Prevent Explosions of Combustible Dusts

If not treated properly, dust layers and clouds of combustible materials can wreak havoc in the plant due to static discharges. However, testing for combustion ratings and following some basic rules will help to prevent problems.

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To sufficiently survey the potential danger of a dust, an engineer is normally forced to carry out numerous laboratory tests that are based on standardized methods. The results are known as safety characteristics (Table 1). Depending upon the effort spent, a more or less comprehensive picture will result, revealed as a mosaic. The scope of the tests has to be determined in close collaboration between the tester and user, working toward the solution of the problem.

Here, we will review these tests, and then show how to apply the results to set up handling procedures that will promote safety. Tests are made for both dust layers and dust suspensions, since these show different behavior. Transforming the safety characteristics to plant conditions is certainly the key for safe operation.

DUST LAYERS
Ignition rating

An unknown product should not initially be tested in large quantities. The following is used at Ciba Speciality Chemicals as a screening test. A small sample (approximately 100 mg) of a dry product is exposed to a hot plate at different temperatures. A reaction is considered to have taken place at a given temperature if the test sample shows any of the following within 5 min: *ignition with flames, emission of sparks, red hot glow, or spontaneous decomposition without fire.* The ignition properties of the product are classified with a rating on the basis of

the ignition temperature level (Table 2). Data from this simple test are only good enough to describe the flammability behavior at a specific temperature.

Combustion rating

This test measures the ignitibility and the combustibility of a dried product according to the following criteria:
- Can the product be ignited at all?
- Is the ignition propagated?
- Is there a fire or a flameless reaction?

The tests are carried out in a ventilated laboratory hood. The air velocity is approximately 0.2 m/s. The superimposed low-velocity air stream is necessary to vent the inert gases generated upon ignition that may inhibit the combustion behavior of the dust (Figure 1) (*1*).

If the combustibility is needed at an elevated temperature (*e.g.*, an anticipated drying temperature), the test can be performed in a drying oven with a guaranteed air supply (*1*). By increasing the dust sample to an overall length of 25 cm (10 in.), the same test procedure can be used to classify a product as a readily combustible solid of Division 4.1 in accordance with the U.N. "Recommendations on the Transport of Dangerous Goods," (*2*) if the burning rate exceeds a certain limiting value.

The combustibility of the product is rated in accordance with the course of the reaction and characterized as a class number according to VDI (Table 3). A temperature increase from 20° to 100°C normally results in a change of the burning class (BC) from 1–3 to 4–6.

Exothermic reaction in an air stream

This test determines the temperature of a product in a hot air stream, in which an oxidation reaction occurs at a significant scale. The test is used for products that are subjected to elevated temperatures in an air stream for a short time period, such as in a spray or fluid-bed dryer. This test allows the dryer's inlet temperature to be set.

The term "autoignition" means the ignition of combustible matter in air subjected to uniform heat. The temperature of the surrounding atmosphere (storage temperature) that initiates autoignition after self-heating of the product is called the autoignition temperature. Self-heating is caused by an already evident oxidation in air at the storage temperature. Such oxidation will liberate a certain amount of heat per unit time and mass. If the heat is not entirely transmitted to the surroundings, the product will heat up and autoignition may result.
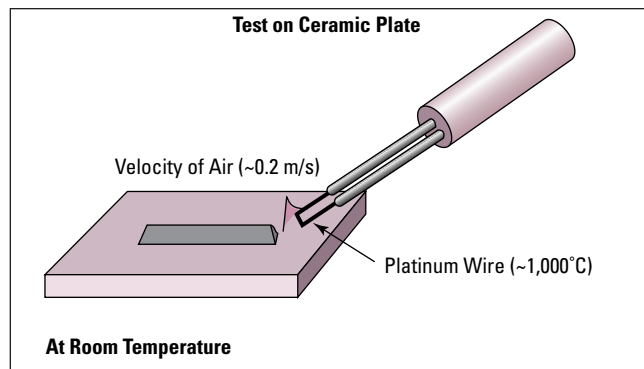
The autoignition temperature is determined in a Grewer oven (Figure 2). A test material (approximately 8 mL) is placed into a stainless steel wire-mesh container and put into the oven. A second container, filled with a reference material (graphite), is also inserted. Air is blown through a heating block. An exothermic reaction is considered to occur if the temperature curve of the test substance rises above that of the graphite. The test reports gives the temperature at which the first exothermic reaction occurs (3).

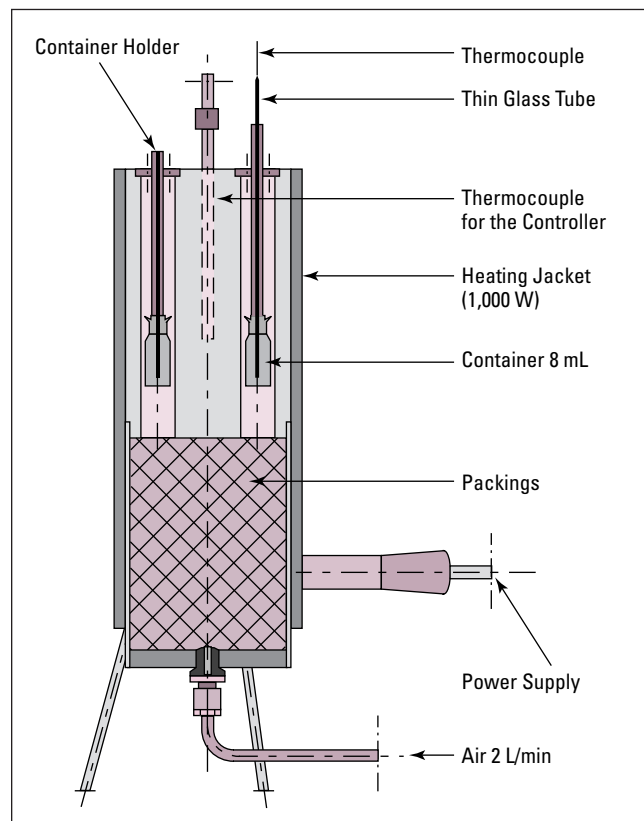## Open-cup test for exothermic decomposition (Luetolf)

Elevated temperature may cause a product to undergo a chemical transformation that will not require oxygen. The reaction may be endothermic or exothermic. The latter greatly affects safety, while the former may only affect operations or quality control.

Exothermic reactions may generate gases upon decomposition. These increase the pressure in a closed ves-

■ *Figure 1. The combustion rating is determined at ambient temperature.*

Test on Ceramic Plate

Velocity of Air (~0.2 m/s)

Platinum Wire (~1,000°C)

At Room Temperature

■ *Figure 2. Grewer oven detects an exothermic reaction in an air stream.*

Container Holder

Thermocouple

Thin Glass Tube

Thermocouple for the Controller

Heating Jacket (1,000 W)

Container 8 mL

Packings

Power Supply

Air 2 L/min

sel. In addition, these gases may be flammable. This could pose an additional explosion risk.

Determining an exothermic decomposition in an open cup (Figure 3) involves measuring the lowest temperature that results in an exothermic reaction in a test tube under lean oxygen conditions. This test is made on products or reaction mixtures subjected to elevated temperatures over long periods, closed off from fresh air. Examples include reactors, and vacuum ovens and dryers (3).

Temperature-programmed conditions (dynamic test)

A test sample and a reference sample (again, graphite) are heated in test tubes at a rate of 2.5°C/min, up to a final oven temperature that depends upon the sample. For distillation residues and products to be milled, the maximum is 350°C, while it is 220°C for final products that are dried during manufacture.

A linear plot of temperature vs. time will reveal a straight, sloped line for the graphite, and, for the sample, a

Table 1. Safety characteristics of dust layers and dust clouds.

Dust Layers	Dust Clouds
Ignition rating	Lower explosible limit (LEL)
Burning class (BC)	Maximum explosion overpressure P_{max}
Constant temperature stability (CTS)	Maximum explosion constant K_{max}
Differential scanning calorimetry (DSC)	Limiting oxygen concentration (LOC)
Exothermic reaction in a fresh air stream (Grewer)	Minimum ignition energy (MIE)
Exothermic decomposition in an open cup	Minimum ignition temperature (MIT)
Shock sensitivity	

Table 2. Ignition-properties classification for dust layers based ignition temperature level.

Result	Rating
No reaction at 360°C (possible at higher temperature)	1
Reaction at 360°C	2
Reaction at 330°C	3
Reaction at 300°C	4
Reaction at 270°C	5
Reaction at 240°C	6

peak above this line will show an exothermic reaction. The onset temperature for this reaction is at the point at which the temperature-time exotherm rises above the line for graphite.

In addition to the above-mentioned procedure, the following tests can be done simultaneously: a flammability test of the decomposition gases; and a procedure measuring the amount of gases.

Constant temperature stability (isoperibolic) test

A sample is stored in an oven at constant temperature for 8 h, and its temperature-time profile is recorded. If an exotherm exists, the sample temperature will rise and peak above the oven reading. If a peak is found, fresh samples are tested and the oven temperature is dropped in 10°C-increments until no temperature rise is found. Thus, the minimum exothermic temperature is found.

Hot storage test

In many products, exothermic processes (decompositions) may take place at relatively low temperatures, with a low reaction velocity and a low heat-generation rate. If a material is discharged at an elevated temperature and stored in large, compact quantities, heat dissipation may be reduced so much that self-heating takes place. Often, this process is slow initially, but, then, with rising temperature, it can accelerate within hours or days and finally change into a thermal explosion, rupturing the container and autoigniting the product.

The hot storage test determines the lowest temperature at which, under insulated conditions, a substance shows an exothermic reaction. This test is carried out under almost adiabatic conditions.

The sample is placed in a 200-mL Dewar flask and stored in a laboratory oven at constant temperature for up to 72 h. If an exothermic reaction takes place, the sample temperature will rise, especially in the center of the flask. The test is repeated with fresh samples at lower temperatures — again, in steps of 10°C — until self-heating is less then 5°C over the oven temperature. This temperature is the Dewar temperature limit (DTL). There is a linear correlation between the adiabatic induction time of a detected decomposition and the oven temperature at a constant volume.

To allow for the difference of scale between the Dewar flask and a 1.5-m³ receiving container used in the test, and to a provide for an adequate margin of safety, the maximum discharge temperature MDT is fixed at:

$$MDT = DTL - 50°C \qquad (1)$$

Differential scanning calorimetery (DSC)

In addition, DSC can determine the onset temperature and quantify the total energy release ΔH of any exothermic reaction. This test is done in addition to the hot storage one.

Shock sensitivity

For grinding processes and paddle dryers with bars, the sensitivity of a product to shock has to be found. A product is impact-sensitive and explosible if it disintegrates with a bang

Table 3. Test results determine the burning class (BC) of a powder layer.

Test Result		Class	Reference Substance
No ignition	No spreading of fire	1	Table salt
Brief ignition, rapid extinction		2	Tartaric acid
Localized combustion or glowing with practically no spreading		3	D+ lactose
Glowing without sparks (smoldering) or slow decomposition without flames	Fire spreads	4	H- acid*
Burning fireworks or slow, quiet burning with flames		5	Sulfur
Very rapid combustion with flame propagation or rapid decomposition without flame		6	Black powder

* 8-amino-1-naphthol-3,6-disulfonic acid.

upon its exposure to impact under given test conditions. A test sample is placed between the upper and lower parts of a stamp (Figure 4). Then, a drop hammer is ejected. This test is carried out in a dark room to observe any kind of reaction. The result is regarded as positive if the sample burns or decomposes with detonation, flame (sparks), or heavy smoke (*1, 3*).

DUST CLOUDS

Any time a combustible dust is processed or handled, a potential for deflagration exists. The degree of the deflagration hazard will vary depending on the type of combustible dust and processing methods. Evaluating a combustible dust explosion hazard and the necessary prevention techniques employed are determined by using test data as described below (*4*).

Modified Hartmann apparatus

This test is designed as a qualitative pretest of the explosion behavior of dust/air mixtures. A test sample is placed in a 1.2-L cylindrical glass tube (Figure 5). By introducing pressurized air into the glass chamber, the dust is blown through an ignition source (a continuous spark with an electrical energy of about 10 J).

A positive reaction is recorded if a dust fire occurs, or if the test equipment's hinged cover opens. As a rule of thumb, only dust explosions leading to an indication 1 in the apparatus are true St 1 dusts. (The St scale, shown in Table 4, will be explained later.) Otherwise, for St 0 and 2, additional tests must be made in a Siwek 20-L apparatus.

Siwek 20-L apparatus

This method measures the deflagration parameters of a combustible dust/air mixture in a near-spherical 20-L (or greater) closed vessel — the Siwek apparatus. The parameters are the dust explosivity, lower explosion limit (LEL), maximum explosion overpressure P_{max}, maximum explosion constant K_{max}, and the limiting oxygen concentration (LOC) (*3, 5–7*).
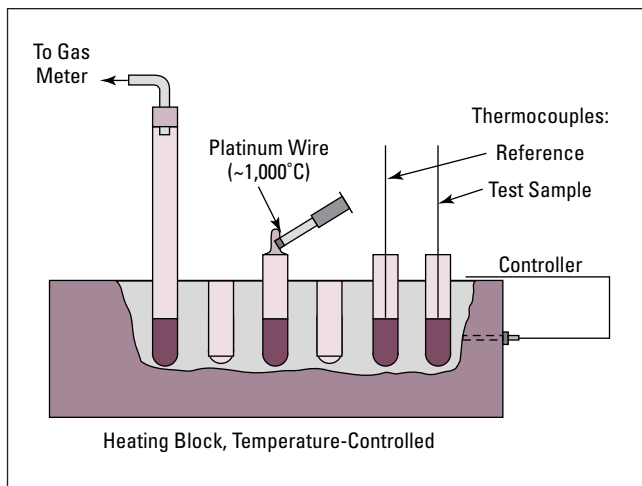
■ *Figure 3. Lutelof oven evaluates exothermic-reaction temperatures for materials exposed to heat for long periods at lean oxygen concentrations.*
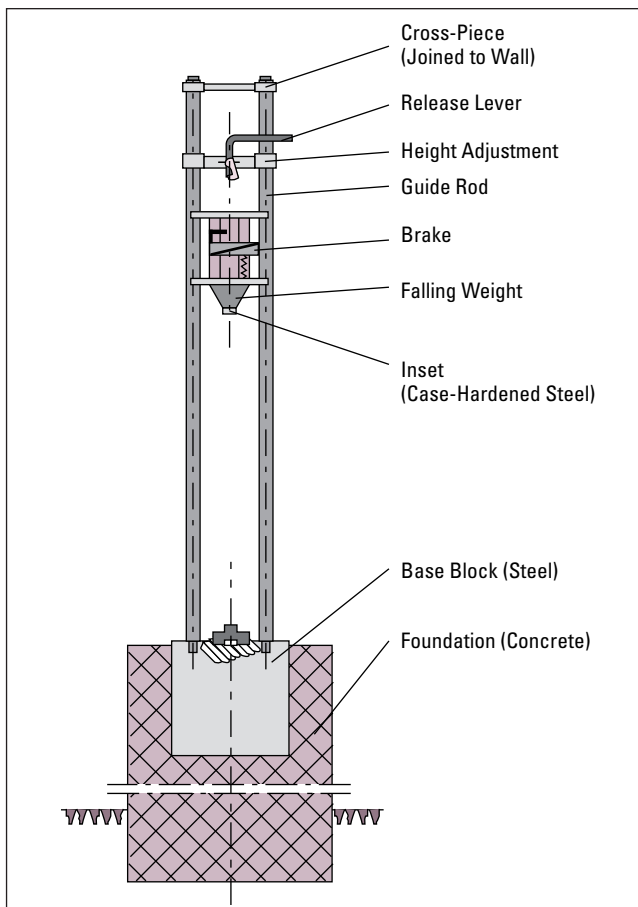
■ *Figure 4. Falling hammer test measures sensitivity to shock, important in operations such as grinding.*
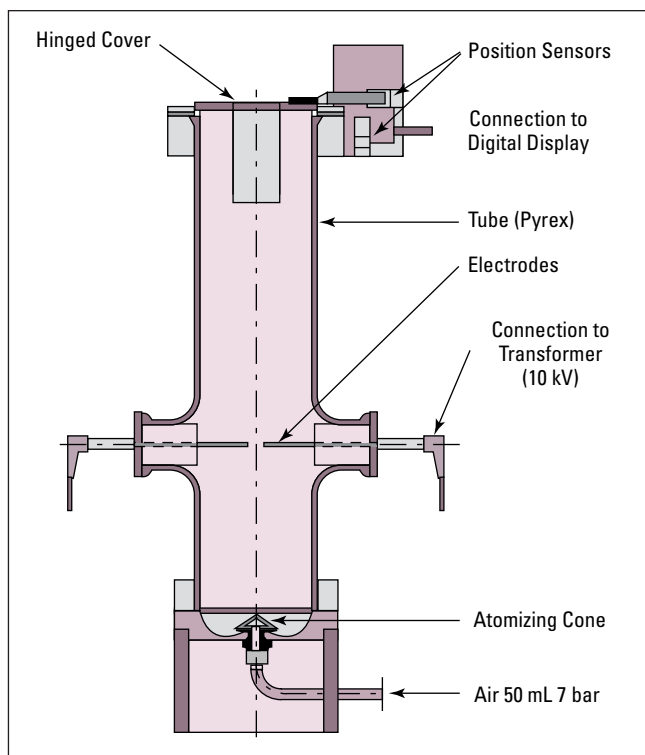
The test uses chemical igniters as the ignition source; the ignition energy (IE) is 10 kJ, and the ignition delay time $t_v = 60$ ms.

The parameters measured are P_{max} and the maximum rate of pressure rise $(dP/dt)_{max}$ (Figures 6 and 7). This test provides information to predict the effects of an industrial-scale deflagration of a dust/air mixture.

P_{max}, when determined in closed, spherical, or cubic vessels of sufficient volume ($V \geq 20$ L) with a central ignition source, is practically indepen-

Hinged Cover

Position Sensors

Connection to
Digital Display

Tube (Pyrex)

Electrodes

Connection to
Transformer
(10 kV)

Atomizing Cone

Air 50 mL 7 bar

dent of the volume of the vessel. But, $(dP/dt)_{max}$ does depend on the volume. It decreases with increasing volume, following the cubic law. K_{max} is dust- and test-method specific, but independent of volume. The cubic law is applicable only for a volume $V \geq 20$ L.

The cubic law is:

$$V^2 \ [\text{m}^3] \times (dP/dt)_{max} \ [\text{bar/s}]$$
$$= K_{max} \ [\text{m-bar/s}] \qquad (2)$$

The large number of dusts produced and handled in processing plants led to a classification of dusts, according to their K_{max} values, into dust explosion classes (Table 4).

Table 4. How dust explosion classes are defined.

Dust Explosion Class	K_{max}, m-bar/ s
St 1	> 0–200
St 2	201–300
St 3	> 300

Minimum ignition energy (MIE)

For an assessment of the hazard situation in dust processing plants, knowledge of the minimum ignition energy is indispensable. This value can conceivably establish the extent and, hence, the cost of protective measures (*4*). Finding the minimum ignition energy involves testing for the failure to ignite (*4*, *8*). The MIE of a combustible substance is the lowest value of the electrical energy stored in a capacitor, which upon discharge, just suffices to ignite the most readily ignitable fuel/air/mixture at atmospheric pressure and room temperature. Various test apparatuses are used worldwide to determine the MIE. To assure a standardized test procedure, a third-generation test apparatus known as MIKE 3 (Figure 8) was developed by Kühner AG, Switzerland.

The MIE is usually quoted as a range: The lower value represents the highest energy at which no ignition is found in at least 10 experiments. The higher value, on the other hand, is the lowest energy at which the dust/air mixture is just ig-

nited: No ignition < MIE < Ignition.

Finding the MIE is described in a standard of the International Electrotechnical Commission (IEC) (*9*), and in an ASTM standard soon to be published (*10*). The MIE is generally obtained with an inductance in the discharge circuit. However, to assess the incendivity of electrostatic discharges in dust/air mixtures, the MIE must also be determined without an inductance in the discharge circuit. With flammable gases, the influence of the inductance is generally not detectable. Dusts, particularly very easily ignitable dusts, also exist where the inductance has also no influence.

Tests should be conducted with dust clouds of optimum dust concentration for ignition and having the lowest turbulence level experimentally attainable. The optimum dust concentration cannot be obtained in one step. Therefore, a special procedure is required. Its main steps are:

1. Start with a value of the ignition energy that will reliably cause ignition of a given concentration in air of the dust. Then, reduce the spark energy in steps (*e.g.*, halving it) at the given dust concentration until the dust cloud no longer ignites at 10 tests at a given energy.
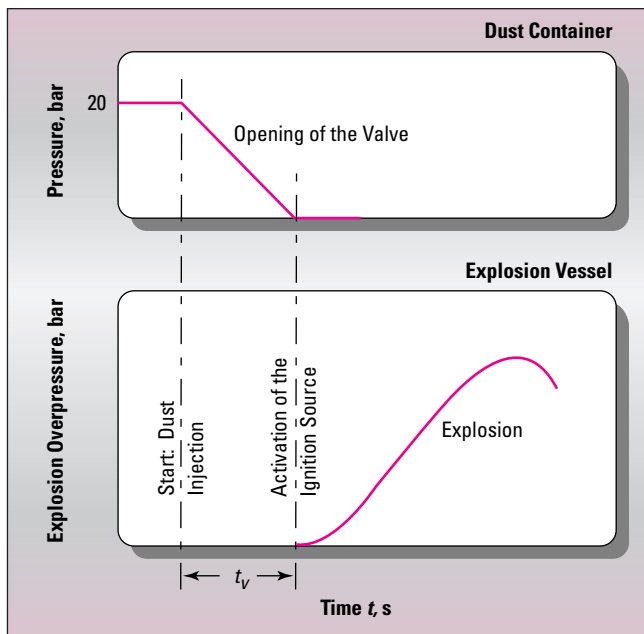
2. Repeat the procedure at different dust concentrations until the lowest MIE is found.

The MIE lies between the highest energy at which ignition fails to occur in 10 successive attempts to ignite the dust/air mixture W_1, and the lowest energy at which ignition occurs within 10 successive attempts W_2 (Figure 9):
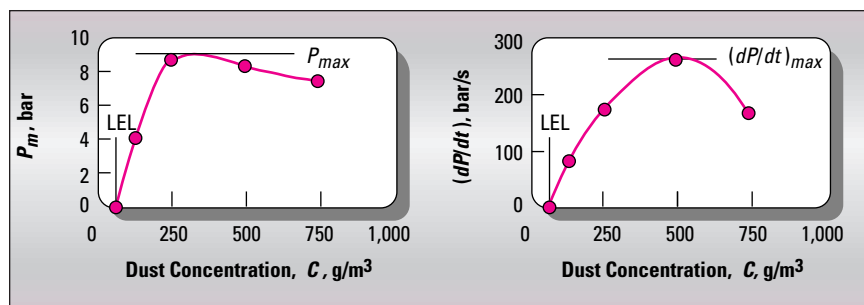
$$W_1 < \text{MIE} < W_2 \qquad (3)$$

Inductance L causes the capacitor to discharge in a protracted manner. As Figure 10 shows, dust/air mixtures are more readily ignited by time-extended discharges than by purely capacitive discharges. The three symbols in the figure represent experiments made at laboratories of different companies.

■ *Figure 6. Results of a dust-investigation procedure done in standard test equipment.*

Dust Container

Opening of the Valve

Pressure, bar

20

Explosion Vessel

Explosion Overpressure, bar

Start: Dust Injection

Activation of the Ignition Source

Explosion

t_v

Time t, s

■ *Figure 7. Determination of maximum explosion pressure and maximum rate of pressure rise.*

P_m, bar

10
8
6
4
2
0

LEL

P_{max}

0   250   500   750   1,000

Dust Concentration, C, g/m³

(dP/dt), bar/s

300

200

100

0

LEL

$(dP/dt)_{max}$

0   250   500   750   1,000

Dust Concentration, C, g/m³

■ *Figure 8. Apparatus for finding the minimum ignition energy (MIE) of dusts.*

over 100 dusts from various laboratories (*5, 9*). The following equation, found by regression analysis, compares values measured by both furnaces:

$$MIT_{GG} = 1.1 \times MIT_{BAM} - 10°C \quad (4)$$

Powder volume resistivity

A material's powder volume resistivity ρ_R characterizes its static dissipative properties. Surfaces of materials will be polluted if exposed to the air, and will consequently adsorb humidity. Resistivity is not an absolute property of a powder, but depends strongly on its moisture content and on the method of measurement. From an electrostatic point of view, dusts are considered to be conductors incapable of storing charge until their resistivity exceeds 10^9 Ω-m.

Test requirements

Where no safety data are available, the required tests must be done before introducing a product into a process.
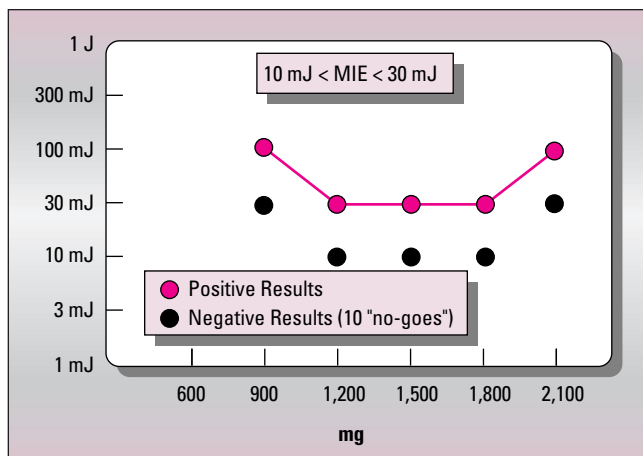
If the MIE is used to assess ignition hazards resulting from electrostatic charges, it must be found without an inductance in the discharge circuit. Only in this way is it possible to make a realistic evaluation of the incendivity of electrostatic discharges in dust/air mixtures.

Minimum ignition temperature (MIT) of dust clouds

This MIT is the minimum temperature at which a dust cloud will autoignite. The cloud is exposed to air and heated to various temperatures in a furnace (*11*). Ignition is indicated by visual observation of a flame. The chemical nature of the dust, as well as its concentration, particle size, moisture, and surface area all affect the result. The MIT can be determined either in the Godbert-Greenwald (GG) furnace (Figure 11a) or the BAM furnace (German Federal Institute for the Testing of Materials (Berlin), Figure 11b). To compare the MIT values measured in both furnaces, these minimum temperatures have been investigated for

■ *Figure 9. Results of a typical test showing boundaries for the MIE.*

1 J

300 mJ

100 mJ

30 mJ

10 mJ

3 mJ

1 mJ

10 mJ < MIE < 30 mJ

● Positive Results
● Negative Results (10 "no-goes")

600   900   1,200   1,500   1,800   2,100

mg

■ *Figure 10. Dust/air mixtures are more readily ignited by time-extended discharges than by purely capacitive charges.*
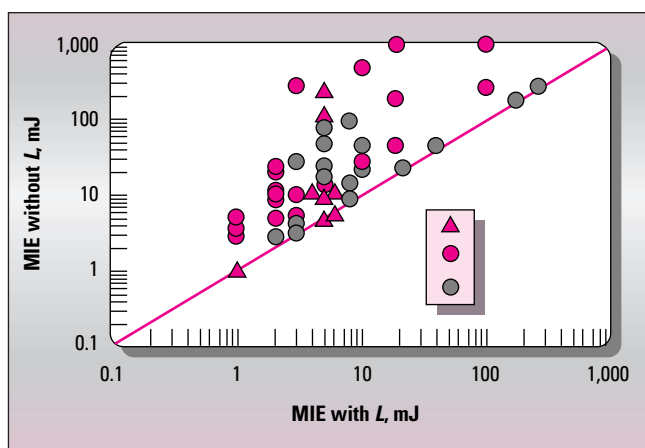
■ *Figure 11. MIT of dust clouds is measured in one of two furnaces.*

a. Godbert-Greenwald Furnace

b. BAM Oven
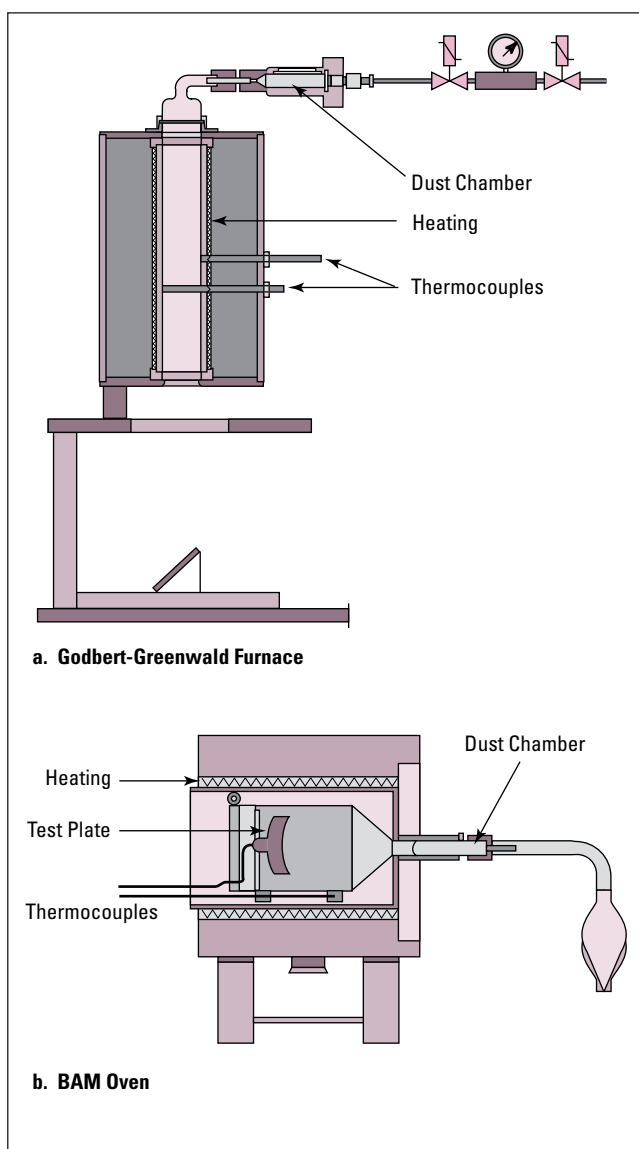
The test laboratory must repeat the requisite tests whenever local management suspects that an operation has become more hazardous. This may increase as a result of:

• Modifications in the production process (including preparatory steps) or equipment substitutions;

• Irregularities during production; and

• Changes in the manufacture or quality of any raw or auxiliary materials.

Due to changes in governmental laws, international regulations, and testing technologies, the specific tests should be repeated at least once every five years.
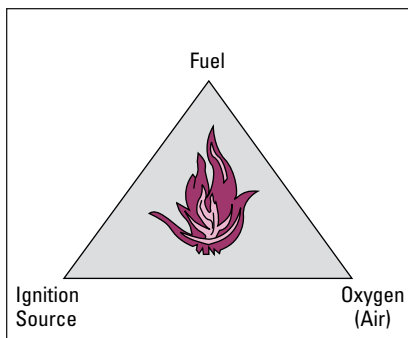
Outlook

Thorough knowledge of the ignition behavior of dust/air mixtures with electrical sparks (MIE) and hot surfaces (MIT) is important for assessing the hazards in dust-carrying plants. The ignition behavior essentially sets the extent, and, hence, the cost of the protective measures to be used. This is especially true for the prevention of ignition sources and for the understanding of the ignition phenomena regarding static electricity, *e.g.*, brush discharges, bulk surface discharges, spark discharges, and propagating brush discharges.

PROTECTIVE MEASURES

Using preventive measures against explosions requires reliably excluding one of the three requirements necessary to generate an explosion, as shown in the familiar hazard triangle (Figure 12), that is, eliminating at least one of the sides of the triangle (*12*). An explosion can, thus, be excluded with certainty by:

• Avoiding the development of explosible mixtures (combustible dusts, flammable gases); or

• Replacing the atmospheric oxygen by an inert gas, working in a vacuum, or using inert dust; or

• Preventing the occurrence of effective ignition sources.

All three measures fall under what

■ *Figure 12. The familiar hazard triangle serves as the basis for explosion protection.*

■ *Figure 13. Filling and emptying operations can pose a serious electrostatic hazard if the powder is combustible.*
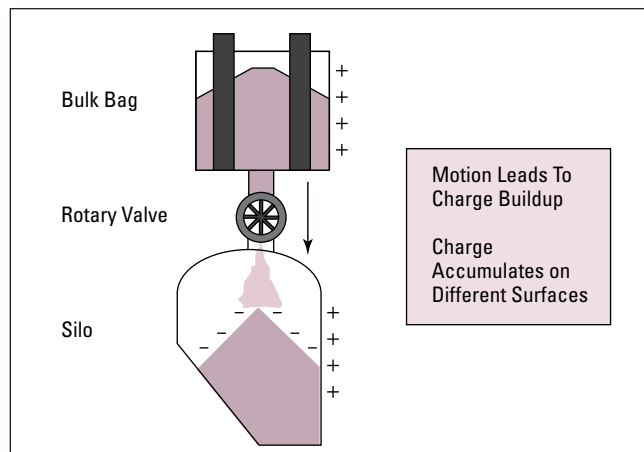
is called preventive explosion protection. For safety, the engineer must ensure that at least one of the three conditions is eliminated or so strongly reduced that an explosion is no longer possible (*8, 12–14*).

When combustible dusts are handled, avoiding an explosive atmosphere by keeping the dust concentration outside the explosive range is rarely possible, due to sedimentation or whirling up of the material. Thus, as a matter of principle, an explosive atmosphere can only be avoided with certainty by reducing the oxygen concentration, *e.g.*, inerting. In practice, however, inerting often cannot be used. For such situations, the only measures become either avoiding effective ignition sources or using explosionproof equipment.

It is acceptable to avoid effective ignition sources as the sole protective measure, if it is established that the occurrence of these ignition sources is excluded with certainty under all normal operating conditions, as well as for all possible deviations. "Trivial" ignition sources (such as welding or smoking) must be excluded by administrative actions.

This article does not look at ignition sources that could result from processes introducing energy into the product being handled, such as from mechanically generated sparks or hot surfaces. Nor does it discuss products that may form glowing particles during handling (*e.g.*, those with a BC ≥ 4 (see Table 3)).

Electrostatic charging is certainly an ignition source not to be underestimated in powder operations. This is a normal occurrence in most such processes and operations, and, therefore, our main topic. As such, we will indicate protective measures. In understanding these measures, the following product and plant properties are keys for an accurate hazard assessment:
• MIE of the bulk material (measured without inductance in the discharge circuit);
• MIT of the bulk material;
• ρ_R of the powder;
• Particle-size distribution of the bulk material and its median value *M*; and
• Volume and shape of the silo or container (volume and shape of the product heap and of the dust cloud).

Unless otherwise stated, the following sections are based on the assumption that the bulk materials are handled without flammable gases or vapors being present.

Filling and emptying operations

In these operations, ignition hazards are of prime importance owing to electrostatic charging. The hazards comprise possible charge accumulation not only on equipment, as well as on drums and containers, but also for bulk materials that are insulating (Figure 13).
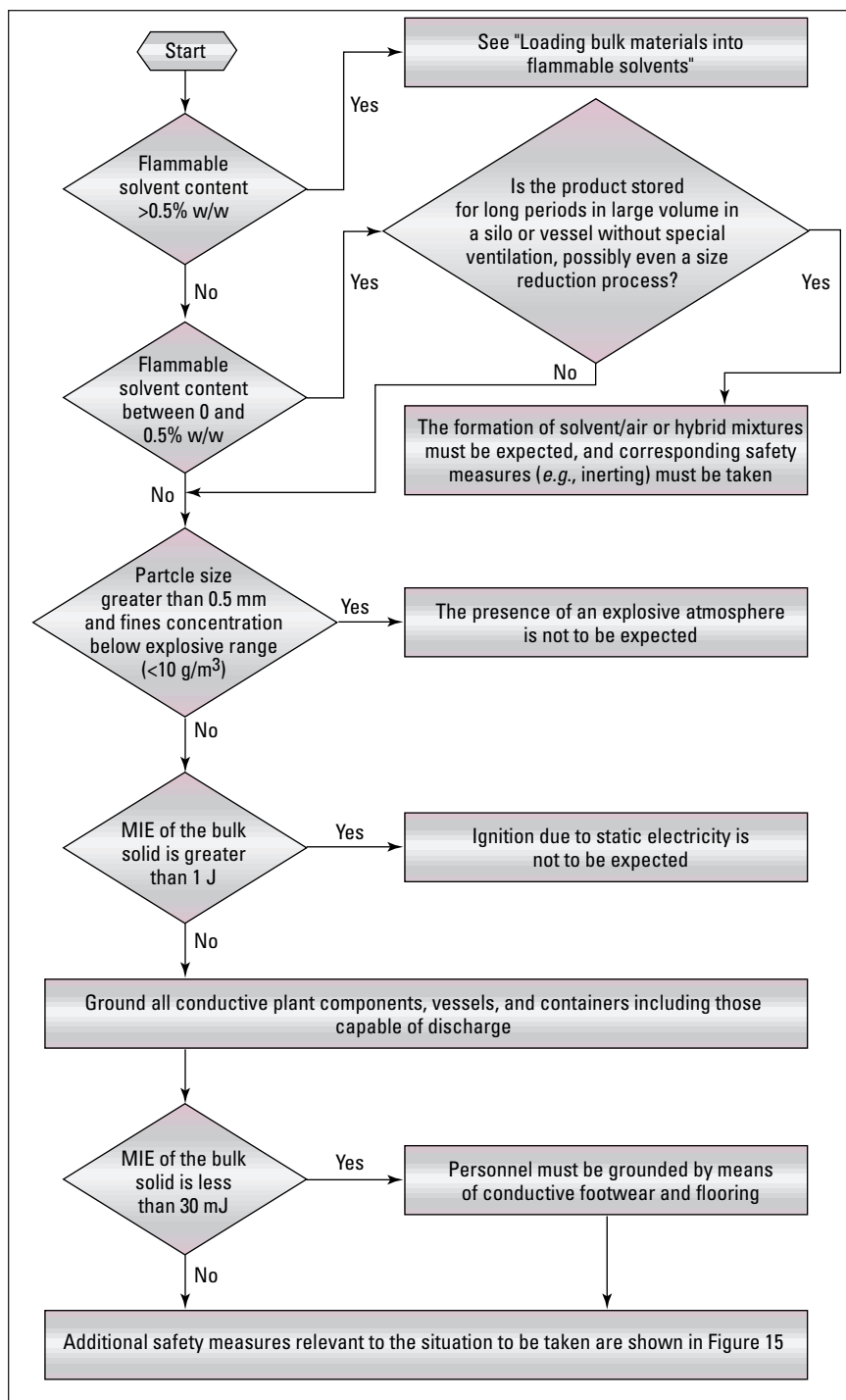
Assuming that the insulating bulk material carries a charge, filling represents the most hazardous operation for the following reason: During this procedure, the material undergoes dispersion (via gravity feed, pneumatic transport, or by some other means) and can, therefore, acquire charge during the separation processes occurring in transport. The bulk material and, hence, its associated charge, are then packed into a small space. Here, the charge is not able to flow to the ground quickly enough, even with a conductive and grounded receiver. This generates a high space-charge density and electric field. In addition to charge accumulation, there can be problems due to heat accumulation and the possibility of entrainment of smoldering lumps.

To help ensure safety, a decision tree is presented for safe handling, based on the product and plant properties listed above (Figure 14). Use this decision tree, along with matrixes in Figure 15 to ensure safe filling and emptying of containers, vessels, and silos of varying volumes.

Loading bulk materials into flammable solvents

Whenever it is possible, bulk materials should be fed into flammable solvents under closed conditions and in an inert atmosphere (Figure 16). This can be accomplished by using a bucket wheel, two-valve system, feed screw, or by conveying by an inert gas. If such a closed introduction system is not possible, the next best thing is either to cool the solvent below its flash point (at least

Start

Flammable solvent content >0.5% w/w — Yes → See "Loading bulk materials into flammable solvents"

No

Flammable solvent content between 0 and 0.5% w/w — Yes → Is the product stored for long periods in large volume in a silo or vessel without special ventilation, possibly even a size reduction process? — Yes

No

Is the product stored... — No / Yes → The formation of solvent/air or hybrid mixtures must be expected, and corresponding safety measures (*e.g.*, inerting) must be taken

Particle size greater than 0.5 mm and fines concentration below explosive range (<10 g/m^3) — Yes → The presence of an explosive atmosphere is not to be expected

No

MIE of the bulk solid is greater than 1 J — Yes → Ignition due to static electricity is not to be expected

No

Ground all conductive plant components, vessels, and containers including those capable of discharge

MIE of the bulk solid is less than 30 mJ — Yes → Personnel must be grounded by means of conductive footwear and flooring

No

Additional safety measures relevant to the situation to be taken are shown in Figure 15

■ *Figure 14. Follow this decision tree to help prevent fires and explosions from occurring with combustible powders in your plant.*

by 5°C) before loading the bulk material, or to introduce the bulk material first and then the flammable solvent.

If it is unavoidable for the open addition of a bulk material into a previously loaded flammable solvent at a temperature less than 5°C below flash point, then the following points must be considered:

• The operator must be grounded;
• All aids to introduction, such as funnels, charging chutes, and the like, must be made in conducting materials and be grounded during transfer;
• Containers for solvent and powders must be of conductive material and grounded during the charging process;
• Conductive vessels for solvents and bulk materials may be used with an insulating internal coating up to 2 μm maximum, if they are grounded during filling and emptying; and
• Normal loose plastic sacks or plastic liners should not be used. Plastic liners or plastic sacks with at least a one-sided nonchargeable surface (surface resistance of <10^{11} Ω at 30% relative humidity) are allowed according to ASTM D257-93(1998) (*15*) (*e.g.*, plastic sacks with an antistatic coating, paper sacks, or paper sacks lined on one side with a normal plastic coating, if the coating thickness is less than 2 mm).

Mixing

Provided that the following conditions are met, effective ignition sources during mixing generally do not occur, even with dusts exhibiting high ignition sensitivity:

• During filling and emptying of the mixer, the considerations and measures that apply are the same as those for the same operations in containers;
• In the filling and emptying of the mixer, the mixing elements must be at a standstill or run at a circumferential speed (relative speed) that does not exceed 1 m/s. This restriction must be assured by technical safeguards;
• In the closed condition and with a fill level of 70 vol. % or more, the circumferential speed of the mixing elements is no longer restricted;
• No insulating inner coatings with high electrical breakdown-strength (breakdown voltage must be less than 4 kV) may be affixed to the inner wall of the mixer (product buildup must be checked);
• Circumferential speeds up to 10 m/s can be tolerated during filling and emptying with a mixer not filled to 70 vol. %, provided that the MIT of the

			Minimum Ignition Energy, MIE, mJ (without Inductance)				
Specific Powder Resistivity, MΩ·m	Median Particle Size, mm		< 3	3 - 10	10 - 30	30 - 1,000	>1,000
<1 Conductive		Any Value	- All parts of the equipment must be conductive* and grounded. - All containers must be conductive* or dischargeable† and grounded.				
>1 (Non-conductive)		<0.5				No additional measures required other than the ones from the decision tree (Figure 14).	
		0.5-1.5	No additional measures are required if the material is charged by gravity from a conductive and grounded installation. **or** Restrict the filling rate to 5 kg/s and use conductive* or dischargeable† /charge dissipative‡ container that is grounded. **or** Apply additional explosion protection measures (*e.g.,* inerting). Otherwise: Seek advice of experts.				
		1.5-3.0					
		3.0-6.0					

* Use only conductive containers, 1 MΩ ($<10^6$ Ω), or those capable of discharge and ground.

† Containers capable of discharge: The leakage resistance to the ground point from any point on the surface of the container must be less than 100 MΩ ($<10^8$ Ω).

‡ Charge dissipative ($\geq 10^8 \leq 10^{11}$ Ω) containers having at least on one side a surface resistance R_{OA} measured according to ASTM method D257-93 (Surface Resistivity) of less than 100 Giga Ω (10^{11} Ω) at 30% relative humidity and more than 100 MΩ at 65% relative humidity.

■ *Figure 15a. For volumes of less than 0.2 m³ (55 gal).*

processed product lies above the limit values specified in Table 5; and

• Mixers that have an orbiting, rotating helical screw inside of a conical shell with bottom support of the screw can heat up during operation, so care must be exercised with substances capable of spontaneous decomposition.

Dust separation

The dust explosion hazard must not be underestimated in dust separators, especially filters. The probability is large of a fine dust atmosphere sensitive to ignition. In addition to the entrainment of ignition sources, which must be assessed based on the product properties (*e.g.*, formation of smoldering lumps) and upstream op-eration, the danger of ignition through electrostatic charging is of prime importance (Figure 17).

Electrostatic charging must be inhibited by the following measures:

• Grounding of all conductive apparatus parts. If a filter cloth made of insulating material is used, particular attention must be paid to grounding all conductive parts that could possi-

Table 5. MIT lower limits for products filled and emptied in mixers while running.

MIE*, mJ	MIT, °C
< 1	Do not process
1–3	530
3–10	500
10–30	465
30–100	430
100-300	395
300–1,000	360
> 1,000	325

* The MIE values must be determined with an additional inductance in the discharge circuit.

Table 6. Requirements for safe use of FIBCs.

Bulk Material MIE	No Explosible Atmosphere	Explosible Dust or Vapors	Flammable Gases
MIE* > 1 J	A	B	C
3 mJ < MIE* < 1 J	B	B	C
MIE* < 3 mJ	C	C	C

* Measured without inductance in the electrical circuit

Key:
A: No special requirements.
B: Breakdown voltage of the FIBC wall material must not exceed 4 kV to prevent propagating brush discharges.
C: The bag material including the slings must be electrostatically conductive. The resistance to the ground measured at any bag location (inside and outside) must be less than 100 MW (10^8 W). The FIBC must have a grounding tap. The conductivity and the necessity for grounding must be clearly marked.

Minimum Ignition Energy, MIE, mJ (without Inductance)

Columns: < 3 | 3 - 10 | 10 - 30 | 30 - 100 | 100 - 300 | 300 - 1,000 | >1,000

Specific Powder Resistivity, MΩ·m — **Median Particle Size, mm**

Specific Powder Resistivity, MΩ·m	Median Particle Size, mm	Measures
< 1 Conductive	Any Value	- All parts of the equipment must be conductive* and grounded. - All containers must be conductive* or dischargeable† and grounded.
1 - 10,000	<0.1 0.1-0.2 0.2-0.5 0.5-1.0 1.0-2.5 2.5-5.0	No additional measures are required if the material is charged by gravity from a conductive and grounded installation. **or** Restrict the filling rate to 5 kg/s and use conductive* or dischargeable†/charge dissipative‡ container that is grounded. **or** Apply additional explosion protection measures (*e.g.*, inerting). Otherwise: Seek advice of experts No additional measures required other than the ones from the decision tree (Figure 14).
> 10,000	<0.1 § 0.1-0.2 § 0.2-0.5 § 0.5-1.0 § 1.0-2.5 § 2.5-5.0 §	No additional measures are required if the material is charged by gravity from a conductive and grounded installation. **or** Restrict the filling rate to 5 kg/s and use conductive* or dischargeable† /charge dissipative‡ container that is grounded. **or** Apply additional explosion protection measures if the fines are in concentration of greater than 10 g/m^3. **or** Seek advice of experts. No additional measures required other than the ones from the decision tree (Figure 14).

* Use only conductive containers, 1 MΩ (<10^6 Ω), or those capable of discharge and ground.

† Containers capable of discharge: The leakage resistance to the ground point from any point on the surface of the container must be less than 100 MΩ (<10^8 Ω).

‡ Charge dissipative (≥10^8≤ 10^{11} Ω) containers having at least on one side a surface resistance R_{OA} measured according to ASTM method D257-93 (Surface Resistivity) of less than 100 Giga Ω (10^{11} Ω) at 30% relative humidity and more than 100 M Ω at 65% relative humidity.

§ Fines in concentrations greater than LEL are not to be expected for dust-free forms during normal discharge or charging operations involving packaging.

■ *Figure 15b. For volumes of 0.2 – 2.0 m³ (55 – 550 gal).*

bly be insulated from the ground (e.g., filter supports, clamps). This must be especially checked after repair and maintenance work;

• With a MIE < 3 mJ or in the presence of flammable gases or vapors in the air being cleaned, electrically conducting filter materials must be used, except when inerting is employed. Continuity of the conductivity and safe grounding must be checked. Multiple washings can have an adverse effect on the continuity of the filter material's conduc-

tivity and, thus, require repeat checking; and

• All inner walls on which dust can impact at high speed must not have any insulating inner coatings with a high electrical breakdown-strength (breakdown voltage must be less than 4 kV; check these periodically).

In general, with dusts with a MIE < 10 mJ, it is advisable either to implement explosion protection measures that go beyond the avoidance of effective ignition sources or consult company specialists. Further, the fan

must be installed on the clean air side and dust deposits must be avoided in the pipe and fan housing (check periodically or install a dust control unit).

Flexible intermediate bulk containers (FIBCs)

FIBCs are used on ever-increasing scale in the powder handling industry. Depending upon the hazard situation where they are used, they must meet different requirements (Table 6) to avoid ignition hazards caused by electrostatic charging.

			Minimum Ignition Energy, MIE, mJ (without Inductance)		
Specific Powder Resistivity, MΩ·m	Median Particle Size, mm		< 10	10 - 1,000	>1,000
< 1 Conductive	Any Value		- All parts of the equipment must be conductive* and grounded. - All parts of the equipment must be conductive* and grounded. - All containers must be conductive* or dischargeable† and grounded.	No additional measures required.
1 - 10,000	< 5.0	- All parts of the equipment must be conductive* and grounded. - All containers must be conductive* or dischargeable** and grounded. - Apply additional explosion protection measures (*e.g.*, inerting). or Seek advice of experts.	Use only conductive* or dischargeable† containers that are grounded. **or** Restrict the filling rate to 5 kg/s. **or** Apply additional explosion protection measures (*e.g.*, inerting). **or** Seek advice of experts.	
> 10,000	< 5.0		Use only conductive* or dischargeable† containers that are grounded. **and** Apply additional explosion protection measures (*e.g.*, inerting). **or** Seek advice of experts.	

* Use only conductive containers, 1 MΩ (<10^6 Ω), or those capable of discharge and ground.

† Containers capable of discharge: The leakage resistance to the ground point from any point on the surface of the container must be less than 100 MΩ (<10^8 Ω).

■ *Figure 15c. For volumes of > 2.0 m³ (550 gal).*

Most FIBCs on the market today are made of polypropylene ribbon fabric. To pass the Type B classification, the following requirements are recommended:

• Any inner polyethylene coating or liner present must not be thicker than 20–30 μm; and
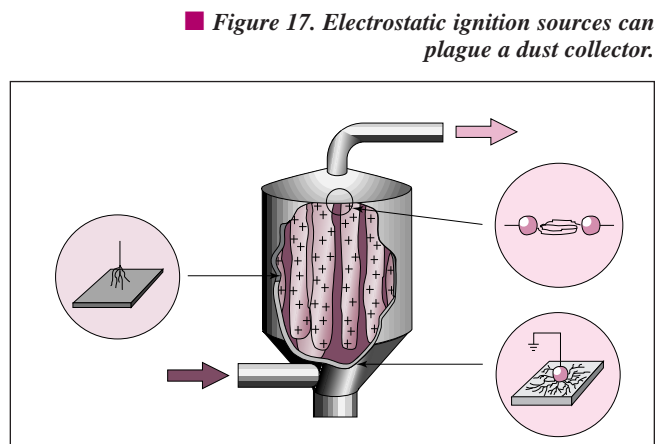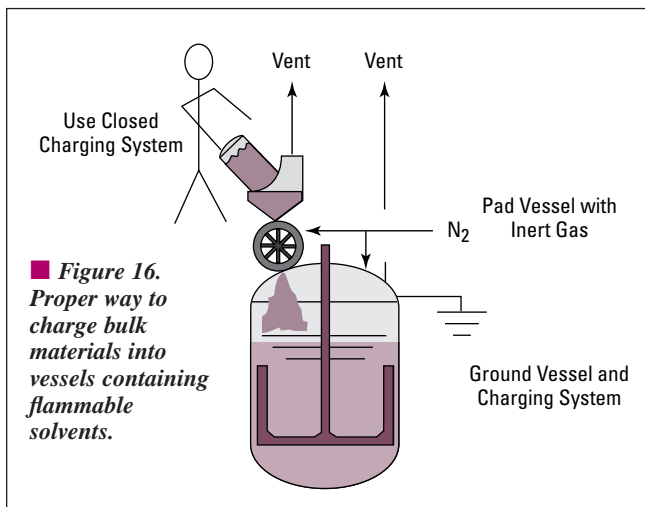
• The inliner must not be made of plastic.

FIBCs meeting the requirement of Type C are constructed as one of the following:

• The basic fabric consists of conductive material (*e.g.*, plastic with a sufficient admixture of carbon); or

• The basic fabric consists of nonconductive material, but the web contains interwoven threads of conductive plastic material that are interconnected; or

• The basic fabric consists of nonconductive material, but the web contains interwoven metal threads that are interconnected; or

• The basic fabric consists of nonconductive material, but the FIBC has an internal conductive coating.

To meet the specification as a Type C bag, the following requirements are recommended:

■ *Figure 16. Proper way to charge bulk materials into vessels containing flammable solvents.*

Use Closed Charging System

Vent   Vent

Pad Vessel with Inert Gas

N₂

Ground Vessel and Charging System

■ *Figure 17. Electrostatic ignition sources can plague a dust collector.*

• The FIBC must have an indication of its conductivity and the grounding requirement during charging and discharging;

• The FIBC must have a clearly marked area for the attachment of the grounding clamps; and

• The lifting straps must also be made of conductive material and have a leakage resistance of less than $10^8 \, \Omega$ to the FIBC body.

Using a Type C bag requires permanent grounding of the bag during the whole period while the bag is filled or discharged (Figure 18). The discharge from an ungrounded bag aligns to a sin-
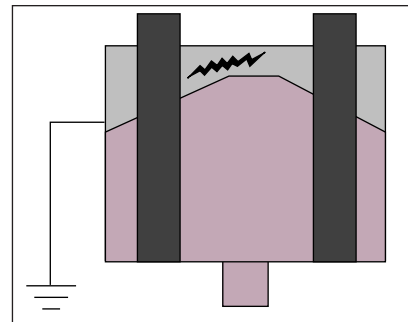
■ *Figure 18. Electrostatic discharges from a permanently grounded Type C FIBC.*

gle discharge point. Such a discharge is strong enough to ignite dust clouds.

The generated charge in the product pile cannot fully dissipate to the ground. Small discharges can occur along the surface of the pile. These are too weak to ignite dust clouds if the volume of the bag is less than 2 m^3, but strong enough to ignite solvent vapors. **CEP**

Literature Cited

1. **Verein Deustche Ingenieure,** "VDI 2263, Part 1: Dust Fires and Dust Explosions, Hazards — Assessment — Protective Measures, Test Methods for the Determination of the Safety Characteristics of Dusts," Verein Deustche Ingenieure (VDI), Dusseldorf, published by Beuth-Verlag, Berlin and Cologne (May 1990).
2. **United Nations,** "Recommendations on the Transport of Dangerous Goods," U.N., Section 33, pp. 323 ff, U.N., New York and Geneva (1995).
3. **Bartknecht, W.,** "Dust Explosions, Course Prevention, Protection," Springer-Verlag (1989).
4. **Jaeger, N., and R. Siwek,** "Safe Handling of Easily Ignitable Dusts," 5th World Congress of Chemical Engineering, San Diego, sponsored by AIChE, New York (1996).
5. **Siwek, R., and C. Cesana,** "Assessment of the Fire & Explosion Hazard of Combustible Products for Unit Operations," International Conference and Exhibition on Safety, Health and Loss Prevention in the Oil, Chemical and Process Industries, Singapore, Butterworth-Heinemann Ltd., London (Feb. 12–19, 1993).
6. **Siwek, R., and C. Cesana,** "Instructions for the 20-L Apparatus," 3rd revised ed., Kühner AG, Birsfelden, Switzerland (1991).
7. **American Society for Testing and Materials,** "Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts," ASTM E 1126-94, ASTM, West Conshohocken, PA (1994).
8. **Jaeger, N., and R. Siwek,** "Determination, Prevention and Mitigation of Potential Hazards due to the Handling of Powders during Transportation, Charging, Discharging and Storage," 31st Loss Prevention Symposium, Houston, sponsored by AIChE, New York (1997).
9. **International Electrotechnical Commission,** "Electrical Apparatus for Use in the Presence of Ignitable Dust: Part 2: Test Methods, Section 3, Method for Determining the Minimum Ignition Energy of Dust/Air Mixtures," IEC, Geneva (1994).
10. **American Society for Testing and Materials,** "Standard Test Method for Minimum Ignition Energy of Dust Air Mixtures," ASTM, West Conshohocken, PA (draft, 1997).
11. **American Society for Testing and Materials,** "Standard Test Method for Minimum Autoignition Temperature of Dust Clouds," ASTM E 1491-92, ASTM, West Conshohocken, PA (1992).
12. **Eckhoff, R. K.,** "Dust Explosions in the Process Industries," Butterworth-Heinemann Ltd, Oxford, U.K. (1991).
13. **Bruderer, R. E.,** "Use Bulk Bags Cautiously," *Chem. Eng. Progress,* **89** (5), pp. 28–31 (May 1993).
14. **National Fire Protection Association,** "Prevention of Fire and Dust Explosions in the Chemical, Dye Pharmaceutical and Plastics Industries," NFPA 654, NFPA, Quincy, MA (1994).
15. **American Society for Testing and Materials,** "Standard Test Methods for DC Resistance or Conductance of Insulating Materials," ASTM D257-93(1998), ASTM, West Conshohocken, PA (1998).

Further Reading

Bartknecht, W., "Explosion Protection, Basics and Application," in German, Springer-Verlag (1993).

Dahn, C. J., "How Safe Are Your Pneumatic Conveyors?," *Chem. Eng. Progress,* **89** (5), pp. 17–21 (May 1993).

International Electrotechnical Commission, "Electrical Apparatus for Use in the Presence of Ignitable Dust: Part 2: Test Methods, Sheet 2-5, Method for Determining the Minimum Explosible Concentration of Dust/Air Mixtures," IEC, Geneva (1990).

International Organization for Standardization, "Explosion Protection Systems — Part 1: Determination of Explosion Indices of Combustible Dusts in Air," ISO/DIS 6184/1, ISO, Geneva (1985).

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