Dust Explosion Scenarios and Case Histories in the CCPS Guidelines for Safe Handling of Powders and Bulk Solids

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Abstract

The new CCPS book, entitled Guidelines for Safe Handling of Powders and Bulk Solids, discusses several different types of accident scenarios, including scenarios that can lead to a combustible dust explosion. The dust explosion scenarios are divided into the following three categories: Explosions within Process Equipment, Explosion Propagation into Interconnected Equipment, and Secondary Dust Explosions in Buildings. Examples of process equipment explosion scenarios include dryer explosions involving particulate clouds or hybrid vapor-dust mixtures ignited by overheated (often smoldering) dust layers, blender explosions ignited by either electrostatic discharge or a failed bearing, and dust collector explosions ignited either by tramp metal impact against the collector wall, by a smoldering nest from upstream equipment, or by an electrostatic discharge. Explosion propagation into interconnected equipment often occurs via either pneumatic or conveyor transport ducting. Secondary explosions in buildings occur when the primary explosion causes a breach of equipment or a weak enclosure, and the associated blast wave creates a suspended dust cloud that is ignited by the vented flame from the primary explosion. Case histories illustrating these common dust explosion scenarios are described in this paper, along with a brief summary of dust explosion assessment tests that can be conducted to make material and facility specific determinations of the most appropriate protection measures.

Introduction

The new Center for Chemical Process Safety **Guidelines for Safe Handling of Powders and Bulk Solids** [1] includes a great deal of material on dust explosion scenarios, case histories, and methods for specific assessments of dust explosion hazards. Excerpts of some of this material are presented in this paper, categorized as Explosions within Process Equipment, Explosion Propagation to Interconnected Process Equipment, and Secondary Dust Explosions in Buildings. This categorization scheme often parallels the escalation of some of the more devastating dust explosions, which originate in one piece of equipment, propagate to other equipment, and finally emerge from the equipment to produce a massive deflagration in a process building.

In many dust explosions the originating event is either a smoldering fire or an exothermic decomposition of particulates. The new CCPS Guidelines book [1] includes detailed background and descriptions of particulate fires and decompositions, but those discussions and descriptions are beyond the scope of this paper.

Explosions Within Process Equipment

Dust explosions occur in process equipment when there is a particulate concentration between the Minimum Explosible Concentration (MEC) and the Upper Explosive Concentration (both of which depend on the oxidant present), and then an ignition source develops or reaches the combustible cloud. The types of process equipment that routinely have combustible dust concentrations in at least a portion of the equipment volume include blenders, dryers, dust collectors, and grinders/pulverizers. Table 1 lists the number and percent of dust explosions that have been reported to occur in these and other equipment in surveys performed in the U.S. [2,3], U.K. and Germany [4] during the time periods indicated.

Table 1
Equipment Involved in Dust Explosions

Equipment	U.S. (FM,1985-95) + (IRI,1975-2001)		U.K. (1979-1988) (HSE)		Germany (1965-85) (Eckhoff, 1997)	
	# Incidents	%	# Incidents	%	# Incidents	%
Dust Collectors	156	42	55	18	73	17
Grinders/Pulverizers	35	9	51	17	56	13
Silos/Bunkers	27	7	19	6	86	20
Conveying System*	32	9	33	11	43	10
Dryer/Oven	22	6	43	14	34	8
Mixers/Blenders	> 12	> 3	7	2	20	5
Other or Unknown	84	23	95	31	114	27
Total	372	100	303	100	426	100

* Conveying systems include conveyors, ducts, and elevators.

Dust Collector Explosion Scenarios

Three possible reasons for the high occurrence of dust collector explosions are 1) they are almost omnipresent in particulate handling facilities, 2) they inherently concentrate the smaller particles which are easier to ignite than the mostly larger particles in other equipment, and 3) dust collectors are often structurally weaker than other process equipment, and therefore more prone to explosion damage. Data from the German compilation of dust explosions indicate that the most frequent ignition sources have been mechanical sparks (41%), smoldering nests (11%), electrostatic discharges (10%), and mechanical heating via friction (7%).

Matsuda and Yamaguma [5] describe a tantalum dust collector explosion that they attribute to an electrostatic discharge in the collector. The small, corral shaped tantalum particles have a high resistivity, and become electrostatically charged by rubbing against the collector wall. Apparently an electrostatic discharge from the charged particles triggered the explosion in the 5-m high, 1.5-m diameter bag type collector.

The following account of an explosion in a baghouse dust collector used to collect a pharmaceutical product from a hammer mill/flash drying operation illustrates how frictional heating in upstream equipment can produce a smoldering nest ignition source for a dust collector explosion . The impact hammer mill had been operating for approximately 10 minutes when the operator heard unusual grinding sounds coming from inside the mill. He immediately shut down the mill just as an explosion occurred within the dust collector, located inside the building on the second floor. The pressure wave caused the explosion vent (a hinged panel) of the dust collector to open, and the explosion products and unburned powder were directed outside the building via a vent duct. However, a screen had been securely fastened at the end of the duct to prevent birds from entering, and as the vent panel swung upward and outward, it struck the screen and opened no further. It is estimated that the screen prevented the explosion vent panel from opening to no more than 50 percent of the vent area.

With the vent partially obstructed, the access door to the dust collector failed under pressure and released a dust cloud into the building, which ignited. The flame front went through the vent duct and followed the dust cloud through the access door, resulting in a fireball at both locations. Also, on the first floor, a fireball was seen exiting the vicinity of the rotary valve outlet at the bottom of the dust collector, which feeds a sifter. There was no secondary explosion on the first or second floors. However, windows were blown out at both floors. The ensuing fire in the dust collector engulfed the wool filter bags (which were burned up) and the remaining powder in the collector hopper, but the fire was quickly extinguished by the automatic sprinkler system inside the dust collector.

A subsequent investigation of the incident revealed that a carbon steel bolt from the inside of the feeder (which feeds wet powder to the hammer mill/flash dryer) had become loose and fell into the hammer mill. The bolt became trapped inside the 3600 rpm mill, where it became heated to above the autoignition temperature of the powder. The hot metal ignited some of the powder in the mill, which was pneumatically conveyed into the dust collector. In the collector, a dust cloud created by the blow ring (pulse jet), was ignited by the hot powder conveyed in from the hammer mill. An inspection of the feeder revealed that six 3/8-inch carbon steel bolts were missing.

Tyldesley [6] described a double fatality explosion that occurred while a pipefitter was trying to clear out a clogged rotary valve at the bottom of a cyclone dust collector at an aluminum powder packaging facility. This was likely an example of an impact spark or mechanical heating ignition event.

The CCPS Guidelines book [1] provides separate listings of recommended explosion protection measures for cyclone collectors, electrostatic precipitators, and fabric filter baghouses.

Blender Explosion Scenarios

The blending of particulates of two or more different compositions inherently involves the kind of inter-particulate friction and particulate-wall friction that causes electrostatic charge generation. If the particulate resistivity is sufficiently high, the electrostatic charge can continue to accumulate with correspondingly increasing voltage differences. Furthermore, if the blender wall is not well grounded, charge and associated high voltages can accumulate on the blender wall. If the particulate Minimum Ignition Energy (MIE) is sufficiently low, and if the eventual electrostatic discharge occurs in a location where combustible concentrations exist, the result is a dust explosion. This has occurred in a plastics manufacturing plant in a blender used to mix the primary polymer with various additives. The primary polymer had a resistivity of 2×10^{16} ohm-cm, a MIE of about 7 mJ, and a MEC of 20 g/m^3. The latter two values are lower than those of most organic powders. However, even with significantly larger MEC values, concentrations above the MEC should be anticipated toward the top of the blender during normal operation and throughout most of the blender volume during batch loading and unloading.

Eckhoff [4] has a detailed description of a 1973 aluminum dust explosion in a screw blender/mixer. A rubber lined steel tube surrounded the center screw of the mixer. Eckhoff states that the explosion was probably ignited by a propagating brush discharge due to electrostatic charge generation on the rubber lining within the grounded steel tube. The aluminum flakes had a specific surface area of 7.5 m^2/g, and Minimum Ignition Energy of only 1 mJ. Even though there was an attempt to nitrogen-inert the mixer, Eckhoff suggests that the volume within the steel tube was not inerted, and oxygen concentrations were also sufficiently high to support combustion. Thus, the explosion was initiated at the 3.3 m long enclosed screw, and then propagated as a flame jet into the 5.2 m^3 mixer.

Recommended blender explosion prevention measures described in the CCPS Guidelines book include blender construction and grounding considerations to minimize electrostatic charge generation, and blender design and operational considerations to reduce the hazards of frictional heating and tramp metal entry into the blender.

Dryer Explosion Scenarios

Overheating of particulate by a hot surface is by far the most likely ignition source in dryers. In some cases, the particulate accumulates on the hot surface and forms a smoldering nest, while in other cases the hot surface temperature is sufficiently high to directly ignite the suspended dust cloud. Although particulates near the dryer inlet may be too wet to be readily ignited, particulates exiting the dryer are both dry and often suspended in concentrations above the MEC.

Drogaris [7] cites an example of a fire and explosion in a batch rotating vacuum dryer used for drying a pharmaceutical powder. An operator had tested dryer samples on a number of occasions without any problems. After the last sampling, he closed the manhole cover, put the dryer under vacuum, and started rotation of the dryer. A few minutes later an explosion and flash fire occurred, which selfextinguished. No one was injured. Investigations revealed that after the last sampling, the dryer manhole cover had not been securely fastened. This allowed the vacuum within the dryer to draw air into the rotating dryer and create a flammable atmosphere. The ignition source was probably an electrostatic discharge (the Teflon coating on the internal lining of the dryer could have built up a charge). No nitrogen inerting had been used. After the incident, the following two precautions were instituted to prevent similar accidents from occurring in the future: 1) Nitrogen purging is carried out before charging or sampling of the dryer. 2) If the absolute pressure rises to about 4 psia, the rotation is stopped, an alarm sounds, and a nitrogen purge starts automatically.

Other dryer dust explosion hazard scenarios addressed in the CCPS Guidelines [1] include hybrid mixture formation due to vaporization of a flammable liquid, direct firing ignition sources, frictional sparks and overheating from failed bearings, misaligned fan blades, tramp metal, and electrical equipment not appropriate for atmospheres containing combustible dust clouds.

Grinder/Pulverizer Scenarios

Grinders, pulverizers, and other size reduction equipment inherently dissipate large energy inputs required to break up the particles. This energy dissipation inevitably causes heating of the particles and metal surfaces. Particles accumulating in the grinder can easily overheat, smolder, and ignite a dust explosion during grinder loading or unloading. Section 5.3.17 of the CCPS Guidelines [1] has two specific accounts of explosions ignited by friction-induced hot spots in grinder/pulverizers. Frictional heating of the housing of a grinder being used to produce 50 µm (300-mesh) silicon powder caused one explosion. Tramp metal was the apparent ignition source in another explosion that occurred in a hammermill being used for an intermediate stage powder with a low MIE and Autoignition Temperature (AIT).

Figure 1 shows evidence of the frictional or impact heating of hammers in a hammermill used to produce powdered sugar. The heating of sugar and metal in that vicinity of the mill ignited a sugar dust explosion that burned the hammermill operator who was responding to the sound of severe vibration due to tramp metal or a broken hammer in the mill.

Figure 1 Scorched hammers in a hammermill.

Specific recommendations in the CCPS Guidelines book [1] for preventing grinder/pulverizer dust explosions include monitoring the mill motor current and having an interlock shutdown upon high current draw, use of magnetic separators to find and remove tramp metal before it enters the mill, and use of special enclosed mills to allow inerting of powders with extremely low MIE and AIT values.

Other Process Equipment

Besides dust collectors, blenders, dryers, and grinder/pulverizers, the CCPS Guidelines book [1] also describes fire and explosion incidents and specific explosion prevention measures for the following process equipment: bag openers, extruders, feeders and rotary valves, sampling systems, classifiers, silos and hoppers, size enlargement equipment, solids charging systems, and weighing systems. Appendix B of the book is an overview description of the equipment itself, including transport equipment and rail car and hopper truck loading and unloading stations as well as the previously mentioned process equipment. In addition to the explosion prevention suggestions, Chapter 6 of the CCPS Guidelines book discusses deflagration mitigation measures such as deflagration venting, deflagration suppression, and deflagration isolation systems.

Explosion Propagation to Connected Equipment

Many dust explosion incidents result in flame propagation through interconnected process equipment. The resulting explosion damage can extend far beyond the site of the originating explosion. The path for the explosion propagation is usually ducting used for pneumatic transport of particulates. In other incidents, the propagation path is enclosed or underground conveyor galleries/tunnels, sometimes leading to large, vulnerable silos.

Any approach to preventing explosion propagation needs to distinguish between the propagation of the ignition source and the propagation of the deflagration itself. If the ignition source is a smoldering nest or burning ember traveling through the ducting, properly designed/installed spark detection and extinguishing systems have been effective in preventing this scenario from escalating into a downstream deflagration. On the other hand, if the particulate loading in the ducting corresponds to a concentration above the MEC, a deflagration, rather than a mere smoldering ember/nest, can propagate through the duct. For example, a wood sander initiated dust collector explosion incident involved a collector duct equipped with a spark detection and extinguishing system, and the deflagration overwhelmed the extinguishing system. Flame from the dust collector was transported through the clean air return ducting back to the processing building, and caused scalp burn injuries to several employees.

Sometimes the dust explosion propagates back in the opposite direction of the air flow through the dust collection ducting. One such explosion was initiated by an electrostatic discharge in a drum situated under a dust collector. The drum was mounted on rubber casters such that it was electrically isolated from the flexible ducting between the drum and collector discharge outlet. The explosion propagated back through the dust collection system to the packaging room where it produced some structural damage but no injuries. One of the correction measures taken at this facility is the use of drum grounding as illustrated in Figure 2. Other aspects of the sequence of explosions in this incident are described by Pickup [8].

Figure 2 Dust collection drum grounded to flexible duct. (courtesy Gowan Milling, LLC)

Isolation of interconnected equipment to prevent full deflagration propagation requires some type of isolation system that can vent or quench both the flame and associated deflagration pressure. A test of one such system under development is shown in Figure 3. A later version of the device shown in Figure 3 is intended for use a sort of check valve to prevent reverse through dust collector ducting. Other isolation systems are described in Chapter 6 of the CCPS Guidelines book [1] and in NFPA 69 [9]. Use of the systems also requires that the ducting be sufficiently strong to withstand the design flame speed and pressure associated with the isolation system certification.

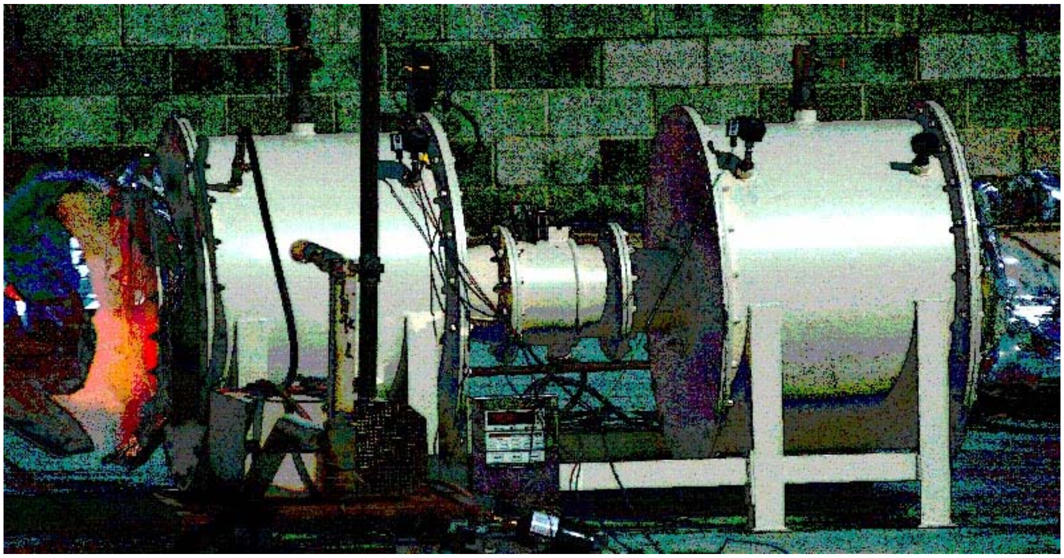

Figure 3 Duct deflagration isolation valve being tested (courtesy Gowan Milling LLC).

Secondary Dust Explosions in Buildings

Perhaps the most devastating dust explosion scenario is the generation of a secondary dust explosion in the building surrounding the equipment in which some primary explosion occurs. The secondary explosion occurs when the blast wave emanating from the ruptured equipment/conveyor lifts the accumulated dust into suspension, and the flame from the primary explosion subsequently ignites the suspended dust cloud. The resulting devastation and casualties are associated both with the burning of building occupants and with the structural damage to the building.

One simple example of explosion propagation from process equipment into the surrounding building occurred in a powdered aluminum plant when somebody was trying to clear out caked aluminum deposits in a dust collector pickup line. The explosion propagated from the cleanout port, injuring two employees and destroying the steel framed process building [6].

A classic example of a devastating secondary dust explosion is the magnesium stearate explosion that occurred in 1976 in a plant manufacturing chewing gum. The magnesium stearate is applied as a lubricant on the freshly produced gum before it is cut into chewable pieces. The primary explosion occurred in the cutting machine several minutes after the machine started vibrating with sufficient intensity to generate a magnesium stearate combustible dust cloud. The rupture of the cutting machine generated a blast wave that displaced and lifted fugitive magnesium stearate powder from beams, ledges, and light fixtures, and the emerging fireball ignited the suspended cloud of powder. According to FM Data Sheet 7-76 [10], the secondary dust explosion blew out windows on two sides of the building, demolished a cinder block wall about 3 m away from the cutting machine, and destroyed the equipment in the vicinity. The fireball and subsequent fires opened 166 sprinkler heads in the building. According to the New York City Fire Department account of this incident, six people were killed, and 50 other people suffered burn and blast wave injuries.

The extensive destruction and casualties that occurred in the January 29, 2003 explosion at the West Pharmaceuticals plant in Kinston, North Carolina, as indicated by the aerial view photograph shown here as Figure 4 are due in large part to a secondary dust explosion. The Chemical Safety Board investigators determined that polyethylene powder accumulations on the upper surface of the ceiling tiles on a suspended ceiling indicated in Figure 5 were dispersed either by either some undefined primary explosion or by some unidentified disturbance, and that the polyethylene dust cloud produced a deflagration in the space between the ceiling tiles and the concrete floor above. [11].

Figure4 Aerial view of the destruction and residual fire in the January 2003 dust explosion at West Pharmaceuticals.

The negative air pressure generated by the HVAC return duct inlets above the suspended ceiling apparently contributed to the collection and accumulation of polyethylene powder on the ceiling tiles. According to the CSB report [11], employees reported seeing accumulations that varied in thickness from 0.125 inch to 0.50 inch across most of the suspended ceiling. The milling and batchoff area under the suspended ceiling was reported to be relatively free of dust accumulations. However, the pressures produced by an incipient deflagration above the suspended ceiling probably blew polyethylene dust into the areas above and below allowing the deflagration to propagate in both the compounding area and milling/batchoff area of the plant.

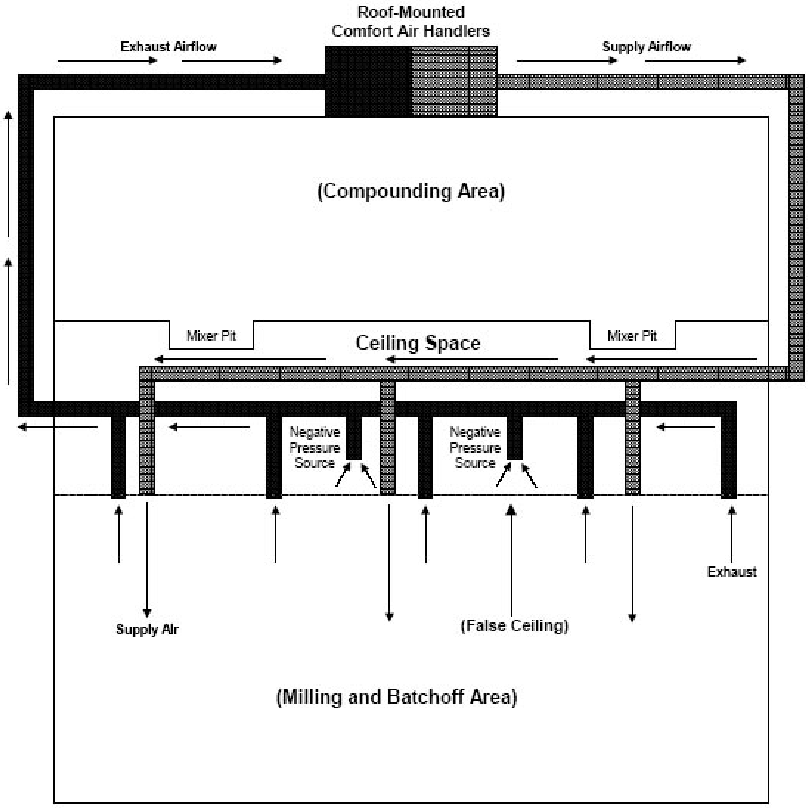

Figure 5 HVAC Ducting at West Pharmaceuticals Compounding and Milling Area (from CSB report)

The West Pharmaceuticals Kinston explosion produced 6 fatalities and 38 injuries, most from burns and blunt force trauma due to falling objects and collapsing walls. Other recent secondary dust explosion incidents with fatalities and multiple injuries include the Jahn Foundry phenolic resin explosion [12], the CTA Acoustics phenolic resin explosion (CSB July 8, 2003 press release), and the Hayes Lemmerz aluminum dust explosion (CSB November 5, 2003 press release).

One inherent issue in the prevention and mitigation of secondary dust explosions is the required level of housekeeping and other maintenance practices to minimize dust leakage and subsequent accumulations. Section 7.5 of the CCPS Guidelines book [1] discusses this issue and the pertinent recommendations in FM Data Sheet 7-76 [10] and NFPA 654 [12].

Dust Explosion Hazard Assessment and Protection Methods

Section 4.3.6 of the CCPS Guidelines book [1] provide descriptions of the laboratory test methods available for determining electrostatic charge and discharge hazards, while Section 4.3.7 describes the various dust cloud explosibility test methods. Table 2 summarizes the standardized test methods for dust cloud explosibility in terms of applications, advantages, and limitations. These test methods can be used in conjunction with flow charts and decision trees in the book to help establish appropriate explosion protection methods for specific materials and installations.

Numerous commercial testing laboratories are available for conducting the tests shown in Table 2 and other tests geared toward powder/dust explosibility and flammability. Appendix A of the Guidelines book lists 11 such laboratories in the U.S. and 11 more in other countries, and indicates which specific tests these laboratories perform.

Table 2

Dust Cloud Explosibility Test Methods

Test	**Standard**	**Applications**	**Advantages**	**Limitations**
Minimum Explosible Concentration (MEC)	ASTM E 1515 CEN prEN 14034-3	Prevention via dust concentration control, e.g. in pneumatic conveying	The measured MEC value can be compared to in-situ measurements of suspended dust concentrations in conveyors and other process equipment, and can be used to verify concentration is < MEC.	Measured MEC value is based on a pressure rise of one atmosphere above the pressure due to the igniter; explosions with smaller pressure rises can occur at concentrations below the reported MEC value.
Minimum Cloud Auto Ignition Temp: (MAIT)	ASTM E 1491 IEC 1241-2-1	Safe operating temperatures in heated process equipment.	MAIT is valuable data for both particulate material manufacturing and for post-production processing by other companies and facilities.	BAM (horizontal) oven yields lower MAIT values than Godbert-Greenwald (vertical) furnace. MAIT value depends on the residence time of the dust cloud in the heated equipment, and with the area of a heated surface.
Minimum Ignition Energy (MIE)	ASTM E 2019 IEC 1241-3	Electrostatic ignition hazard evaluations; FIBC material classes	MIE value determines precautions needed in silo/bag filling and other particulate handling operations.	Measured MIE value depends on dust cloud turbulence level as well as amount of inductance in spark generation circuit.
Maximum Explosion Pressure (P_{max}) and K_{st}	ASTM E1226 ISO 6184	Deflagration Containment, Deflagration Venting or Suppression	K_{st} is often considered the most important parameter to characterize dust material combustibility.	Measured K_{st} value depends on both ignition energy and dust cloud turbulence level as determined by time delay between dust injection and ignition.
Limiting Oxygen Concentration (LOC)	ASTM E 2079 CEN prEN 14034-4	Inerting per NFPA 69 and NFPA 654	Provides valuable explosion prevention data.	Measured LOC values vary with ignition energy and with particular inert gas used in test.

Conclusions

Many reported dust explosions have originated in common powder and bulk solids processing equipment such as dust collectors, dryers, grinders/pulverizers, and blenders. Electrostatic discharges are frequently cited as the ignition source for dust collector and blender explosions, whereas particulate overheating is the most common ignition source in dryer explosions, and friction/impact heating associated with tramp metal or misaligned parts is probably the most frequent ignition source in grinder/pulverizer explosions.

Dust explosions are often exacerbated by propagation through ducting between process equipment, frequently via dust collector pickup and return ducting. Moe widespread use of effective deflagration isolation devices in such ducting would clearly be beneficial in mitigating the damage and injuries from these propagating dust explosions.

Secondary dust explosions in processing buildings probably cause the largest numbers of dust explosion fatalities and injuries. One crucial aspect of secondary dust explosion prevention and mitigation is greater awareness of good housekeeping and maintenance practices to prevent particulate leakage from equipment and subsequent accumulations of dust deposits in large areas of the buildings.

The CCPS **Guidelines for Safe Handling of Powders and Bulk Solids** is now available to provide guidance and elaboration on these issues. It also provides guidance on assessing dust explosion hazards for specific materials and facilities, and various flow charts and decision trees for utilizing the results of those assessments to determine the most appropriate explosion protection measures.

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