy Tests Employing Spark Ignition Chamber
Since the prevention of bulking brush discharges in large containers is typically impractical, it is extremely important to establish the proper magnitude of the effective energy. Some companies have been unduly alarmed by tests [161] suggesting that bulking brush discharges have effective energies up to 1000 mJ or more, implying that large silos containing ignitable dust suspensions may be accidents waiting to happen. The tests were made by channeling the charge collected from bulking brush discharges through a small spark gap in a Hartmann tube, a technique that has also been used to imply that brush discharges can ignite sensitive dusts [34]. As discussed in 2-5.1.1 and 2-6.2.1, this technique is unrealistic since it does not address the power densities of brush or bulking brush discharges. The tests demonstrated only that sparks transferring charge in the range 0.2–4.0 μC can ignite dusts having MIEs in the range 1 < MIE < 100 mJ under the specific test conditions used. The results appear to have been additionally biased by the assumption of the high MIE value using the “step method” (3-5.4.2), so that Lycopodium’s MIE of 30–100 mJ was interpreted as 100 mJ. Numerous other MIE evaluations give Lycopodium’s MIE as approximately 20 mJ.

2-6.3.5. Ignition Probability Considerations
Assuming that the effective energy of bulking brush discharges with respect to dust ignition is a continuum from about 1 mJ up to maybe 10–20 mJ, the infrequent occurrence of silo explosions even where easily ignitable dust is present suggests that most discharges have effective energies at the low end of this range (6–5). The probability of ignition is reduced by the need for an optimum mixture of fine dust in air to encounter the hottest part of the discharge. This occurs at the silo wall (2-5.1.1). After ignition takes place locally, the flame must propagate into the surrounding dust suspension without being quenched. It is additionally possible that the incendivity of these discharges depends on the polarity of the powder bed. Corona and brush discharges occur at a smaller frequency and carry greater effective energy when the charged nonconductor has negative polarity. Recent studies using pellets have concluded either that net polarity has a small effect on the occurrence of bulking brushes [50] or that net positive charging gives a greater frequency of bulking brushes [161]. The interpretation of polarity effects is complicated by the occurrence of bipolar charging. It is usually found that fine particles charge with opposite polarity to the coarse powder predominating in the powder heap. The net polarity is likely to be deter-
mined by the sign of charge carried by the predominant coarse particles. A net “positive” charge on a polydispersed powder stream does not rule out local accumulation of negative charge in the receiving container. To create a positive net charging current the positive charge need only be incrementally greater than the negative charge. As the predominant coarse powder settles, the suspended powder might contain a high net negative charge. Similarly, parts of the bed away from the cone might contain a high net negative charge. Tests in a 100-m³ silo showed that when a powder stream with net positive charge entered near the wall, bulking brushes formed exclusively at the opposite wall [121]. A possible interpretation is that as coarse powder rapidly bulked in the off center powder heap, positive charge was released in the form of corona and brush discharges. The high rate of ionization created by these discharges suppressed formation of bulking brush discharges on the heap. It is unclear whether the appearance of bulking brushes at the opposite wall was simply due to the absence of a local ionized layer or whether the settling of powder having opposite polarity played a role.

It might be irrelevant that bulking brushes apparently occur more frequently with positively charged powder. Since coarse powders such as pellets cannot be ignited, what matters is the occurrence of bulking brushes in the presence of fine particles. It was shown that addition of fine powder to a silo containing a positively charged polyethylene pellet bed suppressed bulking brushes because the fine particles charged negatively and neutralized the bed [160]. As discussed in 6-3.1.1, if fines tend to charge negatively, ignition via bulking brushes might require predominantly negative charging to avoid such neutralization. An unrelated polarity effect that could influence ignition probability is maintenance of a fines suspension. Negative fines might quickly be precipitated on a positively charged bed and hence removed from suspension. Since ignition must occur at the level of the bed surface, fines removal via precipitation should decrease ignition probability. Again this suggests that if the fines are charged negatively, ignition via bulking brushes might require predominantly negative charging. Bulking brushes are discussed further in 6-3.1.1 and 6-4.2.

2.6.4. Spark Discharge

This is a transient discrete electric discharge which takes place between two conductors which are at different potentials, bridging the gap in the form of a single ionization channel (Plate 4). Based on light emission measurements of sparks with symmetrical electrode geometry, the energy is dissipated approximately uniformly along the channel. This is in contrast with asym-
metric sparks which normally exhibit a hotspot close to the cathode [155]. Since sparks are used to determine ignition energies, the effective energy is normally assumed equal to the stored circuit energy, equal to one-half the product of circuit capacitance and sparking voltage squared (C-1.2).

In reality only a small fraction of the energy stored in a spark circuit contributes to ignition. In addition to energy losses caused by nonidealities in the electrical circuit, only part of the energy released in the spark gap is usefully transferred. Energy is lost in the form of shock waves, dissipated as heat at the electrodes, and (in the case of long sparks) may be released outside the thermalization volume in which ignition occurs. The principal variables are spark gap length, spark duration, and electrode geometry, all of which possess optimum values for igniting a given flammable mixture. Additional variables include turbulence and electrode material [42].

Owing to loss of heat and radicals to the surrounding solid surfaces, flame propagation cannot occur in gaps smaller than the “quenching distance,” which is a characteristic of the flammable mixture directly related to its MIE. For parallel plane geometry as described below, the relationship for hydrocarbons is given by $\text{MIE} = 0.06d^2$, where the quenching distance $d$ is given in millimeters and the MIE in milliJoules [224]. It is sometimes incorrectly stated in the literature that ignition cannot occur when spark electrodes are closer together than the quenching distance. However, this is only
true where the quenching distance is properly defined by parallel plane geometry, such as where both electrodes are fitted with flanges (glass etc.) around their tips. In this case, ignition does not occur until the gap is slightly greater than the quenching distance. This gap length best approximates to a point source and yields the lowest MIE values. As the gap is increased beyond the quenching distance the spark becomes better described as a line source, which is less effective in producing ignition [208]. At larger gap lengths the MIE therefore increases from its lowest value. In the absence of parallel plane geometry the concept of quenching distance does not directly apply. If either electrode is unflanged and approximates to a point, ignition can occur in gaps much smaller than the quenching distance. Although MIE is increased, a gap smaller than the quenching distance does not prevent ignition in the general case.

2-6.4.1. Spark Breakdown
Paschen’s law states that the sparking voltage is a function of gas density and gap length alone. The law is usually followed for gas pressures up to a few atmospheres with small dependence on temperature. The sparking voltage in a uniform electric field can be expressed in terms of breakdown voltage or breakdown field. It should be noted that corona and brush discharges may occur at voltages considerably less than the sparking voltage. At atmospheric pressure, the breakdown field of air varies continuously from 45 kV/cm at a gap of 1 mm to 26 kV/cm at a gap of 10 cm. An “average” value of 30 kV/cm, corresponding to a gap of 2 cm, is often used as the approximate breakdown field of air. Atmospheric air, dry air, nitrogen, carbon monoxide, acetone vapor, and methane all have roughly the same breakdown field. Oxygen and carbon dioxide have 85–90% of the value while hydrogen has about half the value and rare gases such as helium about one-tenth of the value. For organic compounds in an homologous series, such as methane through octane, the breakdown field usually increases with increased molecular weight with little effect due to branching. The presence of double and triple bonds also increases breakdown field relative to aliphatic hydrocarbons. When hydrogen in a molecule is replaced by a halogen the breakdown voltage is usually increased; an example is carbon tetrachloride, which has a breakdown field about 170% that of methane or air. Sulfur hexafluoride has been used industrially to prevent charge loss via static discharge, having about 240% the breakdown field of air. The effect of halogens is due to their high electronegativity, facilitating electron attachment to form relatively massive negative ions. Oxygen and water are also electronegative, but less so than halogens; their effect on breakdown field on addition to dry air is
measurable but relatively small. For most practical situations involving flammable vapor concentrations, the breakdown field is essentially determined by the properties of air. Exceptions may occur for vapors or gases having unusually wide flammability limits, such as hydrogen.

The significance of this discussion is that the appearance of a spark may, in addition to charge accumulation rate, involve changes in gas density, gas composition and electrode geometry. Release of flammable gas into an electrically stressed region may initiate spark discharge. An extreme example is lightning striking an atmospheric vent stack. If lightning does not strike the stack, ignition might still occur via brush discharge or via an upward streamer that fails to connect with the downcoming stepped leader from the cloud (see 5-9.4). Lightning strikes are notoriously capricious and often do not strike “obvious” targets. Were this not the case a giraffe would truly be sticking its neck out during a thunderstorm on the savanna.

2-6.5. Propagating Brush Discharge (PBD)

This is a very energetic discharge produced by breakdown of an electrical double layer (capacitor) and is a special case of the phenomenon described in 2-6.2.2. The principal difference is that under certain conditions the electric field parallel to the non-conductive surface becomes sufficiently great for lateral flashover to occur, enabling much of the surface charge to be collected in the discharge (A-2-6.5). The maximum effective energy of a PBD is probably about 1000 mJ (2-6.5.3), although “transitional” cases can have much smaller energies depending on the charged surface area and extent of discharge (2-6.2.3). From an ignition perspective a PBD might be distinguished from a brush discharge by the occurrence of a minimum charge transfer of 10 μC, roughly an order of magnitude larger than the maximum charge transferred by a positive brush discharge. Fully developed PBDs on extensive surfaces with large breakdown voltages typically transfer at least 100 μC of charge. They are accompanied by a bright flash and a loud, sharp report comparable to a rifle shot.

PBDs were first observed in 1777 by G. Chr. Lichtenberg and are sometimes known as “Lichtenberg discharges.” A review of Lichtenberg’s electrophorus work and the “Lichtenberg” powder patterns obtained is given in [187]. These powder patterns are produced by scattering dust over a surface upon which a PBD has recently occurred and give a remarkably clear depiction of the intricate discharge channels. The patterns are found to depend on the polarity and surface charge density. Oak Ridge National Laboratory produced a discharge resembling a PBD after irradiating Pb–Ce glass
with the 10 μA electron beam from a 1.5 meV van de Graaf accelerator and then striking the edge of the glass with a sharp point; the beam penetration was about 1 mm into the 1-cm-thick glass. The discharge propagated from the stressed point parallel to the surface within the 1 mm layer [188].

To understand the mechanism of PBD production, consider powder impact on an insulating layer with grounded metal underneath. Charge accumulation on the insulating layer is balanced by an equal and opposite countercharge induced into the underlying metal surface. Since this creates a capacitor with zero net charge, the external field is due only to the difference in position of the two charged surfaces relative to an object above the insulating layer. The external field increases with the thickness of the insulating layer and for thicknesses above about 8 mm air breakdown occurs before the critical surface charge density of \(2.5 \times 10^{-4} \text{ C/m}^2\) can be attained [36]. Charge otherwise continues to accumulate on the insulating layer until the breakdown voltage of the layer is attained. When the insulating layer breaks down directly under the internal electric field, layer puncture is accompanied by massive lateral discharge to the puncture point owing to very large surface potential gradients. Alternatively, PBDs may be initiated by mechanical stress or by approach of a grounded electrode to the insulating layer. In the latter case, gas breakdown occurs on the approach of an electrode provided the net electric field at the electrode is sufficient. This in turn triggers the PBD (Plate 5). The phenomenon is affected by the rate of charging, the duration of charging, the breakdown strength of the layer and the layer thickness.

PBDs were not observed for layers less than 23 μm thick and the PBD film potential threshold varied from 4–5 kV at 23 μm to 11 kV at 175 μm [228]. A later study, possibly using a less valid method for measuring film potential, reported smaller threshold values [29]. The later study concluded that if film breakdown voltage is less than about 4 kV at 20 μm and about 8 kV at 200 μm, PBDs cannot be produced. This is shown schematically in Figure 2-6.5.

As discussed in 2-6.2.3, the figure has been conservatively drawn and the indicated PBD region includes both brush and transitional brush discharges. The voltage thresholds for fully developed PBDs are therefore higher than indicated. As discussed in 2-6.2.4 and Note 2 of 2-6.5.1, the breakdown voltage line corresponds to an envelope of maximum values for various films rather than specifically to polycarbonate film. The values correspond to breakdown strengths a factor 2–10 greater than those given for plastic films in Appendix B.

2-6.5.1. Principal Criteria for PBDs
The principal criteria under which a PBD can be produced on a nonconductive layer are
PLATE 5. Propagating brush discharge (PBD) on charged layer initiated by grounded electrode.

Figure 2-6.5. Schematic conditions for PBDs (adapted from [29] see text)
1. The layer thickness must be less than about 8 mm or air breakdown will occur above the charged layer before the critical surface charge density of $2.5 \times 10^{-4}$ C/m$^2$ can be attained.
2. The breakdown strength of the charged layer must be adequate to attain the critical charge density, implying a certain minimum layer thickness as shown schematically in Figure 2-6.5.
3. Sufficient charge must be available to supply the required critical surface charge density. Calculations show that 50-pound plastic bags and plastic lined 55-gallon drums are too small to represent a credible risk.

**Note 1:** As discussed in 2-6.2.3, Figure 2-6.5 has been conservatively drawn to accommodate not only PBDs, defined by a minimum charge transfer of 10 $\mu$C, but also brush discharges having charge transfers less than 1 $\mu$C. Charge transfer and discharge energy both increase with voltage across the layer, and this is limited by the layer breakdown voltage. Figure 2-6.5 shows that PBDs can in all cases be prevented by keeping the layer breakdown voltage less than 4 kV. However, greater breakdown voltages are allowed for thicker layers and as noted in 2-6.5, an earlier study [228] reported PBD film potential thresholds that are higher than indicated in Figure 2-6.5. Apart from simple rubbing applications (2-6.2.2) the selection of a “safe” layer thickness has little application for gases since brush discharges are themselves an ignition hazard. However there is valid application for dusts (2-6.2.3 and 6-4.3).

**Note 2:** As discussed in 2-6.2.4 the published breakdown strength of most plastics is less than the 400 V/$\mu$m indicated in Figure 2-6.5. Values for capacitor-grade polyethylene and PTFE films are 39 and 59 V/$\mu$m respectively [183]. The breakdown voltage line shown in Figure 2-6.5 was determined by enveloping the maximum breakdown voltages measured for various thicknesses of plastic film or combinations of films up to about 50 $\mu$m (2 mils) thick. It was concluded in [29] that breakdown strengths differ only slightly between different plastic films, despite the more than 1 order of magnitude range of values cited in [183]. As discussed in 2-6.2.4 the breakdown voltage of thick plastic layers can be much less than suggested by Figure 2-6.5.

### 2.6.5.2. PBDs from Isolated Nonconductors

PBDs may occur on plastic surfaces with no metal substrate, for example the wall of a plastic pipe conveying charged material. In this case the double layer forms between the inner charged wall of the pipe and a countercharge which accumulates on the outer wall via conduction or via corona discharge. In the latter case both layers of charge reside on nonconductive sur-
faces and a PBD on one side of a plastic surface should be accompanied by an equal and opposite PBD as the countercharge discharges to the same puncture point. Following an acrylic powder explosion in a railroad bulk container, meter long PBDs were directly observed in a short section of polyethylene pipe running to the container in an otherwise steel line; it was found that the plastic pipe outer wall had been rendered conductive by moisture and was effectively grounded at several locations. The charged inner wall and grounded outer wall formed a capacitor [13]. A large PBD was photographed on a section of 2-in.-diameter plastic pipe conveying charged diesel oil, where the outer wall was dry but contaminated with dirt and oil residues [8]. The photograph shows a roughly meter-long discharge initiating at a puncture point through the wall. Diesel oil was evaporated and ignited external to the pipe (Plate 6). Following an explosion, a PBD was concluded to have occurred on a section of plastic pipe in a chocolate crumb silo whose outer wall had been wrapped with grounded, conductive tape “to help dissipate static” [14]. Instead, the grounded tape actually contributed to the formation of a capacitor on the plastic pipe. As a final example, a PBD was reported in a 5-mm-thick walled polyethylene tote bin filled with charged, 1-mm polypropylene granules. The bin’s metal support frame supplied countercharge to the outside plastic wall via corona. In this last case, a worker reaching into the bin could short out the capacitor that had formed and receive a severe shock [15].

2-6.5.3. Stored PBD Energy

If it is assumed that PBDs transfer a minimum of 10 μC of charge across a layer with breakdown voltage 10 kV, the minimum stored energy is of the order 100 mJ. The maximum stored energy is limited by the surface area and breakdown voltage $V_b$ of the insulator. For large surfaces an additional limiting factor is the maximum flashover distance; if this is assumed to be about 0.5 m (A-2-6.5), the maximum dimension to consider for layer diameter or pipe length is 1 m. From Appendix C-1.2 the stored energy $W$ is

$$W = CV_b^2 / 2 = QV_b^2 / 2$$

where $Q$ is the product of surface area and surface charge density, and $C$ is capacitance given by

For a layer \[ C = A \varepsilon_r \varepsilon_0 / d \]

where $A = \text{area}$ and $d = \text{layer thickness}$.

For a pipe \[ C = 2\pi l \varepsilon_r \varepsilon_0 / \ln(r_2/r_1) \]

where $l = \text{length}$ and $r_1, r_2 = \text{inner and outer radii}$. 
Since $V_b$ for 1 mm of thickness may be of the order 20 kV (Appendix B) it follows that stored energies can easily achieve 1–10 J. It can be assumed that ignition occurs close to a puncture point through the layer, into which the energy is channeled. Since a large fraction of the stored energy is released remote from the puncture point(s) and cannot contribute to ignition, the maximum effective energy is probably about 1000 mJ.

2-6.6. Surface Streamer

This is the author’s classification for a large surface discharge observed on charged liquids, particularly during road tanker filling, appearing as an approximately 2 ft (0.6 m) long flash and accompanied by a crackling sound. It is not described in current electrostatic texts but was commonly discussed in US publications of the early 1960s, being referred to as the “go-devil” [61] or as “severe sparking” [148]. Its effective energy is unknown, but should be significantly greater than that of the brush discharge; its similarity to the
Plate 7 shows one of a series of surface streamer discharges photographed in a 10 ft (3.05 m) diameter stirred reactor during an inert gas sparging step. The stirrer shaft diameter (4 inch or 10 cm) gives an indication of scale. The discharges were all of similar size and initiated at any of four vertical baffles located at 90 degree intervals around the reactor wall. The baffles were 19 ft (5.8 m) high, 10 in (25 cm) wide and 2 in (5 cm) thick, being spaced 2 in (5 cm) from the wall. Field intensification by the baffles caused the discharges to initiate at these locations around the liquid surface, while there were no visible initiations or terminations at the stirrer shaft. The reactor contained a slurry of solids in a light, non-polar, non-conductive hydrocarbon. Plate 7 shows the potential for formation of unusually large and energetic static discharges under conditions that convect large charge densities to the liquid surface. Stirred slurries in non-conductive liquids are known to generate high charge densities (5-4.5.2). In this case, convection of abnormally large charge densities to the liquid surface was presumably assisted by interfacial charge carried by the rising gas bubbles (5-4.1.2). In the example discussed here, the reactor was operated outside the flammable region at all times and the observed static phenomena did not represent a hazard.
2-7. Personnel Spark and Shock Hazards

These are normally due to charging of people and subsequent discharge in the form of a spark to a conductor. The energy dissipated \( (W, \text{Joules}) \) approximates to the discharge of a capacitor \( (C, \text{Farad}) \) having the same capacitance as the person and charged to the same voltage \( (V, \text{Volts}) \), or \( W = 0.5CV^2 \). Common “doorknob” shocks caused by walking across carpet or after getting out of upholstered chairs are of this type. Shocks can also result from static discharges from charged items of equipment. In the case of sparks, the energy can be calculated directly if the capacitance and voltage of the charged conductor are known. Other types of discharge from charged bodies, with the exception of the propagating brush, will not give significant shocks and in many cases a discharge capable of igniting gas mixtures may be imperceptible. The propagating brush (2-6.5) may be initiated by touching a nonconductor charged in the manner of a capacitor. PBDs commonly have stored energies of about 1 J (2-6.5.3) and in extreme cases could give hazardous shocks approaching the lethal threshold of about 10 J (2-7.3).

2-7.1. Body Capacitance and Resistance

The capacitance of a person is not constant but varies by about a factor of four depending on factors such as the type of shoe, attitude with respect to ground and proximity to neighboring conductors. Human body capacitance is unlikely to be less than 90 pF, corresponding to a person of average height standing on the tip of one rubber boot with 18-mm sole (simulating walking with the smallest contact area with the floor), although an individual who is completely isolated by jumping off the floor may achieve 55 pF. A typical value for a person in standing position is 120 pF. In general, the range of body capacitance can be taken as 100–400 pF with 200 pF frequently used as an
average value. Higher values correspond to unusually high shoe capacitance with respect to ground (such as thin, flat, nonconductive soles on a conductive floor). Body capacitance in this case can be calculated using the equation in C-1.1 for two parallel capacitor plates \( C = \frac{A \varepsilon_r \varepsilon_0}{d} \), total foot area \( A \), sole thickness \( d \). Total body capacitance may be further increased by proximity to large vertical conductors such as steel tanks. The body resistance of an average person, as measured at 30 V between one finger and two bare feet in contact with a metal plate, varies from about \( 4 \times 10^4 \) \( \Omega \) (from ball of finger) to \( 2 \times 10^5 \) \( \Omega \) (from tip of finger), where the exact value varies with skin thickness and dryness [53].

2-7.2. Voltage (V) and Energy (W) Attained

For the purposes of discussion it is assumed that a person has a capacitance of 200 pF. People are most unlikely to achieve voltages exceeding 50 kV, which might correspond to standing in a pile of freshly dumped, highly charged thermoplastic resin \( (W = 250 \text{ mJ}) \). When sliding over carpet in dry offices, voltages up to about 30 kV have been observed \( (W = 90 \text{ mJ}) \). At low values of relative humidity, walking across carpet or getting out of an upholstered chair often results in body voltages up to about 10 kV \( (W = 10 \text{ mJ}) \). Such voltages may be attained even when walking over painted stone floors provided shoe resistivity is high. Since the level of perception is about 1 mJ it can be appreciated that human body voltages exceeding 3000 volts are very commonly attained. Appendix B shows that 1 mJ exceeds the MIE of many gas mixtures in air. Sparks from people have a smaller effective energy for ignition than those between small metal electrodes. This is due to a larger capacitance and effective electrode radius (Figure 3-5.4), energy lost in skin resistance, plus a tendency to continue releasing energy in a series of smaller sparks following an initial large spark [38]. Even though the effective energy may only be 20% or less of an optimized metal–metal spark having the same stored energy, ignition of gas mixtures by charged people may easily occur unless precautions are taken (4-3). Dust ignition is possible although less likely owing to the higher MIEs of dust clouds plus the smaller probability of the spark encountering an easily ignitable mixture. Considering the depressed effective energy of sparks from people and the fact that shocks more severe than that from a spark plug (2-7.3) are extremely unusual, flammable mixtures with a MIE above the range 30–50 mJ are probably not subject to this ignition hazard. In flammable gas atmospheres, sparks from people may be most hazardous where they cause a borderline response and where the situation may therefore continue uncorrected.
2-7.3. Human Shock Response

This depends on the energy and source capacitance of the spark plus personal characteristics including skin resistance, sensitivity and general health. Response to mild shocks is related to the power density passing through the skin. Hence if one is carrying a metal key a larger energy can be dissipated without shock when the key is used to discharge the body to ground. In practical situations involving metal tools this can result in production of sparks of at least several millijoules without any perception of a shock, and the sparks may not be either audible or visible. The following are typical response thresholds for capacitance sparks to the bare hand: 0.5–2 mJ (perceptible), 1–10 mJ (various levels of discomfort), 15–25 mJ (unpleasant shock), 250 mJ (severe shock), 1–10 J (possible unconsciousness), >10 J (possible cardiac arrest). As a reference, a typical automobile spark plug dissipates energy in the 25-35 mJ range, with extreme values (integral of plug VI over time) of 10–50 mJ [48]. Although a shock may be physiologically non-hazardous, the involuntary effects may be extremely hazardous in causing falls or other indirect injuries. The latter includes third party injury from a dropped item, spillage of open or breakable containers and impact laceration from machinery or sharp objects.