National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Dust to Dust

On February 7, 2008, a series of violent explosions devastated a sugar refinery in Port Wentworth, Georgia (Figure 1). Workers inside had little time to escape as pressure waves heaved concrete floors, blasted brick walls, and collapsed stairwells. Combustible sugar dust, along with sugar that had spilled from packing and processing machinery, fueled fires that burned up to seven days after the initial blast. The explosions claimed the lives of 14 workers and critically injured 36 others. The blaze ravaged storehouses, packaging buildings, and processing areas that had been operating for more than eighty years. The U.S. Chemical Safety Board deemed it the most devastating dust explosion in decades.

Figure 1: Imperial Sugar Company's refinery in Port Wentworth, GA, suffered catastrophic damage when combustible sugar dust exploded.

BACKGROUND

Combustible Dust Explosions

Many industries generate fine dust particles when their products pass through processing areas and machinery. Common combustible dusts come from coal, wood, rubber, plastics, chemicals, metals, and food products. According to the Occupational Safety and Health Administration (OSHA), particles with a diameter of 420 microns or less become explosive when dispersed in a confined space. Suspended particles burn rapidly, and when airborne dust meets an ignition source, a deflagration may occur. A deflagration is an exothermic reaction that propagates to unreacted material at a rate that is slower than the speed of sound. If a deflagration occurs in a confined space, gas pressure from the combustion reaction could exceed the strength of the container, resulting in an explosion. Often, machines containing potentially explosive atmospheres use mechanisms that vent overpressure to the exterior, a tactic that preserves the structural capability of the container should a deflagration occur.

An explosion that takes place in an unvented enclosure can quickly become catastrophic. If combustible dust has accumulated in other areas of the facility, shock waves from the initial explosion can dislodge it, and the fireball can ignite the falling dust. This triggers a chain reaction of secondary explosions. Because of the increased concentration and quantity of airborne particles, secondary explosions can be more powerful and destructive than primary explosions. According to the National Fire Protection Agency (NFPA), when 5% of the surfaces in a facility are covered with 1/32 of an inch of combustible dust, that facility faces high risk of suffering a serious dust explosion chain reaction.

Imperial Sugar Company

Savannah Food and Industries built the Port Wentworth sugar refinery in 1917 and sold it to Imperial Sugar Company in 1997. The facility converted raw cane sugar into granulated sugar, then packaged or refined it into specialty sugar products. In 2007, the plant produced 2.6 billion pounds of sugar, making it the second largest sugar refinery in the nation.

Sugar Refinery Explosion Kills 14, Injures 36.

Proximate Causes:
- Combustible dust accumulates in confined space
- Dust ignites, resulting in primary explosion
- Explosion disturbs accumulated dust in other areas of refinery
- Dislodged dust ignites, fuels further explosions

Underlying Issues:
- Absence of risk management
- Lack of operator training
- Normalization of Deviance

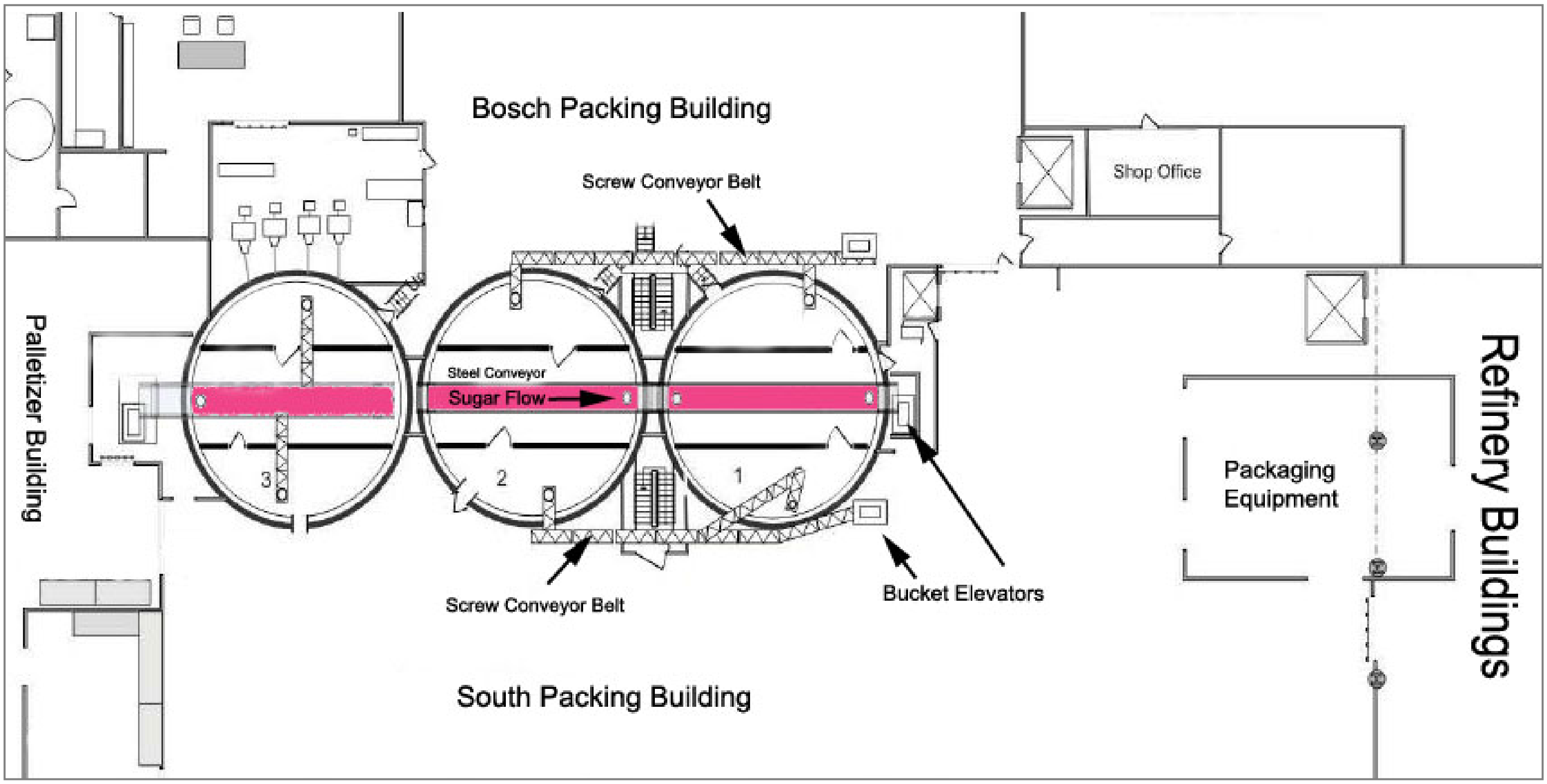

Figure 2: Three storage silos (labelled 1, 2, & 3) held granulated sugar until it was ready for packaging or further processing. Sugar left the silos through chutes built into each silo's base. The chutes emptied onto a steel conveyor (shaded pink) in the silo tunnel. The conveyor carried the sugar to adjacent packing and refinery buildings. In 2007, Imperial Sugar covered the conveyor with a steel enclosure that was one tenth the tunnel's size.

Hammer mills ground granulated sugar into powdered sugar — a process that created fine dust particles that dispersed into the air and settled onto machinery. Designers had attached a dry dust collection system to the hammer mills to prevent dust from accumulating in the work area, but the undersized, outdated system did little to curtail the dust problem. Sugar dust accumulated on machinery, settled on horizontal surfaces, and clouded the air. Workers reported difficulty seeing one another through a persistent shroud of sugar dust.

A transport system consisting of bucket elevators, screw conveyors, and conveyor belts moved sugar around the facility (Figure 2). As the sugar rode various conveyors, some spilled onto the floors of the work areas and dispersed fine dust into the air. These mechanical conveyors used wet dust collectors that sprayed water to collect airborne dust. The machines then returned the water to the refinery which reclaimed the dissolved sugar. However, the collectors did not work effectively. Employees reported consistent problems with sugar spills and leaks from machinery. The depth of the spilled sugar ranged from several inches in some places to several feet in others (Figure 3).

Silo Tunnel Modifications

Three 100-foot tall silos stored granulated sugar until it was ready to move to the 4-story packaging or refining buildings adjacent to the storehouses (Figure 2). Granulated sugar left storage through chutes built into each silo's base. The chutes channeled the sugar onto conveyor belts that ran through a 10-foot wide, 130-foot long tunnel on the ground floor. Occasionally, clumps of sugar clogged the chutes, impeding the flow and causing it to spill onto the floor. This released copious amounts of dust into the tunnel.

Early in 2007, Imperial Sugar enclosed the conveyors in the silo tunnel with steel panels to eliminate the possibility of contaminating the sugar with falling debris or foreign objects. The enclosure did not have an associated dust collection system, nor was it vented. Sugar dust that once dispersed into the large and ventilated tunnel was now trapped in a space one tenth the tunnel's size.

What Happened?

Primary and Secondary Explosions

Close to 7:15 p.m. on February 7, 2008, a massive explosion tore the enclosure in the silo tunnel apart. In adjacent buildings, rafters and pipes upon which inches of sugar dust had rested for decades shook violently. Sugar dust dislodged from these surfaces and rained into the air below. The advancing pressure wave from the explosion heaved concrete floors and blasted through brick walls. As the initial fireball shot through the tunnel and vented into adjacent buildings, it ignited the falling dust, causing secondary explosions that were even more violent than the first. As walls, floors, beams, and conduits collapsed, the dust that had accumulated on top of them poured downward, refueling and intensifying an inferno that already raged below. Security cameras at facilities two miles away from the site recorded massive fireballs erupting from the refinery for as long as fifteen minutes following the initial blast.

The facility burned for four days before firefighters could fully extinguish the flames. Fires in the storage silos reached 4000° F and continued burning one week after the primary explosion. Eight workers died on the scene, and six more perished at a regional burn unit. Thirty-six workers suffered critical burns and injuries, some of which became life-altering. The Chemical Safety Board (CSB) considered it the worst combustible dust explosion since 1980.

Proximate Cause

CSB investigators reported that on February 7, one of the silo chutes became clogged, causing a backup on the conveyor that spilled sugar and released excessive amounts of sugar dust into the new enclosure. Something ignited the sugar dust, but because the damage to the tunnel, enclosure, and conveyor was so extensive, investigators could not point to a single ignition source with certainty. After the accident, Imperial Sugar conducted tests showing that when sugar dust smolders on a hot surface, gasses released from the smoldering reaction mix with air and lower the dust's minimum ignition temperature. Based upon these tests and upon worker reports that fires ignited by overheated ball bearings had been a recurring problem at the plant, CSB concluded that the hot surface from an overheated bearing most likely ignited the sugar dust in the conveyor's steel enclosure, initiating the explosive chain reaction.

Underlying Issues

Ineffective Dust Handling Equipment

Although designers had equipped most of the packaging and processing machinery with either wet or dry dust collectors, the systems proved to be ineffective. Operators did not maintain the collectors, and when an independent contractor examined the collection system less than one week before the accident, it found major problems. The contractor cited issues such as incorrectly installed piping and piping that was plugged with sugar. The fans used to transport the dust were undersized and failed to operate at the required performance curve. This led to air flow in the ducts that was significantly lower than the minimum dust conveying velocity. Such problems went unaddressed for years, allowing sugar and sugar dust to accumulate on horizontal surfaces throughout the facility (Figure 3). One worker told CSB investigators that he often used a squeegee to forge a path to his workstation because the sugar on the floor had amassed to overwhelming proportions. CSB concluded that the secondary dust explosions and ensuing fires would probably not have occurred if the company had performed routine housekeeping practices to remove and prevent large accumulations of spilled sugar and sugar dust.

Inadequate Employee Training

Employees at Imperial Sugar may have allowed the dust to accumulate to extreme levels because they were unaware of the combustion hazards such accumulations entailed. Although Imperial Sugar required its workers to undergo annual safety

Figure 3: Imperial Sugar photo taken in the Fall of 2006 showing machinery, floor, and architecture covered with sugar. The coated machinery would sometimes overheat and ignite the surrounding sugar.

training, CSB's review of more than 10,000 pages of training materials failed to reveal anything on the topic of hazardous dust. The company's Material Safety Data Sheets (MSDS) on sugar warned of sugar dusts' combustible nature, but CSB could not find written dust control programs or dust removal programs.

Workers' lack of information on dust hazards may have led them to maintain a practice that exacerbated the dust problem. Since the installed dust collectors were ineffective, employees routinely used compressed air to blow sugar dust away from packaging and processing machinery. This method removed dust from the machines but dispersed it into the plant's atmosphere, further increasing the concentration of suspended particles. If machine operators had known of the dangers this procedure entailed, they may have pursued alternate methods of cleaning the machinery.

Incomplete Emergency Preparation

Imperial Sugar failed to inform its employees of combustible dust hazards and prepare them for emergencies. Written emergency procedures instructed workers to use the intercom system in the event of a crisis. However, the refinery and packing buildings did not use the intercom system, and workers had to rely on radios and cell phones for emergency alerts. Because the refinery and packing buildings lacked visible and audible alarms, workers could not have had prompt notification when emergencies took place.

Training programs did not include evacuation drills, and although the company posted general evacuation routes, it did not provide work location specific training. Workers unfamiliar with escape routes faced great difficulty when the explosions and fires cut out emergency lighting and exit signs.

Normalization of Deviance

Although employees and contractors may not have been aware of the insidious hazard combustible dust incurs, correspondence dated as early as 1961 shows that Imperial Sugar's management was cognizant of the danger. Over decades of operation, the Port Wentworth refinery experienced dozens of small fires caused by overheated bearings that were fueled by combustible dust. None of the incidents caused fatalities, serious injuries, or catastrophic damage, but they warned of impending danger. In October of 2007, OSHA distributed a *Combustible Dust National Emphasis Program* that should have prompted a housekeeping overhaul and raised awareness of possible ignition sources, such as electrical arcing or hot-surface ignition. As per the CSB, Imperial Sugar's managers failed to act promptly and sufficiently to rectify these hazards.

Since none of the fires at Imperial Sugar ever led to a major catastrophe, it became easier for the organization to keep accepting lower standards. Eventually, the lowered standard became the normal practice. Diane Vaughan, in her book *The Challenger Launch Decision*, identified such a phenomenon as the normalization of deviance. In cases such as this one, errors in judgment begin cascading; when experience allows an organization to practice lower standards without serious consequences, those standards change organizational culture over time. According to the CSB, managers did not suffer major losses during many years of operation, therefore they allowed complacency to rob them of the swift action that likely would have prevented this calamity.

Aftermath

OSHA charged Imperial Sugar with 124 safety violations, and in July of 2010, the company agreed to pay $6 million in fines as a result of the infringements. Based on the findings of its investigation, CSB recommended that Imperial Sugar review its manufacturing facilities and compare them with NFPA standards for preventing fires and dust explosions. In addition, CSB directed Imperial Sugar to implement corporate-wide housekeeping policies, training programs, and evacuation procedures that included emergency alarms and emergency evacuation drills.

Imperial Sugar rebuilt the damaged portions of the Port Wentworth refinery at an estimated cost of $220 million and returned to production in June of 2009. OSHA will intensively oversee plant safety for the next three years.

For Future NASA Missions

NASA Centers have not experienced a catastrophe resembling the explosions that ravaged the Port Wentworth Refinery. Combustible dust does not pose as prominent a threat at NASA as it does in certain industries, but explosions need not be fueled by combustible dust to become catastrophic. Equally hazardous dangers lie in hundreds of chemicals and reactive materials handled at NASA Centers every day, from solid and liquid rocket propellants, to ethylene oxide, to anyhdrous ammonia, to myriad other flammable, corrosive, or radioactive substances. Given such hazards, good housekeeping and maintenance is paramount in preventing combustible liquids, compressed gasses, and dozens of other unstable and reactive materials from initiating a disaster.

The explosion at Imperial Sugar took place in part because plant operators were uninformed of the risks at the facility and because they were vastly unprepared to deal with an emergency. Expanding beyond attention to OSHA workplace safety toward "process safety" (where facility or project-specific processes merit scenario-driven hazard analysis, and ongoing verification of effective controls against process-driven disaster), the organization can ensure that its employees, contractors and the public are not caught in an uncontrolled situation. Making the "case for safety" within a process is a proven, effective approach. Project and facility managers at NASA are well served to maintain careful vigilance over changes to systems under their control. This includes considering effects of day-to-day decisions on safety barriers and controls, and checks to ensure that past choices have not decreased safety or increased technical risk to an unacceptable level.

Questions for Discussion

- Do your training programs cultivate awareness and respect for safety rationales?
- How have you guarded against eroding standards within your organization?
- What have you done to ensure that safety equipment remains updated and functional?
- Do you routinely place your teams under thorough emergency training? Are you confident that your teams are prepared for emergency situations?

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Executive Editor: Steve Lilley
steve.k.lilley@nasa.gov

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