

BULK POWDER ELECTROSTATICS HAZARDS EVALUATION

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INTRODUCTION

As process sizing increases, larger quantities of powders are handled at any location in the process. In the gun propellant manufacturing processes, large blend batch sizes produce more uniform gun ballistic output. In a few facilities, up to 100,000 lb of propellant is blended in a single batch. Other facilities blend anywhere from 200 lb to 5,000 lb.

Flare and pyrotechnic composition bulk powder operations have been scaled up to 1,000 lb blending batch sizes.

In explosive manufacturing operations, several thousand pounds of ingredients can be stored and transported at one time. It is not uncommon to handle 2,000 lb of dynamite powder mixtures.

From an electrostatic safety standpoint, one must question what quantity of bulk powder can be handled at any one time (e.g., blending, mixing, etc.) without potential electrostatic discharge (ESD) ignition. Powder handling electrostatic (ES) charging transfer of large quantities of powder (> 100 lb) to hoppers or process bins can generate very high ES charges. In this paper, evaluation methods will be presented to determine ES process safety in bulk powder operations.

BACKGROUND

Numerous fire and explosion incidents have occurred which have been directly attributed to electrostatic discharge initiation. Numerous dust explosions in silos have occurred where grain and plastic powders were transported by air conveying systems. Several of these were attributed to electrostatic discharge (ESD) on insulated piping. Others were related to ungrounded insulated filter media in dust collectors and bin vents.

Several fire and explosion incidents occurred during filling of large bins and silos in the plastics industry. Also, several flare composition manufacturing process explosions were attributed to ESD during powder transfer.

Some of the above incidents could not be attributed to ESD from charges stored on

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ungrounded conductive materials. All parts were properly grounded and bonded.

In the past, electrostatic hazards were recognized and addressed especially for easily ignitable materials (e.g., primarily explosives (e.g., lead styphnate, lead azide), pyrotechnics (e.g., potassium/ammonium perchloride/zirconium), and very fine particle magnesium, aluminum and zirconium).

Usually, if the minimum ignition energy was less than 100 milliJoules, special electrostatic hazard prevention methods are necessary.¹ (e.g., flooring and personnel grounding).

Recent trends (last 10 years) showed greater tendency to scale up operations so that greater quantities of powdered materials are handled at any location in the processes. From a quality control standpoint, larger quantities (mix and blend batches) yield more consistent final product (explosives, pyrotechnics and solid propellants - especially gun propellants). For solid rocket manufacture, large quantities of raw materials are handled (e.g., fine particle aluminum and oxidizers).

BASIC HAZARDS DEFINITION

An electrostatic hazard exists in a powder if the bulk powder or its dust cloud is sensitive to electrostatic discharge. A powder/air mixture can react explosively once ignited by an electrostatic discharge (ESD) or other energy source igniting the bulk powder. This reaction would propagate into explosion (primary and secondary) over large areas of manufacturing operations. Electrostatically hazardous conditions may occur if one or more of the following exist:

- Powder is reactive (in bulk or in dust cloud).
- Electrostatic charges develop.
- Electrostatic discharges occur.
- Powder ESD ignition energy less than in process ESD energy.
- Propagation of reaction to explosion or massive fire.
- High exposure of personnel and facilities to incident.

In our hazards evaluation, our first step is to determine whether the material is reactive in either a layer or a dust cloud suspension. If it is reactive, the next step in the hazard analysis is to determine the minimum energies required to initiate the particular dust material. If the initiation energies are extremely low (low ignition temperature or low electrostatic discharge initiation energies), the powder electrostatic charging characteristics are evaluated. From this, we can determine whether sufficient electrostatic charge energies can develop in various stages of bulk powder handling to constitute an initiation hazard. The next step is that of

determining ways in which the hazard can develop in the manufacturing or process plant operations and the probabilities that these events will occur. From this information, critical hazards can be defined and corrected before catastrophic consequences can occur. A summary of this methodology is shown in Table I.

TABLE 1

**BULK POWDER HANDLING ELECTROSTATIC
HAZARD EVALUATION METHODOLOGY**

Step 1

- Determine Powder Reactivity In:
 - Dust Cloud
 - Dust Layer

Step 2

- Determine Minimum Electrostatic Discharge Energy To Ignite Powder.

Step 3

- Characterize Powder Electrostatic Charging Characteristics

Step 4

- Determine Powder Electrostatic Dissipation Characteristics

Step 5

- Analyze Bulk Powder Handling System For Electrostatic Charge Buildup, Storage and Discharges

Step 6

- Define Ways That The Electrostatic Hazards Can Arise and Assign Probabilities

Step 7

- Define Critical Electrostatic Hazards

Step 8

- Define And Apply Corrective Actions.

The electrostatic hazard of bulk powder handling systems needs to be systematically evaluated. From our experience, laboratory testing results can be utilized to predict full-scale electrostatic conditions. The following processes are recommended to evaluate the ESD hazards:

- Electrostatic charging evaluation and testing
- Charge drainoff characteristics
- Analysis and prediction of voltage fields
- Analysis of ESD levels expected in the process
- Conduct suitable ESD sensitivity tests
- Compare to ESD sensitivity of powder/air suspensions

The particle size and distribution, particle shape, moisture and volatiles, surface coatings, and foreign materials greatly alter the electrostatic charging, charge drainoff, and discharge sensitivity of the powders.

ELECTROSTATIC CHARGING

The generation of electrostatic charges in powder occur due to stripping or collecting electrons on the surfaces of materials. This can occur in any of the following mechanisms:

- Triboelectrically - Friction or rubbing of powder materials over each other and over materials of construction.
- Induction - Passing through a high voltage field.
- Thermionic (Heating) - Driving electrons off due to heat and differential temperatures.
- Contact - Powder impacting or contacting a surface with residual ES charge.
- Solidification - Meltable powders receiving charge during solidification (e.g., TNT).
- Vaporization of liquids.

In powder handling, a typical example of electrostatic charging is that of filling a bin or receiving hopper. The powder is transported to the vessel by air conveying. See Figure 1.

Figure 1. Illustration of Air Conveying of Bulk Powder to Bin.

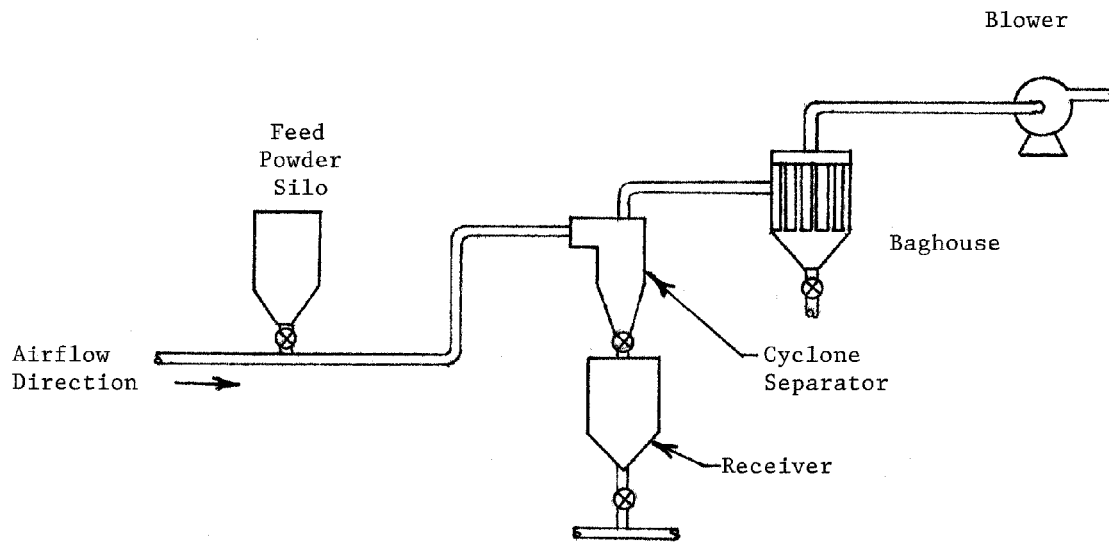


Figure 1. Illustration of air conveying of bulk powder to bin.

Electrostatic charging occurs in the air conveying piping as the powder slides across it. The ES charging rate will be a function of the powder flow rate (Kg/sec) and the characteristic charge generation during sliding across the pipe (coulomb/kg) as follows:

$$Q = \text{ES Charging Rate} = W \times Q/W \dots\dots\dots \text{Eqn. 1}$$

Where:

$$Q = \text{Charge Rate (coulomb/sec)}$$

$$W = \text{Powder Flow Rate (Kg/sec)}$$

$$Q/W = \text{ES Charge/Mass (coulomb/Kg) measured in lab}$$

Note: This applies to an insulating system where no charge is drained off

Also, the charge/Kg will be increased as the powder speed increases in the pipe. Typically, the charge/Kg in air conveying is ~7 times as great as that for sliding down a chute from our testing and evaluation experience.

Thus: For air conveying:

$$Q = W \times K \times Q/W \dots\dots\dots \text{Eqn. 2}$$

Where:

$$K = 7.5 \text{ (From SCE experience with insulating materials)}$$

If the powder is a good insulator (Vol. Resistivity > 10¹⁴ ohm-cm), charges will stay on the powder for long periods of time (> 10 seconds).

If the powder is separated from the airstream by a cyclone separator, additional ES charging will occur. Because of the high peripheral velocities experienced by the powder, very high ES charging is expected.

If the powders are conductive or semi-conductive, the charges can drain off fast.

ES charging is also encountered in bin vents (on top of silos) where filter media is reversed pulsed during operation.

Pouring powder into blender and blending operations will generate ES charges. See Figure 2 as an example. Typical levels of ES charging depending on operations are shown as follows:

<u>OPERATION</u>	<u>CHARGE/MASS (Coulomb/Kg)</u>
Sieving	10^{-9} to 10^{-11}
Pouring	10^{-7} to 10^{-9}
Auger Feed	10^{-6} to 10^{-8}
Grinding	10^{-6} to 10^{-7}
Micronizing	10^{-4} to 10^{-7}
Pneumatic Conveying	10^{-3} to 10^{-6}

In bulk powder operations, ES charges will remain on insulating powders as they are transported through the processes.

Figure 2. Illustration of Mixer Unload into a Bin.

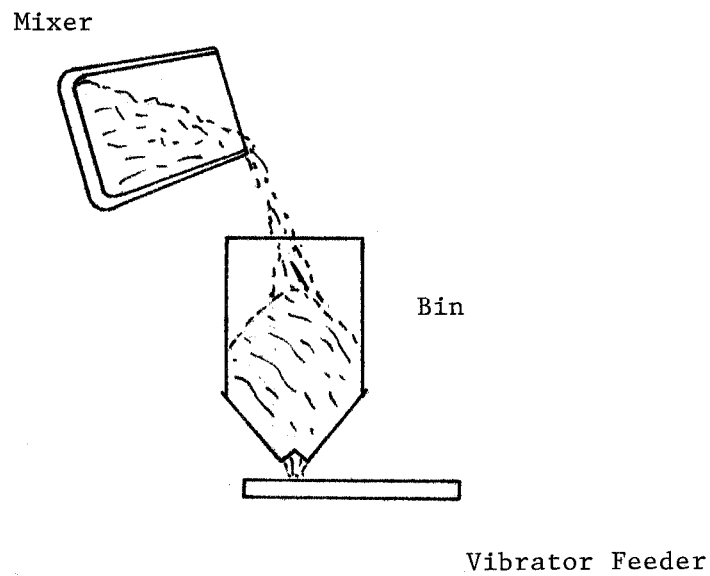


Figure 2. Illustration of mixer unload into a bin.

POWDER CHARGING CHARACTERISTICS

Once the powder is found to be very reactive, a series of tests are conducted to determine its electrostatic characteristics. The first test conducted is usually an electrostatic charging test to evaluate the materials' tendency to generate an electrostatic charge. Basically, this test utilizes an incline chute of various angles whereby powder is poured down the chute and collected in an aluminum (Faraday) pail. The charge and energy developed in this test is measured on the pail by utilizing a high-voltage probe and electrometer. A typical illustration of the test setup is shown in Figure 3. In this test, two or three quantities of powder are utilized, to measure the charge/area, charge/weight and energy per unit weight of powder for its charging efficiency. From this information, in-process ES energies and voltage fields can be calculated.

Typical ES charging values for various materials are as follows:

MATERIAL	CHARGE/MASS (c/Kg)	CHARGE/AREA (c/m²)	ENERGY/MASS (mJ/Kg)
Pharmaceutical Powder	3.0×10^{-6}	1×10^{-6}	20
Plastic Resin	3.0×10^{-6}	10×10^{-6}	15
Aluminum Powder	0.1×10^{-6}	0.2×10^{-6}	0.04
Flaked TNT ²	0.8×10^{-6}	-	-

Figure 3. Electrostatic Charging Test Setup.

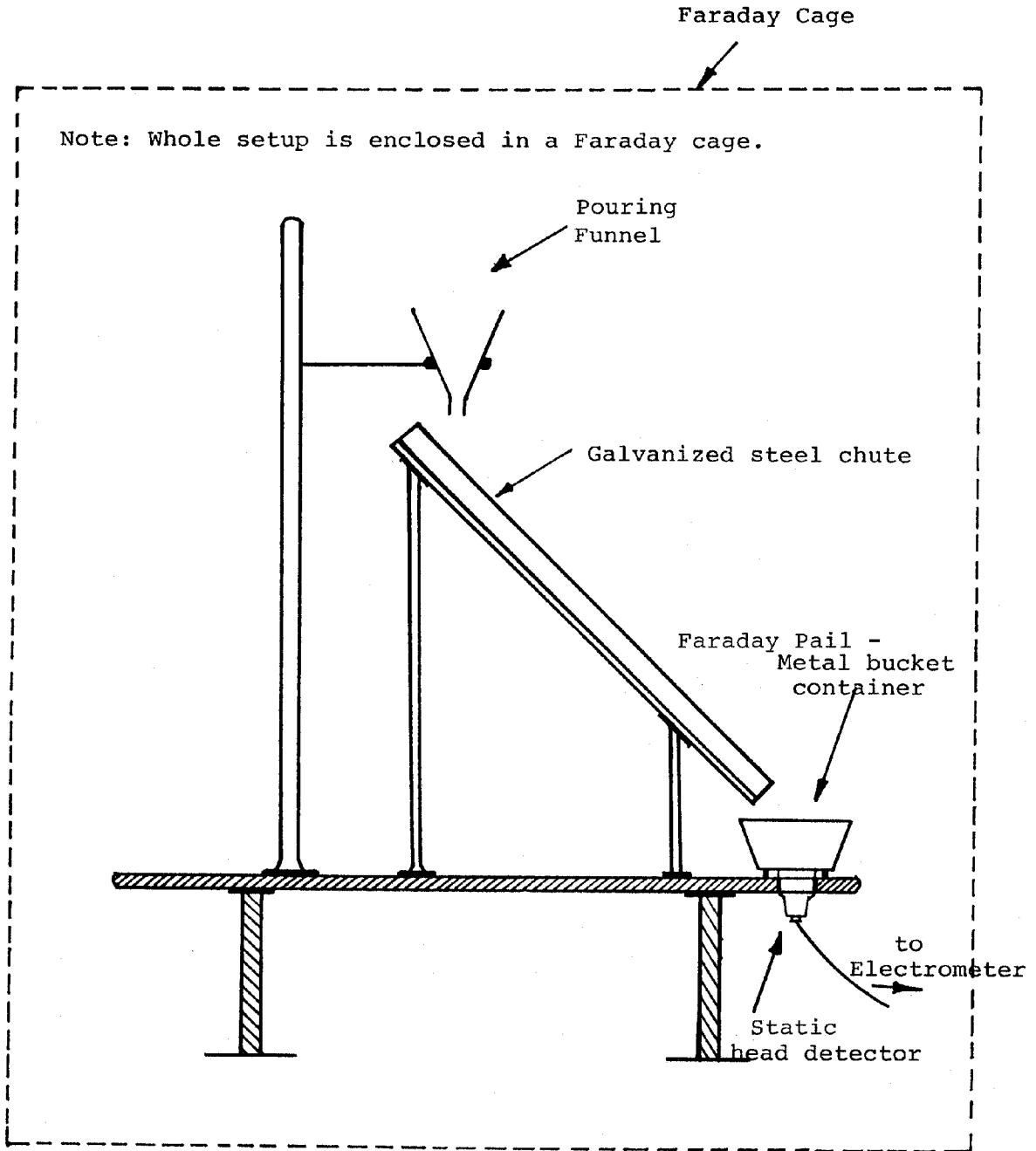


Figure 3. Electrostatic charging test setup.

CHARGE STORAGE

ES charges will collect on any isolated conductor (e.g., process components, isolated doors, augers) and coated conductive materials, (e.g., epoxy coated piping, hoppers, and process components). Most processes today handling ESD sensitive powders are well grounded and bonded. When all conducting parts are grounded, ES charges will be drained off at rates according to the resistance-to-ground. When the isolated conductors are not grounded, charges build up until either ES breakdown or shortout will occur. Then, all of the ES charges will flow through the spark gap to produce high ES discharge energies. Parts with insulating epoxy (e.g., Teflon and nylon) coatings, and metal parts with thin insulating coatings are an exception. Although grounded, highly ES charged insulating surfaces will not drain off charge. Thus potential for discharge is possible.

ES charges collect on insulating surfaces and on the powder itself, depending on the resistance (drain off) characteristics-to-ground. To evaluate actual resistance, the volumetric and surface resistivity measurements are made using the apparatus shown in Figure 4. From these measurements, electrical resistance can be calculated for various geometries as follows:

$$R = (\sigma_v t)/A \dots\dots\dots \text{Eqn. 3}$$

Where:

σ_v = Volumetric Resistivity (ohm-cm)

R = Resistance to Ground (ohm)

A = Contact Area (cm²)

t = Thickness or distance to Ground

Since the voltage potentials can be very high for electrostatic charge generation, resistivity measurements are conducted at increasing voltages up to 20,000 V.

Typical volumetric resistivity values for various powders are as follows:

<u>MATERIAL</u>	<u>σ_v(ohm-cm)</u>
Teflon	10 ¹⁷
Nylon	10 ¹⁴
Nitrocellulose	10 ¹⁴

The time-to-decay charge to 37% of its original value on an insulator is calculated as follows:

$$t_v = 8.85 \times 10^{-14} \epsilon \sigma_v \dots \dots \dots \text{Eqn. 4}$$

Where:

ϵ = Dielectric Constant of Material

σ_v = Volumetric Resistivity of Material (ohm-cm)

From this, we see that for nitrocellulose with a dielectric constant of 3.0, a decay time of the following results:

$$t_v = 27 \text{ sec}$$

Thus, if the powder were to be placed on a grounded conductor, 37% of the original charge would have been drained off within 30 seconds. In contrast, pneumatic conveying time durations are usually less than 3 seconds, which means that the nitrocellulose powder would not drain off charge in the lines.

If the powders have very fine particle size, dust layers can build up in ductwork, hoppers, bins and blenders. When this happens, charges store up on the dust layer and tend to induce additional charges on powder flowing over it.

Major concern recently has been with the ES charge storage and subsequent discharge of insulated powders part coatings, and insulated parts.

Figure 4. Powder Resistivity Test (and Voltage Breakdown Point) Setup (ASTM Method Modified).

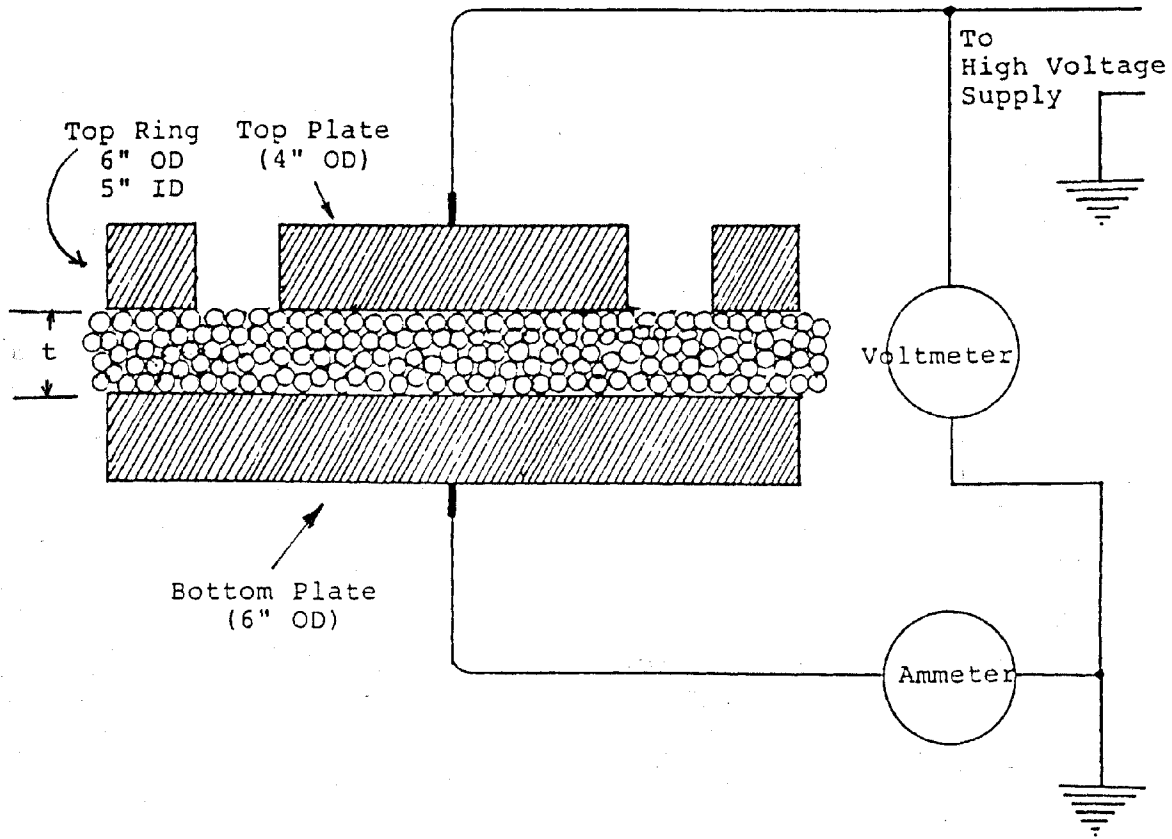


Figure 4. Powder resistivity test (and voltage breakdown point) setup (ASTM method modified).

ELECTROSTATIC DISCHARGE POTENTIAL

Traditionally, electrostatic discharges occur when a charged conductor contacts or approaches a ground (person touching door knob on a dry day) and when charges build up on an isolated conductor until the voltage potential exceeds breakdown in the media (e.g., sparks coming off a conveyor belt at a pulley). In both cases, the energy released in the ESD can be estimated based on the charge and capacitance of the isolated conductor as follows:

$$\text{Charge on Conductor} = Q \text{ (coulombs)}$$

If the charging rate is known, then the charge after a given time is:

$$Q = (dQ/dt) \times t \dots\dots\dots \text{Eqn. 5}$$

Where:

Q = Charge (coulombs)

t = Time (seconds)

dQ/dt = Charge Rate (coulombs/second)

Capacitance of conductor can be estimated if it is a metal plate at a given distance from ground

$$C = \frac{0.225 \times \epsilon \times A}{L \times 10^{12}} \dots\dots\dots \text{Eqn. 6}$$

Where:

C = Capacitance (farad)

ε = Dielectric Constant of Media (ε_{air} = 1.0)

A = Surface Area (in²)

L = Gap Distance to Ground (in)

Voltage potential to ground:

$$V = Q/C \dots\dots\dots \text{Eqn. 7}$$

Where:

V = Voltage

Energy stored on conductor then is:

$$W = CV^2/w = C(Q/C)^2/2 \dots\dots\dots \text{Eqn. 8}$$

$$W = Q/2C$$

Where:

W = Energy (Joules)

When charges accumulate on insulating surfaces, several types of discharge are possible

depending on the nature of discharge. Several are listed below:

- Brush Discharge
- Propagating Brush Discharge
- Powder Heap Compaction or Cone Discharge
- Powder Layer Breakdown Discharges

Brush discharges occur on insulating surfaces when a grounded object is brought close to the surface. Typically, energies up to 1 mJ are possible.³ Gibson and Lloyd⁴ proved that gasoline vapor/air mixtures could be ignited by brush discharges.

Propagating brush discharges occur when a charged insulated surface backed by a conducting surface at ground potential is approached by a grounded conductor. ESD energies up to 10 J are possible. An example is that of lowering a conductive sample container into an insulated dust-covered grounded hopper, approaching the layer, and causing an ES discharge.

Powder heap compaction and "cone" discharges occur in a powder pile as a bin or hopper is filled. When gravitation forces overcome electrostatic forces, the voltage fields in the powder intensify causing ESD along the powder surface nearest to the grounded bin. Glor⁵ has conducted extensive research on this phenomenon. ESD energies in excess of 1 Joule can occur.

Powder layer or an insulating coating breakdown can occur when the voltage potential across it exceeds breakdown levels. For example, a grounded metal bin has a thin coating of Teflon on its interior to reduce friction and a layer of powder collects on the bin surface.

As powder flows into the bin, electrostatic charging occurs as the powder slides over the bin surfaces. Each layer has a finite capacitance/area, dielectric properties of dielectric constant, and resistivity and breakdown voltage field. Thus, the ES charging and breakdown can be illustrated as shown in Figure 5.

Figure 5. Model of ES Charging and Decay Process on Bin Wall.

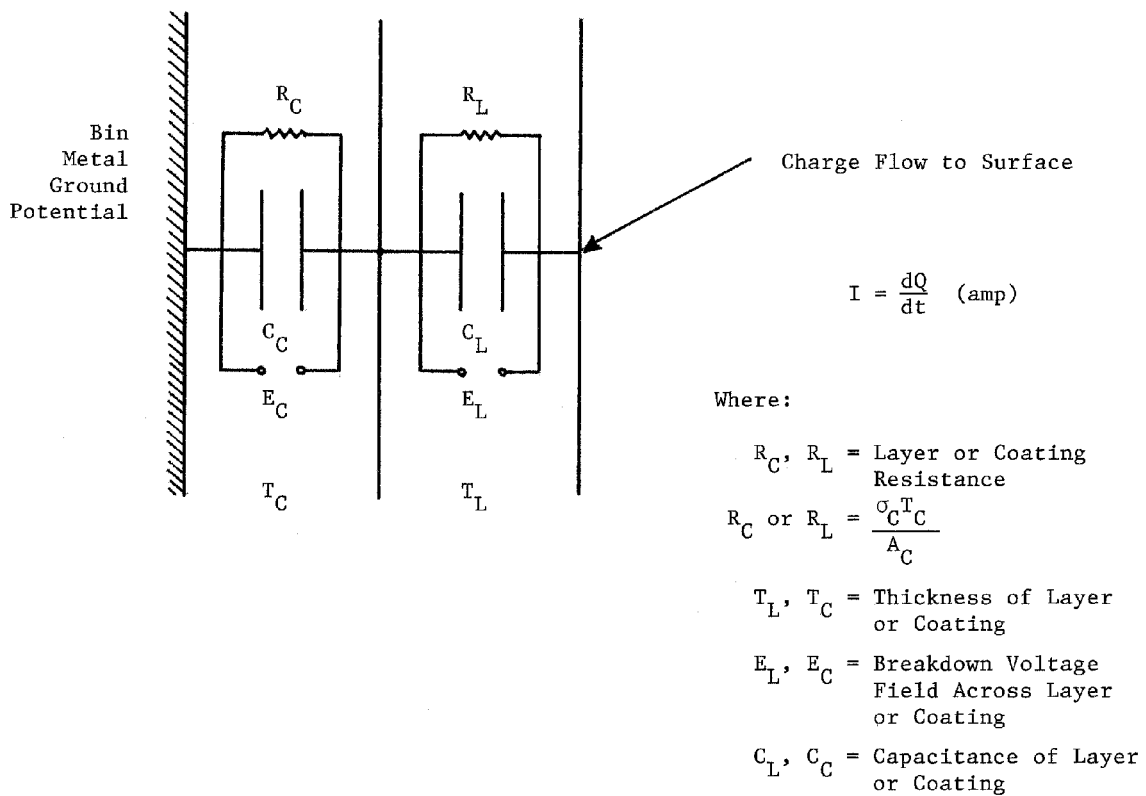


Figure 5. Model of ES charging and decay process on bin wall.

If no coating exists, a powder dust layer discharge can occur when the voltage across the layer exceeds breakdown field levels.

From resistivity testing of powder at increasing potentials, the breakdown voltage field can be determined. To illustrate the magnitude of the ESD from a powder dust breakdown, consider the following:

POWDER COATING THE BIN

From ES charging testing on powder A, the following charging value was found:

$$Q/Kg = 1.8 \times 10^{-6} \text{ coulomb/m}^2$$

The powder is a flare composition using Teflon. From resistivity measurements, the following values were obtained:

$$\sigma = 10^{14} \text{ ohm-cm}$$

$$\epsilon = 2.5$$

$$E_{bd} = 10,000 \text{ KV/m}$$

Looking at a powder flow rate into a hopper of:

$$W = 15 \text{ Kg/sec}$$

and a dust layer thickness of:

$$t_L = 0.01 \text{ inch}$$

and discharge surface area of:

$$A = 400 \text{ in}^2$$

Calculating capacitance and resistance across the powder layer as follows:

$$C_L = 0.225 \times \epsilon \times A_L / T_L \times 10^{12}$$

$$C_L = 7.5 \times 10^{-9} \text{ Farad}$$

$$R_L = \sigma_L \times T_L / A_L$$

$$R_L = 2.5 \times 10^9 \text{ ohm}$$

The current flow into the dust layer then is:

$$\begin{aligned} I &= (Q/Kg) \times Kg/s \\ &= (1.8 \times 10^{-6} \text{ coulomb/Kg}) \times (15 \text{ Kg/sec}) \\ &= 27.0 \times 10^{-6} \text{ coulomb/sec} \end{aligned}$$

As charges accumulate on the powder surface, a voltage potential develops per:

$$V_L = IR_L \dots\dots\dots \text{ Eqn. 9}$$

Then:

$$\begin{aligned} V_L &= (27.0 \times 10^{-6} \text{ amp}) \times 2.5 \times 10^9 \text{ ohm} \\ &= 67500 \text{ V} \end{aligned}$$

Maximum voltage when powder layer breakdown is:

$$\begin{aligned}V_{BD} &= E_{BD} \times T_L \\ &= 10,000 \text{ KV/m} \times (0.01 \text{ inch}) / [(12 \text{ in/ft})(3.28 \text{ m/ft})] \\ &= 2540 \text{ V}\end{aligned}$$

Knowing the capacitance across the layer from above calculations:

$$C = 7.50 \times 10^{-9} \text{ Farad}$$

ESD energy is:

$$W = 24 \text{ mJ}$$

BIN WALLS

If a thin layer of Teflon builds up on the bin, the ESD energy possible can be calculated as follows:

Knowing that:

$$\sigma_v = 10^{17} \text{ ohm-cm}$$

$$\epsilon = 2.1$$

$$E_{BD} = 600 \text{ V/mil}$$

$$t = 30 \text{ mil}$$

$$Q/\text{Kg} = 1.8 \times 10^{-6} \text{ coulomb/Kg}$$

$$w = 15 \text{ Kg/sec}$$

And assuming ESD breakdown on Teflon surface over an area:

$$A = 400 \text{ in}^2$$

Then:

$$C = (0.225 \epsilon A) / (t \times 10^{12})$$

$$C_{\text{Teflon}} = 7.50 \times 10^{-9} \text{ Farad}$$

$$\begin{aligned}R_{\text{Teflon}} &= \sigma_v \times T/A \\ &= 10^{17} \text{ ohm-cm} \times (0.02 \text{ inch}) / (400 \text{ in}^2 \times 2.54)\end{aligned}$$

$$R = 5 \times 10^{12} \text{ ohm}$$

And from before:

$$I = 27 \times 10^{-6} \text{ coulomb/sec}$$

Then voltage buildup is:

$$V = IR$$

$$V = > 10^6 \text{ V}$$

Breakdown voltage in the coating is:

$$\begin{aligned} V_{BD} &= E_{BD} \times t \\ &= 12,000 \text{ V} \end{aligned}$$

Thus energy in breakdown is:

$$\begin{aligned} W &= 1/2(CV^2) \\ &= 1/2(7.5 \times 10^{-9})(12,000 \text{ V}) \\ &= 540 \text{ mJ} \end{aligned}$$

POWDER ESD IGNITION SENSITIVITY

The ignition sensitivity of a powder will depend on its physical condition and chemical nature. As particle size reduces, usually the ESD ignition energy goes down. If the powder is suspended in a dust cloud, lower ignition energies are expected.

The ESD tester configuration will yield different ESD thresholds depending on its electrical characteristics. If the tester utilizes a capacitive discharge circuit without line resistance, only a very small portion of the capacitance energy enters into the spark discharge.⁶ As resistance increases in the circuit, energy transferred to the spark becomes more efficient. See Figure 6 for black powder.

Figure 6. Dependence of 50% Ignition Energy of Black Powder on Series Resistance for Different Capacitances.

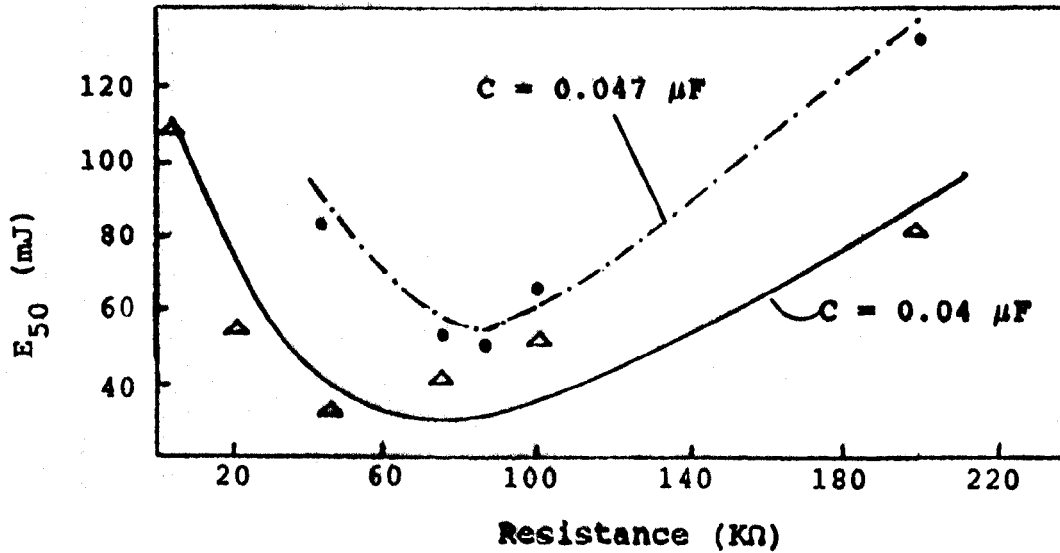


Figure 6. Dependence of 50% ignition energy of black powder on series resistance for different capacitances.

Published data on TNT indicated ignition threshold ranges from 60 mJ to 12 Joules. From our tests on very fine TNT's, minimum ESD ignition energy is 12 mJ.

It is extremely important that ESD ignition sensitivity tests be performed which must closely simulate process conditions and powder characteristics. If the powder is resistive and a propagating brush discharge is a likely scenario, the ESD testing must be conducted using resistance to the spark gap.

HAZARDS EVALUATION

When the potential ESD energy in the process equals or is greater than the ignition sensitivity, a major hazard can exist. If the powder is in a dust cloud, the probability of fire or explosion must account for explosive dust cloud and concentration probability.

Once the ESD ignition thresholds have been obtained for expected process conditions, the electrostatic charging and decay properties are evaluated. See Figure 7 for the process flow.

Figure 7. Flow Chart Utilized to Evaluate Electrostatic Hazards.

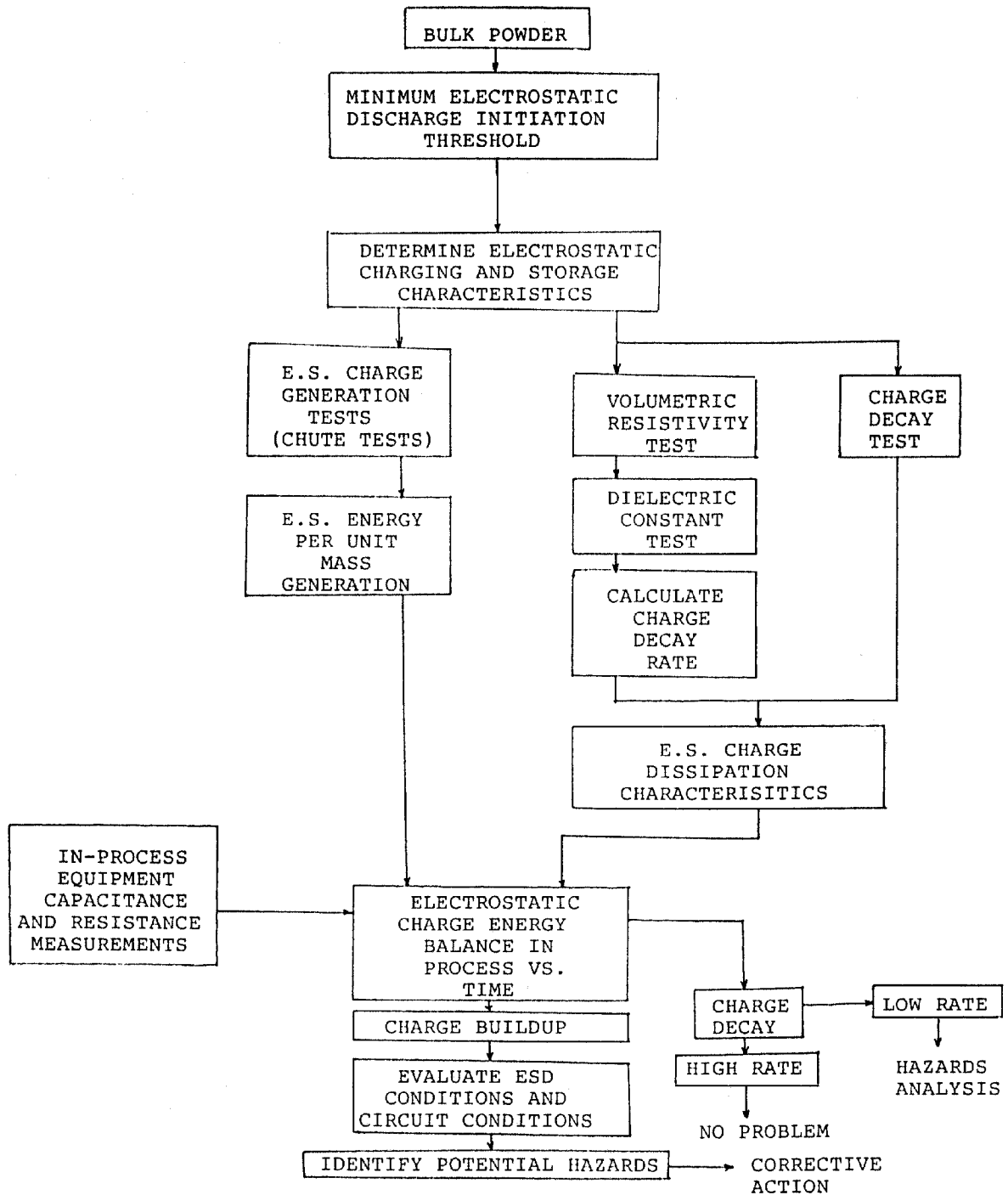


Figure 7. Flow chart utilized to evaluate electrostatic hazards.

If, in the process, ES energies exceed the ignition thresholds, and ES discharges are expected, engineering hazards analysis must be conducted. From this, probabilities of fires and explosions would be developed from the following:

- Failure event probability
- ES charging probability
- Probability of hazardous material condition (dust cloud concentration)
- Fire/explosion propagation probability

For each hazard event, the risks relate to the extent of damage or seriousness of incident should a local fire/explosion occur.

CONCLUSIONS

In this paper, methods were outlined to evaluate electrostatic hazards of bulk powder by analyzing their reactivity, their electrostatic charging characteristics, and evaluating the electrostatic stored energy and discharge characteristics of in process equipment and personnel. Electrostatic discharge energies of 1 to 5 Joules can occur on grounded in-process equipment. Note: up to 100 milliJoules of electrostatic energy can be discharged from the human body.

Handling large quantities of powder can create high ES hazards even when equipment and personnel are grounded. Hazards arise when in-process ESD energies exceed ignition thresholds. Process ESD energy can exceed 1 Joule for propagating brush discharge and powder layer ES breakdown.

Lab testing for ES charging and methods to calculate in-process ES charges, energies and voltage fields have been presented. ESD energy varies with different conditions. Precaution is recommended when testing dust material to determine the minimum electrostatic discharge (ESD) energy.

Electrostatic hazard analysis of complex bulk powder handling systems can be very complex. Extreme caution should be exercised in the analysis

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