Reduce Dust Explosions the Inherently Safer Way

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Apply the principles of inherent safety at the outset of process design or equipment selection to prevent or mitigate dust explosions.

INHERENT SAFETY IS A PROACTIVE approach for hazard and risk management during process plant design and operation. Although it offers an attractive and cost-effective methodology for risk reduction, inherent safety has not been used as widely as engineered (add-on) and procedural (administrative) measures *(1)*. This article is aimed at the development of a framework for dust explosion prevention and mitigation that explicitly incorporates the principles of inherent safety. As distinguished from engineered and procedural safety features, inherent safety seeks to remove hazards in the first instance, thereby addressing both the frequency of occurrence and the consequent severity components of risk *(2)*. Case studies involving dust explosions and inherent safety considerations are also presented.

Trevor Kletz *(3, 4)* was the first to formalize the principles of inherent safety. Table 1 *(5)* presents the commonly used inherent safety principles or guidewords, the first six of which are generally considered to be the most general, and therefore, widely applicable. The remaining principles, and others developed by various workers, are essentially sub-categories of the main principles. For example, avoiding knock-on effects, such as escalation or domino effects, may be viewed as a special case of limitation of effects. Similarly, eliminating the possibility of incorrect assembly of equipment may also be viewed as a form of simplification. It should be noted that in addition to the fundamental concept of hazard elimination, a slightly different set of primary guidewords is sometimes used by loss-prevention practitioners. These principles, with their corresponding entities from Table 1, are as follows:

Table 1. Inherent safety principles.

Principle	Definition
Intensification	Reduction in the quantity of hazardous materials
Substitution	Use of safer materials
Attenuation	Running equipment at safer operating conditions, such as room temperature and pressure, and in liquid phase
Limitation of effects	Changing equipment design and operation for less-severe effects, such as unit segregation
Simplification	Avoidance of multi-product or multi-unit operations, or congested pipe or unit settings
Error tolerance	More robust equipment, processes that can bear upsets, reactors able to withstand unwanted side reactions, etc.
Avoid knock-on effects	Ample layout spacing, fail-safe shut down, open construction
Prevent incorrect assembly	Unique valve or piping systems to reduce human error
Clarrify equipment status	Avoidance of complicated equipment and information overloading
Ease of control	Less hands-on control

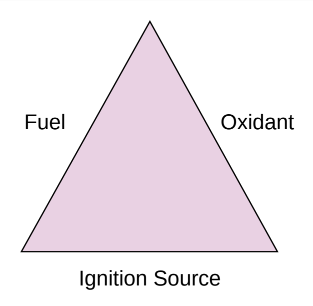
- Minimize (intensification) — use smaller quantities of hazardous materials when the use of such materials cannot be avoided.
- Substitute (substitution) — replace a hazardous substance with one that is less hazardous, or a hazardous process route with one that does not involve hazardous materials.
- Moderate (attenuation/limitation of effects) — use hazardous materials in their least-hazardous forms or identify options that involve less-severe operating conditions.
- Simplify (simplification/error tolerance) — design processes and equipment to eliminate opportunities for errors by identifying ways to eliminate excessive use of add-on safety features and protective devices.

Because of the case studies covered in this article, the authors have chosen to use the principles of minimization, substitution, moderation and simplification. This is consistent with the nomenclature of leading inherent safety advocates *(6)*.

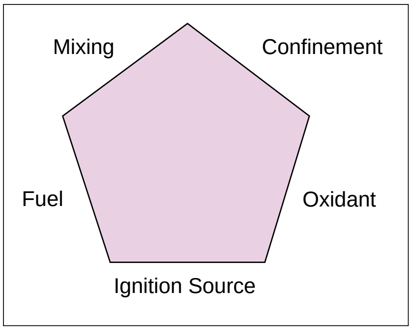
Existing prevention and mitigation frameworks

When selecting dust explosion prevention and mitigation measures, it is helpful to employ a framework for making appropriate choices. Such a framework may be thought of as a problem-solving heuristic, or, as defined by Fogler and LeBlanc *(7)*, a systematic approach that guides the engineer through the solution process, enabling him or her to generate alternative pathways to a solution. Problem-solving heuristics can be graphical, text-based, or a combination of the two. Their usefulness depends on a number of factors, such as ease of use, completeness of information, and level of guidance provided.

The framework suggested in this article builds on various heuristics available in the literature. These include the fire triangle for dusts (Figure 1) and the explosion pentagon (Figure 2). Also available are guides and standards published by professional organizations, including the National Fire Protection Assn. (NFPA); American Society for Testing and Materials (ASTM); Verein Deutscher Ingenieure; International Electrotechnical Commission; and the International Standardization Organization.



■ Figure 1. The simple fire triangle for dusts illustrates the components that must be present in order for an ignition to occur *(11)*.



■ Figure 2. The explosion pentagon expands the basic fire triangle to include mixing of the fuel and oxidant and confinement of the mixture *(12)*, illustrating that engineered safety measures may be taken to prevent a dust explosion.

Strategies for dust explosion mitigation are suggested in Ref. 8 and 9, and in more recent guidelines, such as those published by the Institution of Chemical Engineers (IChemE) *(10)*. IChemE's guidelines assert that in order for dust to be considered a fuel, it must be explosible, airborne, have a particle-size distribution capable of propagating flame, and haveconcentrations (in the carrier gas) that are within the explosible range *(11)*. The explosion pentagon illustrated in Figure 2 expands the basic fire triangle to include mixing or dispersion of the fuel and oxidant, as well as confinement of the mixture *(12)*. This visualization of explosion requirements enables one to identify engineered-safety measures, such as venting, for explosion mitigation.

Further advice on explosion prevention and protection can be found in a number of standards available worldwide. In North America, information documented by the NFPA is widely followed. For example, NFPA 654 provides guidance on where explosion protection is required *(13)*.

Proposed framework

The systematic approach to loss prevention shown in Figure 3 is proposed as a framework for dust-explosion prevention and mitigation. This scheme provides a hierarchy in which inherent safety principles are considered first, followed by engineered and procedural safeguards. This in no way suggests that engineered and procedural safeguards are not important or are not required as risk reduction measures. Rather, Figure 3 (p. 103) stresses that inherent safety achieves its greatest impact when applied early — *i.e.*, during process design or the selection of prevention and protection measures. The problem-solving heuristic represented by Figure 3 can be further analyzed by examining its highlights:

Management and staff — Effective loss prevention requires a clear indication of responsibilities at all organizational levels. The activities listed in Figure 3 can only be successful if they are led by management and adopted by staff. Management must effectively communicate the requirements for hazard identification and assessment, carefully delegate the responsibilities for hazard remediation, and follow up to ascertain that the delegated responsibilities are fulfilled and the recommended risk-reduction solutions are implemented *(14)*. Similarly, it is essential that staff take ownership of the activities by sharing the responsibility for ensuring process and occupational safety.

Standards — Engineered and procedural dust-explosion prevention and mitigation measures must be drawn from relevant internal or external standards (*e.g.*, legislated requirements, company policy, best-industry practice, etc.) and integrated into the safety framework. For example, guidance for venting, which is classified as a passive safeguard, is available in NFPA 68 *(15)*, while automatic suppression, an active safeguard, can be found in NFPA 69 *(16)*. The need for standards-based performance may also extend to hazard identification, such as in the case of dust explosions, where testing is usually required to determine explosion parameters (*e.g.*, the maximum overpressure and the size-normalized maximum rate of pressure rise) *(17)*.

Example-based guidance — Applications of specific inherent safety principles that provide guidance on their use need to be identified. Consider a co-milling operation. Practical application of safety principles would include: waste or byproduct removal or raw material/product inventory reduction; and the substitution of those raw materials with safer materials *(18)*; replacement of process hardware, such as bucket elevators and other mechanical conveying systems, with pneumatic transport; relocation of baghouses to a location outside of process buildings to moderate the consequences of a dust explosion; and simplification of plant design to eliminate long dust-extraction ducts.

Further guidance on the application of inherent safety in solids handling is given by Bollinger, *et al.* *(19)*. These authors suggest that the risk of a dust explosion can be reduced, or in some cases eliminated, by processing the material in pellet or slurry form, processing in solution, inerting the system *(18)*, designing an explosion-pressure resistant plant, or using/specifying a larger particle size.

An increase in particle size brings about a decrease in total particle surface area, which is an important consideration in the evolution of volatiles from particles such as coal dust. A decrease in surface area leads to changes in various explosion parameters, such as a decrease in the maximum explosion pressure and, more significantly, a decrease in the size-normalized maximum rate of pressure rise.

The influence of particle size on the dust explosion hazard is clearly recognized in the literature, and is even acknowledged in the definition of dust. For example, NFPA defines dust as any finely divided solid that is 420 µm or less in diameter (minus 40 mesh). In recognition of the increased hazard posed by fine dust, the ASTM standard for dust explosion pressure and rate of pressure rise testing *(17)* recommends that the test sample be less than 75 µm (at least 95% minus 200 mesh).

The Dow Fire and Explosion Index *(20)* also incorporates a particle-size effect into the index calculation procedure as shown in Table 2. Particle size is indicated by the actual particle diameter and the corresponding mesh or sieve number. This index was developed by Dow based on historical loss data, the energy potential of materials, and the extent to which loss-prevention practices are currently applied. It uses numerical values of hazard potential or "penalty factors" associated with different material and process characteristics to determine the fire and explosion hazards in a step-by-step evaluation. One of these penalty factors deals with the issue of dust explosions. In general, the penalty factor increases as the particle size of the dust decreases.

Table 2. Dow Fire and Explosion Index dust explosion penalty *(20)*.

Particle Size, µm	Tyler Mesh Size, µm	Penalty*
> 175	60–80	0.25
150–175	80–100	0.50
100–150	100–150	0.75
75–ß100	150–200	1.25
< 75	>200	2

* Use 1/2 if carrier gas is an inert gas.

Consider a case involving very small dust particles and a high penalty factor. Dow recommends that the dust explosion penalty be halved if the inherently safer practice of using an inert gas is employed. Substitution of nitrogen for oxygen, or minimization of oxygen by partial replacement with nitrogen would either eliminate the oxidant from the fire triangle or reduce the oxidant concentration to a value below the limiting oxygen concentration (LOC) required to support combustion.

Case studies

The following case studies are drawn from papers presented at previous AIChE Loss Prevention Symposia *(21)*. Each account examines the incident, the application of the explosion pentagon, the remedial actions that were taken, and how the inherent safety principles might apply to the various mitigation measures and explosion pentagon criteria. For those cases where the remedial measures were primarily engineered or procedural, suggestions are made as to what possible inherent safety approaches may have been taken. These suggestions are at times conceptual due to limited data from the cases.

Many of the points raised by these case studies are similar to the recommendations of Kao and Duh *(22)*:

1. Use nitrogen as a conveying gas instead of air
2. Use nitrogen sealing in silos
3. Fill silos using a cyclone to reduce dust cloud dispersion
4. Carefully control particle size
5. Reduce electrostatic problems with silos and bag filters by checking the relative potential of metal construction parts
6. Control moisture in pipes and silos
7. Use lower mass flowrates
8. Use online monitoring of the electric field of compacted powders in silos
9. Use conduction of the electric field, if required
10. Design silos and explosion isolation valves between silos for explosion venting, so that sequential dust explosions will be avoided
11. Keep the dust concentration below the minimum explosible concentration
12. Design and test explosion blocks in conveying pipes.

One may question why some of the items listed above are considered inherent safety measures. For example, bonding and grounding (related to items 5, 8 and 9) are often thought

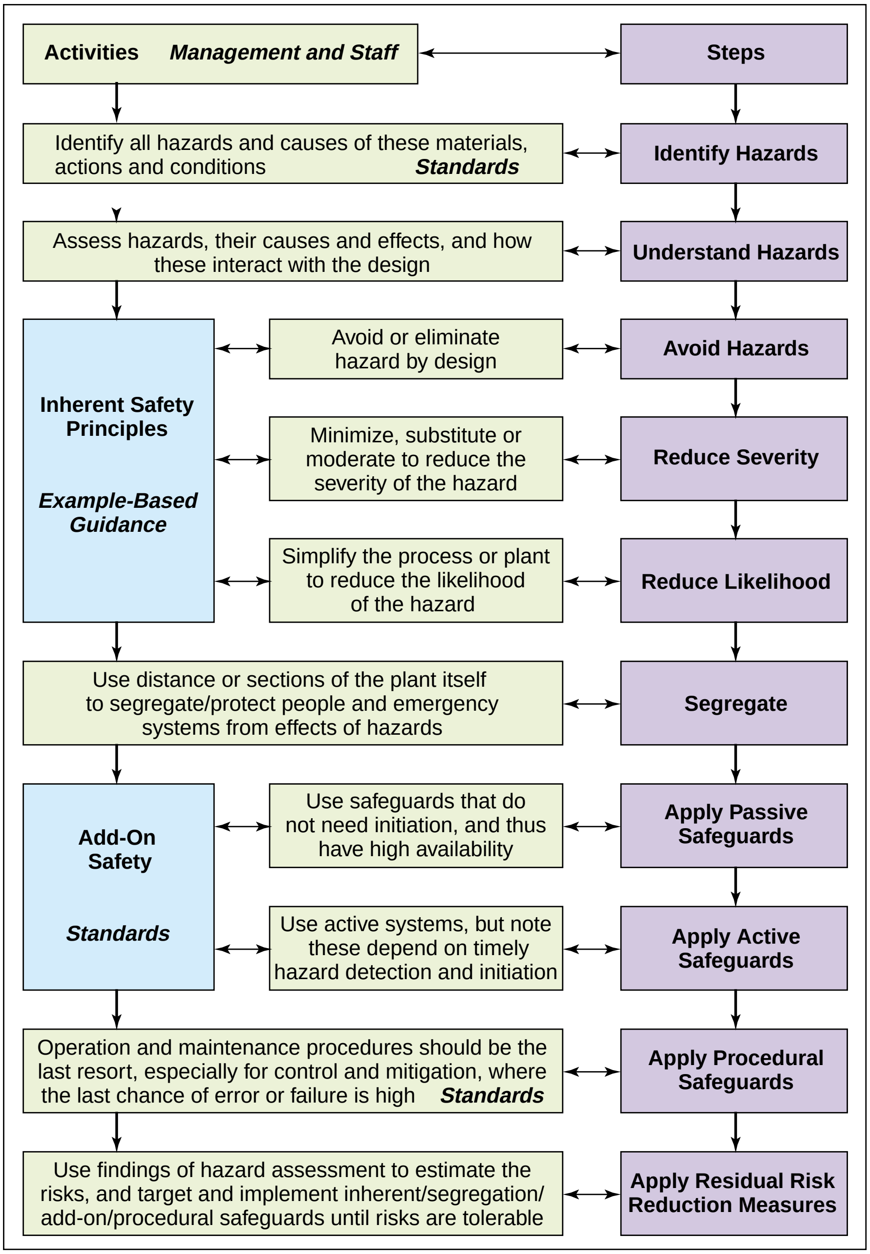


Figure 3. A systematic approach to loss prevention.

of as elements of safe work practices, and therefore, procedural in nature. Explosion venting and isolation valves (item 10) are respectively considered passive- and active-engineered safeguards. However, Kao and Duh may have been thinking of inherent safety considerations within a given engineered or procedural measure. For example, item 12 (explosion blocks in conveying pipes) could be viewed as engineered safety or as inherent safety, depending on one's perspective.

For instance, if a screw conveyor choke is achieved by means of a baffle plate — a passive add-on device *(13)* — then item 12 might be viewed as engineered safety. But, if a product choke is applied, it might be considered equipment substitution, whereby a normal auger is replaced by one with a portion of the conveying screw removed. Mechanical isolation by a valve is likely to be thought of as an active add-on approach because it relies on explosion detection and valve actuation devices. Nevertheless, the end result is the prevention of explosion propagation through interconnecting pipes – viewed by some as moderation (specifically, limitation of effects).

Further discussion on what constitutes inherent safety and the impact of process and equipment on this definition is addressed in Ref. 19. The authors describe an interlock system that uses diverse multiple sensing elements as being inherently safer than an alternative design that uses multiple, but identical, sensors. Another individual might view such a system as not being inherently safer, because if it were, there would be no need for an interlock in such an arrangement. In the cases that follow, we have adopted a broad definition and view of inherent safety.

Case #1 — Pneumatic transport

In March 1966, two dust explosions occurred at General Electric Co.'s Lexan polycarbonate manufacturing facility in Mt. Vernon, IN *(23)*. Both incidents occurred during the filling of storage silos by means of pressurized transport. While this case is several decades old, it involves a common dust-explosion hazard that is still relevant today — that of powder transport. The explosions occurred when Bisphenol-A was being transferred from hopper trucks into 4,500-ft^3 (127-m^3) storage silos, each grounded to grounding rods.

Bisphenol-A is an intermediate chemical that was used by General Electric in their polycarbonate manufacturing process. It was handled in the highly combustible form of a dry powder in small batches, which it received in bags and manually introduced into the process. Eventually, the system was upgraded to incorporate bulk-storage and pneumatic-transfer systems for powder handling. The system had the capability for both vacuum and positive-pressure transport to the silos.

The first dust explosion occurred on March 24, 1966, while the Bisphenol-A was being transferred to the storage silo from a blower truck, both of which were grounded. The process used a rubber hose for transport.

The explosion occurred some time after the process had started. Although the blast pressure was released by means of an explosion-relief vent, the top cover of the silo was dislodged and a fire ensued. The silo itself was not damaged, although cleanup and rewiring of electrical conduits were required. No personnel were injured.

The second incident occurred six days later in the second silo under almost identical circumstances. Bisphenol-A was being transferred from the blower truck into the silo, when, 30 min into the operation, an explosion occurred. The results of the explosion were similar. The blast pressure was released though the top cover of the silo and no injury to plant personnel occurred.

The investigation conducted after both incidents ruled out possible solvent explosions. Due to the nature of the pressurized transfer arrangement, the silo contained a large quantity of dispersed dust in the silo, thereby leading the investigators to believe that the accident was a dust explosion. Four sides of the explosion pentagon are accounted for: the fuel for the explosion was the Bisphenol-A; the oxidant was oxygen in the air; the pneumatic-transfer process served to disperse the dust; and the silo itself provided confinement for the explosion. The missing side of the pentagon is the ignition source. In both cases, the transfer process from the blower truck to the silo used a rubber hose for the filling process. Therefore, the most likely ignition source was static electricity.

GE took remedial actions after the second explosion. The decisions of the company can be broken down into three major changes. First, the transfer of Bisphenol-A was changed by incorporating a vacuum process to transfer the powder from the delivery trucks to the silo, replacing the pressurized pneumatic conveying system. Eventually, the company manufactured Bisphenol-A onsite, and reverted to pneumatic transport.

Next, the process was altered so as not to introduce the powder directly into the storage silo. Instead, the powder was first transported into a cyclone and filter unit desiged with a rotary airlock. This change was necessary in order to use vacuum transport, but the cyclone and filter were eventually emplyed with the pressurized system, as well. Finally, a nitrogen-blanketing system for the storage silo was put in place. The company also decided to explore the possibility of using a recirculating nitrogen pneumatic-transport system.

All these changes were rooted, fundamentally, in inherent safety. For instance, by substituting a vacuum system for a pneumatic-transfer process, flow velocities through the rubber hose were moderated to a point that minimized the static electric charging of the powder. Reducing the static electric potential on the powder would affect the explosion pentagon by removing the most likely ignition source for the explosions. In addition, by substituting in-house production of Bisphenol-A, GE minimized the quantity of the chemical being handled at any given time, since batches could be manufactured on demand and in smaller quantities. The use of a fixed installation also enabled substitution of the nonconductive rubber hose with a conductive metal pipe. This also minimizes the generation of static electricity.

The second change — transporting the solids into a cyclone and filter unit equipped with a rotary airlock for direct injection of the powder into the silo — separated the transport air from the dust, which minimized the amount of dispersing air. By reducing the dispersion level of the powder upon entry into the storage silo, as well as the quantity of powder introduced at any one time, the mixing criterion of the explosion pentagon was addressed.

In the processing and handling of combustible dusts, one of the most common modifications used to reduce the potential of an explosion is minimizing the level of oxygen in the process atmosphere. In that vein, the third change, nitrogen blanketing, substituted the oxidizing atmosphere in the silo with an inert environment. This effectively eliminated the oxidant component of the explosion pentagon.

At about the same time as the two dust explosions took place, an unrelated incident occurred in the manufacturing process of Bisphenol-A. A technician was trying to clear a plugged hose. He followed standard company practice, which at that time, was to use compressed air to blow out the hose. The air cleared the plug, but ended up dispersing the dust and dislodging the hose. A spark, believed to be caused by metal fitting on the hose striking another metal object, or by static electricity, ignited the dust cloud that had formed, with the resulting explosion injuring the technician. The company altered its standard practice (a procedural measure) by substituting compressed nitrogen to blow out plugged lines. This change effectively minimized the quantity of oxygen present in the atmosphere.

Case #2 – Rotary dryer

This case involves two dust fires and explosions that occurred in an adipic acid rotary dryer at a Texas-based plant of E. I. du Pont de Nemours and Co. *(24)*. There was little damage, but the potential for future loss was a significant concern, since the incidents occurred within three weeks of one another. The post-explosion examination of the dryer indicated that the fire had started in the heated zone, but the source of ignition was unknown.

Four sides of the explosion pentagon are immediately apparent in this case: the fuel was the adipic acid that was to be dried; the oxidant was oxygen in the air in the dryer; and the dryer provided confinement and a method of dispersion (mixing). As previously mentioned, the cause of the ignition (the fifth side of the pentagon) was unknown.

Analysis of the explosion residue and the acidic solid material collected after the incident was performed using atomic absorption spectroscopy (AAS), scanning electron microscopy (SEM), thermal analysis, accelerating-rate calorimetry and external heating in a container. SEM of the residue showed that there was a smooth side on many of the powder particles, indicating possible contact with the wall of the dryer. Both the SEM and AAS results indicated the presence of iron. Thermal analysis indicated an endotherm at the melting point of adipic acid. But dryer samples extracted using acetone showed only energetic exotherms. Upon heating, weight loss in the acetone sample occurred at a higher temperature than the other samples and left residue that was mostly iron oxide. Calorimetric analysis of the adipic acid with iron showed strong exothermic reaction tendencies.

Tests involving external heating in a container demonstrated that adipic acid in the presence of iron and the sample residue extracted from the dryer, both went to reaction whereas other adipic acid samples did not. It was surmised that the ignition source was the self-heating of the adipic acid; the self-heating process was catalyzed by the presence of iron contaminants, the most probable source of which were the walls of the dryer. Hindsight raises the question of whether substitution of a different material of construction might have eliminated such a catalytic effect.

The case, as stated in the literature *(24)*, does not offer sufficient information for making conclusive statements on inherently safer manufacturing alternatives. It is not known if moderating the the pH of the adipic acid could have prevented leaching of iron from the walls of the dryer. It is also not known if moderation of the drying temperature would have reduced the explosion risk. Finally, it is not known if substitution of the atmosphere in the dryer with recirculating nitrogen would have prevented self-heating of the adipic acid.

Case #3 — Dust filter

This case involves an explosion in a dust filter located downstream of a rotary dryer in an acrylonitrile butadiene styrene (ABS) polymer-production process at a Monsanto facility in Europe *(25)*. The filter explosion was followed by a fire that took 20 min to extinguish. No plant personnel were injured, but the filter bag and surrounding electrical wiring were damaged.

The plant was constructed to minimize dust explosion hazards and consequences. For instance, the rotary dryer was equipped with venting and suppression systems, and was designed to contain a deflagration. Additionally, a deluge system was in place to protect key process equipment, and the process also featured several redundancies for additional safety.

The incident conditions satisfied four sides of the explosion pentagon: the fuel was the ABS polymer; the oxidant was oxygen in the air; and the process equipment provided the dispersion (mixing) and confinement necessary for an explosion. The missing side of the pentagon was the ignition source. The material was determined to have a relatively high minimum ignition energy (MIE) of 100 mJ. The accident investigators ruled out electrostatic ignition, but they suspected that autoignition, caused by self-heating, was a possible ignition source since the material was held at a high temperature for a long period of time.

Several add-on safety features were incorporated into this process, but the only ones that worked properly during this accident were the passive vent panels. The actively controlled systems — suppression, interlock and deluge — did not function as intended: the deluge heads were plugged; the suppression device was set to discharge at a pressure too close to the opening pressure of the vent panels, thereby negating its effectiveness; and the interlock system that was designed to stop the pneumatic transport of powder had failed, dispersing dust into the combustion zone. The investigators recommended increasing the number of inspections (a procedural approach) and testing (procedural/engineered approach) for this equipment.

The case demonstrates the dilemma of total dependence on add-on safety devices, which can fail when needed the most. An inherently safer approach would be to transport the ABS polymer using reduced-oxygen carrier gas (minimization) or even nitrogen (complete substitution of the transport medium). One could recirculate the nitrogen to reduce operating expenses. However, nitrogen hazards (*e.g.*, asphyxiation) would have to be carefully considered in making such a change *(26)*.

Since the investigators identified autoignition as the most likely ignition source, an inherently safer approach would be to moderate, if possible, the temperature of the dryer. Minimizing the quantity of powder flowing through the system at any given time, or minimizing the hold-up time for the powder, would also be beneficial strategies because they would help to eliminate a potential self-heating ignition source. Nitrogen blanketing, in conjunction with minimizing the self-heating potential of the powder, would influence two sides of the explosion pentagon — the oxidant and the ignition source.

However, such strategies to incorporate inherent safety methodology into an existing operational facility may not be practical. The capital expenditures required to make the changeover would likely be prohibitive. It is most cost-effective to adopt inherent safety approaches at the initial design stages.

Case #4 — Milling operation

This case deals with an explosion in a dust collector attached to a bar-type hammer mill used to grind a rubber additive at a Monsanto plant in Europe *(25)*. The explosion occurred upon restarting the mill after it had been taken down for servicing. The hopper was empty when the mill was restarted, and there was no significant buildup of powder in the vicinity after the explosion. The accident investigation revealed wear marks on the shaft and disk of the mill. Investigators concluded that friction caused parts of the mill to overheat, which resulted in ignition. With reference to the explosion pentagon, the rubber additive was the fuel; oxygen in the air was the oxidant; and the process equipment would confine the powder and also serve as the mixing vessel.

To mitigate future incidents, proper cleaning of the mill and correct assembly (essentially procedural measures) were highly recommended. In addition, inherent safety considerations would be employed, supplementing the explosion-suppression devices already in place, which helped to limit the total loss during the explosion. Inherent safety procedures would include minimizing the explosible atmosphere by substituting recirculated nitrogen for air as the motive force of the mill. As stated earlier, this measure would eliminate or lower the oxidant component of the explosion pentagon.

Although moderation of the mill speed may not be practical with respect to particle-size requirements for the milled product, substitution of a mill that is less prone to overheating might be a consideration worth pursuing. In any event, it is well known that dust explosions occur in hammer mills; such mills are therefore generally constructed to withstand explosion overpressures. This is an example of the principle of simplification, specifically error tolerance — making equipment robust and able to withstand process upsets.

Case #5 — Storage bin

This case involves the review of an explosion that occurred on May 18, 1982, in a calcium carbide storage bin *(27)*. It is important point to note that calcium carbide reacts with water to create acetylene gas. Acetylene has one of the lowest MIEs of all flammable gases — 0.05 mJ —similar to that of hydrogen. The plant in question manufactured a desulphurization flux product consisting of 65% calcium carbide, 35% carbon (from anthracite coal) and 5% limestone.

During the process, partially ground calcium carbide from two surge bins was further pulverized using two vi-

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brating mills. After pulverization, the calcium carbide was transported to a storage silo, where the explosion occurred. The surge bins had an emergency nitrogen-blanketing system and acetylene detectors to shut down the process. One of the two mills served a dual role as a pulverizer for the anthracite coal. The mills were purged with nitrogen before startup and nitrogen was bled in to replenish the purge levels during normal operation. If the mill was shut down for an extended period of time, the nitrogen bleed was terminated. The mills released the calcium carbide into hoppers from which a dry-air transport system was used to transfer the material to the storage silo. The calcium carbide entered through a 3-in. inlet and then settled to the floor of the silo. The air from the silo was passed through a filter, monitored for moisture level, and returned to the conveying system. Dry air was added as needed to make up for any losses. The storage bin was also equipped with an acetylene-monitoring system that could shut down the system if excessive levels of acetylene were detected.

The process was shut down in December 1981 for an extended period of time, due to operational problems, restarted in April 1982 to pulverize anthracite coal, and then shut down again on May 18, 1982. The switch to carbide processing took place before noon on that day. Two explosions occurred nearly simultaneously at 2:10 p.m. in the silo, five minutes after startup. No plant personnel were injured. However, the silo and surrounding buildings suffered extensive damage.

An investigation revealed that the incident most likely started with an acetylene explosion that ignited the dust in the silo. For acetylene to be present, moisture must also have been present. Testing revealed that the acetylene-detection system was working adequately prior to the incident and that there were minimal levels of moisture present. However, it is possible that the acetylene detectors may have become clogged; additionally, the detection system may have been too slow in reacting to acetylene buildup in a near-empty silo. The large volume may have allowed for localized, high acetylene concentrations. This is similar to the situation in coal mines where the large volume of a mine shaft permits high localized concentrations of another highly flammable gas, methane.

In this case, most of the explosion pentagon criteria are apparent: the fuel comprised both calcium carbide and acetylene; the oxidant was oxygen in the transport and storage air; confinement was provided by the silo walls and dispersion was enabled by direct introduction of the carbide into the silo. The ignition source is unknown, but since acetylene has a very low MIE, any form of electrostatic discharge or small quantity of heat input would be sufficient to cause ignition.

The case reviewers recommended five corrective measures:

- substitute the conveying air with dry nitrogen
- maintain the nitrogen bleed at all times, even during long shutdown periods
- use redundant acetylene detectors in the silo
- test the detector response under actual operating conditions (*i.e.*, not offline)
- establish operating and emergency procedures to prevent future occurrences.

The first two recommendations are inherently safer measures. The use of dry nitrogen would help reduce the moisture hazard, thereby minimizing the potential for fuel generation, since moisture is required for acetylene formation. In addition to nitrogen blanketing, a possible consideration would be a cyclone/filter and rotary airlock arrangement, as presented in Case 1, to moderate the flowrate of carbide into the silo and thus minimize the degree of dust dispersion. Additional considerations might be modifying the system to provide calcium carbide as needed; using smaller quantities of calcium carbide (minimization), which would reduce storage space requirements; and the use of a smaller silo, which would enhance the effectiveness of acetylene detection by reducing the potential for localized acetylene buildup in a large volume.

The third measure could be classified as engineered, or perhaps inherent, if the sensors were not all based on the same principle of detection *(19)*. The last two recommendations are procedural measures. CEP

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