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Analysis of Dust Fires and Explosions in the Food Processing Industry

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Nearly all solid granular foods and powdered ingredients, such as sugar, flour, grain, spices, starch, and powdered flavors, have the capacity to sustain a combustion. This may result often in dust fires, originating from dust layers and heaps, and sometimes also in violent explosions, when the dust is suspended and a cloud is formed. Many factors affect the explosion violence or the ignition sensitivity of a dust cloud: these can be related to physical properties of the solid material (particle size, moisture content, minimum ignition temperature, etc.) and to the geometry of the system involved in the explosion (closed vessels, long pipes, degree of turbulence, etc.). While the conditions to have an explosion occur rarely in processing buildings, hazardous dust clouds regularly form during bin filling, powder conveying, or dust collection. The scope of this paper is to review a selection of incidents occurred in the past involving solid food materials and analyze them against the current best industrial practices regarding explosion prevention and protection. Particular attention will be given to the analysis of potential ignition sources and their effectiveness in igniting the flammable dust atmosphere. A selection of "lessons learnt" will also be derived from the analysis of the incidents.
Lastly, the paper shall discuss the most recent trends of combustible dust fires and explosions among other industry sectors (pharmaceutical, wood processing, chemical, energy production), to gain insights about potential areas of improvement to advance in people and plant safety.

1. Introduction

The risk of dust fires and explosions is well known in the chemical industry, but it is still dangerously underestimated in the food processing business. This is a precarious situation, since most of powders in the food industry can form ignitable dust clouds that can explode under the right conditions, as shown in **Errore. L'origine riferimento non è stata trovata.**.

Table 1 Examples of combustible food dusts (data from internal DEKRA laboratories

Product	Explosible?	P_{max} (bar)	K_{st} (bar.m/s)	MIE (mJ)	MIT_{Cloud} (°C)	MEC (g/m3)
Corn	Yes	6.5	112	45 - 100	390 - 400	73
Wheat	Yes	7.4	87	50 - 100	370 - 380	67
Oats	Yes	7.2	43	> 500	420 - 430	30
Barley	Yes	6.3	100	50 - 100	360 - 370	73
Soy Beans	Yes	9.2	110	50 - 100	600 - 620	80
Starch (rice)	Yes	10.0	220	> 30	460 - 470	60
Starch (wheat)	Yes	9.1	156	10 - 30	470 - 480	30
Sugar	Yes	9.0	138	< 10	470 - 480	30

The most important parameters to characterize a combustible dust are:

– P_{max}, the maximum expected explosion overpressure, used to design enclosures and protections;

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- K_{st}, or dust deflagration index, used to quantify the explosion severity;
- MIE, indicating the lowest electrical energy stored in a capacitor which upon discharge is sufficient to effect ignition on a dust cloud
- MIT-Cloud, lowest temperature of a hot surface capable of igniting a combustible dust cloud;
- MEC, indicating the minimum amount of dust, dispersed in air, required to spread an explosion.

Many other factors affect the explosion violence or the ignition sensitivity of a dust cloud: these can be related to physical properties of the solid material (particle size, moisture content, etc.) and to the geometry of the system involved in the explosion (closed vessels, long pipes, degree of turbulence, etc.).

1.1 Particle shape and size

Particle size and shape are crucial factors in dust explosions. 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, 2003). This is because the total area of contact between the solid material and the air increases by reducing the size of the particles and increasing the irregularity of their surface.
As a consequence, smaller and irregularly shaped particles are more reactive and easier to ignite. Additionally, smaller particles remain suspended in the air for longer periods, increasing the likelihood of an explosion.

1.2 Moisture

Water content of dust particles is an important factor in dust explosions. High moisture content can decrease the explosivity of the dust by decreasing the dispersibility of the dust. Increased moisture can increase the energy required to ignite the dust and narrow the explosive range. Suspended water particles can absorb energy and hinder the progress of the combustion reaction by absorbing heat, diluting oxygen, and binding to pyrolysis products. Figure 1 shows the trend in the rate of pressure increase over time in relation to the increase in moisture for a starch sample analyzed under different turbulence conditions (Eckhoff, 2003).

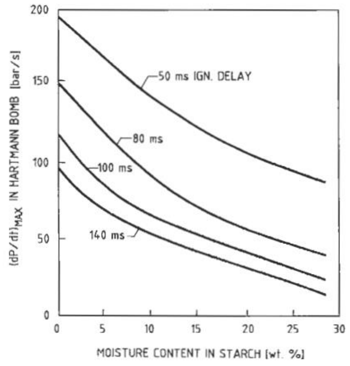

Figure 1: Relationship between $(dP/dt)_{max}$ and moisture

On the other hand, in some situations, high humidity can increase the likelihood of particle agglomeration, which can create denser dust clouds and thus increase the likelihood of violent combustion. In addition, humidity can also create an environment conducive to the formation of condensation, which can lead to the accumulation of water in the dust and thus increase the likelihood of combustion. In addition, moisture can alter the stability of the powder, increasing its sensitivity to pressure or heat. This can lead to an increase in the reactivity of the powder, which in turn can increase the likelihood of combustion and explosion. Overall, the impact of dust moisture on dust explosions is complex and context dependent.

1.3 Turbulence

The degree of mixing is a critical factor in any process that involves the exchange of heat and mass in relation to complex chemical reactions, such as combustion reactions. As far as the turbulence parameter is concerned, it is important to make a distinction between initial turbulence and dust explosion-dependent turbulence. High initial turbulence results in greater mixing of dust with air and greater heat propagation. At the same time, however, heat dispersion also increases, making cloud ignition more difficult. With regard to the turbulence resulting from the dust explosion, the higher the turbulence, the larger the surface area of the flame front, and consequently the more rapidly the pressure builds up. One element that greatly increases the turbulence resulting from the explosion is the confinement of the cloud.

1.4 Concentration

Similar to flammable gases, combustible dusts also have a concentration range within which they can be explosive. Unlike gases, however, dusts tend to be unevenly distributed due to their larger particle size, which makes them more susceptible to the forces of gravity and friction with the combustion agent. This means that in practice it is not possible to consider operating above the upper explosive range as basis of safety. Within the explosive range, the more concentrated the dust cloud, the greater the amount of fuel to be burnt and the greater the energy released during the explosion. In addition, the dust concentration can affect other factors that contribute to the probability and severity of a dust explosion. For example, higher dust concentrations can lead to higher temperatures during the combustion reaction, further increasing the severity of the explosion.

2. Case studies

Three case studies of dust explosions have been selected, due to their significance in combustible dust safety.

2.1 Imperial Sugar Explosion

On February 7th, 2008, an industrial disaster struck the Imperial Sugar facility in Port Wentworth, Georgia, resulting in the deaths of 14 workers and injuring 36 others. The disaster was caused by a massive explosion in the facility's sugar dust collection and storage system, which ignited and rapidly spread throughout the plant (Cheremisinoff, 2014). The sugar refining plant used sugar cane as raw material for the production of granulated sugar. After being refined, the sugar was stored into three silos, from which the product could be sent either to the shipping departments, to the packaging area or to the powdered sugar production unit. The three silos measured 12 m in diameter, 32 m in height and contained more than 2,000 tons of sugar each. Beneath the three silos ran a tunnel, almost 40 m long, housing two conveyor belts. A simplified diagram of the sugar route is shown in Figure 2.

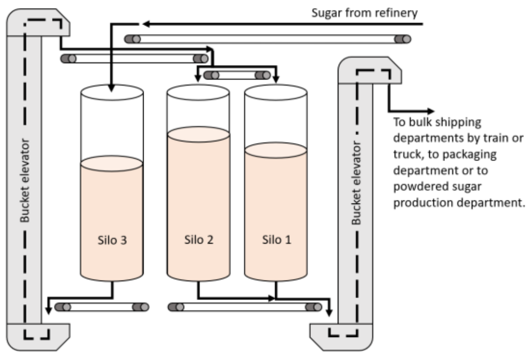

Figure 2 - Simplified Imperial Sugar Silos diagram

Housekeeping conditions

According to the investigation conducted by the CSB after the accident, the equipment used for conveying and processing sugar was not properly sealed, causing significant amounts of sugar to spill onto the floors. Workers reported frequent escape of sugar dust from the machines into the work areas, causing respiratory discomfort. The dust collection equipment was in poor condition, often undersized or incorrectly installed, causing further problems with the dust handling system. Quality audits and worker injury reports highlighted that spilled sugar had accumulated to knee-deep levels in some areas (CSB, 2009).

Causes of the accident

The analysis conducted after the accident showed that it was not uncommon for near misses to occur in the plant due to the poor plant housekeeping conditions. The tunnel under the three silos was one of the most critical places for the accumulation of sugar, as lumps of sugar got stuck in the outlet pipe of one of the silos and blocked the movement of the sugar on the belt, causing it to fall outside the belt, creating dust clouds. In 2007 Imperial Sugar took action to enclose the belt conveyors, without assessing the risks associated with the accumulation and confinement of sugar dust. The enclosures had no dust extraction systems nor explosion vents, thus creating a poorly ventilated and confined volume prone to dust accumulation. The investigation found that the initial explosion likely occurred in the tunnel beneath the silos. The most credible hypothesis for ignition source points to a malfunction and consequent overheating of the bearings on the steel supports of the belt rollers. Site workers confirmed this to be an expected malfunction, having already happened before.

Accident dynamics and effects

The primary explosion, which originated under Silo 2, spread along the entire 40 meters of the tunnel, causing significant damage to the other silos and creating large fireballs. The pressure wave then propagated through the adjacent structures, stirring up the sugar that had settled on surfaces and causing a series of secondary explosions. This resulted in the collapse of walls and ceilings, lifting and deformation of concrete floors, collapse of steel columns, and the destruction of equipment. Additionally, the explosion caused the failure of the emergency lights and sprinkler system, making it extremely difficult for workers to flee to a safe area.

Lessons learned

Although facility management were aware of dust explosion hazards, and emphasized the importance of dust handling equipment and housekeeping practices, very little had been done at the refining facility to minimize dust clouds and layers. Additionally, several fires caused by overheated bearings and electrical devices had occurred in the previous years, but these events did not lead, as they should have, to the development of a comprehensive Dust Hazards Analysis (DHA). This resulted in huge amounts of deposited sugar being available to fuel the devastating secondary explosions that destroyed the facility. Additionally, the change in the layout of the conveyor belts (installation of enclosures) constituted an increase in the pre-existing dust explosion level of risk, by creating a confined, unventilated volume where sugar dust could easily accumulate. It should never be presumed that a small change to a process is not risk-significant, until that change has been properly assessed.

2.2 Halsa fish meal explosion

In August 1975, a fish meal plant in Halsa (Norway) suffered a dust explosion. The facility processed leftover fish by grinding and drying it into a powder, and was made of a tall wooden structure that housed multiple silos used for storage and mixing. The unprocessed fish meal was fed onto a conveyor system, transported to the hammer mills, and then unloaded into the three 12-meter-tall storage silos. The fish meal was then lifted by the screw conveyor to the bucket elevators, screened, and reintroduced into the hammer mill (Figure 3).

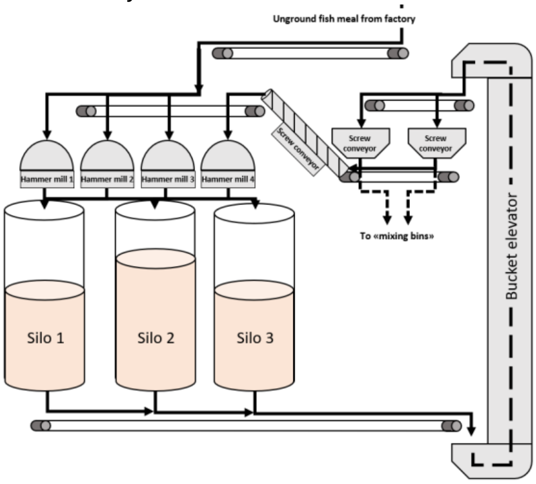

Figure 3 - Simplified Halsa fish meal factory diagram

Housekeeping and ignition source

Due to the use of hammer mills, the process produced a lot of fine dust, but there were no extraction systems or operational procedures for dust removal. Fine particles accumulated inside the silos and spread to other section of the plant, through the openings in common walls (Cloney, 2020).
During hot and dry weather, such as on the day of the explosion, the dust became very dry. Additionally, the production process liberated heat, causing the temperature in the loft of the silo building to rise from standard 25-30°C to 45°C on the exceptionally hot day of the explosion.
The ignition source was most likely a hot surface due to impact/grinding from a loose metal object. It was common knowledge among the plant operators that the bolts connecting the blades to the shaft of the screw conveyor broke regularly, due to material fatigue. These broken pieces would move around with the product, until workers alerted by excessive noise would open a chute to allow them to exit. Despite these frequent bolt failures, the plant did not have any provision for trapping metal parts, such as broken bolts, before it reached the hammer mills. Additionally, there were no instructions for maintenance crews to replace defective bolts in

advance. As a result, the entrance of broken bolts and other loose metals into the hammer mills was a relatively frequent occurrence.

Accident dynamics and effects

On the day of the accident, some workers heard loose material in the hammer mill, and carried out the usual procedure of opening the chutes on the mills and waiting for bolts to be released. Upon opening Mill 1, witnesses reported observing sparks (likely embers of burning material). The metal bolts lodged in the hammer mill became heated from continuous circulation into the process, leading to the ignition of the fish meal. The explosion occurred when the chute was opened, most likely fueled by the intake of fresh oxygen. Witnesses heard a whistling sound as the event propagated through the silos beneath the hammer mills, and a powerful flame was ejected from the chute. Fugitive dust was also dislodged, resulting in larger secondary explosions that caused flames to shoot out of the roof for about half a minute.

Lessons learned

Several contributing causes have been identified for the explosion. A lack of proper dust management system enabled the presence of constant ignitable dust cloud, and extensive layers of accumulated dust on working surfaces. Ignition sources were not controlled nor managed, so sparks and localized hot surfaces were possible. This was worsened by the normalisation of deviance with respect to the regular failure of the bolts: those failures could have been prevented by better design and scheduled / preventive maintenance.

2.3 Blaye grain silo explosion

On August 20th 1997, an accident occurred at the grain storage facilities of the Société d'Exploitation Maritime Blayaise (SEMABLA) at Blaye (Masson, 1998). The company's facilities constituted one of the largest cereal storage centres in the entire Gironde department, with a total capacity of 130,000 tons of cereals, 90,000 tons in flat storage in metal hangars and the remaining 40,000 tons within a vertical silo.
The storage center included a vertical silo (Figure 4) and a number of storage warehouses metal-framed buildings. The vertical silo consisted of 3 rows of reinforced 44 concrete cells of circular cross-section. The total storage capacity of this assembly was 47,240 m^3, so about 37,200 tons of wheat.

Figure 4 – View of the vertical silo before the accident (Masson, 1998)

Causes of the accident

The investigation to determine the accident causes entailed specifying the conditions under which an explosive atmosphere could form, as well as identifying the ignition source. Regarding the formation of an explosive atmosphere, the only possibility was the presence of an explosive atmosphere due to a dispersion of fine dust in air, likely originating from the accumulation over time of finer fractions of cereals within the silos. Based on first-hand accounts collected and observations recorded, the explosion began either in the dust removal circuit or within a structural volume of the silo itself. This led to the definition of two potential ignition sources:

- Mechanical sparks or mechanical friction at the level of the centralized dust removal circuit fan,
- Self-induced heat rise within the bulk of the dust, leading to self-ignition.

Lessons learned

The accident mainly affected a vertical grain storage silo (Figure 5). The collapse of a major part of this facility, notably on the administrative and technical buildings, caused 12 victims (11 deaths and 1 injury).
The Blaye grain silo explosion brings to light several important aspects, when considering the basis of safety of dust storage and handling facilities. First, where massive dust clouds are likely to occur, a control of ignition sources should always be implemented: in this case, spark detectors interlocked to system shut-down could

have prevented the first hypothesized ignition source, while temperature monitoring within the silos could have alerted to the phenomenon of self-heating. Additionally, large volumes such as silos should be protected against explosions with explosion venting devices, to safely discharge the generated overpressure. Explosion venting should always be coupled with isolation devices, to avoid flame propagation from one volume to the next. Lastly, proper facility siting and protection of occupied buildings from overpressures could have mitigated the disastrous consequences of the explosion.

Figure 5 – View of the vertical silo after the accident

3. Conclusions

Explosions and fires due to combustible food dusts have been report as early as 1785, with a flour explosion at a baker shop in Italy, yet they still represent the great majority of reported dust incidents, as illustrated by the trends published in the annual Combustible Dust Reports (Dust Safety Science, n.d.). As shown in Figure 6 below, agriculture and food products are responsible for roughly 50% of the incidents each year.

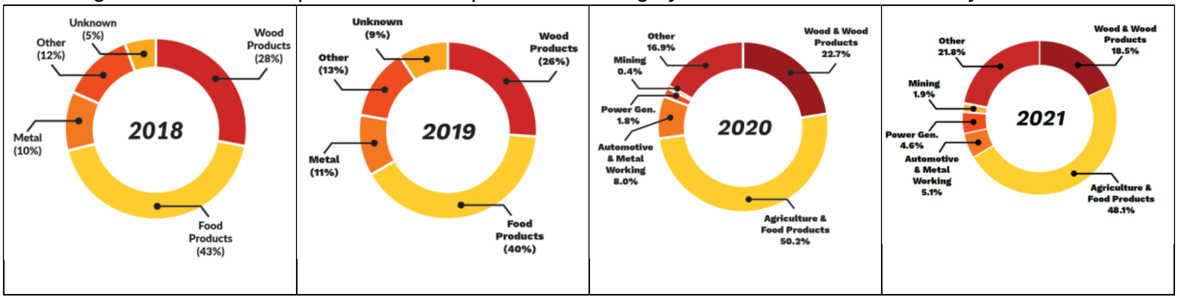

Figure 6: trends of dust fires and explosion in different industry sectors

When analysing the causes, a few elements appear to be common to several accidents: underestimation of the explosion risk, often linked to a lack of knowledge of the main dust explosion parameters (MEC, MIE, P_{MAX}); poor housekeeping and dust control, leading to dust accumulation in working environments; implementation of changes without a solid risk assessment before it.

These aspects should be thoroughly addressed when developing a comprehensive Dust Hazard Analysis (DHA), a dedicated risk assessment for combustible dusts supported by regulatory bodies all over the world. Standards and Recommended Practices, such as NFPA 652 “Standard on the Fundamentals of Combustible Dust”, IEC 60079-10-2 “Classification of areas - Explosive dust atmospheres” and CCPS “Guidelines for Combustible Dust Hazard Analysis”, are intended to increase awareness of dust explosion hazards and to minimise the potential risk to employees. All safeguards intended to prevent dust explosions must be recognized, understood and maintained. Operators should be aware that signs of overheating, excessive vibration, or noise indicating mechanical malfunction or misalignment need prompt attention before a small smouldering clump of dust leads to a serious explosion.

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