

Dust Explosion Fundamentals: Ignition Criteria and Pressure Development

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Basic Concepts

The five ingredients required for a dust explosion are:

- Combustible particulates sufficiently small to burn rapidly when ignited
- A suspended cloud of these combustible particulates at a concentration above the Minimum Explosible Concentration (MEC)
- Confinement of the dust cloud by an enclosure or partial enclosure
- Oxygen concentration greater than the Limiting Oxygen Concentration (LOC) for the suspended dust cloud
- *Delayed* ignition source of adequate energy or temperature to ignite the suspended cloud.

The National Fire Protection Association (NFPA) has had several definitions of combustible dusts over the years. The current definition in NFPA 654 is “a combustible particulate solid that presents a fire or deflagration hazard when suspended in air or some other oxidizing medium over a range of concentrations, regardless of particle size or shape.” Previous editions of NFPA 654 and the 2004 edition of the NFPA Glossary of Terms define a combustible dust as “any finely divided solid material that is 420 microns or smaller in diameter (material passing a U.S. No. 40 Standard Sieve) and presents a fire or explosion hazard when dispersed in air.” The reason for the revision is that many combustible fiber segments, flat platelets, and agglomerates do not readily pass through a No. 40 sieve, but they can be dispersed to form a combustible dust cloud.

In practice, questions of combustibility as well as particle size often arise when evaluating the potential explosion hazard of marginally small particles or mixtures of combustible and noncombustible particulates. Many laboratories doing dust explosibility tests have developed dust explosibility screening tests, also called Go/No Go tests, to deal with these questions. Chapter 4 of the CCPS *Guidelines for Safe Handling of Powders and Bulk Solids* describes some of these tests. The ASTM E27.05 Subcommittee is currently working on a revision to the ASTM E1226-05 Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts to provide a standardized Go/No Go test for potentially combustible particulates.

MEC values are determined in the U.S. per the ASTM E1515 test procedure involving tests with various dust concentrations and a pyrotechnic igniter in a 20-liter sphere. The MEC corresponds to the smallest concentration that produces a pressure at least twice as large as the initial pressure at ignition. Eckhoff (2003) reports that MEC values are not very sensitive to particle diameter for diameters less than about 60 μm , but increase significantly with increasing diameter above this approximate threshold. The majority of the materials listed in Eckhoff Table A.1 (2003) have MEC values in the range 30 to 125 g/m^3 . These concentrations are sufficiently high that a 2 m thick cloud can prevent seeing a 25 watt bulb on the other side of the cloud (Eckhoff, 2003, p.9).

The confinement needed for a dust explosion is usually from the process equipment or storage vessel for the powder or dust. In the case of fugitive dust released from equipment and containers, the room or building itself can represent the confinement. Often, the dust cloud occupies only a fraction of the equipment or building volume, and the resulting explosion hazard is called a partial volume deflagration hazard. Pressures produced from partial volume deflagrations and the corresponding deflagration venting design bases are described in NFPA 68. Example applications include dust collectors and spray driers.

LOC values for combustible dusts are also determined via tests in a 20-liter vessel, and the ASTM E27 Technical Committee is drafting an ASTM standard for LOC values. LOC values for various combustible powders and dusts listed in NFPA 69 Table C.1(b) are mostly in the range 9 v% to 12 v% O₂. Paragraph 7.7.2.5 of NFPA 69 requires that the oxygen concentration for an inerted process system should be less than the measured LOC by at least 2 volume percent for systems in which the oxygen concentration is continually monitored and no greater than 60% of the LOC if the oxygen concentration is not monitored.

Ignition Criteria

Hot Temperatures

One hot temperature ignition scenario entails a dust cloud accidentally entering a hot oven or furnace. This occurred in the CTA Acoustics phenolic resin dust explosion incident investigated by the U.S. Chemical Safety Board (CSB, 2005). The resin dust cloud in that incident was generated during cleaning of fugitive dust from the area around the oven.

The minimum dust cloud oven ignition temperature is determined by oven tests described in ASTM E1491. These include a vertical oven called the Godbert-Greenwald furnace and a horizontal oven called the BAM furnace. BAM furnace minimum Auto-Ignition Temperatures (AITs) are usually 20°C to 60°C lower than the corresponding dust cloud ignition temperatures measured in the Godbert-Greenwald furnace. Most of the Godbert-Greenwald dust cloud ignition temperatures listed in Eckhoff's Table A.1 are in the range 420°C to 660°C.

When the high temperature is on a hot surface of limited area, the required surface ignition temperature is higher than the standard furnace tests. Figure 1 shows some test data for surface areas in the range 20 mm² to 1000 mm², and comparison with the BAM furnace data.

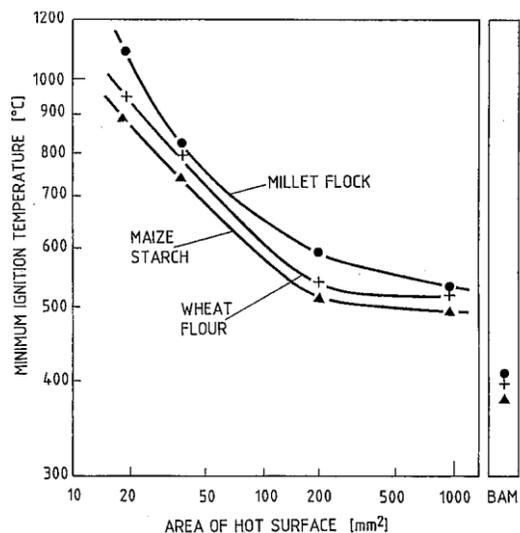


Figure 1 Hot surface ignition temperature versus surface area (Eckhoff Figure 5.25)

Examples of hot surface ignitions in dust explosion incidents include overheated failed bearings and driers. Clearly, the former would require a surface temperature much higher than the ignition temperature measured in the standard oven tests, but the latter might require a lower temperature than the standardized tests because of the possibility of a dust layer remaining in the drier for a long time. An aerated cell test described by Abbot (1990) and the CCPS Guidelines reference (2005) has been developed for drier hot layer ignition scenarios. The aerated cell test produces an exotherm onset temperature at which oxidation reactions leading to layer fires first occur. Most of the exotherm onset data reported by Abbot (1990) were in the range 125°C to 175°C. These temperatures are lower than the dust layer minimum hot surface ignition temperatures measured in the more common tests conducted in ambient air (ASTM E2021).

Burning Embers and Agglomerates

Smoldering or flaming particulate embers or agglomerates (also called smoldering nests) are often produced by frictional heating, e.g. during sanding or cutting, by local heating associated with hot work on equipment and ducts containing dust deposits, by powder accumulations on drier walls, and by small heat sources, e.g. a portable lamp, accidentally embedded in a particulate pile. If the hot embers or agglomerates remain stationary in a larger pile of combustible particulates, a larger fire can develop. On the other hand, if the embers/agglomerates are exposed to combustible dust cloud in an enclosure (perhaps a silo/hopper being filled), there is a potential for the ignition of a dust explosion.

Tabulations of ignition sources involved in 426 German dust explosions from 1965 to 1985 (Eckhoff, 2003, Tables 1.6 and 1.7) indicate that smoldering nests were the most prevalent cause of those dust explosions in silos (28%), and in dryers (29%), and the second most frequent ignition source in dust collector explosions (11%). Zalosh et al. (2005) describe one dust explosion incident in which the hot nest was caused by some bolts falling into a hammermill used for pharmaceuticals production. More recent research (Gummer and Lunn, 2003) has shown that the ignitions in most of these reported incidents were probably due to flaming, rather than smoldering nests/agglomerates since the only dust cloud material that could be ignited by smoldering agglomerates banked up in a 10 cm diameter tray was sulfur, which has an exceptionally low AIT (280-370 °C). Previous experiments cited by Gummer and Lunn

indicated that a minimum agglomerate burning area of 75 cm² and a minimum burning temperature of 900 °C were required to ignite dust clouds with AITs below 600 °C.

The occurrence of agglomerate smoldering versus flaming combustion and versus self-extinguishment depends on the amount of air access and the coherence of the agglomerate. Burning agglomerate transport experiments reviewed by Gummer and Lunn (2003) , showed that glowing agglomerates could be transported large distances through otherwise empty piping with air transport velocities of 10 and 20 m/s, but the glowing was extinguished rapidly when non-burning dust was added to the flow. The glowing particles were not able to ignite the flowing dust even though the dust concentration was above the MEC. Other tests showed that burning nests did not ignite fine sawdust in the transport duct, but did ignite the sawdust cloud when it reached the filter media dust collector at the end of the duct.

Several vendors provide so-called spark/ember detection and extinguishing systems to prevent ignitions by burning agglomerates transported through ducting. Optical detectors sense the radiant energy from the burning embers or agglomerates, and the control module triggers water spray through nozzles situated at an appropriate distance downstream of the detector. Annex C of NFPA 654 describes these systems.

Self-Heating

Certain particulate materials are prone to self-heating that can potentially lead to spontaneous ignition. The predominant chemical reaction is low level oxidation. Examples of materials that can self-heat by oxidation at relatively low temperatures include ABS resin powder, activated carbon, coal (particularly Powder River Basin coal), and various chemical intermediates. Materials such as freshly manufactured/dried wood chips, anhydrous calcium hypochlorite, and hops are subject to self-heating by moisture absorption/condensation. Organic peroxides and other potentially unstable chemicals can self-heat by exothermic decomposition. Various agricultural materials, such as bagasse and soybeans, start self-heating by microbiological processes. In many of these and other materials, multiple self-heating mechanisms overlap and it is difficult to distinguish the dominant mechanism at a given temperature.

Self-heating is typically manifested as smoldering in the interior of a large storage pile of particulates or in an accumulated layer in a dryer. If the smoldering particulates in the pile or dryer are subsequently disturbed and exposed to air, the smoldering can evolve into flaming. When the flaming nest or agglomerate is then transported to a hopper or dust collector, it can ignite the suspended dust cloud as discussed in the preceding section.

Various laboratory tests have been developed to determine self-heating onset temperatures for different sample sizes and configurations. These include particulate basket tests in an isothermal oven, heated air flow tests with a slow rate of air temperature rise, and material in a package test to determine the Self-Accelerating Decomposition Temperature. Application of laboratory self-heating data to plant conditions requires use of appropriate volume scaling methods described in handbook references including Babrauskas (2003), the CCPS Guidelines (2005), and Gray (2002). In addition to showing how the self-heating onset temperature decreases with increasing size of the particulate pile or layer, the scaling relationships also can be used to assess how the expected time-to-ignition increases with the pile or layer size. The combination of laboratory data and the scaling equations can then be used to establish appropriate plant level precautions to prevent self-heating and spontaneous ignition.

Impact/Friction

Impact and frictional heating during combustible powder processing and during maintenance/repairs involving cutting and grinding have been responsible for igniting many dust explosions. Grinders, hammermills, and other size reduction equipment are particularly prone to ignitions during operation. Blenders with rotating element tip speeds greater than 1 m/s are also vulnerable to this scenario. Tramp metal stuck in a screw conveyor or a particle classifier represents another frictional ignition scenario.

The vulnerability of a combustible dust to impact/friction ignition is characterized in terms of the material spark Minimum Ignition Energy (MIE) and cloud Auto-Ignition Temperature (AIT). Testing to measure MIE values is described in ASTM E2019. Figure 2 shows the relationship between MIE and AIT values to determine which dusts can be ignited by impact or frictional contact between steel surfaces. For example, a dust with an MIE of 10 J should be immune to steel-steel frictional or impact ignitions as long as its AIT is greater than 275 °C. Dusts with lower MIE values but have larger AIT values still may not be prone to steel impact or frictional ignitions per Figure 2. Eckhoff (2003) cautions that simple MIE versus AIT correlations cannot be applicable to steel grinding and impact conditions that may be very different from the experiments leading to Figure 2 and similar plots. Babrauskas (2003) presented data on the minimum frictional force needed to ignite various dust clouds.

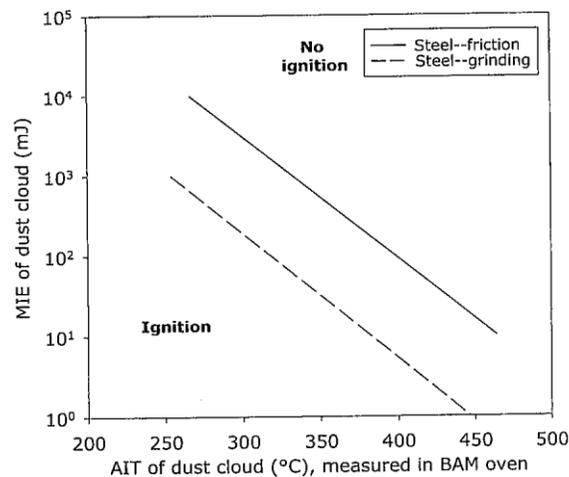


Figure 2 Boundaries for steel surface frictional and impact ignition of dust clouds (from Babrauskas, 2003)

One common friction ignition scenario is a blender with a rotating helical screw impeller. Jaeger (2001) provided guidance on how the mixing speed and blender fill level can be used to control frictional ignition hazards. He states that there is a negligible chance of ignition when the fill level is greater than 70%, no matter what the impeller tip speed is. When the tip speed is greater than 10 m/s and the fill level is less than 70%, there is a high probability of dust cloud ignition. At tip speeds between 1 m/s and 10 m/s and fill levels less than 70%, Jaeger provides a MIE versus AIT relationship analogous to that in Figure 2, to show which combustible dusts can be blended without any likelihood of ignition.

Single impact spark ignition experiments described by Eckhoff (2003) have shown that the probability of igniting a corn starch dust cloud increased with increasing impact energy, and that it also depended on the impact velocity. Lower speed impacts produced a much greater probability of ignition than higher speed impacts for a given impact energy. The metal combinations involved in the impact also play an important role in the probability of ignition.

Steel-steel impacts and aluminum-steel impacts did not ignite corn starch dust clouds, whereas titanium impacts against rusty steel did ignite dusts with MIE values below roughly 10 mJ. The titanium-rusty steel impacts produced thermite reaction sparks, while the aluminum-rusty steel impacts did not.

Electrical Equipment

Electrical equipment and wiring can potentially ignite dust clouds by sparks, arcs, or heated surfaces. Dust Ignitionproof equipment is enclosed in a manner that excludes dusts and does not permit arcs, sparks, or heat otherwise generated or liberated inside of the enclosure to cause ignition of exterior accumulations or atmospheric suspensions of a specified dust on or in the vicinity of the enclosure. UL 1203 describes the design, fabrication, and testing required to certify electrical equipment as Dust Ignitionproof.

When electrical equipment and wiring is used in locations in which combustible dusts can be present, there is a need to establish the Class II hazardous location classification of the area. Per NFPA 70, a Class II Division 1 location is one in which combustible dust is in the air *under normal operating conditions* in quantities to produce explosive or ignitable mixtures, or where mechanical failure or abnormal operation of machinery or equipment might cause such explosive or ignitable mixtures to be produced, and might also provide a source of ignition through simultaneous failure of electrical equipment (NFPA 70 definition). There are three possible conditions for the existence of a Class II Division 2 location. The first condition is a location in which combustible dust *due to abnormal operations* may be present in the air in quantities sufficient to produce explosive or ignitable mixtures. The second and third conditions refer to dust accumulations that could be either suspended or ignited during equipment malfunctions or abnormal operations. Class II locations are further classified as Group E, F, or G depending on the type of dust material. NFPA 499 provides guidance and examples for the assignment of appropriate Class II Division 1 and 2 classifications for combustible powder and dust processing and handling operations.

NFPA 70 Article 500.7 permits Dust Ignitionproof electrical equipment in Class II Division 1 and 2 areas. Similarly, intrinsically safe electrical equipment (in which all circuits cannot produce a spark or thermal effect capable of igniting a dust cloud per UL 913) is also allowed in these areas. Dusttight equipment is permitted in Class II Division 2 areas. Article 502 of NFPA 70 describes the types of acceptable wiring in Class II Division 1 and 2 locations. Threaded metal conduit together with dusttight boxes and fittings is one acceptable method commonly used. The use of electrical sealing putty at boundaries of Class II areas is also described in Article 502.

Electrostatic Discharges

Electrostatic discharges occur are preceded by charge accumulation on insulated surfaces, ungrounded conductors (including human bodies), or particulate materials with high resistivities. The subsequent electrostatic discharge is only an ignition threat if it is sufficiently energetic in comparison to the Minimum Ignition Energy of the pertinent dust cloud. Different types of electrostatic discharges have correspondingly different maximum discharge energy capacities as listed in Table 1.

Table 1 Types of Electrostatic Discharge

Type of Discharge	Maximum Energy ¹ (mJ)	Examples
Corona	0.1	Wires, Type D Bulk Bags
Brush	1 - 3	Flexible boots and socks
Bulking Brush	1 - 10	Piles of powders with resistivities > 10 ⁹ Ω-m in hopper or silo
Propagating Brush	1000 - 3000	Boots, plastic pipe or duct
Spark	> 10,000	Ungrounded conductor, e.g. baghouse cage, or person, e.g. packager

1. Maximum energies are from Figure 5.3.1 of NFPA 77-2006.

Since combustible dust MIE values are substantially greater than 0.1 mJ, corona discharges are not an ignition threat. In fact, Type D bulk bags are deliberately designed and fabricated to safely dissipate accumulated charges via corona discharges. A recent study by Glor and Schwenzfeuer (2005) has shown that brush discharges were not able to ignite clouds of dusts with MIE values less than 1 mJ, thus correcting a different impression obtained from earlier studies. Since brush discharges do ignite flammable vapors, they are an ignition threat for hybrid dust-vapor mixtures such as occur in processes with flammable solvents.

The most hazardous situation for a bulking brush discharge ignition is filling a hopper with a high resistance material combination of large particles with diameters over 1 mm together with fines with a MIE less than 10 mJ. Some of the dusts listed in Eckhoff's Table A.1 (2003) with MIE values less than 10 mJ include certain wood dusts (with 39 weight % < 20 μm), naphthalene with a median diameter of 95 μm, zinc stearate with a 13 μm median diameter, and toner with median diameter of 23 μm and less. Transport and processing of these easily ignitable dusts require special precautions to prevent brush and bulking brush discharges. Precautions provided in NFPA 77 Chapter 9 and in Britton's (1999) chapter 6 are especially important for these dusts.

A propagating brush discharge can occur when a charged non-conductor is in direct contact with a conductive surface, such as a metal surface coated with a plastic film or a layer of high resistivity powder (Glor, 2005). The Propagating brush discharge occurs when the surface charge density is sufficiently large to cause electrostatic breakdown at the nonconductor surface. Streamers carry the surface charge to a central region where it intensifies as shown in Figure 4. Propagating brush discharges can ignite dusts with MIE values less than about 3 J.

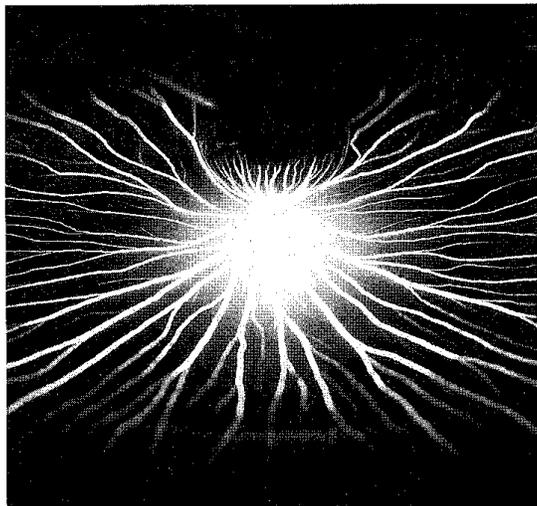


Figure 3 Propagating brush discharge (from Britton, 1999)

Sparks are the most energetic type of electrostatic discharge. Spark prevention requires rigorous grounding and bonding of conductive objects such as duct sections and connections to hoppers. FM Global Data Sheet 5-8 also recommends maintaining humidity levels at 60% to 70% as another spark prevention measure.

Pressure Development in Dust Deflagrations

Pressures in Single Enclosures

Deflagration pressures resulting from an ignition in process equipment depend on the dust material, particle size distribution, and concentration distribution within the enclosure, and the size and location of equipment openings that allow the burning and unburned dust to be vented. If there were no openings in the equipment, the deflagration pressure would correspond to the pressures measured in ASTM E1226 tests. Since these pressures are greater than 2 bar gauge, even at concentrations near the MEC, most process equipment cannot withstand the closed vessel deflagration pressure. Pressures at the worst-case dust concentration often range from 7 to 10 bar. Therefore, NFPA 654 paragraph 7.1.2.1 requires process equipment with an explosion hazard to be equipped with one of six specified alternative methods of explosion protection.

The most commonly used dust explosion protection method is deflagration venting. The effectiveness of deflagration vents depends on the level of turbulence in the process vessel and the vessel size and shape as well as the vent design and the dust characteristics cited above. NFPA 68 Chapter 7 provides dust deflagration design requirements.

Deflagrations Involving Interconnected Equipment

When process vessels are connected by pipe and ducting, a dust explosion ignited in one vessel can often propagate into the interconnected vessels. Pressures produced in the interconnected vessels can be significantly greater than the pressure that would be experienced in isolated vessels. The reason for the enhanced deflagration pressure in a totally enclosed system is that the initiating explosion pressurizes the interconnected vessels, so that the deflagration that eventually occurs when the flame reaches the dust cloud in the other vessels starts at a higher initial pressure. This effect is called pressure piling. Lunn et al. (1996) conducted interconnected vessel tests with coal dust and toner that had P_{max} values of 7.7 bar g and 7.1 bar g, respectively, in single closed vessel tests. When the explosions were initiated in a 20 m³ vessel and allowed to propagate via a 25 cm diameter pipe into a 4 m³ vessel with a dust cloud, the measured pressures were 16 to 20 bar g, i.e. more than twice the P_{max} values.

Inter-vessel deflagration propagation and pressure piling does not always occur. Lunn et al. (1996) did not observe deflagration propagation in tests with a 15 cm diameter pipe, and later vented explosion tests using a pipe with a sharp 90 degree elbow produced pressure enhancement in only one of many tests conducted (Skjold, 2007). However, when the deflagration does propagate into the interconnected vessels, the jet flame ignition of the dust cloud in the second vessel produces a much more rapid rate of burning and associated pressure rise. The more rapid burning and pressure rise can render explosion venting or explosion suppression systems ineffective in the second vessel. Hence, there is often a need for explosion isolation systems to supplement the installed explosion protection for an individual vessel. NFPA 69 provides the requirements for various types of passive and active explosion isolation systems.

Secondary Dust Explosions

Most of the casualties from dust explosions occur when the initiating explosion within some equipment or enclosure breaches the equipment/enclosure and causes a secondary explosion in the surrounding building. The secondary explosion occurs when dust deposits on exposed surfaces in the building are lifted by the blast wave emanating from the breached equipment/enclosure, and then are ignited by the flame vented from the breached equipment/enclosure. Figure 4 shows a dust cloud formed when an air blast wave propagated over a corn starch layer in experiments conducted by Scherpa (2002). Air blast velocities of 12 to 48 m/s lifted 13% to 44% of the deposited cornstarch.



Figure 4. Corn starch dust cloud produced from air blast over dust layer (from Scherpa, 2002)

These secondary dust explosions are particularly devastating because they produce large burning dust clouds and pressures beyond the strength of most buildings. The two critical prevention measures are the installation of effective explosion protection for the combustible powder/dust processing and handling equipment (including explosion isolation), and minimizing combustible dust layer accumulations on equipment and building surfaces. NFPA 654 provides requirements for maximum allowable dust layer thicknesses and surface areas with dust accumulations. Some of the other papers at this Symposium offer guidance on how different types of industrial facilities are attempting to meet these requirements, and possibly improve them.

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