Prevention and Control of the Combustible Dust Threat

Introduction

Many modern industrial operations create dust as either a by-product or an end product. In certain conditions, some of these dusts can release hazardous amounts of energy when ignited. But, questions then arise as to which dusts are susceptible, what can be done to reduce the risk of a dust explosion, and why do they occur? It is the purpose of this presentation to answer these questions. This knowledge will enable a systematic method of hazard assessment and mitigation to provide the maximum protection of the employees and assets within the organization.

It should be the intent of every Safety Professional, Manager, Technical Engineer, and Operator to work diligently to prevent these incidents of explosions from happening. One of the best preventatives is to understand how they occur and then put irreversible corrective actions in place to keep them from occurring. The pages that follow offer a primer on the conditions leading to and the prevention of dust explosions in industrial settings.

A Brief History of Dust Explosions

One of the first recorded dust explosions occurred in Turin Italy in 1785 at a flour mill. Since that time dust explosion events have continued to cause devastation, destruction, and death. In a study completed by the National Fire Protection Association in 1957, 1123 dust explosions occurred between 1900 and 1956 in the United States, across many industries (NFPA, 1957). Figure 1 illustrates the scale of destruction and potential danger from dust explosions.

In the early 1900s coal-mining incidents occurred in Monongah, West Virginia, and in Darr, Pennsylvania, with a combined total of over 600 deaths. These two explosions were so devastating because of the number of people who lost their lives that the United States Government began an explosive testing program under the Federal Geological Survey. The laboratory was later transferred to the Bureau of Mines in the U.S. Department of Interior. Testing was conducted on a laboratory scale and in a full-scale mine trial in Pennsylvania. The results from these tests were helpful to the mining industry by reducing the number of mine dust explosion events. Testing continued in the United States through the 1940's and 50's under the Bureau of Mines and the Department of Agriculture (Cashdollar and Hertzberg, 1987). During this time, researchers at the Bureau of Mines developed a cylindrical tube dust explosion apparatus with the capability of testing dusts for explosive potential. The Hartmann Test Apparatus, as it was called, has been used by the Bureau of Mines to study many different dusts over the past century (see Figure 2). This machine, which measures the rate of pressure rise and the maximum pressure resulting in an explosion, was used to develop much of the explosibility data found in most of the reference books of the 1950's, 60's and 70's. Continued research identified and corrected flaws in the design of the Hartmann tube which, in general, tends to underestimate key measures of dust deflagration energy. Around 1977 an alternate machine was developed in Europe known as the Siwek 20-Liter Apparatus (see Figure 3). The 20-Liter Apparatus has been found to give highly accurate estimations of explosion energy. It is now the standard instrument used to determine dust explosion hazards.

The need for fine sized products for a variety of applications is expanding rapidly. At the same time, the hazards of producing and handling these materials are also increasing. From a general industry perspective, iron and steel leads the way in dollar losses while food product manufacturing experiences the highest number of incidents. Other industries suffering losses include saw/planing/milling, electric generation, paper/pulp, textiles, machinery manufacturing, pharmaceutical processing and furniture manufacturing (Factory Mutual Engineering Corp, 1996).

Generation of Design Data

Data generated in the 20-Liter Apparatus tend to be more accurate than those from the Hartmann Test Apparatus. The spherical test chamber of the 20-Liter Apparatus avoids the nonsymmetrical energy waves that are developed in the tubular Hartmann Test Apparatus. The wave patterns in the 20-Liter Apparatus propagate symmetrically within the chamber, thus giving more accurate measurements for both measures of rate of pressure rise and maximum pressure developed in the test vessel. Information generated in the Hartmann Test Apparatus and published in the majority of older reference manuals is not considered to be as accurate as that from the newer test apparatus (Bartknecht, 1989). Therefore, when using information generated from the Hartmann Test Apparatus, uld be tempered with additional safety factors to compensate for the inaccuracies of the technique.

Importance of Testing Specific Materials

It is essential to use data generated for specific products. It may seem expensive to classify each product separately but the benefit of quantitative estimations of material hazards used for decision making far outweighs the cost of testing. Use of explosion data from what are believed to be *similar* dusts to those in question is not recommended. Many variables significantly affect dust ignitibility and explosive force. Data generated using American Society for the Testing of Materials (ASTM) methods employs precise standards for preparation of samples that include concentrations, size, and ignition energy (ASTM, 2000). If the material is smaller in size than that used in generic testing, the reaction potential is generally greater. If design engineers have used generic data for *similar* dusts, they may not have used the correct design parameters for an actual dust's explosive characteristics. See Appendix A for an illustrative example of typical dust explosion characterization results.

Important Characteristics to Obtain from Testing

Testing of explosive dusts using ASTM and other methods generates several important quantitative measures of specific material explosivity and combustibility. Measures that can be used to help design and operate explosive dust processing facilities safely include:

1. Maximum pressure developed in an unvented vessel. Symbol: P_{max}
2. Maximum Rate of Pressure Rise. Symbol: $(dP/dt)_{max}$
3. Deflagration index for dusts. Symbol: K_{st}
4. Minimum Ignition Energy Symbol: MIE
5. Minimum Explosive Concentration Symbol: MEC
6. Maximum oxygen level that will not allow combustion Symbol: $O_{2\ max}$

Maximum pressure (P_{max}) developed is the greatest pressure generated by a particular dust at the optimum concentration, in a closed vessel. The units are commonly expressed in bars (1 bar=14.7 psi). This information is used to determine the maximum pressure a vessel or other structure will be exposed to in the event of a dust cloud deflagration. It can predict failure of the structure. The greater the value, the more total energy is released by the material, and the greater the potential hazard.

The value given by the *maximum rate of pressure rise,* $(dP/dt)_{max}$, is the rate of pressure increase over time at the steepest part of the pressure-versus-time curve (see Figure 4). It is reported in bar/s. This measure is used to determine necessary venting capacity of closed vessels such as dust collector bag houses. The higher the number, the greater the energy release per unit of time, and, hence, the greater the potential hazard.

The *deflagration index* for dusts (K_{st}) is the maximum dP/dt normalized to a 1.0 m^3 volume and is reported in bar-m/s. The formula used to generate the index is:

$$K_{st} = V^{1/3} (dP/dt)_{max}$$

where V equals the volume of the test vessel (ASTM, 2000). This quantity is also used in vent sizing to describe the explosibility of a particular dust. It allows a comparison of data from different sized test vessels (with the exception of the Hartmann Apparatus). The higher the number, the greater the explosive energy release, and the greater the potential hazard.

The *minimum ignition energy* (MIE) is the minimum amount of thermal energy released at a point in a cloud of suspended dust that will cause indefinite flame propagation away from that point, under specified test conditions. It is reported in mJ. This number is used to determine what energy sources must be controlled to prevent ignition of a dust cloud. The lower the value the more easily ignitable the material is, and the greater the potential hazard.

The *minimum explosive concentration* (MEC) is the lowest concentration of a dust that can support a self-propagating explosion. It is reported typically in mg/m^3. This measure is used in designing and operating explosive dust handling systems below the level of suspended fuel that will support combustion. The lower the MEC, the greater the hazard of explosion.

The *maximum oxygen level* ($O_{2\ max}$) is the level of oxygen at or below which a dust is not capable of sustaining combustion. It is reported as a percentage of oxygen in a volume. $O_{2\ max}$ is used in designing inerted atmospheres for systems processing explosive dusts. Calculations of the necessary amounts of inerting gas are required to displace enough oxygen in a vessel to create an atmosphere below the $O_{2\ max}$ for the specific material, eliminating the potential of ignition.

The most important concept from this discussion is: **Always obtain test data generated from real, specific products.** Great variation exists in the many variables that come together to create the explosive characteristics of a particular dust. It is the authors' experience that each process creates unique behavior characteristics for the dust material it generates. Only by quantifying these characteristics for a particular dust can the hazards be understood and the risk properly managed. Table 1 gives example values of these measures for a selection of dusts and illustrates the variability of these measures.

The Anatomy of a Dust Explosion

To understand dust reactions, a general understanding of the anatomy of an explosion is essential. A dust is often defined as any finely divided solid matter that passes through a No. 40 USA Standard sieve or has a size less than 425 microns. A combustion reaction occurs when five parameters are met: dust concentrations (fuel), ignition source (energy), atmosphere (oxygen), confinement, and suspension (see Figure 5). Factory Mutual Research Center refers to this as the Explosion Pentagon (Factory Mutual Engineering Corp., 1996). Once all of these conditions have been met, the likelihood of a dust reaction (deflagration or detonation) is great. An important fact related to the theory of the dust explosion pentagon is the dust must be capable of propagation of a burning reaction in order to have explosive potential.

When an explosion occurs, the fuel rapidly oxidizes. One particle of fuel or dust burns releasing enough energy in the form of heat and light to start the particle of fuel adjacent to it oxidizing via convective, conductive and/or radiant heat transfer. The place where the first burning or oxidation occurs is called the *point of ignition*. As the reaction continues it generates a flame front of hot gases. In front of this flame front is a wave of relatively cool compressed gas, called a pressure wave (see Figure 6). Standing beside a road when a tractor/trailer goes by, one will feel the pressure wave coming off of the truck. In this analogy, the tractor/trailer is the heat and flame front pushing the cool air in front of the truck.

The Role of Shock Wave Compression of Gases in Dust Explosions

The compression of fuel/air mixtures by the pressure wave is a key component in the development of destructive levels of energy usually generated by dust explosions. Much like the compression of gasoline and air in the automotive engine increases the power generated from the fuel, compressed mixtures of dust fuels and air release more energy. This accounts for the rapid increase in pressure created by dust explosions in confining vessels. This effect is called "pressure piling". Eckhoff (1997) describes pressure piling as an increase in the pressure of the unburned dust cloud in the downstream process units that increases above atmospheric pressure due to compression caused by the expansion of the hot combustion gases in the unit where the explosion starts. This example assumes that ducts or other passageways connect the units. There is a nearly proportional relationship between the initial pressure of a dust cloud prior to ignition and the maximum pressure attained from a dust reaction. Figure 4 illustrates the accelerating rate of pressure rise for a typical dust. As the pressure wave compresses the fuel/air mixture, the flame front ignites the mixture in a rapidly increasing area of over-pressurization. This rapid increase in pressure frequently results in surpassing the ultimate strength of the enclosure containing the dust explosion, sometimes creating catastrophic levels of destruction in facilities.

The Special Hazard of Secondary Explosions

The phenomenon of secondary dust explosions is created by unintended conditions from process equipment used in facilities that produce or handle fine sized explosive materials. Secondary explosions are often much more powerful than the primary explosion and can create the greatest extent of injury to personnel and damage to facilities (Nagy and Verakis, 1983). Normally associated with dust accumulated on the horizontal surfaces of the work area, secondary explosions result when the dust becomes suspended by the pressure wave and is then ignited by the flame front of the primary explosive event. The prevention of secondary explosions is the most important aspect of catastrophic dust explosion hazard mitigation. Proper housekeeping and effective venting are important methods of control.

Identification of Explosive Dusts

When considering which materials may be explosive, a leading author provides the following guidance: "Any solid material that can burn in air will do so with a violence and speed that increases with increasing degree of subdivision of the material" (Eckhoff, 1997). Metals are a special case, as they typically will not burn in air in bulk form. However, the effect of dramatically increased surface area of the fine particles greatly enhances the combustion process of metal dusts. Any material that is not already composed of stable oxides is capable of rapidly oxidizing in the form of a dust deflagration or explosion by the following chemical reaction:

$$\textit{fuel} + \textit{oxygen} \rightarrow \textit{oxides} + \textit{energy}$$

Sand is an example of a material that will not explode as a suspended dust due to its composition as SiO_2, a stable oxide. The practical implication is that not all dusts are explosive.

A well-proven theory regarding dust explosion violence is that an inverse relationship exists between particle size and explosion violence. The smaller the particle size distribution, the greater the energy release of a dust/fuel clouds during deflagration. Characterization of size distribution for specific dusts should always be obtained.

Fuel material, size, and concentration can affect the intensity and duration of the reaction. Some common fuels are coal, wood, cornstarch, and flour. Some of the less common fuels are egg whites, walnut shells, aluminum, manganese, chromium, plastic resins, and sugar. Aluminum will oxidize at a rate greater than 10,000 psig/second and can generate a maximum pressure of over 100 psig (Baumeister and others, 1969). Aluminum and copper alloys will generate a maximum pressure of 27 psig. The purity of the product has a drastic effect on the reactivity of the material. Size also significantly impacts the rate of propagation. When building a fire, one starts with kindling or small pieces of wood. The smaller the size the more surface area to oxidize. The same holds true with powders. The smaller the size, the less energy it requires to ignite the particles. The more concentrated the fuel, the closer the particles are to one another to enable the adjacent piece to burn. For explosive dusts, terms like Minimum Explosive Concentrations (MEC) and Upper Explosive Concentrations (UEC) describe the limits of the explosive range. Most testing is conducted using standard sizes and concentrations of dust loading in order to make a correlation between different products or materials. Frequently, products of concern for a given process do not exist in a uniformly sized state but rather a distribution of sizes. This is why it is so important to obtain samples representative of specific materials typically existing in the work area of interest.

Ignition sources necessary to achieve an explosion also vary in intensity. Each material will require a different ignition energy intensity to get it to react. Ignition energies listed in the Standard Handbook for Mechanical Engineers by Baumeister and others (1969) vary from 15 to 1900 millijoules. It is important to keep in mind the test parameters and guidelines in effect when the data were generated. As a point of reference, even a static spark from clothing falls between 15 and the 1900 millijoules.

Prevention of a Dust Explosion

The Dust Explosion Pentagon (given in Figure 5) can be used to illustrate methods of dust explosion prevention. Removal of any one or more of the five factors will eliminate the potential for an explosion. The factors in the Dust Explosion Pentagon are:

1. Fuel (Explosive dust)
2. Oxygen (Typically at atmospheric levels: 21%)
3. Energy (Ignition source: arcs, sparks, hot surfaces and light)
4. Suspension (Fuel suspended in a cloud at a concentration that supports combustion)
5. Containment (Containing vessel that maximizes the process of increasing compression of fuel thus accelerating the rate of pressure rise and maximum pressure generated)

Use of the Pentagon to Help Prevent Dust Explosions

Fuel may be impossible to remove because, in many cases, it is also the product being processed. One method for removing the fuel is to reduce the concentration of dust below the Minimum Explosive Concentration (MEC). This can be used as an effective method for transferring dust in ducts, such as dust collectors. Once the duct gets to the collector, it normally increases in concentration above MEC. Another method of fuel control is the mixing of a non-reactive dust with a reactive dust, creating a quenching effect on the propagation of particle combustion. The use of "rock dust" in coal mines is an example of this method. However, if the ultimate product is a fine sized material, quenching with a second, non-reactive component may serve to introduce an unacceptable contaminant.

Removing the oxygen or the oxidizer is also another method for controlling the reaction. Inert gases like nitrogen and argon, in some cases, can be used effectively. Choosing the gas is important. Some gases that are normally considered to be inerting agents could prove to be oxidizers for specific solids. For example, nitrogen can react violently with lithium and titanium; carbon dioxide can react violently with lithium, potassium, and aluminum. When processing materials small amounts of oxygen are necessary to oxidize the surface of the product when fresh surfaces are formed. Milling and grinding systems that are fracturing materials and exposing fresh surfaces hungry for oxidation must supply a limited amount of oxygen to ensure some surface oxidation without providing enough to support rapid combustion or explosions once the milled product is introduced into a standard atmosphere. Oxygen concentrations that will not lead to combustion but will still allow adequate surface oxidation can be found by experimentation.

Eliminating ignition sources can be challenging. Bonding and grounding can reduce the potential for static sources, but are not always effective. Completely eliminating static sparks continues to draw a lot of interest, but it has not yet achieved practical effectiveness. The National Electric Code (NFPA, 2002) should be used as a guideline and provides the best practical advice for bonding, grounding, and static elimination.

Suspension can be controlled more easily than other factors. Dust collection systems can be used to minimize concentrations of fuel in suspended clouds inside and around process equipment. They also can serve to reduce or eliminate accumulations of dusts on horizontal surfaces that might otherwise be suspended and lead to a powerful secondary explosion as discussed above. A flocculent agent or water can decrease the ability of the dust to remain suspended. Care must also be taken to ensure that other hazardous reactions between the fuel dust and flocculating or wetting agents do not occur.

Finally, containment can be adjusted to minimize or control the rapid buildup of pressure. Much work has been done on explosion venting of vessels. This control method involves the construction of venting devices in closed vessels to release pressure during the early stage of an explosion to significantly reduce the maximum pressure developed. The reader is directed to the National Fire Protection Association Standard No. 68-Guide for Venting of Deflagrations. Containment vessels can also be strengthened to survive expected levels of over-pressurization from dust explosions. Recently, high speed extinguishing and quenching systems have been developed to protect containment vessels as well.

Engineering Out the Dust Explosion Hazard

When designing a system for explosive dust, one must assume at some point it will react. The system should be designed to protect the operator or maintenance personnel who will work near the equipment. The design should also incorporate ways to minimize damage to the process equipment if it does explode. Potential environmental concerns resulting from an explosion should also be evaluated.

Equipment selection is one of the most important aspects of explosion protection. Typical processing equipment for handling fine powders is not configured by the manufacturer to withstand 50 to 150 psig internal pressures. It is also not designed to withstand a rate of pressure rise of over 10,000 psig per second. As a result, when an explosive dust is involved, alternative ways to control the reaction should be explored. By using the data generated from the 20-liter sphere test, relief ports can be designed and installed in the process to relieve the internal pressure before reaching the yield strength of the equipment. Some companies specializing in explosions protection have designed equipment to detect sparks and apply fire suppression materials in the duct to extinguish the fire from the reaction. By installing this type of equipment, the course of the reaction can be directed to protect the equipment and the operator.

Only recently have design standards for hazardous powder processes received the necessary focus. Although testing in the United States has been ongoing since 1907, most standards have been generated over the past ten to fifteen years. The aluminum industry set the stage along with the National Fire Protection Association by authoring guidelines for handling and processing aluminum powder. Today, additional standards have been developed by the NFPA for guidance on explosive venting, equipment selection, location, and design parameters. Companies like the Fike Corporation, FM Global, and others are bringing their equipment and technical expertise to the market in a new and dynamic way. They are sharing information with industry and selling technology, testing, and technical expertise to help keep the industry workplace safe.

A critical area often overlooked in most designs is maintenance. Upset conditions such as malfunctioning equipment and inerting/collection system shutdown coupled with repair activities such as welding, cutting and manual disassembly, create increased potential for explosive reactions. Most engineering companies will design the process for the operation mode, not the maintenance mode. Each piece of equipment should be designed with consideration of isolation, cleaning, and removal or repair as well. Emphasis should be given to two specific and common maintenance activities. How can each piece of equipment be removed without using spark-generating tools? How can this equipment be accessed if a bolt is broken? Maintenance employees must be involved in the design phase of the process.

Human Factors in Dust Explosion Risk Reduction

At the heart of any explosive dust processing facility are the employees who run it. Like many other facets of industrial safety, engineering can mitigate much of the hazard of dust explosion, but the human beings involved ultimately have the greatest impact on the safe operation of the system. The authors believe that the interaction of human operators must be as carefully designed into dust processing systems as any of the "hard engineering" factors. Five important human factors are presented below:

1. Employee Knowledge
2. Employee Behavior
3. Design of Process Controls and Displays
4. Task Analysis
5. Proper Job Design

Employee knowledge of the process is critical to effective and safe operation. Put simply, employees must know what they are doing! Training must be effective and continuous to keep employees informed of all aspects of the operation. Lowenberg and Conrad (1998), for example, present a detailed discussion of training methods and goals. Procedures must be in place that clearly define the proper actions to operate all aspects of the process.

Employee behavior has been identified as far back as 1943 as the leading cause of accidents (Heinrich, 1943). In a process with low error tolerance such as explosive dust processing, the importance of consistent employee compliance to operating rules is obvious. Yet this is an area where organizations frequently struggle. In the past 20 years, a new tool for improving behavior on the job has emerged in industrial safety and has been successful in motivating employee safe behavior. The concept is to identify critical safety related behaviors, measure their mass, and manage their levels so that a workforce does not precipitate accidents (Krause, 1990). The process uses workplace culture to ultimately enhance employee safe behavior. The advantage is clear in the application to explosive dust processing: organization culture ensures the practices and behaviors of safe operation are followed.

For processes with low tolerance for error, design of controls and displays is crucial to prevent human errors resulting in catastrophic events. Of concern for process displays and controls are aspects such as labeling, warnings and instructions, arrangement, and warning/emergency signals. For an excellent treatment of the subject see Kroemer and others (2001).

Task analysis is a systematic method used by ergonomists, designers and operators to describe and/or evaluate the human-machine and human-human interactions of discrete parts of a system. Put simply, it is the study of what an operator’s job duties consist of and how these duties allow a system goal to be accomplished. The use of task analysis allows optimization of the human elements of a system in three principal areas: safety, productivity and availability (Kirwan and Ainsworth, 1992).

Finally, proper job design increases employee satisfaction, which, in turn, has an influence on performance. Jobs with more variety, task identity, and feedback significantly increase satisfaction (Conrad and others, 1998). Employee needs, inclinations, and tendencies lead to desired organizational outcomes when aligned with job requirements.

Managing the Risk of Dust Explosions

The hard work begins once the system is designed and ready to install. A good engineering company with some experience can design equipment based upon the test results and sound engineering practice. But, it takes good committed management and operating personnel to develop the Standard Operating Procedures (SOP) and Maintenance Operating Procedures (MOP) to operate and maintain the system to avoid an explosion. Illustrative examples of an SOP and MOP are given in Appendices B and C. This is the most critical area in which Safety Professionals need become involved. Understanding how the process is supposed to operate and translating it into a step-by-step manual is the first order of business before any switch is turned. This part of the SOP development should be conducted at the same time as the design phase. A committee/team should be used to review this development. This review committee should be used for as long as the system is operating to oversee the SOP and MOP updating and accuracy. It should include personnel from operation management, safety, operations, staff engineering, and maintenance, at a minimum. The committee make-up should have all of the technical, operation, and maintenance knowledge available to provide the manager with accurate advice so decisions will be made on the best information available. Once each area of the process is reviewed and the SOPs and MOPs have been developed, this committee should have final review before any modification or changes are made to any standard. They should seek technical expertise when questions arise that cannot be answered in detail by the group.

Once the Standard Operating/Maintenance Procedures have been developed, they should be the bible for operating the process. Training and understanding are the keys to running a safe system. Each operator should be trained on the SOP. Each maintenance employee should be trained on the MOP. All people involved with the system should be keenly aware of the potential for a reaction. They should be trained on the basic knowledge of what causes a reaction as well as the possible dangers and damage if one should occur. Each operator should become the key rule enforcer. Training, training, and more training are the key to a successful operation. The more knowledge the operations and maintenance personnel have about the process, the fewer incidents will occur.

Standard Operating Procedures should contain all of the information for the operator to run the equipment and produce a product that meets customer requirements. The SOP should contain enough detail for the operator to make adjustments within the confines of the process, without placing himself/herself or the process equipment in an out of control condition. It should contain Go/No Go standards that define abnormal conditions, so the operator will know the boundaries for operation. Examples of Go/No Go criteria are given in Appendix D. Every question should try to be answered before the system is commissioned. Even after the operation is started, many questions will likely arise with some leading to revisions in the SOP to include required modifications. The SOP should contain checklists for operating equipment and housekeeping accountabilities.

Maintenance Operating Procedures should contain all of the information the Maintenance person will need to prepare, clean, isolate, repair and replace the component needing attention. It should contain any special requirements such as: special clothing, grounding straps, no cutting or burning, no open flames, no generation of dust clouds, no grinding equipment, special non-sparking tools, *etc*. The MOP should contain checklists for pre and post work accountabilities. Appendix C gives an illustrative example of a typical maintenance checklist.

Clothing and tool requirements should be well defined. In some cases where the energy to ignite a powder lies in the static spark range of the energy scale, grounding straps and grounded shoes might have to be used. Garments should be selected to prevent melted clothing from adhering to the body if a reaction should occur.

The operator should be used as an additional safety person for the maintenance personnel. The operators are the manager's eyes and ears in the field. Managers and supervisors cannot be at the operating equipment at all times. The operator should take the lead for safety on the piece of equipment. How is this type of commitment achieved? By training and letting the operators know what is expected of them, a culture is built that drives adherence to safe operating practices. Expect operators to shut down the system when it does not conform to the procedures and to take steps to resolve the situation.

A good Quality Control System for documentation, process control, and audits is the best method of policing hazardous process systems. Use of Quality Control Systems in conjunction with the review committee has the maximum impact on the safety of an explosive dust processing system. The utilization of a Quality Control sign-off system for changes to Standard Operating/Maintenance Procedures will assure the system is being operated under the guidelines of current information. This does not assure that the operator is following the procedures. Only trust, knowledge, and a watchdog control system will monitor equipment operation. If the operators are trained to respect the explosive product, they will not want to modify the operation.

Housekeeping has only been mentioned once thus far, but it is probably the most important aspect to keeping minor incidents from turning into major disasters. When catastrophic damage and/or loss of life occurs, it is likely the consequence of secondary explosions. A small reaction creates a pressure wave in front of the hot expanding gases. As this pressure wave travels through a building or structure, it moves the dust from the horizontal surfaces into the air -- suspension. If the concentration is above the MEC, a secondary reaction starts. Primary explosions normally occur inside of the equipment either during an upset condition in operation or during a downtime for maintenance. During maintenance downtime, the explosive reaction may occur when the equipment is not cleaned thoroughly before maintenance is started or by someone who is allowed to shortcut a procedure. When this happens in a dirty building, the containment area becomes the building. Housekeeping, housekeeping, and housekeeping should be the continued and relentless commitment everyday. The importance of stopping dust leaks and assuring clean floors, rafters, building ledges, nooks and crannies of every area cannot be stressed enough!

Damage Control: Considerations Regarding Explosive Dust Fires

The complexity of the dust deflagration/explosion process can lead to undesired consequences despite the most diligent effort. Organizations that encounter dust hazards must prepare for the worst case as a result. Two likely dust explosion fire scenarios exist. The first is the smoldering remains of dust piles or unreacted piles after an explosive event. In this situation, great care should be taken not to suspend dust in the air. If a smoldering pile is contacted with a high pressure, high volume stream of water, the water will likely agitate and help suspend the burning dust in the air. The result is a potentially explosive cloud with ignition sources already present in it. The risk of explosion is great in this situation.

The second scenario is a smoldering pile or nest of explosive dust that has not yet been involved in an explosion. Smoldering nests are areas of reacting material inside larger masses of material such as might be found in a silo. Again in this situation, great care must be taken to avoid suspension of the dust in the air. Water streams capable of pushing dust into suspension must be avoided. Another aspect of the use of water is the potential for the buildup of explosive concentrations of hydrogen due to the dissociation of the oxygen and hydrogen in water. Metal dusts in particular are capable of creating this hazard.

Important Considerations for Fighting an Explosive Dust Fire

The recommended actions below are important when fighting an explosive dust fire. As always, special situations may be present and will require more than a shallow understanding of the process of dust explosions. The time to gain that knowledge is before it is needed. Hazard assessment and preparation with plant personnel and local fire departments is paramount in successfully fighting these fires.

Important considerations:

1. Immediately de-energize all electrical power feeds and valve off all natural gas supply lines to the area to minimize ignition sources.

2. Conduct a field assessment of the structural integrity of a building after a dust explosion has occurred. Are the walls or other supporting structures obviously damaged to the point of imminent collapse? Are roof members damaged to the point of imminent collapse?

3. If potentially explosive dust is heavily suspended in the air, consider conducting fire-fighting activities from outside the building, from a safe distance.

4. Assess the potential for primary or secondary explosions. Is vision reduced to a few feet by suspended dust? Has dust accumulated on elevated horizontal surfaces? The existence of any of these conditions indicates a dust explosion is still possible. Avoid additional suspension of dust and all ignition sources.

5. Determine the proper fire extinguishing media to use for the involved material. Is water indicated? Refer to Material Safety Data Sheets, the Department of Transportation Emergency Response Guide (DOT, 2000) or Sax's Dangerous Properties of Industrial Chemicals (Sax, 1996) for verification. Other media frequently called for are Ansul Met-L-X, Sand or foundry flux (NFPA, 1991). Use water on metal fires only with expert guidance, following specific safety measures.

6. Use only fog nozzles oriented so as to spray liquid extinguishing media lightly onto piles of material. (Never direct a high-pressure spray at a smoldering pile of dust.)

Only properly trained and equipped personnel should attempt to fight any fire. Refer to OSHA Regulations 29 CFR 1910.120-Hardous Waste and Emergency Operations and 1910.156-Fire Brigades, for more direction.

Conclusion

It is the responsibility of safety professionals to gain the basic knowledge to influence management, operators, maintenance craftsmen, engineers, quality control personnel, and process technology personnel to design, maintain, and operate, explosive dust processing systems with the maximum level of safety. It was the purpose of this paper to provide an introduction to the topic of dust explosions and identify important references. As we have seen, the need for management of dust explosion risk in all phases of industrial activity is paramount to the protection of people and property.

Appendix A

Typical Dust Explosion Testing Results for a Specific Material

To:	Ronald Brandon	At:	Elkem Metals Company, Alloy Plant
From:	John Smith	At:	Acme Testing Labs
Subject:	Metal Dust Sample A 20-Liter Dust Explosion Characterization		
Date:	January 1, 2002		

We have completed the 20-Sphere testing of the dust sample identified as:

Metal Dust Sample A

The testing was performed per the request of the insured, Elkem Metals. The test results are as follows:

Kst	= 77 bar m/s
Pmax	= 5.7 bar (83 psig)
MEC	= 125 mg/m^3
Bulk density	= 1860 kg/m^3 (116.1 lb./ft^3)
MIE	= Did not ignite when MEC was exposed to a 400,000 millijoule ignition source.

The samples were tested as received. The as received samples met the specifications of greater than 95% smaller than 200 mesh (75 microns) and less than 5% moisture as recommended in ASTM test Procedure E1226.

Combustibility

The sample was combustion tested by exposing a small mound of sample to a match flame application with no noticeable affect of the sample.

Next, the sample was subjected to the flame of a Meeker burner. The sample glowed within the flame impingement area. When the flame was removed, the glowing immediately subsided, with no visible change to the sample. No further signs of combustion were observed.

Note: While modeled after genuine explosive dust testing reports, this report is fictional and only intended for illustrative purposes. Acme Testing Labs is a fictitious name.

Appendix B

STANDARD OPERATING PROCEDURE

1.0 <u>PURPOSE AND SCOPE</u>:
The purpose of this procedure is insure that the proper protective equipment is utilized in the various areas of the department.

2.0 <u>DESCRIPTION</u>:

2.1 Restricted Area

- 2.1.1 Flame Retardant clothes are required. These include jackets and pants, or coveralls. Wool coats are acceptable on the outside of the above mentioned clothes.
- 2.1.2 Grounding straps or conductive shoes are required.
- 2.1.3 Rain suits are acceptable for use over required protective equipment except when the operator is required to open and/or clean any piece of equipment rendered inert.
- 2.1.4 Rubber boots are approved only when ground straps are on the outside of the boots.
- 2.1.5 All plant required personal protective equipment as outlined in the plant PPE policy will be worn.
- 2.1.6 Personnel coming into the department from other areas may not utilize fire retardant clothing from outside the area. Only fire retardant clothing issued by Briquetting will be worn.

2.2 Bagger Area

- 2.2.1 Flame retardant clothes are not required.
- 2.2.2 All plant required personal protective equipment as outlined in the plant PPE policy will be worn.

3.0 <u>STANDARD EXPECTED END RESULT</u>:

3.1 To provide a procedure to ensure that the proper protective equipment is worn.

4.0 <u>DEVIATION AND CORRECTIVE ACTION</u>:

4.1 Any deviation to this procedure shall be reported to the Shift Supervisor for resolution.

5.0 <u>RESPONSIBILITY FOR IMPLEMENTATION</u>:

5.1 The Shift Supervisor is responsible to assure that this procedure is implemented exactly as written.

5.2 The Production Engineer or his designee is responsible to conduct a procedure assessment annually.

6.0 <u>APPROVALS</u>:

______________________	______________________
Department Manager	Manager, Quality Assurance

7.0 <u>SYSTEMS CONNECTIONS</u>:
None

8.0 <u>ATTACHMENTS</u>:
None

Appendix C

MAINTENANCE SAFETY CHECKLIST

BATCHING & BLENDING SYSTEM

JOB DESCRIPTION: ____

DATE: ____________ SHIFT: ____________ CHARGE NO.:__________

MINIMUM REQUIREMENTS
(To be Used Only in Conjunction with the SYSTEM/AREA Safe Work Permit)

PART I – PRE-WORK CHECKLIST: (To be completed PRIOR to starting work)

Done	N/A	Item
		1. Safety Orientation Meeting Held & Understood: **NO MEETING …NO WORK**
		2. Safe Work Permit Issued: Check Type – ( ) Area ( ) System
		3. Supervisor(s) Present – ( ) Operations
		4. Signed In On Log Book
		5. Personal Protective Clothing Issued
		6. Grounding Straps Issued
		7. Department Preparations and Clean-up Completed
		8. Proper Tools Available (Conventional Tools)
		9. Inert Gas System Operating: **IF NOT…NO WORK**
		10. Oxygen Monitoring System Operating: Oxygen Below 8%: **IF NOT…NO WORK**
		11. Hydrogen Monitoring System Operating: **IF NOT…NO WORK**
		12. Equipment Locked Tagged, Tried by Maintenance Personnel— **ZERO ENERGY**
		14. Blanks Inserted in Feed & Discharge Lines: Refer To EM Briq. Maint. Safety Program; Section V-A
		14. Nitrogen Supply Line Valve to Equipment Closed
		15. Equipment Inspected for Cleanliness

COMPLETED BY: ___________________________

PART II – POST-WORK CHECKLIST: (To be completed at **END** of shift)
Was All Work Completed? ( ) Yes ( ) No

Done	N/A	Item
		1. Worked performed & equipment for loose/missing bolts & debris that may have been left inside equipment.
		2. Equipment checked for Inert Gas/Dust Leaks.
		3. Completed work reviewed with Operating Supervisor, and is Satisfactory.
		4. Work site cleaned and tools, equipment removed.
		5. Lock-Out locks, tags removed from equipment.
		6. Safe Work Permit signed and returned to Operations Supervisor.
		7. Tools, protective clothing & grounding straps returned to Operations.
		8. All abnormal incidents/situations reported to Operations Supervisor.
		9. List of spare parts used or needed for future maintenance submitted to Operations Supervisor.
		10. Signed out on Log Book.

COMPLETED BY: ___________________________

Note: This checklist is to be attached to the Safe Work Permit issued for this particular job, and will be kept on file in the Department Office for a period of at least one year.

Appendix D

Example of a Go/No Go Standard

Milling System

Situation	Go / No Go	Action to be Taken
1. High Oxygen Reading:		
a) One analyzer	Go	a) Rpt. Within 8 hours
b) Both analyzers	No Go	b) Rpt. Immediately
2. Dust leaks on boots, chutes, ducts, or equipment.	No Go	Rpt. Immediately
3. Holes in connecting boots	No Go	Immediately
4. Dust leaks while raising or lowering DCL spout.	Go	Normal situation
5. Oil leaks on VBM:		
a) minor drips	Go	Rpt. Within 24 hrs.
b) large leaks or pooling	No Go	Rpt. Immediately
6. Bucket Elevator:		
a) Bagging or hammering inside	No Go	a) Rpt. Immediately
b) explosion ports damaged	No Go	b) Rpt. Immediately
c) bad bearings	No Go	c) Rpt. Immediately
7. Rotex screener leaking at lid or hole in box.	No Go	Rpt. Immediately

Figures and Tables

Figure 1: These pictures demonstrate the destructive potential of dust explosions. Note that explosion propagated through the facility with multiple secondary explosions. This facility processed and stored grain. Seven employees where killed in the explosion (Grose, 1998).

Types of Dusts	Maximum Pressure Developed in an Unvented Vessel Unit: bar(g) (P_{max})	Maximum Rate of Pressure Rise Unit: bar/s $(dP/dt)_{max}$	Deflagration Index Unit: bar-m/sec (K_{st})	Minimum Ignition Energy Unit: mJ (MIE)	Minimum Explosive Concentration Unit: mg/m^3 (MEC)	Maximum oxygen level supporting combustion Unit: % O_2 by Volume ($O_{2\,max}$)
Aluminum	11.5*	681.3	1100*	15	30*	2
Coal	9.1*	156.5	59*	60	60*	17
Cornstarch	9.7*	612.2	158*	300*	60*	9*
Epoxy resin	10.0*	408.2	64*	20	60*	12

Table 1: This table lists explosibility parameters for selected materials and is intended only to illustrate the range of values that can be encountered. As stated in the text, measurements should always be obtained on specific materials from the work area. The measures listed in this table were obtained from different test methods and samples. A single asterisk (*) indicates data obtained from Eckhoff (1997) in either a 20 Liter Apparatus or a 1 M^3 Apparatus. All other data was obtained from Baumeister (1969) in a 1.3 Liter Hartmann Apparatus. The values for maximum rate of pressure rise are given in psi/s by Baumeister and have been converted to bar/s by the authors for this table.

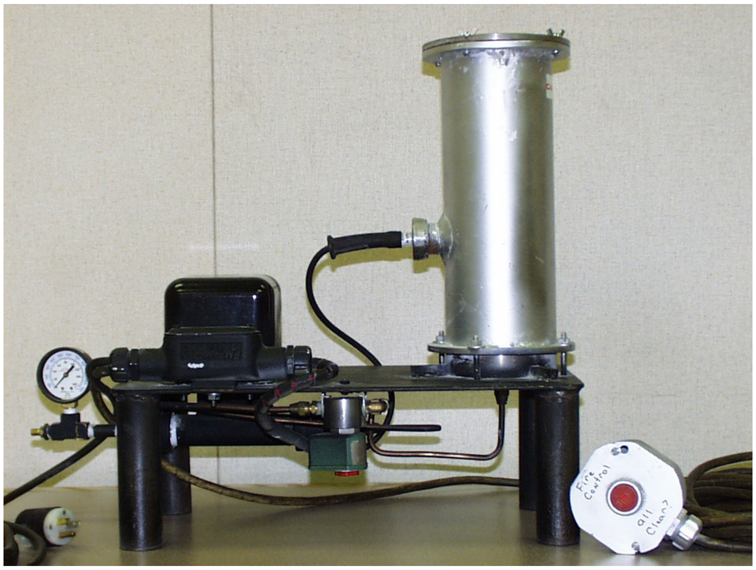

Figure 2: Pictured above is a simple version of the Hartmann 1.3-Liter Apparatus used for much of the early work by the U.S. Bureau of Mines to study dust explosions.

Figure 3: The 20-Litre Apparatus owned by the Fike Corporation is pictured here.
Source: Fike Corporation, used with permission.

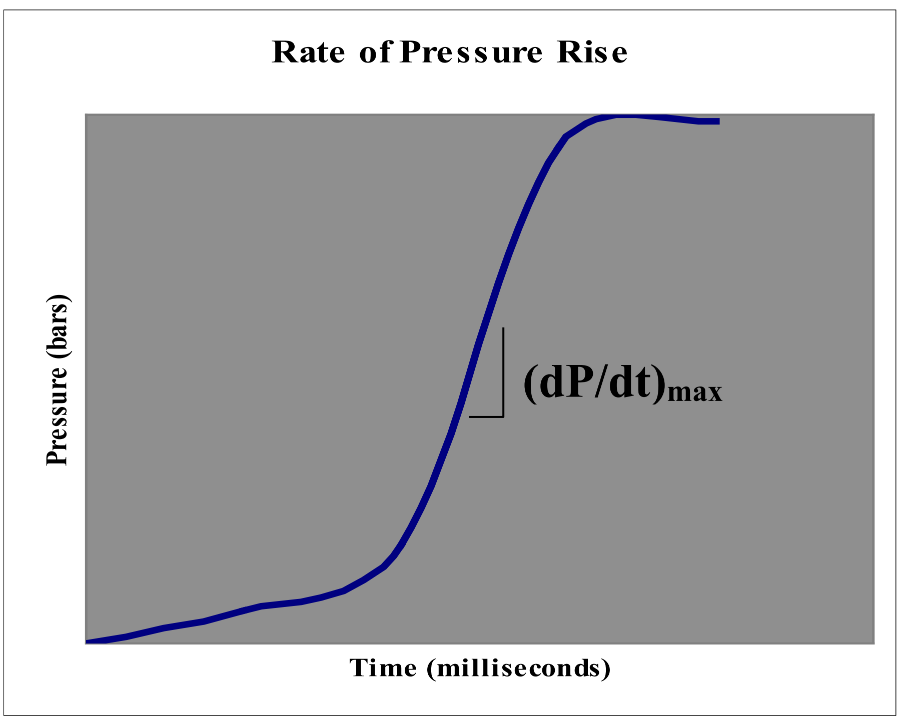

Figure 4: This graph shows the accelerating rate at which a typical dust reaction generates pressure over time in a confining vessel. Note the nearly vertical rate mid-way through the axis.

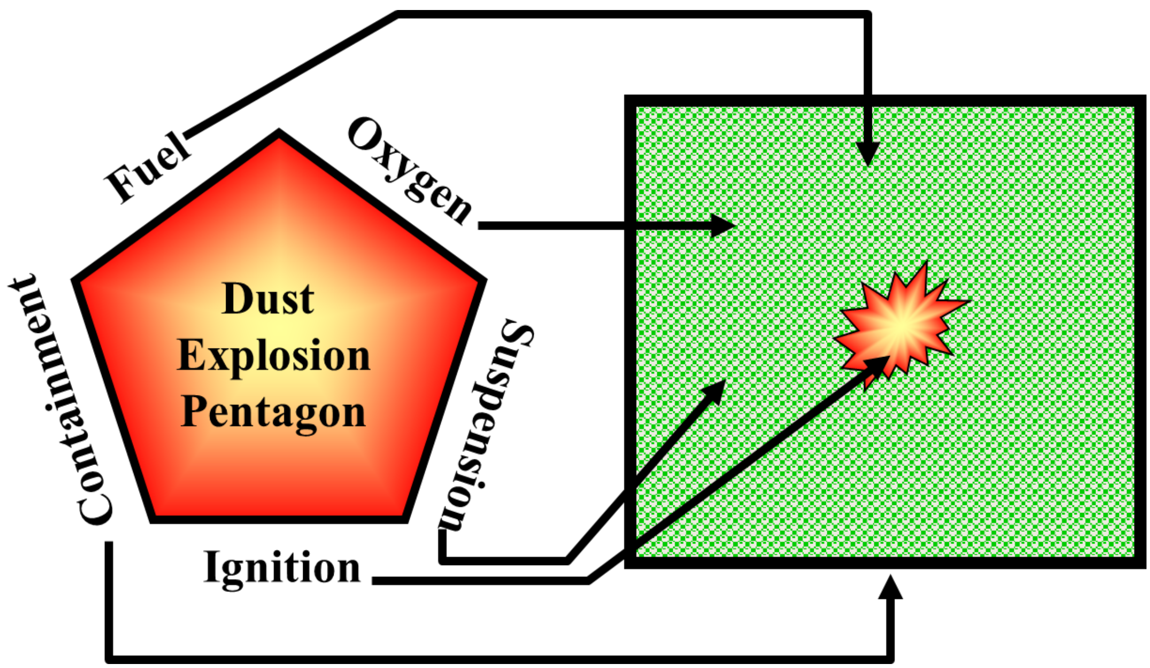

Figure 5: This diagram illustrates the Dust Explosion Pentagon described by Factory Mutual Engineering Corp. (1996). All five conditions must exist for a dust deflagration to occur.

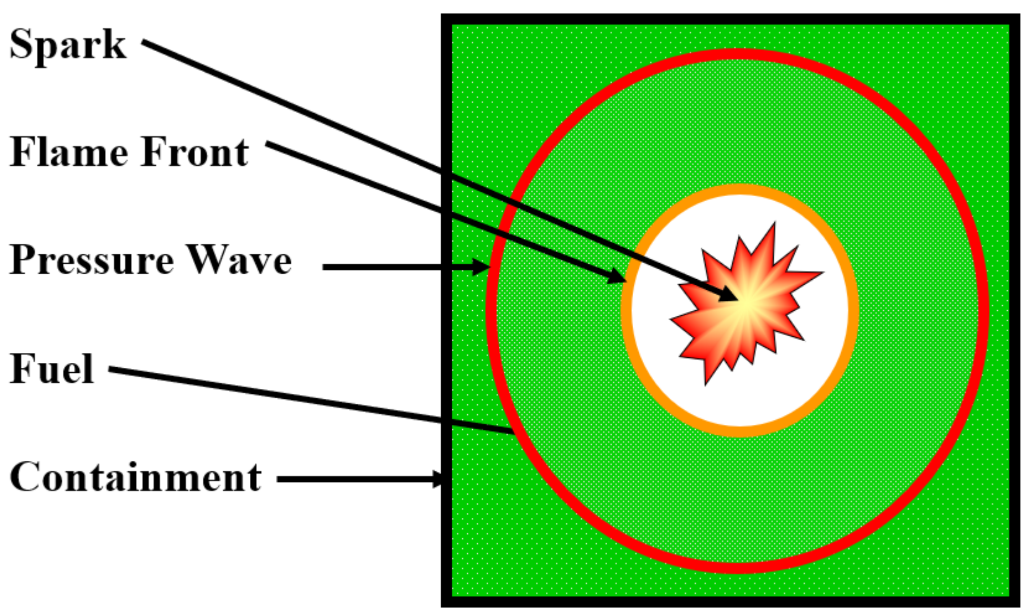

Figure 6: The major elements of an explosive dust deflagration are illustrated with this figure. Note the pressure wave travels faster that the flame front, increasing the amount of suspended fuel for the flame front to ignite.

References

American Society for Testing of Materials, (2000), ASTM Standard 1226-00 for Pressure and Rate of Pressure Rise for Combustible Dust, Annual Book of ASTM Standards, Vol. 14.2. ASTM. Philadelphia.

Bartknecht, Wolfgang, (1989), Dust Explosions, Apparatus for Testing of Airborne Dusts, Berlin, Springer-Verlag.

Baumeister, Theodore, and Marks, Lionel S., Editors, (1969), Standard handbook for Mechanical Engineers, 7th ed., New York, McGraw-Hill Book Company.

Cashdollar/Hertzberg Editors, (1987), Industrial Dust Explosions, ASTM.

DOT, (2000), Emergency Response Guide, U.S. Department of Transportation.

Eckhoff, Rolf K., (1997), Dust Explosions in the Process Industries, 2nd ed., Chapter 1: Dust Explosions-Origin, Propagation, Prevention and Mitigation: An Overview, Oxford, Butterworth-Heineman.

Factory Mutual Engineering Corp, (1996), Loss Prevention Data Sheet 7-76 Prevention and Mitigation of Combustible Dust Explosions and Fires, Norwood, MA, FM Global, p. 34.

Grose, Vernon L., Editor, (1998), Executive Summary of the Report on the Explosion of DeBruce Grain Elevator, Kansas City, Occupational Safety and Health Administration.

Heinrich, H.W., (1941), Industrial Accident Prevention, Basic Philosophy of Accident Prevention, New York, McGraw-Hill Company.

Kirwan, B. and Ainsworth, L.K., (1992), A Guide to Task Analysis, London, Taylor and Francis.

Krause, Thomas R., Hidley, John H. & Hodson, Stanley J., (1990), The Behavior Based Safety Process: Managing Involvement for an Injury-Free Culture, Foundation Concepts of Behavior Based Safety Management, New York, Van Norstrand Reinhold.

Kroemer, K. H., Kroemer, H.B. & Kroemer-Elbert, K.E., (2001), Ergonomics: How to Design for Ease and Efficiency, 2nd ed., Selection, Design, and Arrangement of Controls and Displays, Upper Saddle River, Prentice-Hall, Inc.

Lowenberg, Geula & Conrad, Kelly A., (1998), Current Perspectives in Industrial/Organizational Psychology, Training and Development, Needham Heights, Allyn & Bacon.

Nagy, John & Verakis, Harry, (1983), Development and Control of Dust Explosions, Control and Prevention of Explosions, New York, Marcel Dekker, Inc.

NFPA, Cote, A. E. and Linville, J. l., editors, (1991), Fire Protection Handbook, Section 1: Basics of Fire and Fire Science, Chapter 6: Theory of fire Extinguishment, Quincy, National Fire Protection Association.

NFPA, (1957), Report of Important Dust Explosions, National Fire Protection Association, Quincy, MA.

NFPA, (2002), Standard No. 70E: The National Electric Code, National Fire Protection Association, Quincy, MA.

Sax, Irving, (1996), Sax's Dangerous Properties of Industrial Chemicals, New York, Van Nostrand Reinhold.

Disclaimer

This paper and the information contained herein is intended solely for the purpose of making a presentation at the American Society of Safety Engineers 2002 Professional Development Conference, and is not a complete and authoritative resource for purposes of dealing with dust problems. Anyone who has to handle dusts as referred to herein should consult with an expert in the field.

Additional Resources (2020 Update)

CSB, (2016), Combustible Dust Safety web page, Chemical Safety Board, Washington, D.C. Retrieved at: https://www.csb.gov/recommendations/mostwanted/combustibledust/

Eckhoff, Rolf K., (2003), Dust Explosions in the Process Industries, 3rd. ed., Gulf Professional Publishing, New York, NY.

NFPA, (2019), Standard 652: Standard on the Fundamentals of Combustible Dust, National Fire Protection Association, Quincy, MA.

NFPA, (2020), Standard 654: Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids, National Fire Protection Association, Quincy, MA.

OSHA, (2008), CPL 03-00-008 - Combustible Dust National Emphasis Program, Occupational Safety and Health Administration, Washington, D.C. Retrieved at: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=directives&p_id=3830

OSHA, (2013), Firefighting Precautions at Facilities with Combustible Dust, Occupational Health and Safety Administration, Washington, D.C.

Authors

Ronald C. Brandon "Chet"
Certified Safety Professional & Certified Hazardous Material Manager

Dale S. Machir
Mechanical Enginer (Retired)

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Chet Brandon (co-author) can be contacted at chet.brandon@LeadingEHS.com