DUST DEFLAGRATIONS: RECOGNIZING AND REGULATING THE HAZARD

by Scott Stookey

Although the I-Codes® currently suggest that dusts "explode," the correct term for the ignition of a sufficient volume of combustible dust in an enclosure is "deflagration." A deflagration is defined in Section 2702 of the *International Fire Code* (IFC) as follows.

> *An exothermic reaction, such as the extremely rapid oxidation of a flammable dust or vapor in air, in which the reaction progresses through the unburned material at a rate less than the velocity of sound. A deflagration can have an explosive effect.*

The only ways that a combustible dust can explode in the sense employed in the IFC and *International Building Code* (IBC) is if the dust itself is also an explosive or if there is an initiator present that detonates.[1] Neither condition occurs in typical manufacturing environments.

Investigations conducted by the U.S. Chemical Safety and Hazard Investigation Board (CSB)—an independent federal agency whose mission is to ensure the safety of workers, the public and the environment by investigating chemical incidents—have determined that there have been 197 dust deflagrations in the U.S. since 1980, resulting in 109 fatalities and 592 injuries. Despite the common assumption that such events occur only in grain elevators or wood finishing facilities, the majority of the incidents investigated by the CSB took place in fairly large buildings which would probably be classified as business/factory/storage occupancies under the 2003 IBC. The limited data further reveals that natural organic materials like wheat, sorghum or wood flour are not the typical fuels—manufactured organic compounds and refined natural materials like coal flour or powdered rubber are more likely.

In any case, each incident began with a small ignition and deflagration that disturbed accumulated dust, suspending it in the air and forming an ignitable concentration. The initial fire then ignited the suspended dust, producing a larger secondary fire and deflagration. The source of combustible dust was either an unoccupied or not easily accessed area of the building. For example, the fuel source for a 1999 deflagration at the Ford Motor Company facility in Dearborn, Michigan, was an accumulation of combustible coal dust on the building's structural members. An initial natural gas deflagration suspended the coal dust, resulting in a more powerful secondary deflagration. Similarly, the fuel source for a 2003 deflagration at a West Pharmaceutical Services building in West Kingston, North Carolina, was an accumulation of polyethylene dust above a suspended ceiling.

The point is that dust deflagrations occur in unoccupied areas where fuel is allowed to accumulate such as elevated structural elements, cable trays, exhaust ducts and wall surfaces, and areas not typically subject to inspections such as the space above a suspended ceiling. In order to prevent dust deflagrations, building areas which have limited accessibility or are confined should be carefully inspected to determine if a sufficient amount of combustible dust is present that it could be suspended in air and ignited.

When is Dust Combustible?

A dust is combustible when its particles will burn. Table salt is small enough to be considered a dust, but it is chemically noncombustible. Wood is combustible, but dimensioned lumber is not dust: it is a solid mass with a surface area large enough to make it difficult to ignite in air using an oxygen-acetylene torch. However, if that same wood has a water content of 25 percent or less and is reduced to the size of baking flour it is definitely combustible.

Particle size is important. When particles become smaller their mass is reduced, causing their surface area to become proportionately larger. This increases the energy of a potential dust deflagration because the material is more easily ignited. The energy required to ignite a combustible dust is defined as the minimum ignition energy and is measured in millijoules. The lower the minimum ignition energy value, the less energy is required for ignition to occur. Consider for example an agricultural dust such as wheat flour with an average particle size of 80 microns. The minimum energy required to ignite such dust is approximately 95 millijoules. If the particle size is doubled to 160 microns, the required ignition energy is over 400 millijoules.

Section 1302 of the IFC defines combustible dust, in part, as material with a particulate diameter of less than 420 microns or 0.017 inches (a micron is 1/1000 of 1 millimeter or 0.000039 inches). There are no criteria for comparing the 420-micron value to other sizes other than the indication that the particles are smaller than the openings found in a standard U.S. number 40 sieve. Appendix E of the IFC does not explain what constitutes a dust given a particle size, when to consider it to be combustible or offer guidance correlated to the definition. Table 1 contains the size of some common materials, measured in microns.

Table 1. Particle size of common materials.

MATERIAL	SIZE (microns)
white granulated sugar	450–600
sand	50 or greater
talcum powder	10
mold spores	10–30
human hair	40–300
flour	1–100

The IFC definition also seems to assume that the particles are round, whereas the particles in a dust cloud can have varying shapes. They are usually spherical but platelets, needles and other shapes are also found.[2]

The chemistry of the dust is important as well. As has been noted, given its typical particle size, table salt is a dust but sodium chloride is not combustible. Dusts found in common industrial applications can be organic formulations of carbon, oxygen, hydrogen or nitrogen molecules and may or may not be combustible. Dusts may also be metals like aluminum, magnesium or titanium. Determining if a dust is combustible requires laboratory testing in accordance with ASTM International standards. The IFC does specify that the dust be ignitable "when dispersed in the air in the proper proportions," but lacks test criteria for determining the required amount of dust and how it is dispersed. Similarly, the code indicates that a concentration of combustible dust within a flammable range is ignitable by "a flame, spark or other source of ignition" but lacks criteria for measuring the required ignition energy of a dust cloud. The requirements for ignition are also based on anecdotal assumptions that may not always be valid. For example, spark energies generated by impacting two pieces of steel or steel against concrete and the sparks generated by grinding some metals have been shown not to generate sufficient energy for the length of time necessary to ignite dusts inside of an explosion test chamber.[3]

Moisture can affect the ignitability of dust layers. Increasing the water content in dusts increases the minimum ignition energy and the lower flammable limit. Moisture also decreases the maximum rate of pressure rise—although raising humidity (the water content in air) has no significant effect on a deflagration once ignition occurs.[4] Despite what might seem like an obvious mitigation measure, adding water to a combustible dust is not necessarily appropriate. Water will extinguish a fire in a sugar manufacturing facility but will convert the sugar to syrup, which may damage or destroy equipment. Adding water to powdered metals like aluminum, tantalum and magnesium produces hydrogen, which can actually increase the strength of a deflagration. That is why National Fire Protection Association (NFPA) 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing and Handling of Particulate Solids*, requires that fire extinguishing agents be compatible with the materials being conveyed in a manufacturing process. In order to accomplish this, a chemical and physical analysis of the dust must be performed so that the proper extinguishing agent can be used when required.

While not very common, hybrid mixtures—combustible dust mixed with air and a flammable gas or vapor—can be present in certain industrial operations such as coal processing or drying solvent-wet combustible dusts through the use of fluid bed dryers. Hybrid mixtures can form in enclosures when air is mixed with a concentration of flammable gas that is less than its lower flammable limit and the combustible dust concentration is less than its minimum explosive concentration. This means that a dust that presents a minimal deflagration hazard combined with flammable gases or vapors may result in a deflagration producing much greater pressure at a faster rate of pressure rise. NFPA standards referenced in Chapter 13 of the IFC provide technical guidance for this particular hazard, but neither a definition of nor inspection criteria for hybrid mixtures are given in the code itself.

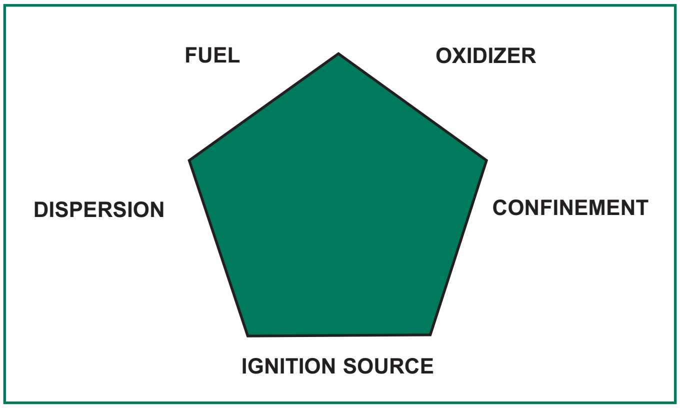
The Mechanism of a Dust Deflagration

All building and fire safety officials know that an unwanted fire results from improper handling of fuel, introducing an uncontrolled ignition source and combining it with an oxidizer (typically air, which contains 21 percent oxygen). This relationship is often represented as a "fire triangle" assigning the contributing factors to a three-sided geometric shape, with the understanding that other variables like the temperature of the ignition source and the fuel/oxygen mixture must reach specific limits for combustion to occur.

The mechanism of a dust deflagration is somewhat more complicated. Along with an ignition source and proper mixing of the fuel with an oxidizer, a dust deflagration also requires that the fuel be in a confined enclosure and that it can be easily dispersed within the enclosure. A deflagration can occur when enough dust particles are suspended in an enclosure; the concentration of particles exceeds the minimum explosive concentration; and the ignition source is greater than the minimum ignition energy, causing ignition of the dust. During a dust deflagration the particles undergo pyrolysis, producing combustion fuel gases. Ignition of these fuel gases inside of an enclosure results in a deflagration. The required conditions for a deflagration can be illustrated using a pentagon.

Table 2. Summary of variables involved in dust deflagrations.

ELEMENT	VARIABLE	SIGNIFICANCE
FUEL	Particle Size	The smaller the dust particle, the more easily it is suspended. Small particles have large surface areas in relation to their mass and do not require a strong ignition source
	Moisture Content	Moisture affects ease of ignition and ability to sustain a deflagration. Water in dust particles absorbs the energy of an ignition source. The greater the moisture content, the more difficult it is to ignite the dust. It also reduces the severity of the deflagration.
	Dust Deflagration Severity (K_{st})	The dust deflagration severity index measures the relative energy of a dust deflagration. The test criterion is ASTM E1226, *Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts*. The test uses a minimum 20-liter sphere and a standard ignition source to measure the maximum rate of pressure increase within the test sphere. The test results are normalized to a 1-cubic-meter volume. The higher the K_{st} value, the more energy will be liberated during a dust deflagration.
OXIDIZER	Minimum Oxygen Content (MOC)	The lower its MOC, the greater the energy required to ignite the dust. However, reducing oxygen concentration may not prevent a deflagration. The ignition of cornstarch is possible in atmospheres containing only 5-percent oxygen.[5] Using nitrogen or argon gas to inert atmospheres can lower the MOC to 0 percent.
DISPERSION	Dust Layer Depth	For many combustible dusts, a layer depth of 1/32-inch or greater covering more than 10-percent area above the floor that is not accessible may present a dust deflagration hazard. For example, NFPA 664, *Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities*, states that in buildings with ceiling heights greater than 10 feet and areas greater than 5,000 square feet but less than 20,000 square feet housing wood working or wood processing operations, a deflagration hazard may exist if the wood flour layer depth is 1/8-inch or greater and the area of wood flour layer covers more than 10 percent of the building area.
	Dust Layer Location	Combustible dusts or flours in areas that are not easily inspected or accessed such as building structural members, ventilation ducts, electrical bus ducts, cable trays or conduits are locations that allow for the accumulation of dust layers where the depth is sufficient to provide enough fuel to propagate dust deflagration. Dust accumulations on the floors of buildings or on the working surfaces of equipment cannot be suspended in air in sufficient volume to propagate a dust deflagration.
CONFINEMENT	Minimum Explosive Concentration (MEC)	Combustible dusts are like flammable gases and vapors: the volume of dust must be within a certain range of flammability to form ignitable concentrations. The minimum concentration of combustible dust and air required to propagate a deflagration is referred to as MEC and is determined by testing in accordance with ASTM E1515, *Standard Test Method for Minimum Explosive Concentration of Combustible Dusts*. Combustible dusts do not, for practical purposes, exhibit an upper flammable limit in air. Therefore, maintaining high dust cloud concentrations cannot prevent deflagrations.[6]
IGNITION SOURCE	Minimum Ignition Energy (MIE)	MIE is the lowest amount to ignite the most readily ignitable dust/air mixture at normal temperature and pressure. The lower the MIE, the more easily ignited the dust/air mixture. Ignition energies for dust clouds are typically higher than for flammable gases or vapors—dusts generally require 1–10 millijoules, versus a gas like hydrogen which only requires 0.3 millijoules. MIE is determined by testing the material in accordance with ASTM E2019, *Standard Test Method for Minimum Ignition Energy of a Dust Cloud in Air*.



Deflagration pentagon.

The required steps for ignition of combustible dust clouds are basically the same as for common solid materials:

1. the material is heated,
2. heat causes pyrolysis,
3. the pyrolysis produces combustible gases,
4. the combustible gases are liberated from the dust,
5. the combustible gases mix in the atmosphere with oxygen, and
6. ignition and deflagration occur in the gas phase.[7]

All five of these conditions must occur for a deflagration to take place. Of course, there are variables associated with each condition which also influence the outcome. Table 2 details how each variable contributes to or reduces the potential for a deflagration.

For flammable liquids, it is understood that those with lower boiling points generally will have a higher vapor pressure and lower flash point temperature when compared to liquids with higher boiling points. The same logic holds true for combustible dusts: those with a larger surface area per unit of mass within a given volume exhibit a lower MIE, lower MEC and higher K_{st} when compared to dusts with a smaller surface area and larger mass within the same volume.[8]

Identifying Conditions that May Result in a Dust Deflagration

When we think of a manufacturing building such as the West Pharmaceutical Services facility, which produced products used in the packaging of pharmaceuticals, we might be tempted to assume that the environment is clean and sterile, yet a sufficient amount of combustible dust accumulated above a suspended ceiling to contribute fuel to a dust deflagration. The lesson for building and fire safety officials is to look in areas not easily or typically inspected. An engine company inspection above the ceiling at West Pharmaceutical may have discovered that a substantial layer of combustible dust was present and, if properly trained, the company officer could have required that the material be removed and evaluated to determine if a dust deflagration hazard existed. However, identifying a potentially hazardous situation may not always be that easy.

The location, area, and depth of the dust layer are critical measures as to when a dust deflagration hazard exists. Of the six NFPA standards that address combustible dusts, four require some form of engineering controls such as damage-limiting construction, dust collection systems or deflagration venting. Two of the standards, NFPA 654 and NFPA 664, offer guidance for determining when a deflagration hazard exists based on the location, area and depth of a dust layer. This information is summarized in Table 3.

The thorough enforcement of IFC Chapter 13 would require that the appropriate building or fire safety official research the applicable NFPA standards. Once again, however, while the standards provide guidance on when a dust deflagration hazard may be present, a final determination would require testing to discover the dust's MEC, MIE and K_{st} values, and particle size and moisture content also influence the potential for a deflagration.

An additional concern is the accuracy of material safety data sheets (MSDSs) prepared by manufacturers. The CSB identified one manufacturer of phenolic resins whose MSDSs failed to accurately convey combustion and ignition hazards, contributing to two deflagrations. A subsequent review of MSDSs prepared by several manufacturers of similar phenolic resins found that the information about the hazards and proper storage and use of the materials varied widely. As a result, building and fire safety officials are strongly encouraged to exercise prudence when reviewing MSDSs. If in doubt, an official should require a technical opinion and report in accordance with Sections 104.7.2 and 414.1.3 of the IFC and IBC, respectively (note that this is not currently a prescriptive requirement of the codes).

Not My Job?

Some building and fire safety officials may think that the conditions that lead to dust deflagrations are Occupational Safety and Health Administration (OSHA) issues and should not be considered their responsibility. These officials would be wrong. Many of the facilities investigated by the CSB were located within governmental jurisdictions authorized and required to enforce the provisions of the IBC, IFC and *International Mechanical Code* (IMC). Those that were not had most likely adopted some or all of the NFPA material specific hazards for combustible dusts. These codes and standards authorize regulatory officials with the authority to identify and abate potential deflagration hazards.

Identifying dust deflagration hazards is above all a training issue. Although the OSHA Hazard Communication Requirement mandates that companies with more than ten employees prepare and implement programs explaining the hazards of stored materials to employees, the CSB found that employees at incident sites had not been trained on the hazards of combustible dusts and dust deflagrations or how to identify and mitigate those hazards. Building and fire safety officials should also receive appropriate training.

Working with Current Requirements

While the adoption and enforcement of the I-Codes will reduce the risk of a dust deflagration hazard, a lack of continuity between the codes and their referenced standards presents a challenge to design professionals and building and fire safety officials. The current minimal level of correlation between the IBC and IFC requirements for combustible dusts can further complicate plan review and inspection processes.

For example, consider a 120,000-square-foot manufacturing occupancy. The building is classified as a Group F-1 occupancy and is protected throughout by an automatic sprinkler system. During an inspection, it is learned that a portion of the facility grinds plastic resins into small particles using a ball mill. The ball mill is connected to a mechanical ventilation system that terminates at a dust bag house outside the building. The inspection also reveals that a dust layer is present on light fixtures and the building's metal trusses. The dust layer ranges from $^1/_8$- to $^3/_{16}$-inch deep and covers an approximate area of 3,000 square feet.

The code official applies Section 1303 of the 2003 IFC and uses NFPA 654 as the review criteria. Section 2.2.3.1 of the standard states that a dust deflagration hazard exists if the dust is combustible, it has a density of 75 pounds per cubic foot or less, the layer depth is greater than $^1/_{32}$-inch, and the area of the dust layer is greater than 1,000 square feet.

Neither the IFC nor the IBC establish a maximum allowable quantity for combustible dusts. One of the reasons is because when the 1988 edition of the legacy *Uniform Building Code* was published, an exempt amount of 1 pound of combustible dust within a given 1,000-cubic-foot volume was established. Code users found that attempting to make this measurement in an existing facility with any real degree of accuracy was very difficult. Trying to determine the value in a new building was even more challenging because it required a detailed analysis of possible sources. For this and other reasons, the requirement was subsequently deleted from the *Uniform Codes*.

Even without a maximum allowable quantity requirement, however, the IBC is very restrictive. Section 307.4 requires that the introduction of a combustible dust into a building trigger a Group H-2 occupancy classification. In our example of the plastic resin grinding operation, a layer of plastic dust 30 microns in size covering a 3,000-square-foot area of the manufacturing building would burn rapidly and may be suspended in air in a volume that could result in a deflagration. A deflagration hazard is therefore considered to exist and the occupancy must be changed to Group H-2.

Table 3. Minimum dust layer depth and area for a dust deflagration hazard by material or facility type.

MATERIAL OR FACILITY TYPE	DUST LAYER DEPTH	DUST LAYER AREA
COMBUSTIBLE PARTICULATE SOLIDS	$^1/_{32}$-inch	5 percent when the building area is less than 20,000 square feet, or a maximum dust layer area of 1,000 square feet when the building area is 20,000 square feet or greater.
WOOD PROCESSING AND WOODWORKING FACILITIES	$^1/_8$-inch	

What is gained by changing the occupancy? IBC Table 302.3.2 and Section 415.7.1.2 would require that the manufacturing area be separated from the remainder of the building by a 2-hour fire barrier. An H-2 occupancy classification would also permit the application of IBC Section 415 and Table 414.5.1. In this case, a deflagration hazard is deemed to be present and the code official could require deflagration venting or equivalent mechanical ventilation complying with the IMC per IBC section 415.7.1.4.

It must be noted that while these controls may be beneficial, they may not control the specific hazard. A deflagration vent will only operate after a deflagration occurs. NFPA 654 recognizes and allows deflagration venting but also offers other engineering controls such as inerting systems, high-speed duct dampers or fire-suppression systems to limit the damage that results during a dust deflagration. Cleaning the occupancy in accordance with NFPA 654 is an inexpensive option that will temporarily remove the hazard, and these controls may offer better protection at lower costs when compared to passive fire protection or chemical safety features.

Conclusions and Recommendations

The I-Codes' requirements for controlling the hazards that can contribute to a dust deflagration could bear some improvements. The applicable requirements given in the IBC, IFC and IMC are not sufficiently coordinated, do not easily align to the referenced standards, and lack clear criteria for the identification and evaluation of flours and dusts to determine if they pose a deflagration hazard. It is also important to recognize the challenge that a dust deflagration is likely to pose to emergency responders, who will often face a severely damaged structure, an active fire, and numerous injured or threatened occupants. As such, the CSB is actively soliciting the assistance of ICC members in the development of updated code provisions. These should include:

- improved criteria as to what constitutes a combustible dust,

- means for identifying when conditions are favorable for a dust deflagration to occur and where the hazard typically exists,
- complete and sufficient criteria for the design of systems that can reduce the hazards of fuel accumulation or protect the occupants and buildings in the event of a dust deflagration,
- a mechanism for code officials to have materials tested or evaluated to determine if the materials can produce a dust deflagration,
- options for mitigating or controlling dust deflagration hazards.
- an allowance for performance-based designs so that building owners and users have maximum flexibility while maintaining proper control of dust hazards, and
- measures to ensure that dust deflagration hazards are identified to emergency responders. ◆

Notes

1. Babrauskas, V.E. *Ignition Handbook*. 2002. 152–153. Fire Science Publishers. Issaquah, WA.
2. ibid 143.
3. ibid 153.
4. NFPA 68, *Guide for Venting of Deflagrations*. Section 4.5.3. 2002 edition. National Fire Protection Association. Quincy, MA.
5. Babrauskas 156.
6. NFPA 69, *Standard on Explosion Prevention Systems*. Section 4.3.4.6. 2002 edition. National Fire Protection Association. Quincy MA.
7. Babrauskas 144.
8. *Investigation Report, Combustible Dust Explosions and Fire CTA Acoustics Incorporated, Corbin, KY, February 20, 2003*. Report Number 2003-09-I-KY. U.S. Chemical Safety Hazard and Safety Investigation Board. Washington, D.C.

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