U.S. CHEMICAL SAFETY AND HAZARD INVESTIGATION BOARD

INVESTIGATION REPORT

ALUMINUM DUST EXPLOSION

(1 Killed, 6 Injured)

Photo: Andrew Hancock, Huntington (IN) Herald-Press

HAYES LEMMERZ INTERNATIONAL–HUNTINGTON, INC.

A WHOLLY OWNED SUBSIDIARY OF

HAYES LEMMERZ INTERNATIONAL, INC.

HUNTINGTON, INDIANA

OCTOBER 29, 2003

KEY ISSUES:

- ALUMINUM DUST HAZARD AWARENESS
- DUST COLLECTOR EXPLOSION PROTECTION
- INCIDENT INVESTIGATION
- MANAGEMENT OF CHANGE

REPORT NO. 2004-01-I-IN

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Acronyms and Abbreviations

CSB	U.S. Chemical Safety and Hazard Investigation Board
EMT	Emergency medical technician
HLI	Hayes Lemmerz International, Inc.
IFC	International Fire Code
ICC	International Code Council
IOSHA	Indiana Occupational Safety and Health Administration
K_{ST}	Explosion severity
MOC	Management of change
MEC	Minimum explosive concentration
Mm	Millimeter
NFPA	National Fire Protection Association
OSHA	U.S. Occupational Safety and Health Administration
PPE	Personal protective equipment

Executive Summary

An aluminum dust explosion and fire on October 29, 2003 at the Hayes Lemmerz International–Huntington, Inc. (Hayes) facility, Huntington, Indiana killed one employee and burned two other employees, one critically. Three other Hayes employees and one contractor received minor injuries.

The facility manufactures cast aluminum alloy wheels. The U.S. Chemical Safety and Hazard Investigation Board (CSB) determined that the dust that exploded originated in a scrap re-melting system. The explosion completely destroyed the dust collection equipment outside the building and damaged equipment inside the building. The explosion also lifted a portion of the building roof above one furnace and ignited a fire that burned for several hours.

CSB identified the following root causes of the incident:

- Hayes did not perform a review to address why the chip system was releasing excess dust. The hazards of aluminum dust were neither identified nor addressed.

- Hayes did not ensure the proper design of the dust collector system.

- Hayes did not ensure that the dust collector design and installation followed the guidance in National Fire Protection Association (NFPA) 651.

- Hayes had no formal, documented program to investigate and implement corrective action for incidents involving fires in the foundry area, especially those fueled by aluminum dust.

CSB also determined that the following factors contributed to injuries and damage:

- Employees did not wear flame-retardant clothing when performing routine work near the melt furnace.
- Housekeeping and maintenance in the chip-processing and dust collector areas were inadequate.
- Facility personnel received no formal training for operating and maintaining the chip-processing and dust collection systems.

In this report, CSB makes the recommendations to Hayes, a few of which are listed below:

1. Develop and implement a means of handling and processing aluminum chips that minimizes the risk of dust explosions.
2. Implement a program to provide regular training for all facility employees on the fire and explosion hazards of aluminum dust.
3. Develop and implement written operating procedures for chip processing and train all affected employees. Ensure that procedures address maintenance and housekeeping.

To Premelt Systems, CSB recommends that they communicate the findings and recommendations of this investigation to owners/operators of facilities to which Premelt supplies similar aluminum chip-melting systems, including specific information that the chip drying process liberates small particles of aluminum, and that such particles may be explosive.

CSB also makes recommendations to the Aluminum Association and the Fire Protection Research Foundation to jointly research improved explosion protection for dust collectors in aluminum dust service.

1.0 Introduction

1.1 Background

At about 8:30 pm on Wednesday, October 29, 2003, an aluminum dust explosion and fire occurred at the Hayes Lemmerz International–Huntington, Inc. (Hayes) facility in Huntington, Indiana. One employee was engulfed in fire and died within hours. Two other employees were burned, one critically. Four individuals (three Hayes employees and one contractor) received minor injuries.

The explosion occurred in the scrap reprocessing area, near one of the furnaces in the aluminum casting plant, completely destroying dust collection equipment located outside the building (adjacent to the aluminum melt furnace area). Equipment inside the building received minor damage. The explosion also lifted a portion of the building roof above one furnace and ignited a fire; insulation and other combustible materials burned for several hours. There were no offsite injuries or damages.

Because of the death and injuries and the recent history of other industrial dust explosions, the U.S. Chemical Safety and Hazard Investigation Board (CSB) launched an investigation to determine root and contributing causes and make recommendations to prevent similar occurrences.

The dust that exploded came from equipment in and connected to a process used to re-melt chips of aluminum scrap from wheel machining operations. The CSB investigation focused on applicability of fire prevention standards, dust generation and hazard awareness, engineering project management, safety reviews for new and modified systems, and operating and maintenance practices.

1.2 Investigative Process

At CSB's request, the local fire department and highway patrol had secured the site on October 29 during efforts to extinguish the fire. CSB investigators arrived on the scene late in the evening on October 30, one day after the explosion. CSB presided at a meeting on October 31 of Hayes personnel and inspectors from the Indiana Occupational Safety and Health Administration (IOSHA). CSB and IOSHA then conducted concurrent, independent investigations of the incident.

In the course of its investigation to determine the underlying root causes of this incident, CSB photographed and diagrammed equipment and blast damage; analyzed samples of materials in the scrap processing area; interviewed eyewitnesses and management personnel at all organizational levels of the company; interviewed the chip melt system designers; and reviewed relevant standards, regulations, aluminum industry guidance, and Hayes' management practices.

CSB contracted with Safety Consulting Engineers, Inc., of Schaumburg, Illinois, to test samples of material from the site for explosivity. Refer to Appendix A for test results.

At the same time it was investigating Hayes, CSB was investigating two other serious dust explosions that occurred in early 2003—West Pharmaceutical Services in Kinston, North Carolina, and CTA Acoustics in Corbin, Kentucky. Those two accidents resulted in 13 fatalities. The three CSB teams assigned to the dust explosions compared findings, especially in the areas of dust hazard awareness and available industry guidance.

1.3 Hayes Lemmerz International

Hayes Lemmerz International, Inc. (HLI) is the parent company of various subsidiaries that manufacture automotive components. HLI began operation in 1908 as Hayes Wheels, a supplier of wooden-spoke wheels for Model T Fords. The company acquired wheel maker Lemmerz in 1997.

On October 29, 2003, HLI's North American Business Unit had five subsidiary plants in the United States, four of which produced aluminum wheels. One of those subsidiaries is Hayes Lemmerz

International-Huntington, Inc., based in Huntington, Indiana. HLI emerged from Chapter 11[1] protection in spring 2003.

HLI also has facilities in South America, Asia, Africa, and Europe. The company supplies wheels to nearly every major automotive manufacturer for use on new vehicles.

1.4 Hayes Lemmerz International–Huntington, Inc.

The Hayes facility in Huntington manufactures cast aluminum alloy wheels. It has operated since 1984 and employs about 300 people. In 1985, Hayes (then known as Kelsey-Hayes) purchased the plant from CMI International, a company specializing in automotive castings. The Hayes facility is located alongside other manufacturing facilities in a light industrial park outside Huntington, Indiana. The entire facility—including the foundry furnaces, casting machines, and finishing equipment—is housed in a single, 220,000-square-foot steel-frame, steel-clad industrial building (Figure 1).

The wheel production operation is highly automated, with robots performing repetitive tasks—including those that involve molten aluminum (such as casting), as well as some lifting and most machining. The production line operated 24 hours per day, 6 days per week.

[1] Chapter 11 refers to a reorganization bankruptcy, usually involving a corporation or partnership. A Chapter 11 debtor usually proposes a plan of reorganization to keep its business open and pay creditors over time. The company filed for bankruptcy protection in December 2001.

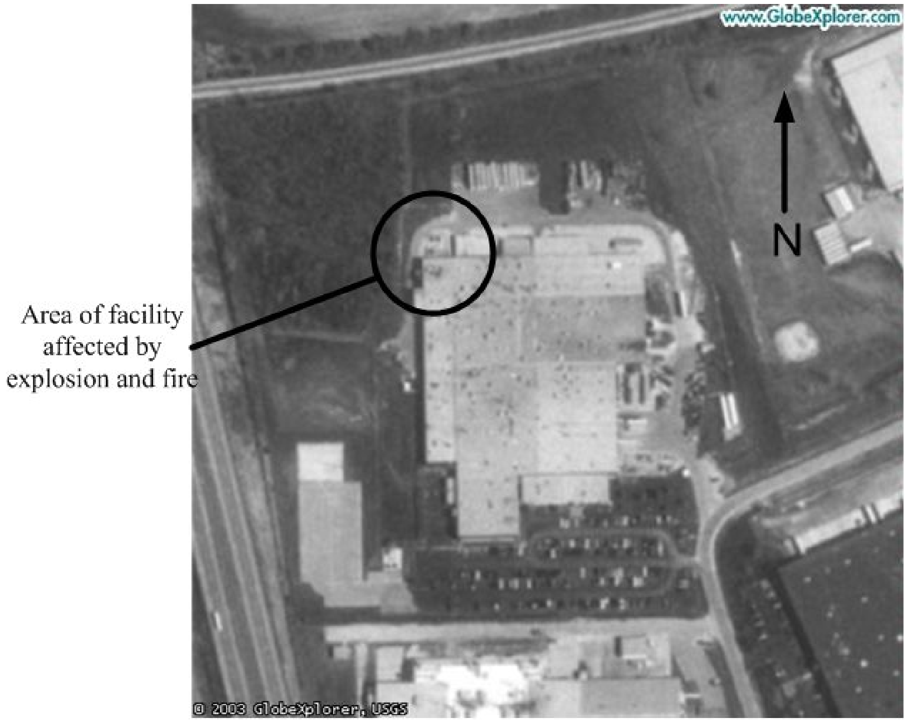


Figure 1. Satellite image of Hayes-Huntington facility, taken before the explosion.

1.5 Premelt Systems, Inc.

Aluminum scrap process at Hayes was designed and provided by the company eventually known as Premelt Systems, Inc. (Premelt). Premelt designed and installed its first chip-melting system in 1964 at an appliance manufacturing facility. Premelt has built more than 50 aluminum chip de-oiling and melting systems, including five for Hayes. In addition to the system at Huntington, Premelt designed and furnished the scrap-processing systems for the HLI aluminum wheel casting plants in Gainesville, Georgia, and La Mirada, California.[2] HLI discontinued using the Premelt chip reprocessing systems in all of its facilities shortly after the explosion on October 29, 2003.[3]

[2] According to Premelt, the company also provided chip-processing to HLI facilities in Somerset, Kentucky and Howell, Michigan. However, these facilities are no longer in operation.

[3] Although the Huntington facility is no longer operating the Premelt chip system, the facility continues to collect, chip, and dewater scrap aluminum for offsite processing.

At present, Premelt is a division of Lectrotherm, Inc., North Canton, Ohio. Premelt engineers custom design each installation. Premelt supplies the equipment, and its personnel oversee installation and startup of the systems. Premelt supplies a maintenance and operating manual with each chip- melting system.

1.6 Process Description

The Hayes Huntington facility manufactures cast aluminum automotive wheels. The wheels are rough cast, then finished by machining, coating, and polishing. The machining activities create scrap aluminum. A chip-processing system, provided by Premelt, was installed in 1995 to process the scrap aluminum for remelting in one of the facility's melt furnaces. The October 29 explosion involved portions of the chip-processing system. Figure 2 shows a simplified block flow diagram of the system. Shaded equipment was designed and supplied by Premelt. Non-shaded equipment was designed and provided by others.

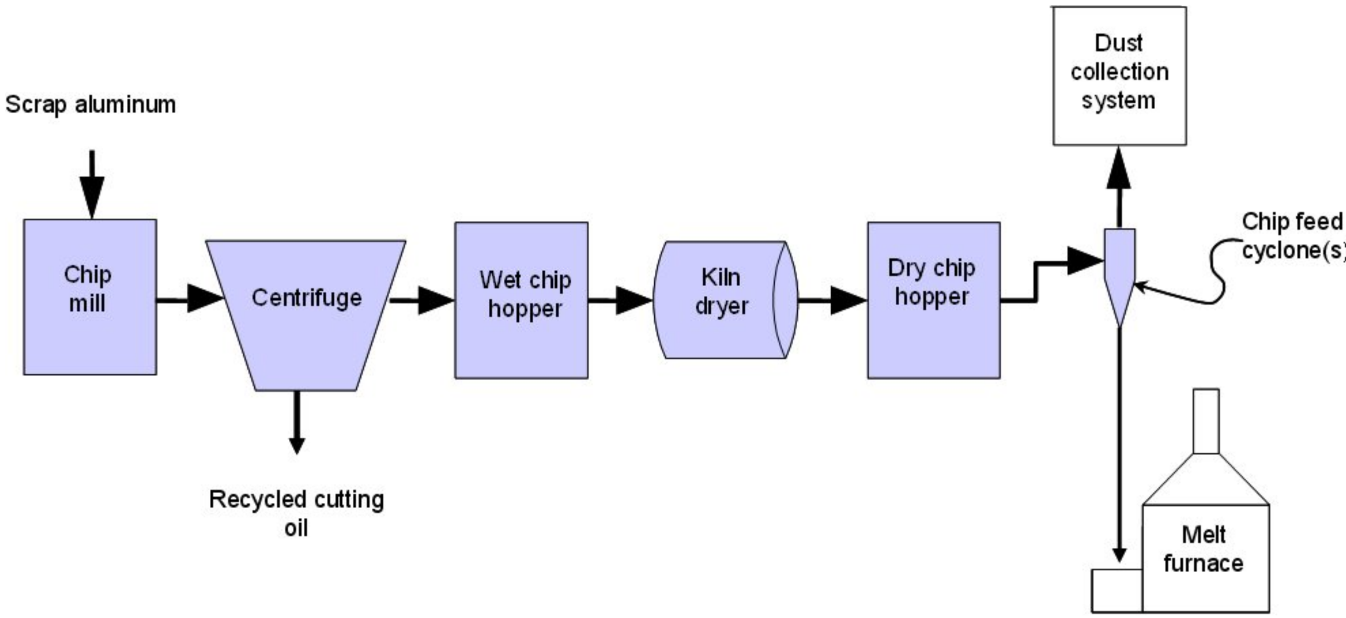


Figure 2. Scrap (chip) process flow diagram.

1.6.1 Scrap Collection and Dewatering

Scrap from finishing is collected in bins at machining stations and various other locations throughout the wheel-manufacturing facility. [3] This scrap contains a cutting oil and water emulsion from the machining processes. The bulk of the aluminum scrap is in the form of 1/8- to 3/16-inch wide strips (turnings from wheel machining) of less than 1/64-inch thickness. These strips are mechanically chopped into pieces about ¼- inch long (called "wet chips") and spun in a centrifuge to remove the cutting emulsion. Prior to the explosion, these chips (Figure 3) were conveyed by high-velocity air through steel pipes to a hopper in the foundry area adjacent to one of five reverberating furnaces[4] (two of those furnaces were equipped for chip melting). Because any fine particles in the wet chip stream adhere to the surface of the chips, no significant amount of dust is associated with wet chip handling or transfer.

[4] A reverberating furnace is a direct-fired, open-hearth furnace fired with an open flame above the melt directed down (reverberated) to the melt surface.

Figure 3. Close-up photograph of wet chip sample.

1.6.2 Chip Drying

The wet chips do not actually look wet, but they retain a surface coating of cutting oil sufficient to cause particulate emissions (smoke) from the furnace. In the chip processing system at Hayes, a rotary kiln dryer dried the chips to remove the cutting oil.[5] The tumbling in the dryer loosened small particles stuck to the chips and broke some chips. These actions likely created aluminum dust in various particle sizes.[6]

The dryer burner was designed to operate with incomplete combustion. To accomplish this, the air damper was automatically controlled so the amount of air allowed into the process was less than what would be needed to completely combust the fuel gas. This ensured that little or no free[7] oxygen was in the dryer chamber, because free oxygen at elevated temperatures inside the dryer could cause accelerated

[5] A kiln is a general term for any type of oven used to dry ores, ceramics, cement, wood or other materials. The dryer at the Hayes facility had a rotating inner core that tumbled the chips as they were dried by a gas-fired hot-air stream. The dryer temperature was controlled at 550-630º F (288-332 º C).

[6] CSB testing of dry chip samples showed that they contained aluminum dust particles of less than 200 mesh, i.e. less than 74 µm in diameter (3 thousandths of an inch [0.003 inches]). This size particle is approximately equivalent to powdered milk (Eckoff) and is in the explosive range for aluminum dust.

[7] "Free" oxygen is available for reacting with other materials, such as fuel (for burning) or aluminum (for oxidation.)

oxidation of the aluminum chips. Since the chips were very thin, surface oxidation could cause chips to break into smaller pieces, increasing the amount of dust produced in the dryer.

The dryer exhaust routed through a high-temperature afterburner to burn off the evaporated cutting oil and any unburned fuel gas.

1.6.3 Chip Melting

From the dryer, the chips were transferred by pressurized air to a dry chip hopper, where they were held until fed to one of two furnaces. Screw conveyors at the bottom of the dry chip hopper fed aluminum chips to a duct, where they were blown through a 6-inch-diameter pipe to the melt furnace. Furnace 5 was the primary furnace used for melting the aluminum chips, while furnace 4 was used when furnace 5 was out of service for maintenance.

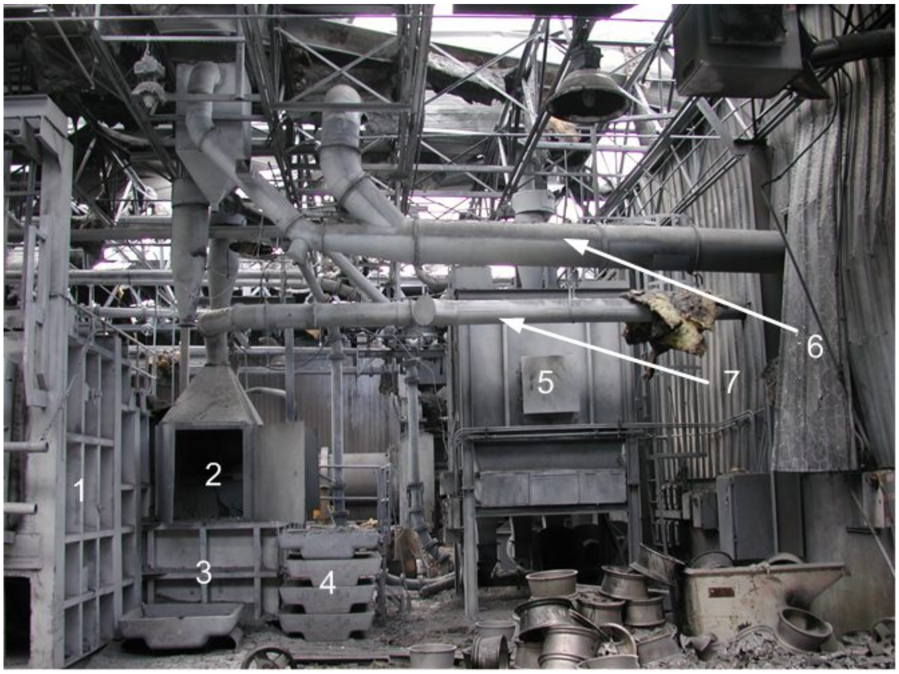
The chip-melting furnaces have a sidewell, a protruding structure that is an open-top chamber containing a pool of molten aluminum (Figure 4). The sidewell is used for fluxing[8] the aluminum melt and removing dross.[9] It also received the dry chips through an associated vortex box. A vertical submerged pump in the sidewell created a liquid vortex of molten aluminum (similar to the swirl in a pool of draining liquid), into which the chips were fed.[10] The vortex quickly drew the chips into the molten aluminum (instead of having them float on the surface), where they melted rather than burned.[11] A hood covered the sidewell to draw smoke generated above the sidewell (Figure 5).

[8] Fluxing is the process of adding a mineral to the molten aluminum to facilitate the removal of dirt and contaminants.

[9] Dross is scum that forms on the surface of molten metal as a result of oxidation.

[10] The vortex, a conical whirlpool, is created by rapidly circulating the molten aluminum around inside the sidewell.

[11] The melting point of pure aluminum is 1,220 °F (660 °C). The auto-ignition temperature for aluminum chips is not reported in the literature; however, small aluminum particles ignited at temperatures as low as 840 °F (450 °C). Babrauskas (2003).



1. Furnace No. 5 Wall
2. Fume Hood over Side Well
3. Side Well
4. Aluminum Ingots
5. Dry Chip Hopper
6. Dust Duct
7. Fume Duct
8. Reject Wheels for Remelting

Figure 4. Photo of furnace 5 sidewell, showing fume hood, ingots, and dry chip hopper.

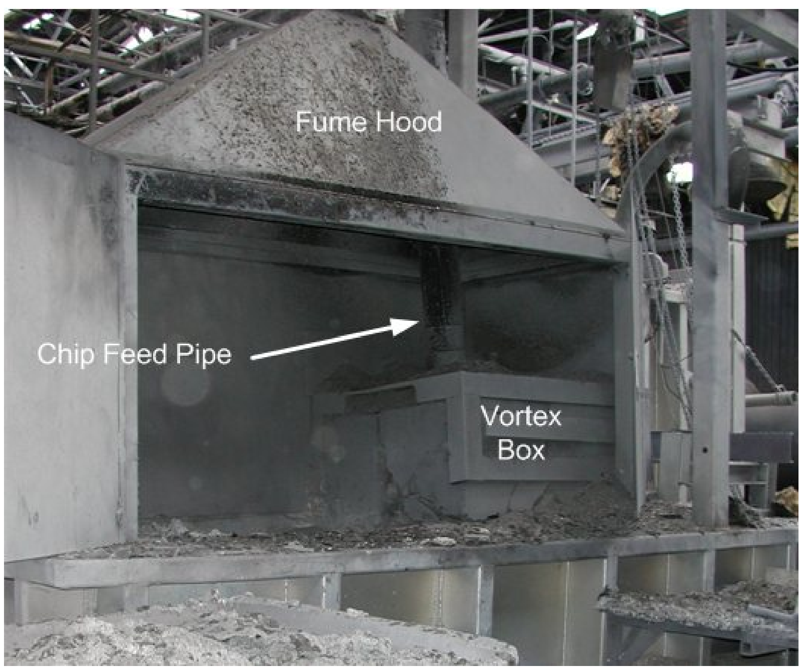


Figure 5. Vortex box and chip discharge pipe above furnace sidewell.

The hood connected to a cyclone separator with an induction[12] fan located outside the building. See Figure 6 for a diagram of the furnace chip feed.

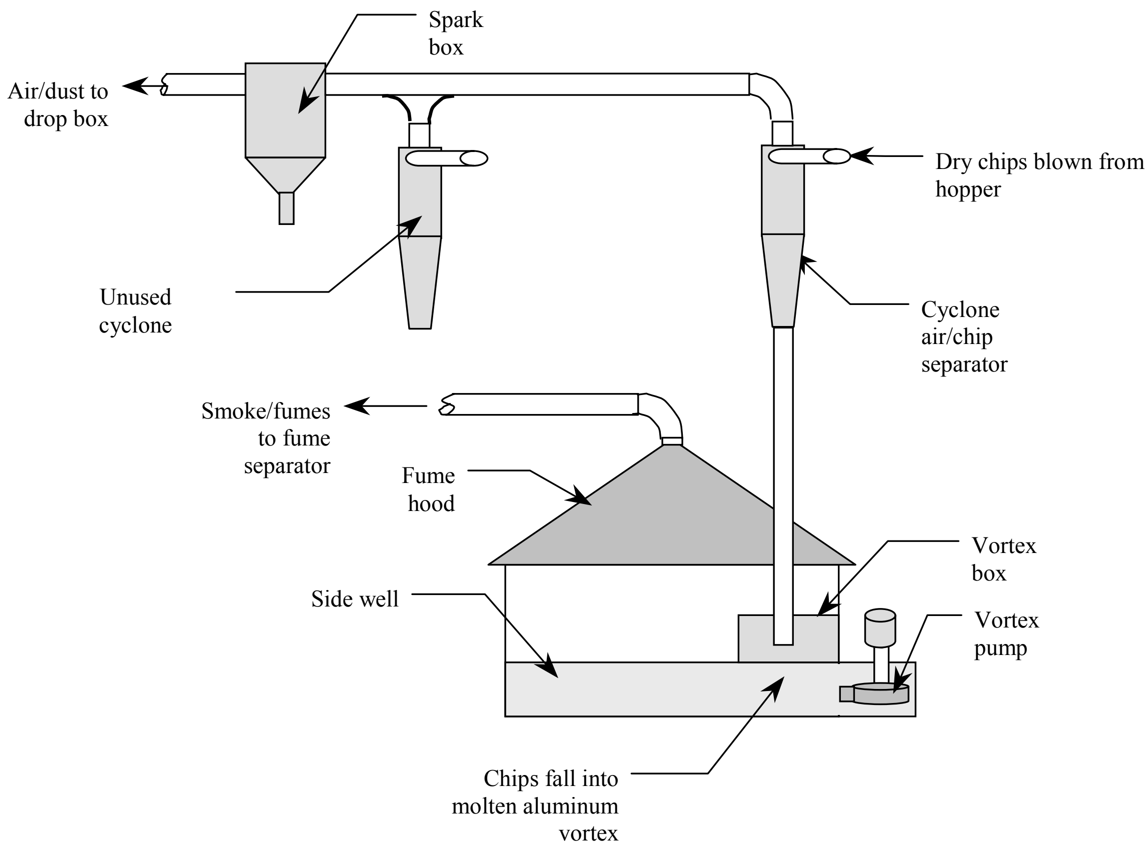


Figure 6. Diagram of furnace 5 chip feed.

Above the vortex box, the dry chip feed enters a cyclone separator (Figure 7) that disengages the chips from the air stream. Their weight then causes them to fall into the vortex. The transport air and fines[13] exit the top of the cyclone.

[12] An induction fan *pulls* air through a system and is located at the exhaust of the dust collector. By contrast, a forced draft fan *pushes* air through the system and is located at the air inlet.

[13] Dust and other particles, that are too small to be separated in the cyclone.

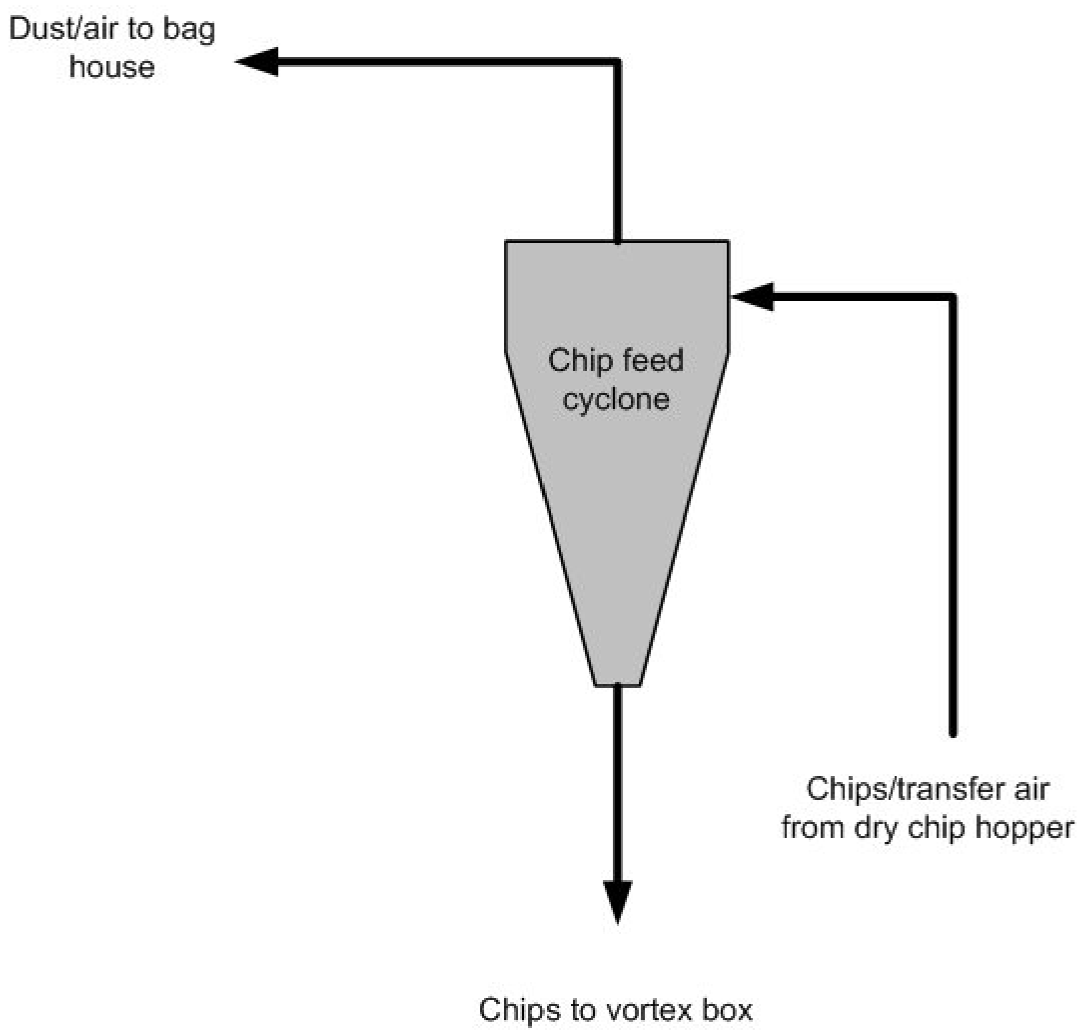


Figure 7. Chip feed cyclone separator.

1.6.4 Dust Collection

About three years after installing the chip melt system, Hayes added a dust collection system. The collection system consisted of ducts connected to the top of the feed cyclones, a drop box, dust collector and draft fan (Figure 8). The chip feed transfer air was transported from the top of the cyclone through ducts into the drop box, and then into the dust collector.

The system operated on a “push-pull” balance. Chips and dust were pushed from the dry chip hopper into the cyclone; dust and air were pulled into the dust collector by the draft fan. If clogged filter cartridges in the dust collector impeded the airflow through the dust collector, it would direct air and dust out of the bottom of the cyclone. The dust could ignite on the hot aluminum and/or accumulate around the vortex box.

The drop box, dust collector, and fan were located outside the building. Spark boxes installed in the ducts near the furnaces used a baffle plate to deflect large embers or heavy objects that might cause a spark in the duct system.[14] The dust collector, located outside the foundry building, operated with slight negative pressure. Steel ducts connected the dust collector system to the chip feed cyclones at furnaces 4 and 5, the dry chip hopper, the dryer hood, and the wet chip hopper. These ducts merged into a single 20-inch duct that passed through the building wall and entered the drop box. An additional duct connected the dry chip hopper directly to the drop box.

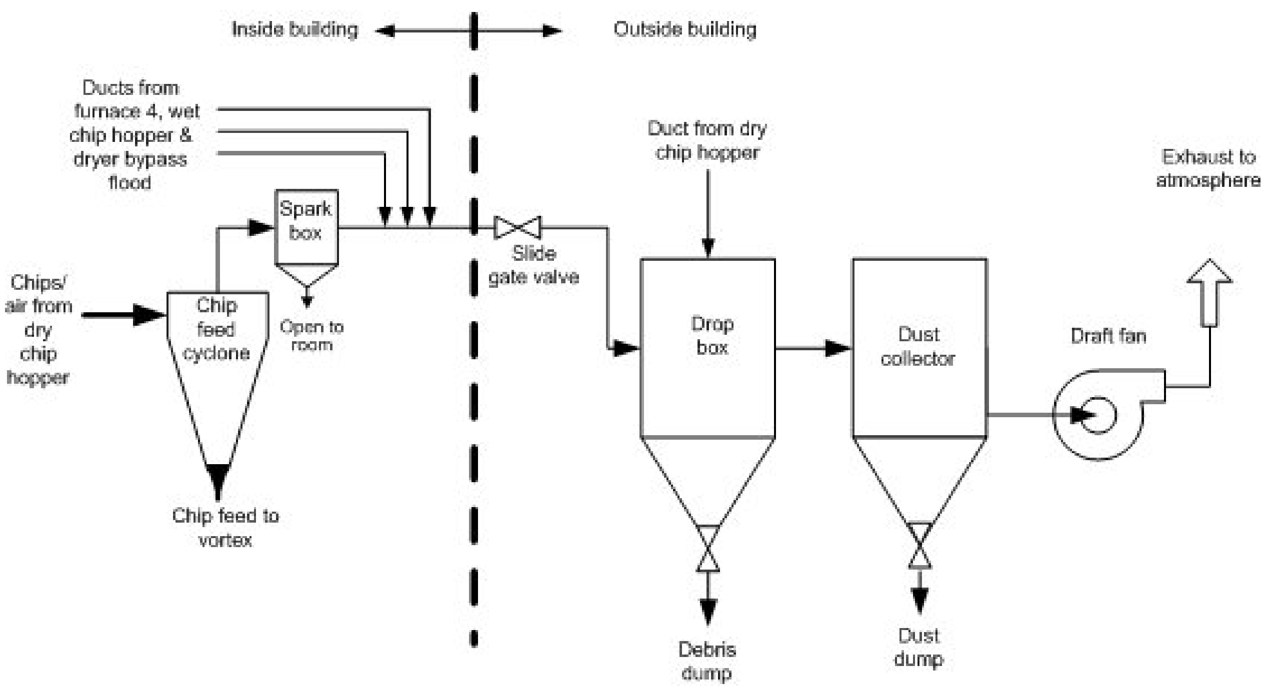


Figure 8. Dust collection diagram.

[14] For example, iron or steel objects could cause sparks if they strike the steel walls of a duct or the drop box at sufficient velocity. The spark boxes are open at the bottom. Material dropped out of the bottom of the box falls freely approximately 10 feet to the foundry area floor.

The drop box was a carbon steel container about 6 feet square and 8 feet tall, with a tapered lower section below a square chamber and a manual cleanout valve. The box trapped heavy particles before they entered the dust collector. As the dusty air entered the drop box, the sudden decrease in velocity caused heavier particles to fall to the bottom of the box.

From the top of the drop box, the air flowed through a short rectangular duct (Figure 9) into the bottom side of the dust collector (Figure 10). The dust collector used 24 pleated filter cartridges to collect fine dust from the air stream. Automatic air-pulse jets within the dust collector dislodged accumulated dust from the filters; the dust then fell to the conical bottom of the dust collector for removal through a manual valve. The pulse jets used high pressure air from the facility's compressed air system and operated on a 90-second cycle.

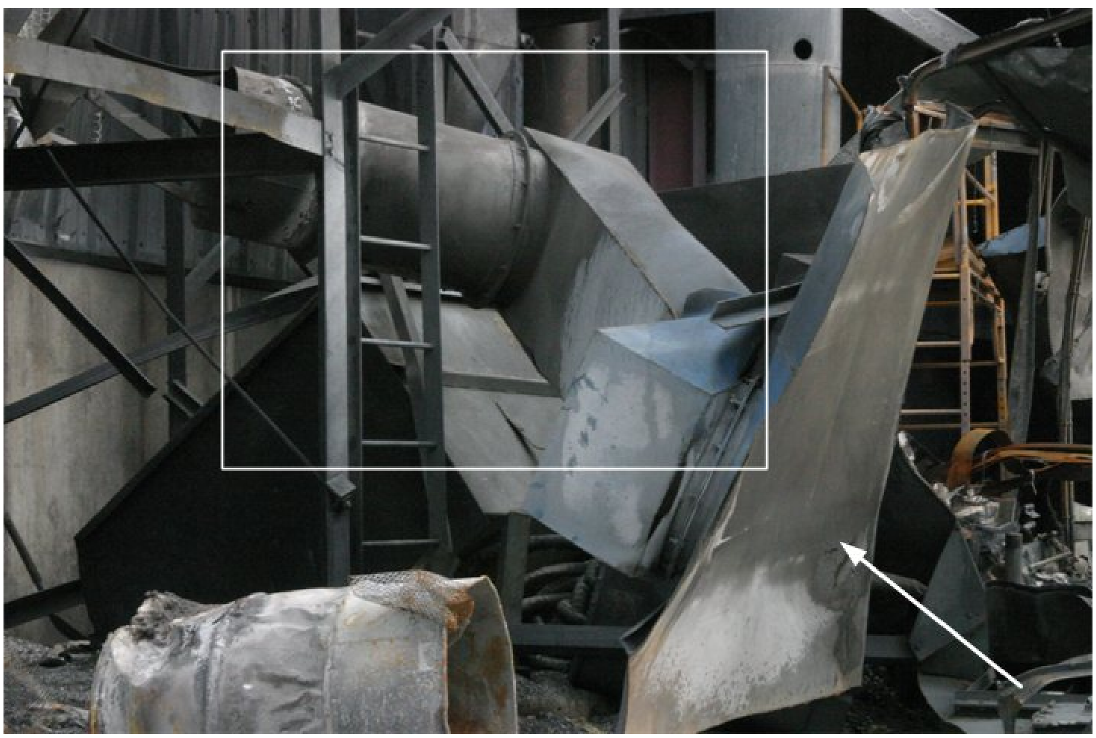


Figure 9. Drop box side panel (arrow) with outlet duct (box).

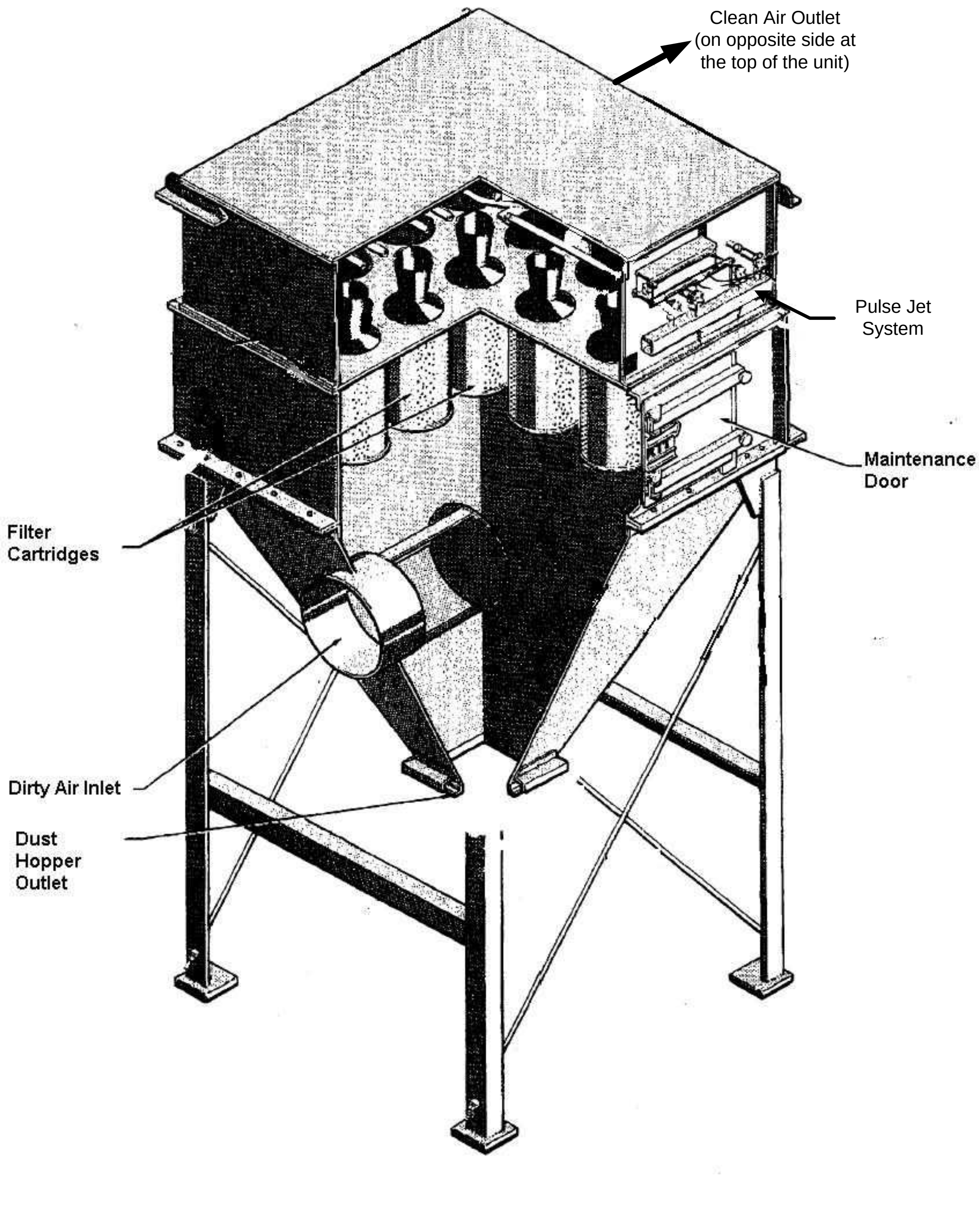


Figure 10. Diagram of the dust collector (explosion vents not shown).

The draft fan drew air from the top side of the dust collector and exhausted the air to the atmosphere. A pressure gauge on the dust collector monitored the pressure drop across the filter cartridges. Maintenance personnel stated that they used that gauge to determine when the cartridges required cleaning. The dust collector included explosion relief vents (blowout panels) on three sides that were intended to open if the aluminum dust accidentally ignited (see Section 3.1). Doors on the collector housing provided maintenance access.

1.6.5 Fume/Smoke Ventilation System

A fume hood was installed above the sidewell of the furnace to draw smoke out of the building. Some wheels were machined after they were painted, therefore the chips also contained acrylic paint that burned off when the chips entered the molten aluminum. Trace amounts of cutting oil that remained on the chips also generated smoke, as did fluxing and drossing activities.

A circular steel duct connected the fume hood to the fume separator located outside the building. The fume separator (Figure 11) was a carbon steel box about 3 feet square and 8 feet tall, containing two cyclones.[15] This device separated smoke and other particles from the fume hood exhaust before drawing it through the draft fan and exhausting to the atmosphere. An automatic valve in the base of the separator dropped accumulated solids into a drum for disposal.

A layout (plan view) of the furnaces, ducts, and dust collection equipment is shown in Figure 12.

[15] The fume separator cyclones are similar to the chip feed cyclone. The fumes from the furnace fume hood enter at an angle into a cylindrical container with a conical bottom. Centrifugal forces cause smoke and other fine particles to separate out of the air stream. These particles fall out the bottom of the cyclone into a collection drum. Cleaned air exits via a stack at the top of the separator.

Figure 11. Fume separator and draft fan.

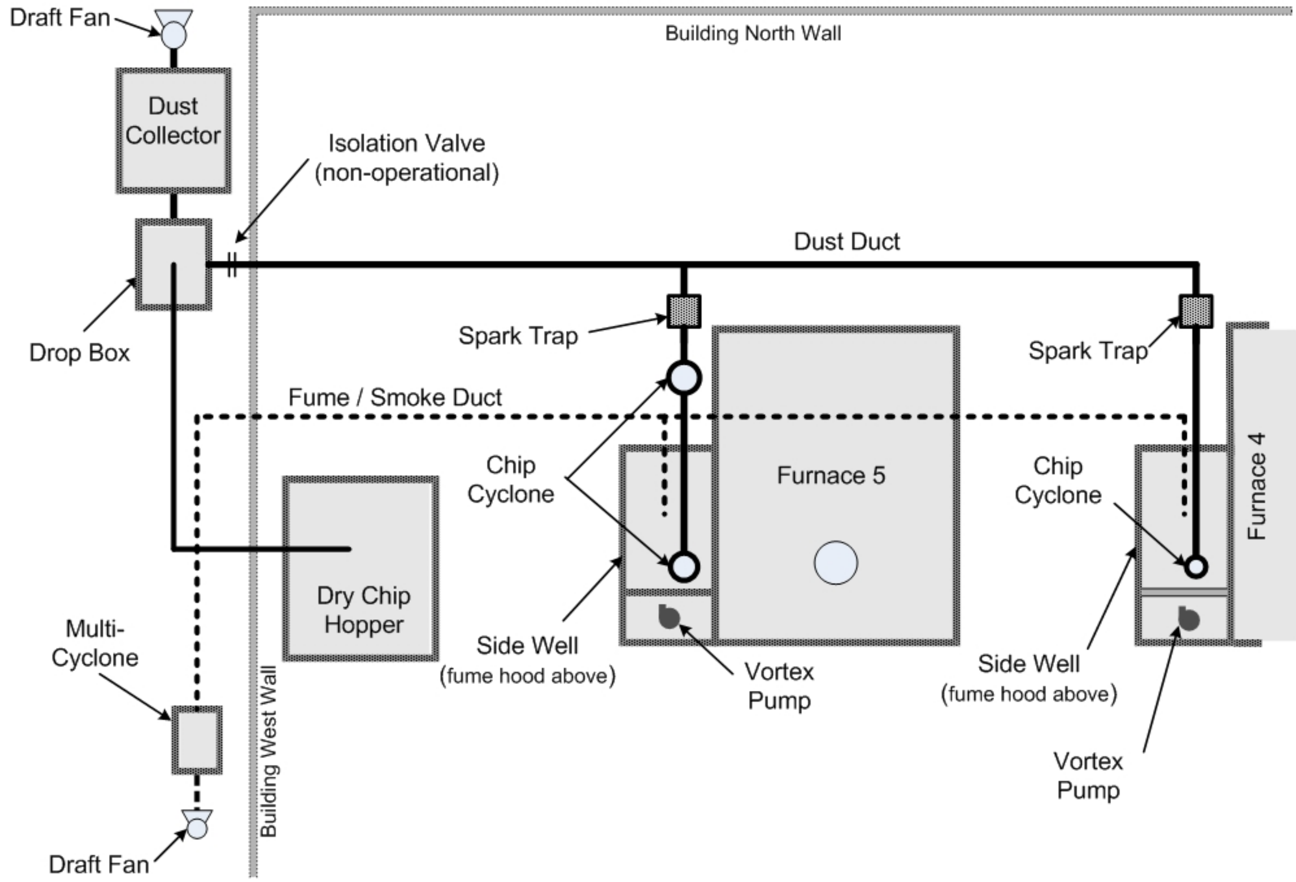


Figure 12. Layout of dust collection, furnaces, and ducts. Some ducts and equipment omitted for clarity.

2.0 Incident Description

2.1 Fume Hood Duct Fire

At about 2:30 pm on October 29, 2003, Hayes maintenance personnel shut down the chip feed system because of a smoldering fire located near furnace 5 inside the duct connecting the fume hood to the fume separator (see Figure 4, item 7). The glowing red duct alerted employees to the fire. According to plant personnel interviewed by CSB, fires in this duct were not uncommon. On this particular day, employees followed the usual practice for dealing with these fires by shutting down the dry chip feed and the fume hood draft fan (but not the dust collector draft fan), and allowing the fire to burn itself out. Employees judged that the fire was out when the duct had cooled, and they found burnt material that had broken free in the fume separator solids drum. They then opened the fume duct and cleaned out the remaining residue within reach. The October 29 duct fire had been out for at least 2 hours before maintenance personnel restarted the dry chip feed.[16]

2.2 Chip Feed Restart

At about 8:20 pm, three Hayes maintenance personnel restarted the dry chip feed system. Employees reported that after the restart, chips fed steadily to the furnace 5 sidewell for about 10 minutes. At that point one of the employees—who was standing on the north side of the furnace, about 10 feet from his coworkers —noticed chips falling out of the spark box (see Figure 6) in the dust collector duct.

[16] CSB concluded that the only likely connection between this fire and the incident later that evening was the fact that restarting the chip feed system afterwards placed the maintenance employees in the vicinity of furnace 5 at the time of the explosion.

Maintenance personnel were familiar with this phenomenon, which typically indicated that a crust had formed in the vortex, impeding chip feed and that chips were overflowing into the dust duct.[17]

2.3 Fireball at Furnace 5

The mechanic who noticed the chips falling from the spark box turned to tell his coworkers to stop the dry chip feed. As he turned, a fireball erupted from beneath the furnace fume hood. The fireball ignited his clothing[18] and totally engulfed another mechanic standing near the sidewell vortex pump. The flames also singed a third mechanic, who was standing near the system control panel.

2.4 Roof Blown Open

The fireball expanded, rose upward, and blew open the roof of the building (Figure 13). A contractor was on the roof, having just finished testing emissions[19] at furnace 4 and was moving his equipment to furnace 5, when the explosion occurred. As recorded in CSB interviews, he heard a boom, was knocked down as the roof panels beneath his feet heaved upward, and saw flames erupt through the roof. The contractor ran east approximately 200 feet, descended at ladder and attempted to call 911. He was not seriously injured.

[17] The clearance between the end of the chip feed pipe and the surface of the molten aluminum vortex was only a few inches. It was common for the surface of the vortex to cool down and begin to solidify into a crust, especially during chip feed startup. This crust prevented the chips from entering the melt. The chips bridged across the gap, and the pipe quickly filled up with chips. Maintenance personnel stated that human intervention was needed to clear the blockage.

[18] The Hayes facility had a standard practice of requiring personnel to wear all natural fiber clothing (as opposed to synthetics such as nylon and polyester.) Injured employees were wearing cotton clothing at the time of the incident. Employees wore fire retardant aprons during drossing and fluxing activities, but not during routine maintenance or operations tasks.

[19] The contractors were testing the furnace stack emissions as part of the Hayes air emissions permit requirements.

Figure 13. Damaged roof above furnace 5.

Outside the building, another stack emission-testing contractor was working in a mobile laboratory trailer parked near the drop box. He said he heard a "boom," and was knocked down as the trailer lurched backward. The contractor looked out the trailer door to see the dust collector totally involved in a bright, hot fire. Something was lodged against the rear door of the trailer, making that exit impossible to use. He was forced to exit the side trailer door, which was closer to the fire than the rear door, but he also escaped serious injury.

2.5 Employee Evacuation

Within minutes of the explosion, employees used the intercom system to report the emergency. The plant emergency alarm sounded, and employees evacuated the plant. Coworkers assisted burn victims until emergency medical technicians (emergency responders) arrived. A headcount accounted for all employees and contractors.

2.6 Structural Fire

The fireball ignited roofing material and insulation, along with a small accumulation of combustible material stored behind the kiln dryer control panel. North-west of the furnace sidewell, plastic pallets containing rejected aluminum wheels waiting to be re-melted were also ignited, and some of those wheels eventually melted (Figure 14).

Figure 14. Melted wheels near furnace 5 after the fire.

2.7 Emergency Response

The Huntington fire chief resided close to the industrial park, and heard the explosion. Within minutes, he was at the nearby firehouse. Within 5 to 10 minutes of the explosion, he was on the scene. Because of prior visits to the plant, he knew that the Hayes plant worked with molten aluminum, and understood the proper techniques and materials for fighting aluminum fires. The fire was contained and extinguished in about 2 hours using Class D[20] fire extinguishers. The fire chief reported that he inspected the facility for any signs of a natural gas fire and found the gas piping intact.

[20] Class D extinguishers are rated for metal fires and typically use sodium chloride or some other noncombustible salt as a smothering agent.

Fire department emergency responders attended the burn victims. There were no injuries to emergency responders in this event, and no fire equipment was damaged or lost. Full-time fire fighters staff the Huntington fire department.

2.8 Injuries and Damage

Figure 15 shows the location of most of the interior and exterior damage and the location of employees at the time of the explosion. One stack-testing contractor was on the roof above furnace 5; the other was in a trailer just southeast of the drop box. Not shown in the figure are damage to the wall south of the kiln dryer and the exterior wall southwest of the kiln, water damage inside the compressor room south of the kiln, and damage to the wet chip hopper.

2.8.1 Injuries

The employee who was closest to the furnace sidewell was totally engulfed in flames and died of thermal burn injuries the day after the incident. A second employee received serious burns over nearly half his body. He remained in critical condition for days and was hospitalized for weeks. The third injured employee received only minor localized burns and returned to work to assist investigators the day after the explosion. Four additional workers (three Hayes employees and one contractor) received treatment by emergency responders for minor injuries on the scene; none of these workers required hospitalization.

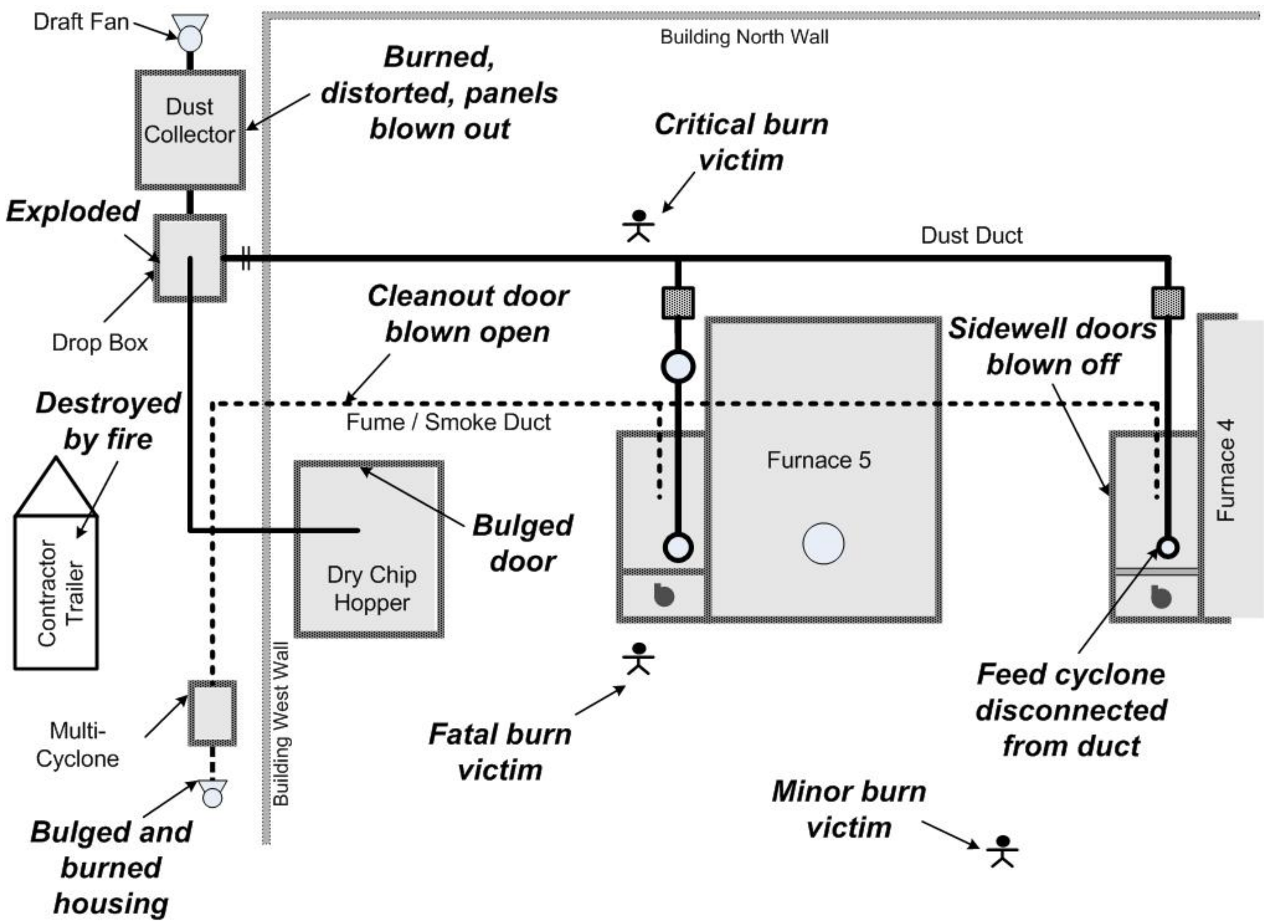


Figure 15. Damage overview and location of employees (plan view). Roof over entire area sustained damage.

2.8.2 Exterior Damage

The explosion vent panels in the dust collector were blown open, and three of four maintenance doors were blown open or off. The ensuing fire completely consumed the aluminum dust and combustible filter cartridge materials inside the dust collector, destroying it (Figure 16). The drop box was split open at the seams into four large pieces; one piece was thrown 20 feet to the south and lodged against the back of the contractor's mobile lab trailer (Figure 17). Another large fragment apparently hit the side of the foundry building, slightly deforming a vertical steel wall support beam near furnace 5.

Overpressure caused the fume separator exhaust fan housing to bulge and disconnected the supply duct.

The fume separator housing was undamaged, though its paint burned off.

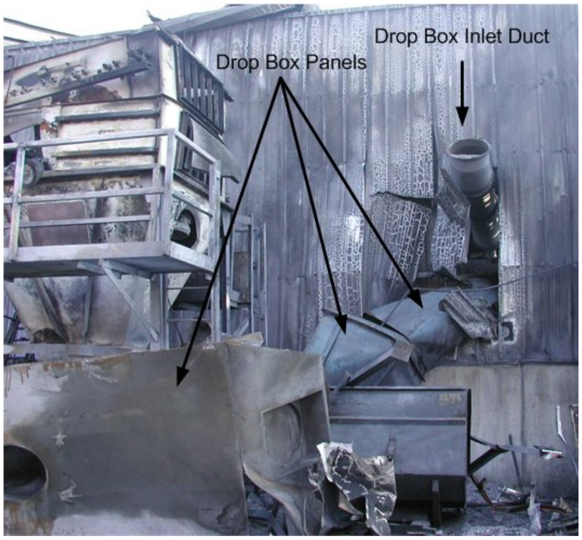


Figure 16. Dust collector (left) and drop box panels destroyed by aluminum dust explosion.

Figure 17. Remains of stack testing contractor's trailer after fire.

The facility air compressor room adjacent to the furnace area was damaged when the wall panel was blown out, and a water line ruptured causing water damage to some compressors. Exterior vent panels near the compressor room were blown out.

2.8.3 Interior Damage

Inside the building, the large, approximately 200 lb sidewell doors on furnace 4, which were closed before the explosion, were blown off by the pressure wave. One of the doors was found on the ground about 50 feet from the furnace. Overpressure also caused the dust collector duct to disconnect from the furnace 4 cyclone.

The fire damaged the chip system control console. Internal overpressure bulged the access doors on the side of the dry chip hopper and on the wet chip hopper inlet target box[21] (Figure 18 and 19).

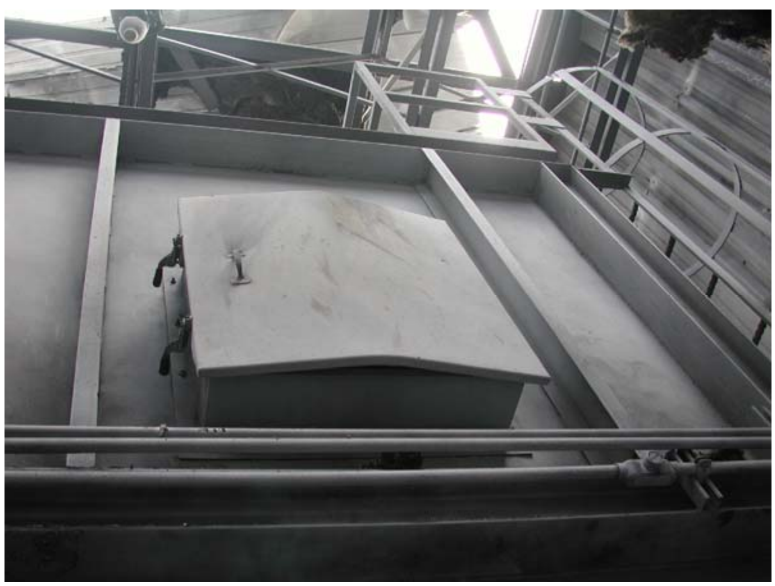


Figure 18. Bulged door on dry chip hopper.

[21] A target box is a steel box, containing "wear plates", designed such that the chips blown into the hopper hit the plates, lose velocity, and fall into the hopper. The target box prevents the chips from eroding the wall of the hopper. The wear plates require periodic replacement.

Figure 19. Wet chip hopper target box, with bulged access door (arrow).

Much of the roof above furnace 5 and the chip handling system was blown off. The west wall was deflected inward from the impact of drop box fragments. The explosion damaged the south wall adjacent to the compressor room, caused minor damage to the building walls, and caused significant roof damage (several trusses needed replacement.) A structural engineer verified the building was safe prior to re-entry by inspectors and employees. The total value of the property losses resulting from the incident were not known when this report was published.

2.8.4 Post-Incident Chip Processing

Although wheel-casting operations were suspended for several days, the plant was in full production one week after the explosion. Hayes decided not to repair the dry chip-processing system and dismantled it soon after the initial phase of the investigation was completed. Following the incident, Hayes arranged for a contractor to collect the wet chips for processing offsite. Now, that aluminum is returned to Hayes as ingots for remelting in one of the five furnaces.

3.0 Analysis

The purpose of CSB incident investigations is to determine root causes and make recommendations to prevent similar incidents from occurring. CSB focuses on underlying systemic issues. In this case, investigators used a comprehensive, logical approach, and the process of elimination to postulate scenarios for this incident, based on collective evidence.

CSB evaluated and reviewed all available facts to develop the scenarios, and to determine root and contributing causes and remedies. The CSB investigators measured and photographed on-scene damage and equipment, and obtained samples of chips and dust in and around processing equipment. Investigators also relied on inspection of the equipment and the explosion scene, witness interviews, and records and documents provided by Hayes and others. CSB had aluminum dust samples tested for explosiveness and other characteristics.

3.1 Dust Explosions and Aluminum Dust

The following background information is helpful in understanding the nature of aluminum dust explosions. This report then presents possible incident scenarios and analysis results.

3.1.1 Dust Explosions

Dust explosions have been documented as early as the late 18th century, when an Italian count reported his analysis of an explosion in a baker's flour warehouse.[22] Much has been learned about dust explosions since that time. Among the known facts are:

[22] Eckoff (1997)

- Dust clouds, when ignited, can produce deflagrations, which are flame fronts that move at speeds below the speed of sound.[23] Although not technically explosions, these deflagrations are commonly referred to as dust explosions.[24]

- Typically, for dust explosions to occur, all of the following conditions must be present: combustible dust is suspended or lofted in air; the dust ignites; and the dust is confined such that damaging pressures can accumulate.

- If lofted into a cloud and ignited, accumulated dust can become explosive. Dust layers can ignite and will smolder, but if disturbed, they may transition to a dust explosion. This phenomenon, known as a “secondary dust explosion”, refers to settled layers of dust that are lofted by some event or another explosion to create an explosive cloud.

- The explosive suspension of most dusts appears as an opaque cloud and, for many materials, is much denser than the amount considered “breathable”.

- The finer the dust particle and the more easily the dust oxidizes, the greater the explosion potential.

3.1.2 Aluminum Dust

The explosive properties of aluminum dust are in the literature, including the National Fire Protection Association (NFPA) fire prevention standards. In NFPA 68, *Guide for Venting Deflagrations* (2002a), aluminum is ranked among the most explosive of metal dusts. Preliminary data collected by the CSB indicate that nearly one fourth of all dust explosions in the United States in the last 25 years involved metal dusts, and that aluminum accounted for the majority of these events.[25] Metals account for

[23] In contrast, a detonation flame front moves at speeds greater than the speed of sound.
[24] For purposes of this report, “dust explosion” includes deflagrations.
[25] Data presented at CSB public hearing June 22, 2005.

about 19 % of dust explosions worldwide.[26] This data indicates that metal dusts are particularly hazardous and all appropriate precautions need to be taken to prevent dust explosions.

Dust explosivity is typically expressed using the deflagration constant, K_{ST}.[27] This constant is determined experimentally by measuring how fast the pressure rises when dust of a known concentration is ignited in a container of a specific volume (20 liters). The higher the K_{ST}, the more severe a dust explosion can be. Three "dust hazard classes" indicate relative explosiveness. For comparison, Table 1 shows K_{ST} values for a few known explosive dusts and a sample collected from the scene of the incident. Pure aluminum has a high K_{ST} and is rated as a Class ST-3[28] dust.

Actual explosivity values vary significantly with the size and shape of dust particles, the concentration of dust in the air, and the degree of surface oxidation (which, for metals, reduces flammability.)

CSB determined the aluminum dust that accumulated on surfaces in the building was explosive—though lower in explosivity than reported for pure aluminum powder. CSB samples were primarily of accumulations outside equipment, and included chips and dust with a wide distribution of particle sizes. These samples[29] generated pressure up to 155 pounds per square inch gage in the test chamber; sufficient to have caused the damage observed at Hayes. The dust in the dust collector was likely comprised mainly of finer particles,[30] therefore exhibiting a higher explosivity. The explosion and fire completely consumed this material.

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[26] CCPS (2005)

[27] $K_{ST} = (dP/dt)_{max} \times V^{1/3}$, where $(dP/dt)_{max}$ is the maximum measured rate of pressure rise and V is the container volume.

[28] ST-1, ST-2, and ST-3 are hazard classes assigned to dusts by NFPA to indicate relative explosiveness. ST-3 dusts are the most explosive, with K_{ST} values above 300 bar-m/sec.

[29] The tests were run on material that passed through a 200-mesh screen, which has openings approximately 75 µm across.

[30] The cyclone separators and drop box cause heavier particles, including chips, to separate out and fall into the furnace or into a container under the drop box. The material that flows into the dust collector is composed of the finer particles. The bulk material spilling out of a chip transfer line leak has not been through the cyclone separator and contains the full range of particle sizes (Zalosh et al.,, 2005).

Table 1. Comparative Explosivity of Various Dusts

Dust Type	Average Particle Size (microns)	K_{ST} (bar-meter/sec)	Dust Hazard Class
Surface dust sample* from Hayes	<85	131	ST-1
Pure aluminum powder**	29	415	ST-3
Coal**	<10 to 38	55-108	ST-1
Wheat flour**	57	87	ST-1
Wood dust**	43	102	ST-2

*This sample was collected from the top of an electrical enclosure, about 6 feet above the floor near furnace 5.

**SOURCE: Eckhoff, 1997.

3.2 Dust Collector Explosions

Collective data on dust explosions in the United States, United Kingdom, and Germany indicate that more than one fourth of all dust explosions occur in dust collectors. Within the United States, the ratio is higher at more than 40 percent. Zalosh, et al. (2005) states that:

> Three possible reasons for the high occurrence of dust collector explosions are: 1) they [dust collectors] are almost omnipresent in particulate handling facilities, 2) they inherently concentrate the smaller particles, which are easier to ignite than the mostly larger particles in other equipment, and 3) they often employ pulse jet cleaning, which by nature, periodically generates dust clouds inside the collector. Data from the German compilation of dust explosions indicate that the most frequent ignition sources have been mechanical sparks (41 percent), smoldering nests (11 percent), electrostatic discharges (10 percent) and mechanical heating via friction (7 percent).

3.3 Dust Explosion Scenario

CSB believes that the scenario presented in this report is the one that is supported by the totality of the evidence and therefore it is the most likely explanation of the events of October 29, 2003.

CSB determined through witness accounts, damage patterns, and other available evidence that the fireball[31] that erupted from the furnace sidewell was likely the result of an aluminum dust explosion in the dust collector system. According to the findings, the explosion originated in the dust collector after chips had been feeding to furnace 5 for about 10 minutes. The explosion propagated from the dust collector to the drop box, causing the drop box to rupture before breaking into several fragments. A pressure wave then traveled to the furnace 5 sidewell via the duct connected to the drop box, lofting and igniting accumulated dust in the vortex box. The pressure wave also caused minor to moderate damage in other equipment connected to the dust collector system.

Figure 20 is a schematic showing the approximate order of events in the above scenario. Evidence supporting this proposed scenario follows the schematic.

[31] Employees reported that it was common to see a flare-up or bright flash above the sidewell whenever chip feed was started. However, eyewitnesses reported the fireball in this incident was significantly larger than they had seen in the past, and was orange, in contrast to the bright white flashes seen in the past.

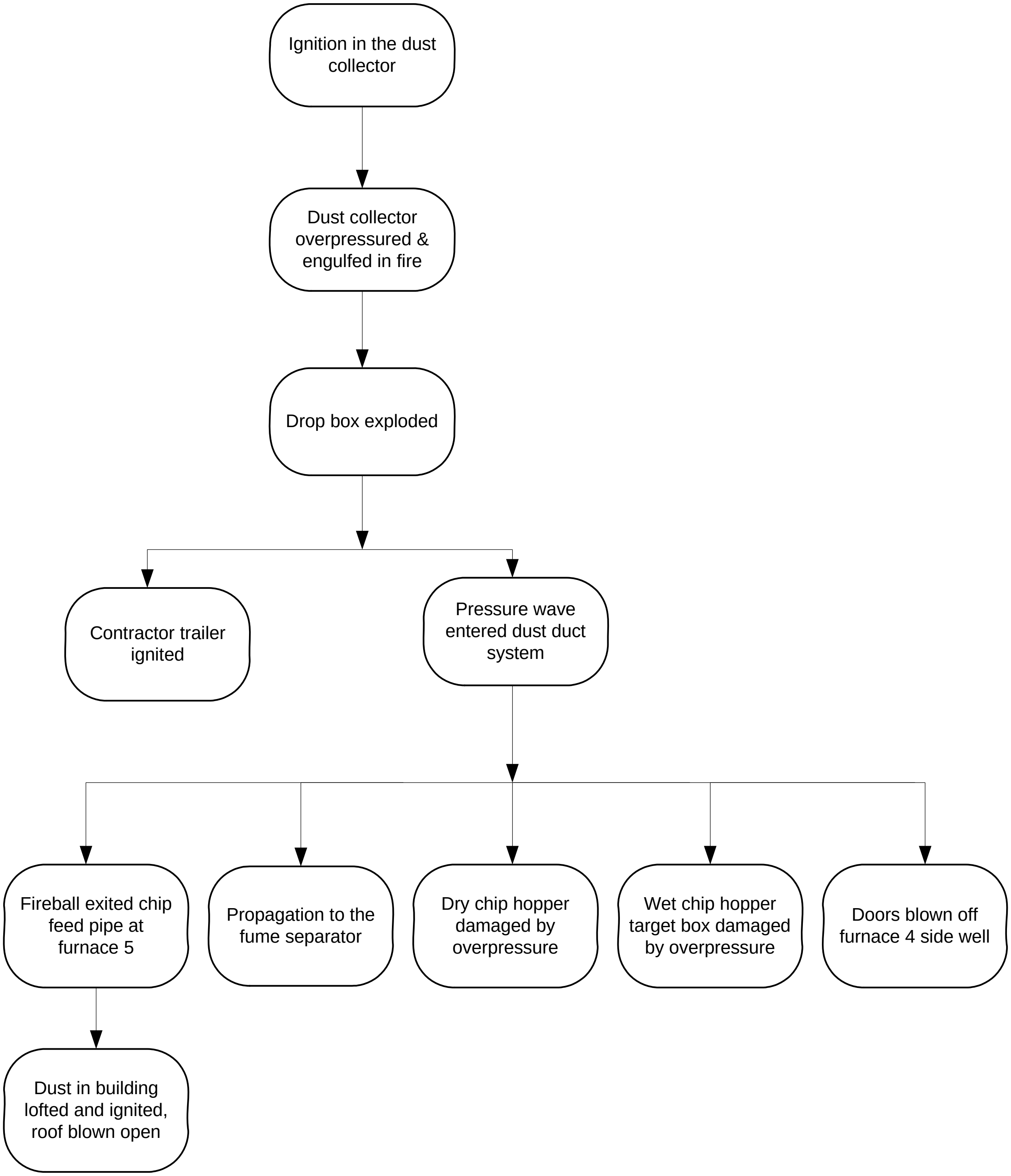

Figure 20. Sequence of events for CSB dust explosion scenario.

3.3.1 Ignition in the Dust Collector.

A witness in the contractor trailer (which was near the dust collector) emerged from the side-door of the trailer within seconds after the explosion. He stated that the dust collector was already involved in a very intense, bright fire (typical of aluminum powder fires). CSB concluded that the drop box had exploded at this point because:

- The drop box otherwise would have blocked the contractor's view of the dust collector from the trailer.
- A large drop box fragment was lodged against the trailer door, supporting the contractor's statements that the rear door was blocked.

The explosion vent panels and maintenance doors (Figure 21) on the dust collector were blown open by the internal deflagration.

Figure 21. Explosion vent panel and maintenance door (arrows) blown out on dust collector.

3.3.2 Propagation to the Drop Box

The drop box was pushed away from the dust collector, indicating that the pressure wave traveled into the drop box from the dust collector. The single explosion vent panel was blown and the drop box ruptured (Figure 22). The short duct connecting the drop box to the dust collector was pulled out and away from the dust collector (Figure 23), also indicating that the pressure wave traveled toward the drop box.

Figure 22. Drop box fragment, with blown explosion vent panel.

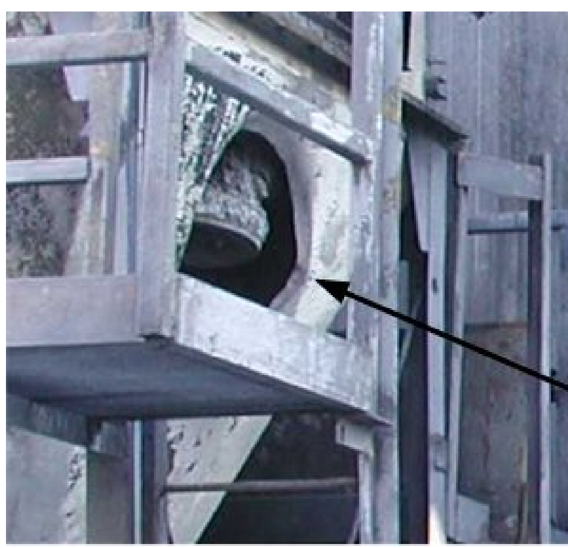

Figure 23. Air inlet (arrow) on the south side of the dust collector.

The drop box may have experienced significantly higher pressure than the dust collector, since an explosion propagating between two containers can result in a phenomenon referred to in literature as pressure piling.[32] However, the drop box was a much weaker structure than the dust collector, lacking substantial framing and joined only by small corner welds, and it was relatively unprotected by explosion venting. The drop box failed mainly along the seams and fractured into several large pieces.[33] One of the larger fragments impacted the building wall and was found resting below the impact point (Figure 24). The impact slightly bent the vertical steel wall support beam inward (Figure 25).

Figure 24. Drop box fragment after impact with building wall

[32] Eckoff (1997) attributes the pressure piling effect to increases in the pressure of an unburnt dust cloud in a second vessel. The second vessel's internal pressure from the deflagration is increased *above* the pressure created by the expanding gases from the first vessel.

[33] CSB calculations indicate that the rupture pressure for the drop box was between 2 and 5 pounds per square inch gage.

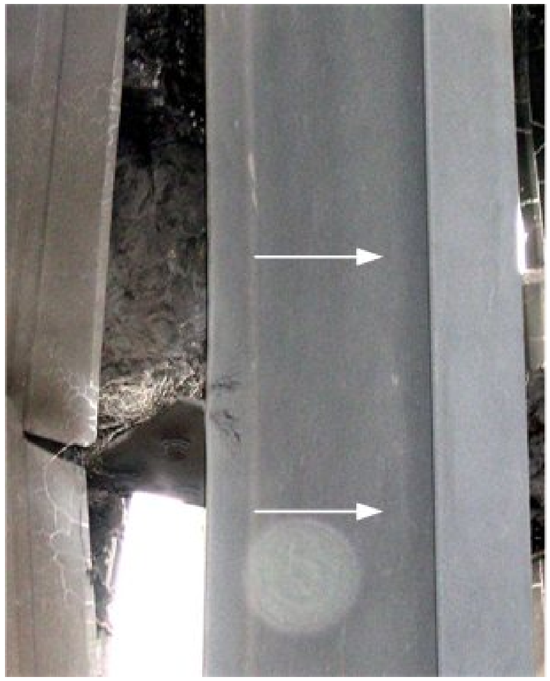

Figure 25 Beam slightly deflected by drop box impact. Arrows on either side of the point of impact show the direction of bending

3.3.3 Propagation to the Dry Chip Hopper

A 6-inch pipe attached to the drop box roof and the dry chip hopper (Figure 12) provided a direct path for pressure to travel to the dry chip hopper and damage the access door. This pressure was sufficient to bulge the door of the dry chip hopper (Figure 18).

3.3.4 Propagation Through Ducting

By lofting and igniting dust settled in the ducts (Figure 26), the deflagration also propagated upstream to the furnace 5 chip feed cyclone. CSB concluded that the deflagration traveled down the chip feed pipe and into the vortex box, causing the large fireball to erupt into the room. Witnesses recalled seeing the fireball exit the fume hood and wrap around the furnace. CSB also observed molten aluminum on the front of the victim’s safety glasses and splashed onto nearby equipment—further indication that a pressure wave was directed into the vortex box and down into the sidewell.

Figure 26. Interior of main duct between the chip equipment and the drop box with significant dust and chip accumulation.

3.3.5 Secondary Deflagration

CSB observed aluminum dust settled on most horizontal surfaces, including overhead beams, ledges, and the top surfaces of equipment in the area of furnace 5. Some beam and piping surfaces directly above the furnace sidewell had little or no accumulated dust on top of them after the explosion. However, CSB found neither documentation nor witnesses that these surfaces had been cleaned in several years. CSB determined that the fireball emerging from the fume hood at furnace 5 lofted and ignited dust that had accumulated on surfaces directly above the furnace. This caused a secondary dust deflagration that expanded upward and blew open the building roof.

CSB concluded that the outside dust collector explosion and interior deflagration occurred at the same time or in rapid succession. This conclusion was partly based on the accounts from the two contractors, who were the only direct eyewitnesses to both events.

3.3.6 Ignition in Fume Separator

The erupting fireball above the sidewell entered the fume hood, causing burning material to be pulled by the fume separator draft fan along the ducting into the fume separator. This material likely ignited deflagrations inside the ducting and fan housing severe enough to damage the draft fan housing and duct (Figure 27). The cleanout door was blown open on the duct between the fume hood and the fume separator (Figure 28). CSB found that the duct leading to the fume separator contained hard deposits and dust, which likely were the fuel for the fires in this duct (Figure 29).

Figure 27. Fume hood exhaust fan cover damaged by overpressure.

Figure 28. Cleanout door blown open on duct from furnace 5 fume hood to fume separator. Insulation from the roof rests on the duct (Figure 4 shows the location of this duct in the building).

Figure 29. Interior of fume duct to fume separator (near the cleanout door.)

3.3.7 Subsequent Explosions

Employees and the Huntington fire chief reported that a series of smaller explosions occurred about 11 minutes after the initial explosion. The fire chief concluded that some of these small explosions could have been the four tires on the contractor trailer failing. After the fire department extinguished the fire, investigators also discovered the remains of high-pressure gas cylinders used for instrument calibration, which had been in the contractor trailer. Figure 30 shows one of the cylinders, lying in the remains of the trailer.

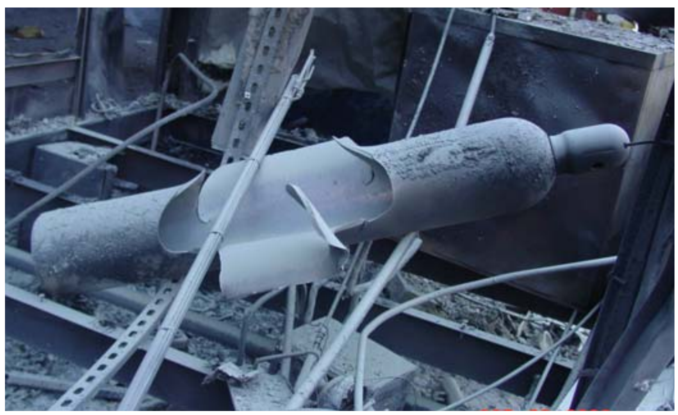

Figure 30. Ruptured gas cylinder in the contractor trailer.

3.3.8 Fuel for the Explosion

The Huntington fire chief inspected the natural gas piping in the areas damaged by the explosion and fire. The piping was intact with no evidence of leaking. Eyewitnesses did not smell natural gas odorant before the explosion.[34]

[34] Gas companies add a strong odorant that smells like rotten eggs to natural gas to help people detect a leak. Pure natural gas has no odor.

No other fuels capable of producing the explosion damage were present in the damaged area other than aluminum dust.

By design, the greatest accumulation of aluminum dust was in the dust collector. To be explosive, dust must be suspended in air. The dust/air suspension must also contain more than a minimum explosive concentration (MEC).

Premelt designed the chip system to feed at 3,500 pounds of chips per hour. CSB testing (Appendix A) indicated that the fraction of dust in the chip feed was below 0.7 % by weight. CSB estimated that the dust flow was, at most, about 25 pounds per hour. Therefore the air flowing through the ducts or drop box during normal operations would not exceed the MEC for aluminum dust.[35]

CSB concluded that the location most likely to contain an explosive suspension of aluminum dust was the interior of the dust collector on the inlet side of the air filters. This area might have an explosive concentration whenever the pulse jets operated, blowing aluminum dust off the filters from the inside-out. Within a few seconds,[36] the dust would settle into the tapered bottom of the dust collector.

3.3.9 Ignition Source

The exact point of origin and ignition source for a combustible dust explosion is often very difficult to determine. Dust explosions often involve secondary dust explosions; the largest explosion is not always the initiating event. Further, the ignition source itself often lasts only a short time and either is over

[35] The MEC for similar aluminum grit is 50 grams per cubic meter (0.0031 pounds per cubic foot). CSB estimated the concentration of dust in the ducting and drop box to be at or below 1.5 grams per cubic meter (0.000092 pounds per cubic foot).

[36] CSB investigators observed that when small quantities of the dust at Hayes were hand-lofted, the dust completely settled in less than 5 seconds.

by the time damage occurs, or evidence of the source is destroyed in the ensuing explosions and fires. In most explosions, the possible ignition source must be deduced or determined indirectly by process of elimination.

CSB considered several possible sources for ignition of the dust in the dust collector or chip system in the Hayes incident. These included:

- Thermite reaction
- Impact spark
- Burning ember
- Electrostatic discharge
- Electrical fault
- Hot surface

These potential ignition sources are consistent with historically prevalent causes of ignition for dust clouds, as reported by Babrauskas.[37] They are each discussed below.

3.3.9.1 Thermite Reaction

When aluminum contacts iron oxide at high temperature[38] or at sufficient velocity for frictional heating, a reaction can occur that releases sufficient energy to ignite most flammable mixtures. The typical thermite reaction is:

$$Fe_2O_3 + 2Al \rightarrow Al_2O_3 + 2Fe$$

[37] Babrauskas (2003) p. 152

[38] Above 500 ºC (932 ºF). Babrauskas (2003) p. 481

A common mechanism for thermite reactions is a large aluminum particle striking rusty steel or iron, or a piece of rusty metal striking a coating of aluminum powder on a hard surface. After the explosion at Hayes, the interior of the dust ducts were found to have a light coating of aluminum. Although aluminum dust deposits were not noted in the dust collector and drop box remains after the explosion, this does not rule out the possibility such deposits were present before the explosion and then eliminated by the blast or the subsequent fire. Employees stated that metal pieces, such as screws, small tools, and other items, were sometimes found in the dry chip feed and drop box. Therefore, CSB deduced that a thermite reaction initiated by a rusty piece of metal striking a surface in the drop box or dust collector was a possible ignition source.

3.3.9.2 Impact Spark

When steel objects strike steel or an abrasive surface with enough momentum, the impact can generate a spark. A common example is the spark observed when a steel hammer strikes a steel nail. For this reason, refineries and other workplaces that may have flammable atmospheres often use tools of bronze or other non-sparking metals.

As stated above, employees sometimes found steel objects in the chip feed system and small items such as screws in the drop box. The dry chip stream had no magnetic separator to remove such objects. Investigators theorized that a steel object could strike the drop box with enough momentum to cause an impact spark. If the spark landed on combustible material, that material might ignite and become a smoldering nest. The drop box was designed with a manual slide valve to allow dumping of accumulated material. Employees stated that the drop box was not regularly cleaned. Therefore, a pile of dust, chips, and other material likely accumulated in the drop box. If these materials were ignited, an ember could eventually be carried into the dust collector and ignite an explosive mixture. CSB investigators did not rule out an impact spark as a possible ignition source.

3.3.9.3 Burning Ember

Routine operation of the aluminum melt furnace requires periodic fluxing and drossing to remove impurities from the molten aluminum. Employees recalled that these activities sometimes lofted significant amounts of burning embers.[39] At least two openings (one at the bottom of the spark box and another on an unused cyclone separator above and close to the sidewell) existed where such embers could be pulled into the dust stream (Figure 31).

Figure 31. Unused spark box and cyclone, with openings (see arrows) where sparks could be pulled into the dust stream by the airflow.

However, Hayes added a direct duct from the dry chip hopper to the drop box (see Figure 12) in an effort to vent what employees described as “positive pressure” within the dry chip hopper. In correspondence with CSB, Hayes opined that embers might migrate from the kiln dryer to the dry chip hopper. CSB believes that such an ember could have been pulled by the draft fan into the drop box.

[39] No witnesses stated that fluxing or drossing activities occurred on the day of the explosion.

Finally, hydrocarbon deposits from cutting oil residue or other combustibles reportedly accumulated inside the fume hood. These deposits could break off, fall onto the molten aluminum in the sidewell, ignite, and release embers. CSB investigators believe that an ember pulled into the dust collector system was a possible ignition source.

3.3.9.4 Electrostatic Discharge

The phenomenon of electrostatic charge accumulation on powders and dust particles is well documented in literature. Whenever these particles rub together or against other surfaces, static charge accumulates similar to when a person walks across a carpet in winter. The amount of charge generated depends on many things, including the relative humidity within the equipment, particle size, chemical composition, and the type of surfaces.[40]

Aluminum dust particles will generate static charge during transfer, as demonstrated in CSB testing (see Appendix A). However, to ignite a dust cloud a discharge must occur within an ignitable dust mixture. CSB consulted with experts in the field of electrostatics and aluminum dust collectors. Experts generally agree that sufficient charge could be generated to ignite an aluminum dust cloud. However, the conductive nature of aluminum particles makes it likely the charge would dissipate before ignition could occur.

The filter medium used in the dust collector at Hayes was a pleated cellulose cartridge on a steel cage frame, with steel end pieces (Figure 32). Each cartridge was mounted in the dust collector housing on a threaded rod through its center. The pleated filter media was non-conductive material similar to paper. A thick foam gasket separated each cartridge from its steel support plate. Further, a washer used to help hold the cartridge in place had a non-conductive coating on one side. The features of the cartridges and

[40] Ebadat (2003)

installation provided an opportunity for static charge accumulation. The conductive aluminum particles in and on the filter would tend to dissipate that charge to the ground via the central rod.

The dust collector pulse jets lofted aluminum dust into the air stream every 90 seconds, resulting in dust concentration within the explosive range. If a static discharge were to occur, the most likely location would be the across the hold-down washer, since this is the smallest insulated gap in the cartridge assembly. It is unlikely that such a static discharge with sufficient energy would occur within that dust cloud created by the pulse jets. CSB concluded that electrostatic discharge is unlikely to be a credible cause for igniting the explosion in the dust collector.

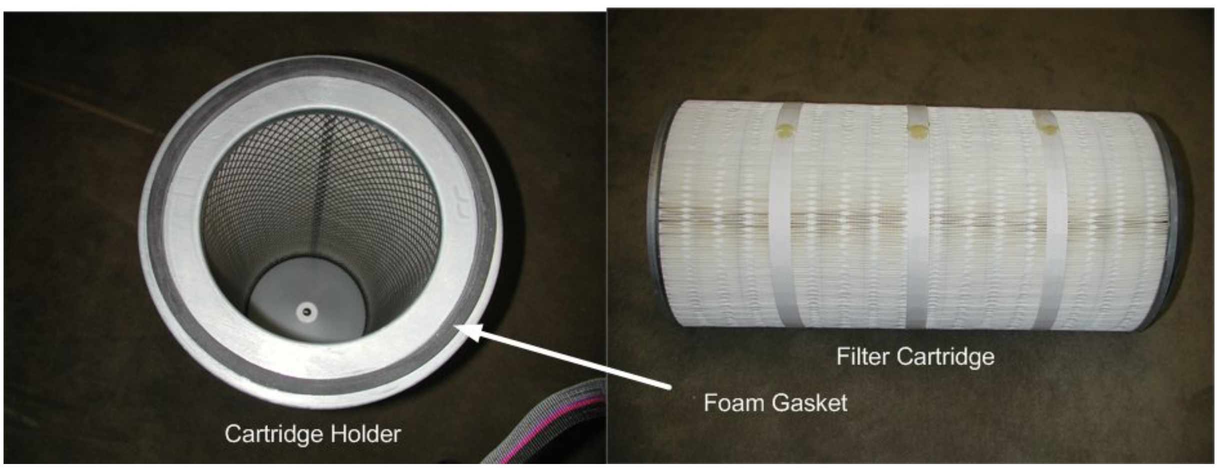

Figure 32. Dust Collector Filter Cartridge

3.3.9.5 Electrical Fault

A faulty electrical circuit, damaged wire, or other electrical component can cause sparking or arcing, which in the presence of an explosive mixture, can ignite an explosion. However, no electrical components were in the drop box, ducting, or dust collector where an explosive dust cloud might be present[41]. Therefore, investigators did not believe that electrical fault was a likely ignition source.

3.3.9.6 Hot Surface

As noted in section1.6.3, the melting point of aluminum is 1,220° F, which is above the temperature at which aluminum powders self-ignite (about 800 °F).[42] Any small particles of aluminum (dust, flakes, chips) that landed on the surface of the molten aluminum in furnace 5 sidewell would immediately ignite. For this reason, the chips were fed into a vortex to ensure they were incorporated into the melt instead of incinerating.

If dust accumulated on a ledge in the vortex box or other surface were disturbed and fell onto the molten aluminum, that material would immediately ignite. Ignited materials could enter the cyclone and be pulled into the dust duct. CSB believes (based on analysis of the system design and employee statements) that the bright white flashes employees typically saw during chip feed startup were the result of dust that accumulated in the feed pipes during system outages, and ignited as it exited the feed pipe.

However, an eyewitness reported that he saw chips falling out of the spark box just before the explosion; it is likely that the chip feed pipe was completely filled with chips. This chip-filled pipe would likely prevent a flame from progressing up through the cyclone into the dust collector system, similar to how an industrial packed-column flame arrestor works.[43] CSB investigators believe it unlikely a small fire from the vortex box would travel through the chip feed into the dust duct before being extinguished. Therefore, CSB does not consider the hot surface of the molten aluminum to be a likely cause for igniting the explosion in the dust collector.

[41] The pulse jet solenoids and timer were electrically operated, however these were located outside the dust collector housing. The only component of this system that penetrated the dust collector housing was small pneumatic tubing.

[42] Eckhoff (2003)

[43] A flame arrestor is a piece of equipment designed to slow a flame front traveling through a pipe, cooling the gases below ignition temperature, and extinguishing the flame. Source: Grossel (2002)

3.4 Alternate Scenarios

CSB investigators developed a detailed fault tree to examine potential causes of the incident. For a potential scenario to be considered likely, it had to have two outcomes: injuries near furnace 5 and injury to the contractor in the trailer outside the building. The complete fault tree, along with a brief explanation, is included in Appendix B.

Hayes presented an alternate scenario in which the chip feed may have spontaneously self-cleared, causing a sudden onrush of chips into the vortex box and dislodging accumulated dust on surfaces inside the vortex box. In this scenario, a small deflagration of the dislodged dust may have propagated to and ignited the explosion within the dust collector.

3.5 Pre-existing Conditions

3.5.1 Chip Feed Duct System Erosion

Aluminum chips are thin, curly, ragged pieces with many exposed sharp edges. The pneumatic transfer of the abrasive chips eroded the circular duct and deteriorated the transfer piping and equipment. Holes wore through the ducts and chip hopper components. Maintenance personnel frequently replaced sections of ducts and installed temporary patches when replacement parts were not immediately available. CSB found numerous locations in the system where temporary patches were installed or locations where holes wore through the pipes. Dust and chips blew though un-repaired leaks.

3.5.2 Housekeeping

Whenever a hole developed, chips and dust were expelled, and deposited on nearby surfaces. Hayes hired a contractor to clean the top of the furnace and inside the ductwork. However, following the October 29 incident, investigators observed significant accumulations of chips and dust on most horizontal surfaces (including floors, the tops of the chip hoppers, piping supports, and cable trays); in some areas, the material was up to several inches deep (Figure 33). Employees stated that this was typical of conditions before the incident. Managers and employees CSB interviewed indicated that they were not aware such accumulations presented an explosion hazard.

Figure 33. Typical chip and dust accumulation on floors.
The 4-inch blade of a trowel is buried in the pile.

Investigators observed that a layer of dust topped off piles of spilled chips they found throughout the furnace 5 area. Surfaces above the furnace (e.g., ducts, beams, ledges) were covered with even finer dust, which had been carried aloft in air currents. In many areas, dust layers were at least 2 inches thick. (Figure 34). In a dust release of mixed particle sizes, the smaller particles stay aloft longer on air currents and are carried higher. CSB found that dusts on the higher ledges appeared as fine as talcum powder (commercial talc particles are typically in the range of 10 to 20 microns [4-8 ten thousandths of an inch] in diameter.)

Figure 34. Dust accumulation on roof trusses.

3.6 Dust Collection System

3.6.1 Dust Load

Premelt Systems manufactured and installed the chip-processing system at Hayes in 1995.[44] The system operated without a dust collector for 3 years; the top outlets of the feed cyclones were open to the room. Employees stated that after the chip system was in operation for some time, they saw dust in the air, which migrated into working areas. Employees recalled seeing suspended dust in the air at all times.

Premelt representatives stated that the chip systems they designed typically do not generate significant dust. However, the small amount of dust the system did generate would require routine removal to prevent hazardous accumulations. CSB was not able to directly observe an operating Premelt chips processing system. However, CSB conducted telephone interviews with the operator of a similar system at a facility in Ohio. He stated that the chip system at his facility had cyclones open to the work area, had

[44] Premelt supplied the wet chip transfer to the dryer, kiln dryer, hoppers, and chip feed system. The wet chip collection, dewatering, and crushing equipment was supplied by others.

no dust collector, and that there was not appreciable visible dust coming from the system. He further stated that minor accumulations of dust in the work area were periodically cleaned.

Through samples of the dry chips and interviews of Premelt and Hayes personnel, CSB finds that the process of transporting and drying aluminum chips results in the production of some amount of fine aluminum particles. CSB feels that the potential for dust generation and the hazards of aluminum dust explosions should be communicated to all owners and operators of Premelt chip processing systems.

According to witnesses and documents reviewed by CSB, after the chip system was put in service, Premelt suggested to Hayes that a vibratory screen separator at the dryer outlet and a dust collector to collect the dust from the cyclones would be beneficial to the operation at Huntington. Premelt provided price quotations for this equipment in 1996 and again early in 1998.

3.6.2 Dust Collector Project

In 1998, corporate acquisition of another facility made a dust collector and drop box available to Hayes. Hayes installed the equipment on the chip-processing system to reduce dust in the foundry area. According to documents obtained by CSB, Premelt provided an opinion about the capacity of the dust collector and a Premelt technician connected the dust collector controls to the existing chip system control panel. However, Premelt personnel stated that they were not asked to evaluate the overall dust collector system design, including the points of connection to the chip feed system. Documents supplied by Hayes suggest that the involvement of Premelt during the dust collector installation was limited to interfacing the controls.

Hayes arranged to have both a representative for Donaldson Torit (the manufacturer of the dust collector) and a local engineering firm[45] assist in designing the dust collection system. The Hayes purchase specifications included a requirement that the system be designed according to NFPA standards.

[45] The engineering firm is no longer in existence. CSB attempted, unsuccessfully, to locate the engineer or anyone associated with this firm to obtain records of the project.

However, Hayes did not maintain documentation of the work the local engineering firm performed. Thus, CSB could not determine whether the dust was sampled and tested, or whether calculations were performed to determine how adequate the ducts, fans, and vents were for the conditions of the actual process.

Hayes was unable to produce documentation, and employees could not recall whether they verified that NFPA standards were met when the dust collector was installed. There also was no evidence that the chip transfer system flow balance was adjusted after the dust collector was installed (see section1.6.3).

3.6.3 Operating Experience

The facility preventive maintenance program included a weekly dust collector inspection, where employees recorded readings on a differential pressure gauge (which indicated pressure drops across the dust collector and whether the cartridges were dirty). Records indicate that the pressure drop was recorded each shift as part of the facility's air permit requirements. However, there is no indication that the gauge was calibrated or verified as functioning properly; therefore, this reading may not have accurately indicated the status of filters. Employees stated that, at the time of cleanings, cartridges were completely filled with dust to the point that pleats in the filters were not visible, and the filters were almost too heavy for one person to lift.

Employees could not recall the last time cleaning occurred; the most recent documented cleaning was 4 months before the explosion. Maintenance records include dates when the vacuum gauge was read, but no record of action. If the gauge was plugged—indicating a false reading—the filters likely would have been clogged, as well. Clogged filters result in high pressure drops across the dust collector and low air velocity.

According to the designer of the Premelt equipment, low air velocity to the dust collector would result in dust being deposited in the ducts and flow imbalance at the chip feed pipe. If the airflow to the dust collector were not equal to or greater than the chip transfer airflow, dust and air would flow to the vortex box. Dust flowing into the vortex box would accumulate and/or be ignited on the surface of the molten aluminum.

The condition of the dust collector draft fan (Figure 35) was another indication that dust collector maintenance was inadequate. CSB found that the fan housing was eroded, which is typically caused by dust leaking through or past the filters.

Figure 35. Interior of dust collector draft fan housing, showing significant erosion damage (arrow)

3.7 Explosion Protection

3.7.1 Explosion Venting

The dust collector and drop box were equipped with explosion relief vent panels designed to open should deflagration cause overpressure. This venting is intended to relieve pressure in a safe direction, and to prevent deflagration pressure from exceeding the design pressure[46] of the dust collector and attached equipment.[47] , The vent panels and three maintenance doors on the dust collector were blown open during the deflagration, as shown in Figure 21. The top section of the housing was dislodged and the cleanout section was distorted; this damage shows that the venting was not sufficient to prevent structural damage to the dust collector caused by the overpressure generated in this incident.[48] The total destruction of the drop box clearly shows that the vent panel on the drop box (Figure 22) was inadequate for venting the overpressure generated.

3.7.2 Explosion Isolation

Explosion isolation typically consists of a pressure sensor connected to a fast-acting valve, designed to close rapidly in the event pressure rises in the dust collector. This was to prevent the explosion from propagating back into the building. However, because aluminum powder explosions are particularly energetic, designing an effective explosion isolation system for aluminum powder is problematic.[49] NFPA 484 (see section 5.1.3) indicates that explosion isolation is not mandatory for aluminum dust applications; however, design guidance is provided for explosion protection in NFPA 68 if an isolation system is used.

A slide valve was installed in the 20-inch line outside the building, upstream of the drop box (Figure 8). The purchase specification for the dust collector installation required an isolation valve with a high temperature activator; however, employees were not aware that this valve was intended to fulfill that requirement. Employees stated they believed this valve was intended to close when the dust collector pulse jets activated (about every 90 seconds). Because of operational problems, the valve actuator was

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[46] Design pressure is the internal pressure that a container is designed to withstand, and is typically significantly lower than the pressure that will cause damage to the container.

[47] NFPA 68. 2002. NFPA 68 was first issued in the 1950s and has been in its current format since 1998.

[48] No samples remained of the dust actually deposited in the dust collector. Coupled with the lack of data on the actual operating conditions for the dust collector, CSB was unable to calculate the theoretical explosion vent area for the dust collector.

[49] Snoeys, 2004

eventually disconnected. Maintenance personnel stated they manually closed the valve whenever they changed filters in the dust collector. CSB concluded that this valve, as observed, did not provide explosion isolation.

Sources[50] have reported that a combination of explosion isolation and suppression (using an inert material to cool and extinguish dust explosions within a vessel or duct) may be effective for protecting against aluminum dust explosions. NFPA 69 (2002b) contains design considerations for suppressing deflagrations, however it does not address the feasibility of such suppression for aluminum dust. Other sources (members of the NFPA-484 committee) have stated that these systems may not be entirely effective due to the high flame speed of aluminum dust. CSB believes further research in this area is warranted in order to improve aluminum dust collector safety.

[50] Going and Snoeys, 2002 and Zalosh, et al. , 2005.

4.0 Previous Incidents

4.1 Incident Investigation Program

Smaller incidents and "near misses" often foreshadow serious accidents. If companies learn from and respond to smaller events, they can prevent more serious incidents. Events occurred throughout the history of the Huntington dry chip system that might have alerted Hayes to the potential for a dust explosion. However, Hayes management was not made aware of, and did not investigate those events.

An effective incident investigation program includes written procedures to ensure that fires, accidents, and "near misses" are reported, documented, evaluated, and addressed, and lessons learned are shared with affected employees.[51] Such a program also includes training for all employees on what constitutes a near miss, and the importance of reporting and investigating these events. CSB believes that an incident investigation program could have led Hayes management to consult guidance for preventing dust explosions available in standards and literature. The following describe some of the events witnesses recounted to CSB investigators.

4.1.1 Duct Fires

The duct fire that occurred several hours before the explosion was, by employee accounts, a frequent event treated with varying degrees of concern. In some cases, employees simply shut down the dry chip feed and fume exhaust systems, and waited for a smoldering fire to go out. According to employees and fire department records, the fire department was called on a few of these occasions. Firefighters would stand by and observe the smoldering material until it burned out. Typically, employees would open and clean the duct after determining the fire was out.

[51] CCPS, *Guidelines for Investigating Chemical Process Incidents,* AIChE, 1992.

These fires illustrate that aluminum dust or other materials in the system were combustible, yet the incidents were not reported to management, or investigated for root causes. Contrary to written statements from Hayes that, employees were trained on an accepted approach to duct fires, each employee CSB interviewed recounted a different approach to handling these fires. Hayes had no record of any of these fire events, including those involving fire department responses.

4.1.2 Dust Flashes

The bright flashes employees saw when the chip feed was started (see footnote31, Section 3.3) were also warnings of aluminum dust's combustible nature, yet employees treated the flashes as "normal". Through interviews, CSB learned that some members of management were aware of the flashes, but these events were not documented, investigated, or addressed.

4.1.3 Smoldering Fire

Perhaps the most serious near-miss incident involved the furnace 5 fume hood. Two employees recalled that on one occasion they discovered a large portion of the fume hood glowing red. They traced the cause to accumulated dust and chips smoldering on top of the hood. They attempted to rake the smoldering debris off the hood. As they disturbed the debris, the two employees dispersed dust into the air, initiating a deflagration. Although both employees related that the incident "shook them up", neither was hurt.

Employees also reported small fires occurring in the roof rafters over the years. The Huntington fire department had records of responding to some of these fires. The fact that Hayes management had no record of—and in some cases was not aware of—these incidents and that they did not investigate them indicates lack of an effective incident recognition and investigation management system.

5.0 Regulatory Analysis

5.1 Fire Codes and Standards

Published fire standards protect the public and property by conveying basic facility safety requirements. Two standards are commonly used in the United States:

- Uniform Fire Code[52], published by NFPA.
- International Fire Code (IFC), published by the International Code Council (ICC).

Both standards address the hazards of combustible dusts. States, localities, and cities typically set minimum fire safety standards by adopting a code or by incorporating one by reference into regulations or administrative requirements.

5.1.1 Combustible Dusts

Both the Uniform Fire Code and IFC have a distinct approach to addressing dust hazards:

- The Uniform Fire Code (UFC) is based on NFPA standards. The standards are in directive language and are highly prescriptive. Several different NFPA standards set out extensive and specific minimum technical measures for managing the hazards of agricultural dusts, powdered metals, coal dust, sawdust, chemical dust, and plastic dust.
- Unlike the extensive hazard coverage in various NFPA standards, IFC contains only a single page on combustible dust. IFC Chapter 13, "Combustible Dust-Producing Operations", contains limited housekeeping and ignition source precautions.

[52] The Uniform Fire Code, also known as NFPA 1 (2003) is a compilation of NFPA fire safety and life safety standards, adopted in its current form in 2003. *The Uniform Fire Code* is a registered trademark of the Western Fire Chiefs Association.

Chapter 13 references various NFPA standards for combustible dust hazards. Instead of mandating compliance with these standards, however, IFC "authorizes" the "code official" (the government authority having jurisdiction) to enforce "applicable provisions" of NFPA standards on a case-by-case basis. IFC promotes enforcement by requiring that a government authority issue an operating permit to facilities that use or generate combustible dust.

5.1.2 Indiana Fire Code History

From 1985 to 2003, the state of Indiana operated under the Indiana Fire Prevention Code, which consisted of various NFPA standards, adopted by reference. The Indiana code contained very limited guidance on combustible dust hazards. In 2003, Indiana adopted the IFC and mandated enforcement of the NFPA standards that are referenced in IFC Chapter 13. The state excluded IFC paragraph 1301.2 (which requires permits for combustible dust-producing operations) when the IFC was adopted. In fact, Indiana does not require fire permits in any chapter of the fire code, except those applying to amusement parks and entertainment centers.

5.1.3 NFPA Metal Dust Codes

NFPA 484, *Standard for Combustible Metals, Metal Powders, and Metal Dusts* (2002c), adopted in 2002, combines several earlier standards on metal dusts, including NFPA 651, and is the current NFPA standard for aluminum powders and dusts. The following activities are among the specific measures recommended in both NFPA 651 and NFPA 484 that were *not* in place at Hayes:

- Daily cleaning of the dry dust collector.
- Weekly inspections of bonding and grounding for dust collection equipment.
- Elimination of unused capped outlets, pockets, or other dead-end spaces that might allow dust accumulations.
- Separation of the dust collector from occupied buildings.

NFPA 654, *Standard for the Prevention of Fire and Dust Explosions From the Manufacturing, Processing, and Handling of Combustible Particulate Solids* (2000), addresses combustible dusts in general industry. This standard—which applies to plastics, rubbers, and other nonmetallic combustible dusts—includes guidelines for housekeeping and management of change (MOC). NFPA 654 (which does not apply to Hayes) contains the following guidance for managing change in processes that handle combustible dust:

> The management of change procedures shall ensure that the following issues are addressed prior to any change:
>
> 1. The technical basis for the proposed change.
> 2. The safety and health implications.
> 3. Whether the change is permanent or temporary.
> 4. Modifications to operating and maintenance procedures.
> 5. Employee training requirements.
> 6. Authorization requirements for the proposed change.

NFPA has recently revised NFPA 484 to include change management and to make the standard easier to navigate. Previously, CSB had found that the way information in NFPA 484 was organized led to confusion on the various recommendations pertaining to aluminum dust versus aluminum powder.[53]

5.1.4 NFPA Standards Applicability for Hayes-Lemmerz

When installing the dust collector system at the Huntington facility, Hayes specified in their purchase order that the system comply with NFPA standards. At that time, the relevant standard was NFPA 651, *Standard for the Machining and Finishing of Aluminum and the Production and Handling of Aluminum Powder*. This standard provided recommendations for preventing fires and explosions involving

[53] Aluminum powder is a manufactured product. Aluminum dust is an undesirable waste material that may be generated by activities in a manufacturing process.

aluminum powder and dusts. It also referenced other NFPA standards that address explosion venting, isolation, and electrical classification. Hayes indicated in their purchase specification for the dust collector project that the "collector must have the necessary explosion doors/vents installed necessary to meet all safety regulations per NFPA, OSHA and the equipment manufacturer." The document also stated that the system was to be designed with "involvement of Hayes Wheels Engineering". However, the project engineer stated in interviews that he had not researched the applicable standards. Further, there is no evidence that Hayes required the system designer to certify that the dust collector met the standards.

5.1.5 Recognized and Generally Accepted Good Engineering Practice

The OSHA Process Safety Management standard (29 CFR 1910.119) and, the EPA Risk Management Program regulation (40 CFR 68)[54] require that facility owners ensure their equipment conforms to Recognized and Generally Accepted Good Engineering Practice (RAGAGEP). NFPA standards are a commonly used RAGAGEP source. Such source documents represent the practices to which a facility owner is often held accountable, through regulatory citation or civil liability, when an accident occurs.[55]

5.1.6 Code Enforcement

Inspections conducted by local fire authorities typically enforce the fire regulations. The Huntington fire inspector reported to CSB that he only recently began to inspect industrial facilities but expected to inspect all industrial facilities in the city about every three years. The focus of these inspections is on fire extinguishers, fire exits, sprinkler systems, and other "life safety" issues. The local fire inspector had not inspected the Hayes Huntington facility prior to this incident.

The Indiana Office of the Fire Marshal has fire inspectors with the authority to inspect any facility except for single- and two-family dwellings. Priorities include schools, hotels, nursing homes, hospitals and

[54] The Hayes facility at Huntington was not covered by either of these cited standards, however, CSB believes these standards to be indicators of the importance of RAGAGEP issues in accident prevention.

[55] Vernon, 2002.

other structures used by the public, but not industrial facilities. By request, the state inspectors assist local authorities with local inspections.

Both state and local officials reported to CSB that inspectors have very little knowledge of combustible dust hazards, and such hazards are not the focus of industrial inspections. While local officials have received periodic training on the IFC, there was no training on the subject of combustible dust.

5.2 Workplace Safety Regulations & Enforcement

Indiana regulates workplace safety through a state plan approved by the federal OSHA. IOSHA enforces federal occupational safety and health standards in Indiana. IOSHA has not promulgated any separate state regulations. IOSHA Industrial Safety Division conducts inspections and issues enforcement citations for general industry.

5.2.1 Federal OSHA Standards Addressing Combustible Dust Hazards

The following OSHA standards address the hazards of combustible dusts:

- 29 CFR 1910.263, Bakery Equipment.
- 29 CFR 1910.265, Sawmills.
- 29 CFR 1910.272, Grain Handling.

29 CFR 1910.272(j)(3) requires that grain-handling facilities implement a written housekeeping program that sets the frequency and methods for controlling dust on exposed surfaces. These facilities must remove dust in priority areas whenever it exceeds 1/8th inch.

In addition, 29 CFR 1910.307, Hazardous (Classified) Locations, defines the requirements for electrical equipment where combustible dusts are present. Certain other OSHA standards address potential ignition sources for combustible dusts. Federal OSHA has adopted certain NFPA standards (which IOSHA enforces), but has not adopted NFPA 651 or 484—which address the hazards of aluminum dusts such as what was found at Hayes. There is no federal safety regulation specifically addressing the prevention of combustible dust explosions in general industry. The broader CSB study on combustible dust hazards addresses this and other similar issues.

5.2.2 IOSHA Action Pertaining to the Incident

Following the October 29, 2003 incident, IOSHA issued citations to Hayes, one of which cited what is commonly referred to as the "general duty clause". This clause, defined in Section 5 of the Occupational Safety and Health Act of 1970 (29 USC 654), requires employers to furnish a place of employment free of recognized hazards. It is independent of other specific OSHA safety and health standards.

IOSHA also cited Hayes for inadequate housekeeping and for violation of the Hazard Communication Standard, because Hayes did not train its employees about the hazards of combustible dust. As part of a settlement agreement with IOSHA following this incident, Hayes agreed to suspend operation of pneumatic conveyance systems for dry aluminum chips. HLI also agreed to suspend similar operations at other subsidiaries. The Huntington plant has agreed to employ different methods of chip reclamation to reduce the possibility of aluminum dust explosions. Hayes also agreed to obtain and use relevant combustible dust standards. Finally, Hayes agreed to engage a dust explosion expert to provide training on explosive dusts and firefighting protocols for such hazards to members of the Huntington Fire Department and employees of IOSHA.

5.2.3 Personal Protective Equipment

OSHA standard 29 CFR 1910.132, General Requirements ("Personal Protective Equipment"), requires employers to evaluate and assess hazards to which its employees may be exposed (including health and physical hazards such as fire and explosion). The standard also requires employers to provide or require appropriate personal protective equipment (PPE).

CSB reviewed the record of the PPE hazard assessment conducted at Huntington. This document only indicates that melt operators exposed to hot surfaces should use flame-retardant jackets ("greens"). The maintenance personnel wore their "greens" during cleanout of the fume duct earlier in the day, however none of the injured employees were wearing flame-retardant work clothing at the time of the incident. The Aluminum Association, Inc. (see section 5.3), advocates such apparel for workers in foundry and casting operations. Likewise, federal OSHA has interpreted the standard[56] to include requiring workers who potentially may be exposed to flash fires to wear flame-retardant clothing.

Laboratory tests have demonstrated that burn injuries are more severe when clothing ignites and that use of flame-retardant clothing can reduce the severity and extent of burns.[57] Historically, the conflicting demands of protecting against flash fire and molten aluminum splashing complicated fabric selection for aluminum foundry workers. However new fibers such as Vinex are reported in literature to protect against flash fire and repel molten aluminum and may provide improved protection for aluminum foundry workers.[58]

Following the October 29, 2003 incident, IOSHA cited Hayes for failing to provide flame-retardant work clothing to maintenance personnel under 29 CFR 1910.132.

5.2.4 Inspection History at Hayes Huntington

Federal OSHA maintains records of IOSHA inspections, that are available through the agency's website.[59] A facility search of this database revealed records of four IOSHA inspections of the Hayes Huntington facility. In at least one case, IOSHA issued citations for serious safety violations; however, these citations did not involve hazardous dust or other issues pertinent to the October 29 incident. There

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[56] OSHA Standard Interpretation 03/27/1998, fire-retardant PPE requirements and PPE hazard assessment.

[57] Dale, et al., Instrumented Mannequin Evaluation of Thermal Protective Clothing, *Performance of Protective Clothing, Fourth Ed.,* 1992.

[58] CSB does not promote or recommend a specific fiber or apparel. Vinex is a registered trademark of Westex, Inc., Chicago, Illinois.

[59] http://www.osha.gov/pls/imis/establishment.html

were no citations regarding combustible dusts or housekeeping, nor were there any citations pertaining to the scrap-processing system.

5.3 Industry Guidelines

Hayes is a member of the North American Die Casting Association (NADCA). NADCA provides safety literature for members, but has not published guidelines for handling aluminum dust or chips. However, The Aluminum Association, Inc.[60] publishes guidelines on safe handling of aluminum scrap and dusts. These include:

- *Guidelines for Handling Aluminum Fines Generated During Various Aluminum Fabricating Operations*, Publication F1 (2000).
- *Recommendations for Storage and Handling of Aluminum Powders and Paste*, Publication TR-2 (1990).

[60] Hayes is not a member of the Aluminum Association, however the Association lists similar casting companies among its membership.

These publications are available to the public for a nominal fee, and include guidance on design and operation of systems that involve aluminum dust and powders. Specific recommendations address:

- Adherence to referenced NFPA standards for aluminum dust.
- Constructing ductwork and dust collectors using non-sparking metal.
- Daily removal of dust from dust collectors.
- Control over ignition sources, including smoking and welding.[61]
- Bonding and grounding of equipment and containers.
- Housekeeping to minimize dust accumulation
- Use of flame-retardant work clothing.

5.3.1 Risk Insurance Provider Inspections

Hayes management stated that various providers of risk insurance inspected the Huntington facility annually. These inspections typically addressed fire equipment; however, Hayes personnel stated that insurance carriers never identified aluminum dust hazards as an issue of concern. CSB reviewed the carriers' Property Conservation Reports dating from September 1997 through April 2003. These reports identified a fire and explosion of a propane storage tank as the worst-case loss scenario. None of the insurance carrier reports contained any reference to the dust collection system or housekeeping practices in the chip-processing area. One carrier recognized the chip-processing system in its May 2000 summary of the facility occupancy and use. However, the report said:

> "… 95 to 98 percent of the chips are not powder-sized, which relieves suspicion about the potential for an explosive powder."

[61] Prior IOSHA citations addressed hot work permitting. CSB observed employees on several occasions walking through many areas of the facility carrying lit cigarettes.

Considering that Premelt designed the system for a dry chip flow of 3,500 pounds per hour, 2 percent powder-sized material would equate to about 70 pounds of dust per hour in the dry chip flow. Using the CSB estimate of the actual dust flow (25 pounds per hour), the dust collector system could be handling more than 600 pounds of dust per day. CSB further estimated that enough aluminum (about a third of a pound) to be explosive if lofted, could collect in the dust collector in less than a minute.

The preceding calculation demonstrates that the quantity of dust being handled was sufficient to make explosions in the dust collector a very credible concern, therefore the insurance carrier's assertion about the potential for an explosive powder was erroneous.

CSB investigators compared findings from this incident investigation with other concurrent CSB dust explosion investigations (the West Pharmaceutical Services polyethylene powder explosion in January 2003 and the CTA Acoustics phenolic resin dust explosion in February 2003). Insurance carrier audits also failed to raise the issue of combustible dust explosion hazards in those cases. These circumstantial findings suggest the need to instill greater awareness of these hazards in the risk insurance community. While it is not the responsibility of insurance carriers to ensure prevention programs are carried out at clients' facilities, those companies typically inspect the facilities on an annual basis. An inspector who is knowledgeable about combustible dust hazards could recognize and inform facility management of potential risks.

5.3.2 CSB Combustible Dust Hazard Study

During the course of this and other investigations, CSB identified gaps, on a national level, in the current understanding of dust explosion risks and shortcomings in approaches for prevention of explosions. CSB commissioned a comprehensive study to define the nature and scope of dust explosion risks in industry and identify initiatives to prevent dust fires and explosions. Such initiatives may include regulatory action, better voluntary consensus standards, or other measures that industry, labor, government, and other parties could take.

6.0 Management Systems

6.1 Overview of Management Systems

Management systems include policies, procedures, work instructions, records, and other activities critical to accomplishing management objectives. Such systems are a key component of good management practices and chemical process safety.[62]

Hayes management was familiar with management system concepts and design. As an original equipment supplier for major automotive manufacturers, Hayes obtained certification that it met the requirements of QS-9001, the product quality standard for the automotive industry. CSB understands the purpose and scope of QS-9001 and acknowledges that it has no direct bearing on this incident. By mentioning it in this report, CSB intends to demonstrate that Hayes management and staff, throughout the organization, have a clear understanding of management systems. However, management personnel stated that these requirements were applied only to systems that directly affected the quality of final products. Support systems such as scrap processing were not subject to the quality standards. Therefore, the management systems and written procedures in place to ensure quality wheels were not applied to chip processing system.

6.2 Management of Change

MOC is one key element of effective management systems. The intent of MOC is to assess and control the effects of process changes on safety and product quality and other critical aspects of facility performance. Hayes had an MOC procedure as part of its QS-9001 quality assurance program, but did not apply it to changes in the chip-processing system or other systems that did not directly affect product quality. The chip handling and dust collector projects should have been subject to an MOC review that includes looking at engineering calculations and documents to determine if they met applicable safety,

[62] CCPS, *Technical Management of Chemical Process Safety,* 1989

fire, and engineering codes and standards. Hayes specified that the installer meet NFPA requirements, but did not take an active review role in ensuring the requirements of the codes and standards were met.

The existence of MOC guidance in NFPA 654 and inclusion as a key element in widely used industry quality standards (such as QS-9001) indicates that industry recognizes the value of managing change.

6.3 Hazard Evaluation

Premelt Systems, Inc., which specializes in scrap melting systems designed and supplied the wet and dry chip-processing systems. According to the designer, the systems are based on a design used for over 40 years with few modifications. Hayes modified the chip-melting system by adding the dust collector to the system, and produced no documents indicating that they performed any formal, comprehensive hazard evaluation.

A hazard review of the scrap system might have revealed significant hazards, especially if the review was repeated after the system was operating. In such a review, experienced employees with hands-on knowledge can discuss the difficulties inherent in operating and maintaining a system—which provides an opportunity to recount past incidents, such as those at the Huntington facility mentioned earlier in this report. NFPA 484, Annex A[63], which is available today, provides guidance on performing hazard evaluation of processes that produce aluminum dust (NFPA, 2002c).

6.4 Engineering Project Controls

Hayes management stated they had a formal engineering control and approval process with various levels of review. It was applied only to "major capital projects" and incorporated only an informal review of safety issues. Expense projects, maintenance modifications, projects that did not require capital funding,

[63] NFPA states that the Annex is explanatory material for informational purposes.

and projects that did not affect the quality of the finished product—including the chip-melting and dust collector installation projects—were not subject to an extensive internal engineering review.

Hayes relied on the chip system supplier, an outside engineering firm, and the dust collector manufacturer's representative to provide the necessary engineering expertise for designing and installing the chip-processing and dust collector systems. Premelt has provided chip-processing systems for decades and remains a leading company in this field. Hayes assigned engineers to coordinate the installations; however, these individuals (by their own admission) did not have the depth of knowledge necessary to fully understand chip-processing and dust collection systems. Since Hayes did not retain any engineering documentation for the dust collector project, it is unclear if any engineer with dust collection expertise performed a review. Such an engineer would likely have known the hazards of combustible dust collection and been familiar with the applicable NFPA standards.

6.5 Procedures and Training

Hayes had written procedures for operating the chip-processing and dust collector systems. Hayes did not conduct formal training for employees on operating these systems. When the systems were first put in service, certain individuals were made familiar with the systems. Knowledge of how the systems were intended to function deteriorated as the information was passed informally through various personnel changeovers. Methods of responding to non-routine situations varied from person to person. Employees did not refer to the written procedures, and some were unaware that the procedures existed. No one recorded critical systems operating parameters (pressures, flow rates, temperatures, etc.) and there were no written emergency operating procedures.

The lack of formal training for the chip and dust collection systems' operators and maintenance personnel led to acceptance of abnormal conditions—the "normalization of deviations,"[64] such as flashes during

[64] Vaughn, 1996

chip feed startup and fires in the fume exhaust ducts. When the systems were installed, personal involvement by the project engineer ensured proper operation, such as maintaining a balance between the dust collector air flow and the chip transfer air flow (see section 1.6.3). Over the years, the knowledge of process controls was lost as this engineer left the company, and employees changed assignments. Likewise, employees no longer understood the importance of dust collector cleaning and maintenance of good airflow through the system.

6.6 Corporate Best Practices

Hayes had an established program of hosting "best practice" meetings within various divisions of its North American facilities. These meetings addressed a variety of production, quality, and maintenance issues, and provided opportunities for sharing lessons learned. Although Hayes had chip-melting systems in use at three facilities, none had held best practice meetings to discuss these systems.

Through the implementation of quality programs such as QS-9001, industry has learned that — to be effective—management systems (even informal ones) require a degree of structure. This systematic approach to management systems is one of the eight basic principles of the ISO 9001 program.[65] The Hayes best practice meeting program was informal, not defined in a written procedure, and had no accountability process in place to ensure the uniform implementation of best practices. Further, there were no written records kept of the lessons shared at those meetings.

[65] http://www.iso.org/iso/en/iso9000-14000/iso9000/qmp.html

7.0 Key Findings

CSB makes the following key findings in this investigation.

1. Aluminum dust sampled from various areas in the chip system was proven, through standard testing protocols, to be explosive.

2. Metal dusts, particularly aluminum, present a significant explosion hazard.

3. The explosion that occurred on October 29, 2003 was likely the result of a dust explosion in the dust collector system for the aluminum scrap processing area.

4. The damage patterns, employee statements, and analysis indicate that ignition of the lofted dust occurred in the dust collector.

5. A single explosion, likely originating in the dust collector, caused the deflagration that erupted around the furnace 5 sidewell and injured the three Hayes maintenance personnel (one fatally).

6. A secondary deflagration of dust accumulated on overhead surfaces caused the pressure wave and fireball that damaged the building roof.

7. The process of transporting and drying aluminum chips results in the production of fine particles of aluminum, which can be explosive.

8. Inadequate housekeeping in the foundry area and insufficient maintenance of the chip feed ducts lead to the dust accumulation that fueled the secondary deflagration.

9. Infrequent cleaning of the dust collector filters likely contributed to the size of the explosion outside and the extent of dust collector system and chip system damage.

10. The dust collector was not separated from the foundry building and personnel (including the trailer used by the stack-testing contractor) by at least 50 feet, as recommended in NFPA 484. This lack of separation increased the risk of injury to personnel in the event the dust collector exploded.

11. Explosion protection in the dust collector and drop box was not adequate for existing conditions.

12. There was no explosion isolation device installed to prevent deflagrations from traveling through ducts back into the foundry building.

13. Additional research is needed in the area of explosion protection (venting, isolation and suppression) for aluminum dust collector applications.

14. The kiln dryer was a significant source of aluminum dust.

15. High velocity pneumatic transfer of dry chips resulted in frequent duct leaks caused by erosion. These leaks resulted in accumulations of chips and dust throughout the furnace 5 area.

16. Previous incidents involving fires and deflagrations in the scrap processing area were not reported by employees, or investigated by management. Corrective action to prevent recurrence of these incidents was not implemented.

17. Maintenance personnel in the foundry area were not wearing flame retardant work clothing at the time of the explosion.

18. Hayes did not ensure that NFPA requirements as set forth in its purchase specifications were applied in the design and installation of the dust collector system.

19. Formal written maintenance procedures and employee training were not in place to ensure proper maintenance of the scrap processing and dust collection systems.

20. Fire inspectors in Indiana have not been trained on recognizing or preventing combustible dust hazards.

21. There is no existing OSHA regulation pertaining to metal dust explosion prevention.

22. Prior inspections by Indiana OSHA did not identify dust accumulations as hazardous.

8.0 Root and Contributing Causes

8.1 Root Causes

1. Hayes did not perform a review to address why the chip system was releasing excess dust. The hazards of aluminum dust were neither identified nor addressed.

2. Hayes did not use a management-of-change review to ensure the proper design of the dust collector system.

3. Hayes did not ensure that NFPA 651 guidance for dust collector location and explosion protection were applied.

4. Hayes had no formal, documented program to investigate and implement corrective action for incidents involving fires in the foundry area, especially those fueled by aluminum dust.

8.2 Contributing Causes

1. Hayes did not require maintenance personnel, who were potentially exposed to flash fires, to wear flame-retardant work clothing when performing routine activities.

2. Maintenance and housekeeping in the chip-processing area were inadequate, leading to significant flammable dust accumulations that contributed to secondary deflagrations at furnace no. 5.

3. Hayes did not implement a formal training program for personnel involved in operating and maintaining the chip-processing system and dust collector system.

4. Hayes did not ensure adequate cleaning and maintenance for the dust collector system.

9.0 Recommendations

Hayes Lemmerz International, Huntington, Indiana (Hayes)

1. Develop and implement a means of handling and processing aluminum chips that minimizes the risk of dust explosions. (2004-01-I-IN-R1) Refer to:

    - The Aluminum Association Pamphlet F-1, *Guidelines for Handling Aluminum Fines Generated During Various Aluminum Fabricating Operations.*

    - NFPA 484, *Standard for Combustible Metals, Metal Powders, and Metal Dusts.*

2. Implement a program to provide regular training for all facility employees on the fire and explosion hazards of aluminum dust. (2004-01-I-IN-R2)

3. Develop and implement policies and procedures for conducting engineering, hazard, and management of change (MOC) reviews of plant projects and modifications to support systems such as chip processing. In particular, ensure that a hazard analysis is conducted during the design phase, as well as during the engineering and construction phases, and when changes are made to the system. (2004-01-I-IN-R3)

4. Implement a program to conduct management reviews of incidents and near-miss incidents, including duct fires and dust flashes. Apply this program to all plant areas, including support areas such as chip processing. Address the root causes of the incidents and near-misses and implement and track corrective measures. (2004-01-I-IN-R4)

5. Develop and implement written operating procedures for chip processing and train all affected employees. Ensure that procedures address maintenance and housekeeping. (2004-01-I-IN-R5)

Hayes-Lemmerz International (HLI)

1. Conduct regular audits of all North American facilities that produce, process, or handle aluminum chips or dust, in light of the findings of this report. Emphasize engineering, hazard, and MOC reviews and compliance with NFPA-484. (2004-01-I-IN-R6) Ensure that:

    - Audits are documented and contain findings and recommendations,
    - Audit findings are shared with the work force at the facility.
    - Audit recommendations are tracked and implemented.

2. Communicate the findings and recommendations of this report to the work force at Hayes and other HLI facilities with similar operations. (2004-01-I-IN-R7)

Premelt Systems

Communicate the findings and recommendations of this investigation to owners/operators of facilities to which Premelt supplies similar aluminum chip-melting systems. Include in your communication specific information that the chip drying process liberates small particles of aluminum, and that such particles may be explosive. (2004-01-I-IN-R8)

Indiana Occupational Safety and Health Administration

Develop and distribute an educational bulletin on the prevention of metal dust explosions.
(2004-01-I-IN-R9)

Indiana Department of Homeland Security

Provide training for fire inspectors in Indiana jurisdictions on the recognition and prevention of aluminum dust explosion hazards. (2004-01-I-IN-R10)

Fire Protection Research Foundation

Conduct research into the feasibility and design of improved explosion protection for aluminum dust collector applications, including explosion venting, isolation and suppression systems. Coordinate this research activity with the Aluminum Association, Inc. (2004-01-I-IN-R11)

Aluminum Association, Inc.

Conduct research into the feasibility and design of improved explosion protection for aluminum dust collector applications, including explosion venting, isolation and suppression systems. Coordinate this research activity with the Fire Protection Research Foundation. (2004-01-I-IN-R12)

9.1 Recommendations to Communicate the Findings From the Investigation

In an effort to widely distribute lessons learned from investigations, CSB recommends that organizations communicate relevant findings and recommendations to their memberships. CSB intends for those organizations to use multiple avenues to communicate, such as having presentations at conferences, placing summaries of reports and links to full CSB reports on their websites, developing and holding training sessions that highlight report findings, and summarizing relevant findings in newsletters or direct mailings to members. CSB encourages the organizations to use all their existing methods of communication and explore new ways to more widely distribute these messages.

The Aluminum Association, Inc.

Communicate the findings and recommendations of this report to your members (2004-01-I-IN-R13):

Risk Insurance Management Society, Inc.

Communicate the findings and recommendations of this report to your members (2004-01-I-IN-R14):

North American Die Casting Association

Communicate the findings and recommendations of this report to your members (2004-01-I-IN-R15)

International Union, United Automobile, Aerospace and Agricultural Implement Workers of America (UAW)

Communicate the findings and recommendations of this report to your membership who work in facilities with similar combustible dust hazards. (2004-01-I-IN-R16)

United Steelworkers of America (USWA)

Communicate the findings and recommendations of this report to your membership who work in facilities with similar combustible dust hazards. (2004-01-I-IN-R17)

National Association of State Fire Marshals

Communicate findings, recommendations and sections applicable to fire codes and standards to your membership. (2004-01-I-IN-R18)

National Fire Protection Association

Communicate findings, recommendations and sections applicable to fire codes and standards to your membership. (2004-01-I-IN-R19)

International Code Council

Communicate findings, recommendations and sections applicable to fire codes and standards to your membership. (2004-01-I-IN-R20)

By the

U.S. Chemical Safety and Hazard Investigation Board

Carolyn W. Merritt

Chair

John S. Bresland

Member

Gary L. Visscher

Member

September 27, 2005

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Appendix A

APPENDIX A: Analytical Results

Appendix A

Analytical Results

1.0 Background

CSB contracted with Safety Consulting Engineers, Inc. (SCE) to test samples aluminum chips and dust collected from the Hayes Lemmerz incident site. The objective of the testing was to determine explosion and ignition characteristics of the dusts found in the CSB samples. The results of this testing enabled CSB to identify aluminum dust associated with the chip melting process as the fuel for the October 29, 2003 explosion, and to evaluate possible ignition sources.

1.1 Safety Consulting Engineers, Inc.

SCE is an independent testing laboratory and consulting firm located in Schaumburg, Illinois[66]. The SCE laboratory is equipped to perform chemical analysis, explosivity testing, electrostatic measurements and other tests of combustible dusts according to methods established by the American Society for Testing and Materials (ASTM).

1.2 Samples

CSB collected many samples of dust and chips that were deposited in the portion of the foundry area involved in the incident, on ledges, the tops of equipment, the floor and on other horizontal surfaces. A total of 16 samples were sent to SCE for testing. Ultimately, only those samples that CSB estimated to most resemble the material in the dust collector were tested.

[66] http://www.sceinc.com

2.0 Testing

2.1 Test methods

SCE performed the following tests. Please refer to the corresponding ASTM standard test methods[67] for details on the methods and equipment used.

- Micrographic analysis at 100x magnification.
- Particle size analysis (ASTM D1921-96)
- Dust explosion severity (ASTM E1226-00)
- Electrostatic chargeability (not an ASTM test method)
- Volume resistivity (ASTM D257-99)

2.2 Test Results

2.2.1 Micrographic Analysis

A small quantity of each of the16 samples was viewed at 100x magnification under a microscope. In general, the samples appeared to be flakes and strips of aluminum, with fine, to very fine particles included. The shape of the aluminum particles under magnification is important; experiments have shown that aluminum flakes tend to produce a lower explosivity than spherical particles.[68] Nearly all the samples included a small fraction of what appeared to be plastic particles of varying shapes and sizes. This finding is consistent with the fact that some of the wheels produced at Hayes are machined after they are coated with clear or opaque acrylic powder coating.

[67] ASTM test standards are available at http://www.astm.org.
[68] Eapen (2003)

2.2.2 Particle Size Analysis

This test was conducted according to ASTM D1921-96, "*Standard Test Methods for Particle Size (Sieve Analysis) of Plastic Materials.* Selected samples containing aluminum chips and dust were passed through various sieve sizes and weighed to determine the weight fraction, as a percent of the total sample weight, of material retained in each sieve.

The resulting particle size distribution is given in Table 1.

Table 1. Results of particle size distribution analysis

Sieve Mesh Size (mesh #)*	**Sieve opening (µm)**	**Percentage retained** Sample A**	**Percentage retained** Sample B**
8	2360	81.31	49.66
50	300	17.83	10.86
100	150	0.14	9.22
Remainder (-100 mesh)	<150	0.72	30.26

*Larger mesh size corresponds to a smaller particle size that can pass through the sieve.
**Material either passes through a sieve or is retained above it. Retained material, therefore, is of larger particle sizes than the openings in the sieve mesh.

Sample A was collected from inside the dry chip hopper. Investigators observed that this sample was predominantly chips with very little dust evident. Sample B was collected from the duct leading to the drop box from the furnace 5 feed cyclone. As was expected, this sample had a higher percentage of smaller particles.

2.2.3 Dust Explosion Severity

The explosion severity test was performed according to ASTM E1226-00, "*Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts*". The material was tested in a standard 20-liter chamber. The objective of the testing was to determine:

- P_{max}: the maximum absolute pressure inside the vessel at the time of ignition reached during the course of a deflagration for the optimum concentration of the dust tested.

- $(dP/dt)_{max}$: the maximum rate of pressure increase per unit time reached for the optimum concentration of dust tested.

- K_{St}: the deflagration index, calculated as follows:

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

  Where V is the volume of the test vessel in m^3

Various samples of dust were placed in into the test chamber, lofted by air pulse and ignited by electrical arc. Pressure is measured over time to calculate the deflagration constant.

The results of the testing are given in Table 2.

Table 2. Explosion severity test results

Sample	**Dust concentration tested** (g/m^3)	**Pmax** (psi)	**(dp/dt)max** (psi/sec)	**Kst (max)** (bar-m/sec)
A	500	126	3150	59
B	250	123	3600	
B	500	125	4770	
B	750	155	7000	131
B	1000	152	5940	
C	500	143	6510	122
D	500	134	5355	101
Lycopodium (reference material)	500	121	7360	134

2.2.4 Electrostatic Chargeability

No ASTM test method was available for this analysis. The procedure was as follows: Dusts were poured through a funnel into a stainless steel inclined chute. The dusts fell into a metal pail on an electrically isolated table, and connected to an electrometer by a static detecting head. The static charge generated by the movement of dust down the steel chute was then measured.

Table 3. Electrostatic Chargeability Results

Sample	Charge per mass μC/m^2	Char per Volume μC/m^3	Streaming Current μC/sec
E (Outside the drop box)	0.85	30.57	0.002
F (Chip feed)	0.220	136.48	0.026

Measurable static charge was generated on the sieved material. Whether this would be sufficient ignite a dust cloud depends upon the minimum ignition energy of the dust cloud and the rate at which the charge dissipates from the material.

2.2.5 Volume and Surface Resistivity and Charge Relaxation Time

Resistivity is a measure of a material's ability to hold a static charge. The greater the resistivity, the more likely that a material will accumulate and retain sufficient charge to ignite a flammable mixture. Tests for volume resistivity were conducted according to ASTM D257-99, "*Standard Test Method for D-C Resistance or Conductance of Insulation Materials."*

Charge relaxation time is the time required for the voltage to drop to about 37 % of the initial value. This, too, is a measure of the material's ability to hold a static charge.

The resistivity tests are performed by placing the material to be tested between electrodes, applying a known voltage to the electrodes, and measuring the current passing through the material.

Eight samples were sieved to 100 mesh (150 μm) and tested. The results were as follows:

- Volume resistivity ranged from 1.7 x 10^{12} ohm-cm to 1.5 x 10^{14} ohm-cm.

- Surface resistivity ranged from 1.2 x 10^{13} to 6.4 x 10^{13} ohm.

- Charge relaxation time ranged from less than 1 second (for 6 of the 8 samples) to more than 2 minutes for two of the samples. The latter two samples were taken from the dust duct and from within the chip dryer.

Material with charge resistivity greater than 1 x 10^6 ohm is considered electrically insulative[69]. The conclusion drawn from these results is that the dust in the dust collector at Hayes could possibly have accumulated and retained sufficient charge to ignite a dust cloud, provided that the dust collector and internal components were not well grounded.

[69] Pratt (1997)

Appendix B

APPENDIX B: Initiating Event Analysis

Appendix B

Investigative Analysis

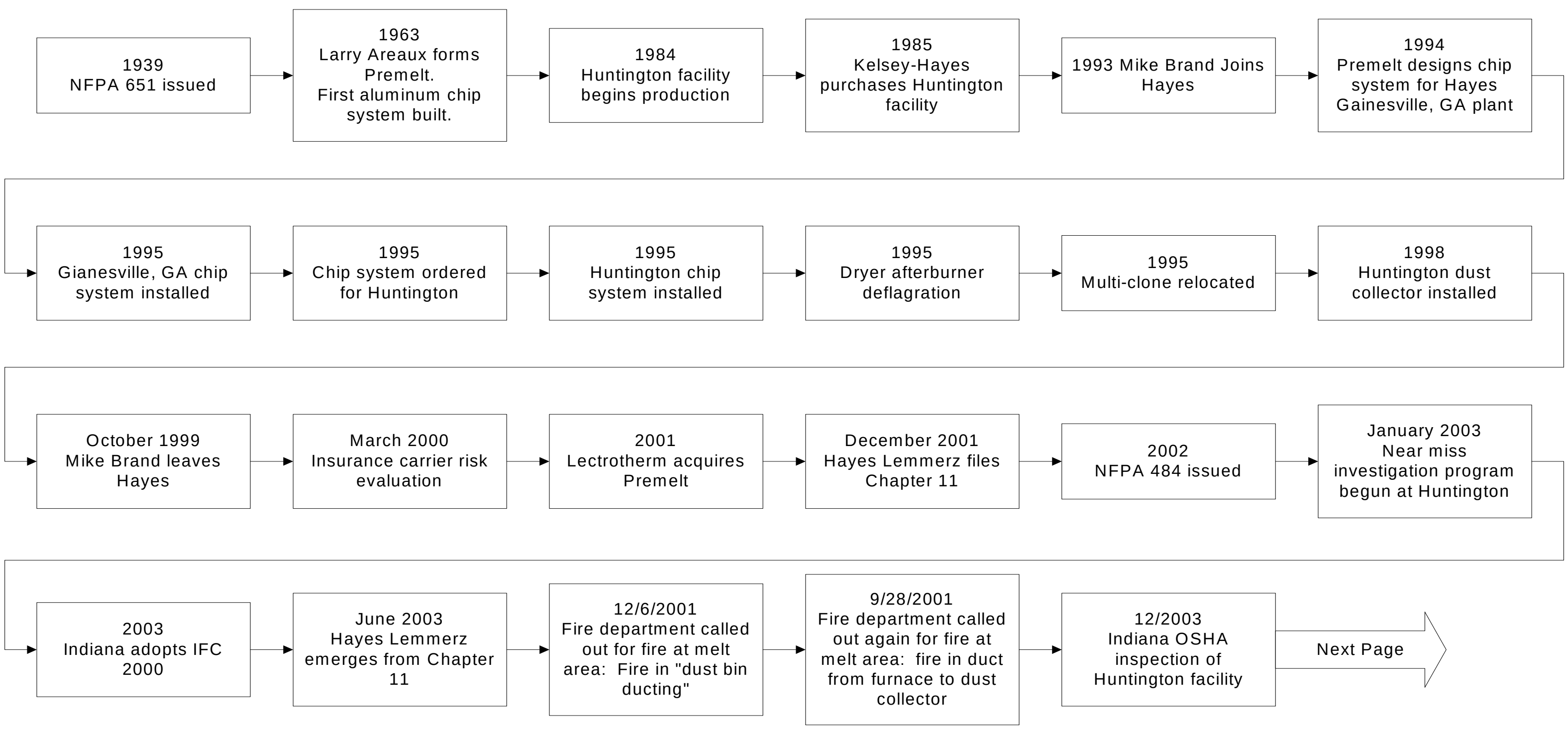
CSB used structured brainstorming and analytical tools, that included constructing an incident timeline and fault tree analysis techniques, to organize the evidence and evaluate possible scenarios. The results of this analysis are presented here.

1.0 Timeline

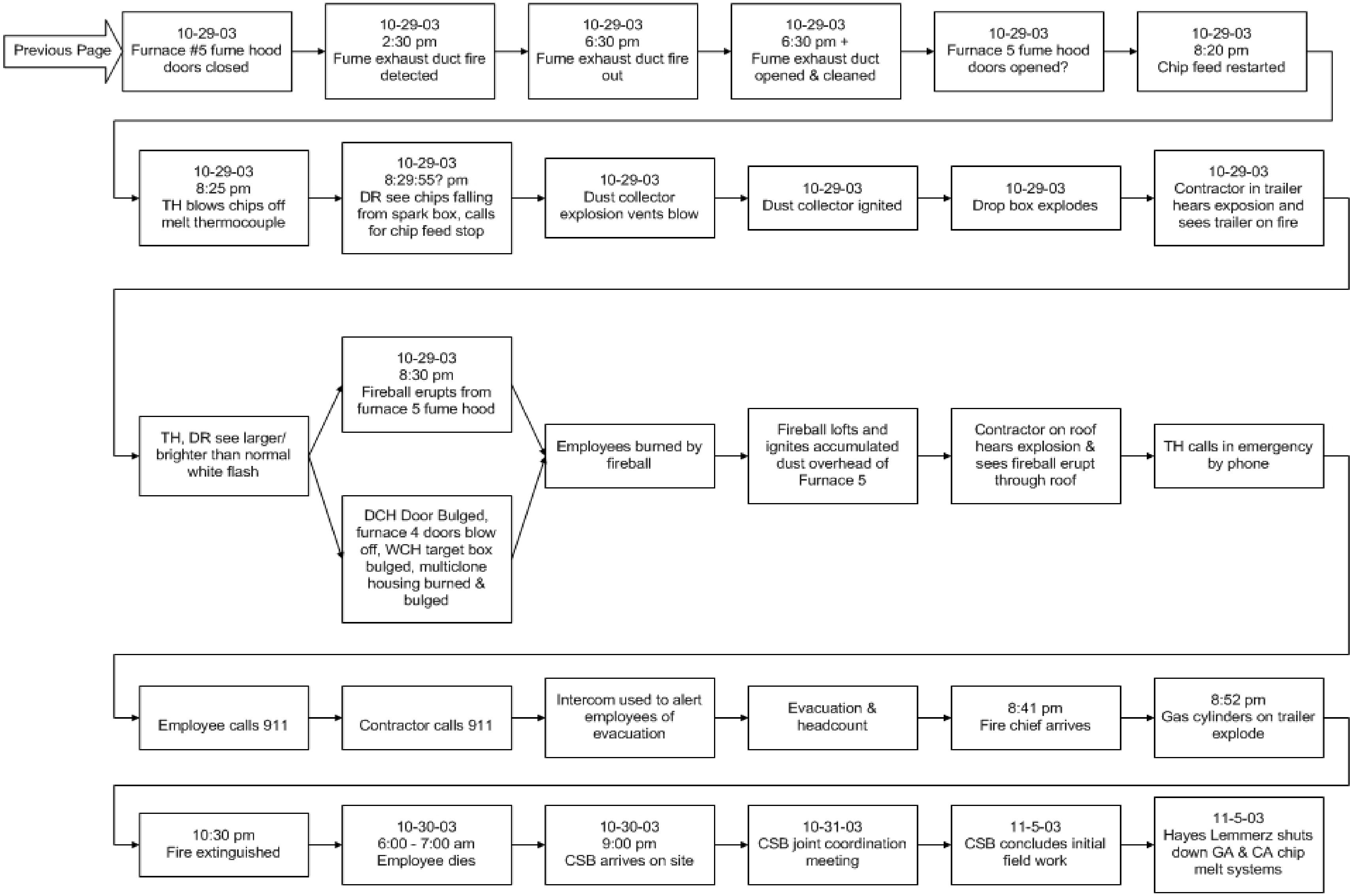
A timeline is a graphical tool that is particularly useful in organizing the facts of an event into sequential order. Facts obtained through interviews, observations, photography and other means are placed on a diagram in the relative order in which they occurred. CSB developed an incident timeline based on fire department records, witness statements and call records obtained from the emergency dispatcher. If the actual or approximate time of an event is known from the evidence, it is listed with the event description.

Hayes Lemmerz Timeline

Historical Events



Incident Timeline

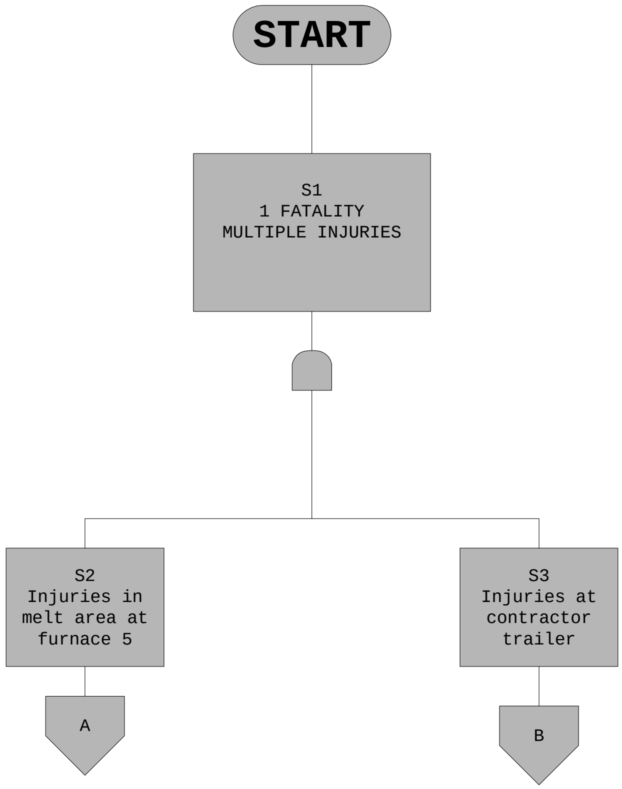


3.0 Fault Tree Analysis

CSB investigators constructed a fault tree to analyze the incident for possible causes. A fault tree is a top-down, logic-driven technique for postulating all possible causes of an event. The team begins with the top level event and develops possible causes for that event. Each of those causes is, in turn, treated as an event for which causes are proposed. The tree development continues in this manner until a root cause or basic event is reached for which there is no further development within the scope of the investigation.

The fault tree is constructed using "AND gates" and "OR gates." If there are two or more conditions that must exist in order for an event to occur, the event and the conditions are connected by an "AND gate." An "OR gate" is used when any one or more of a number of conditions listed could lead to the event, but it is not necessary for ALL conditions to be present.

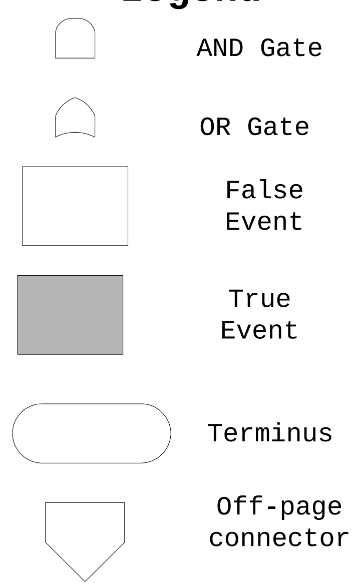
Once the tree is constructed, the team analyzes the branches of the tree and rules out (marks as false) any branches that are contradictory to the available evidence.

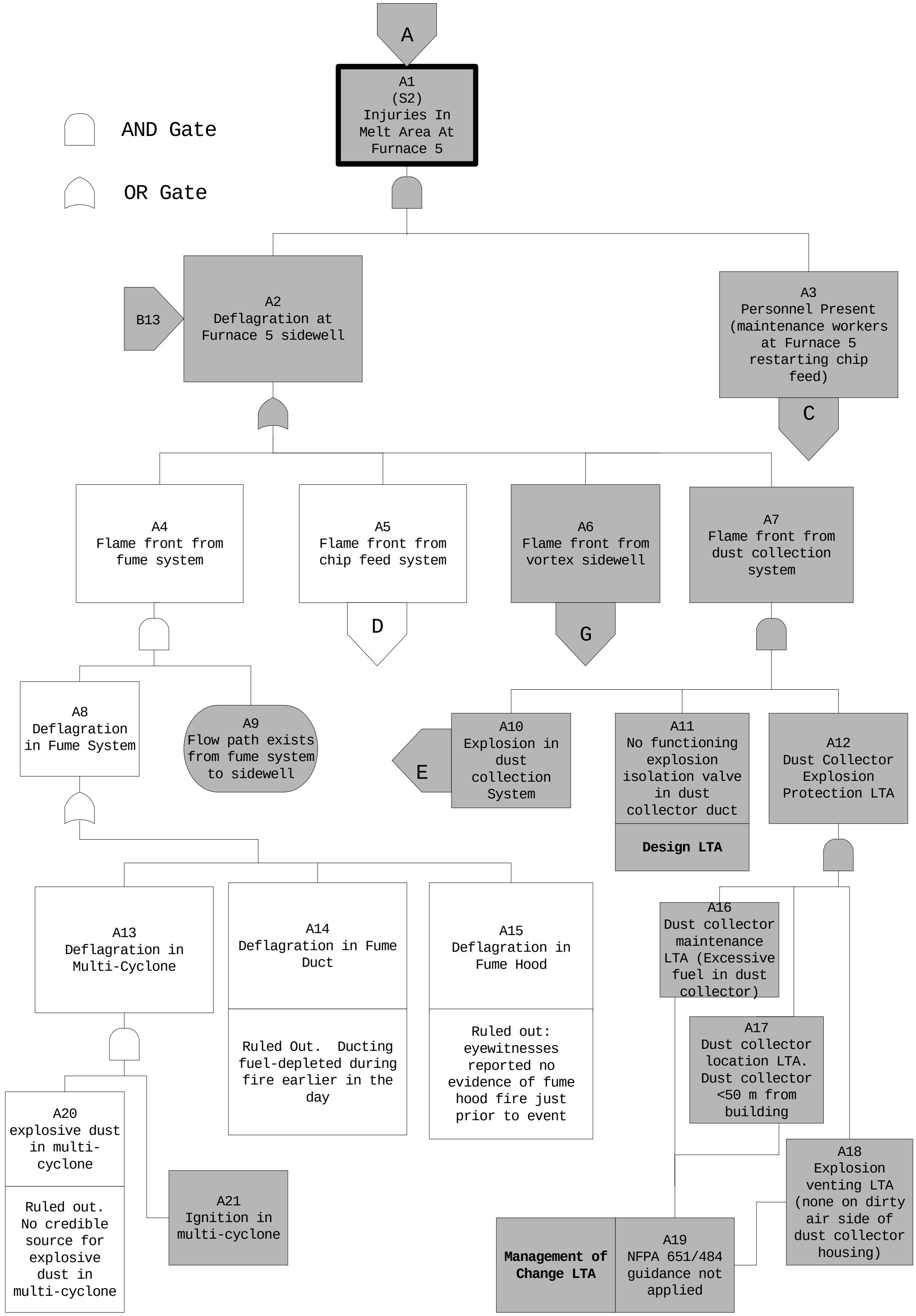


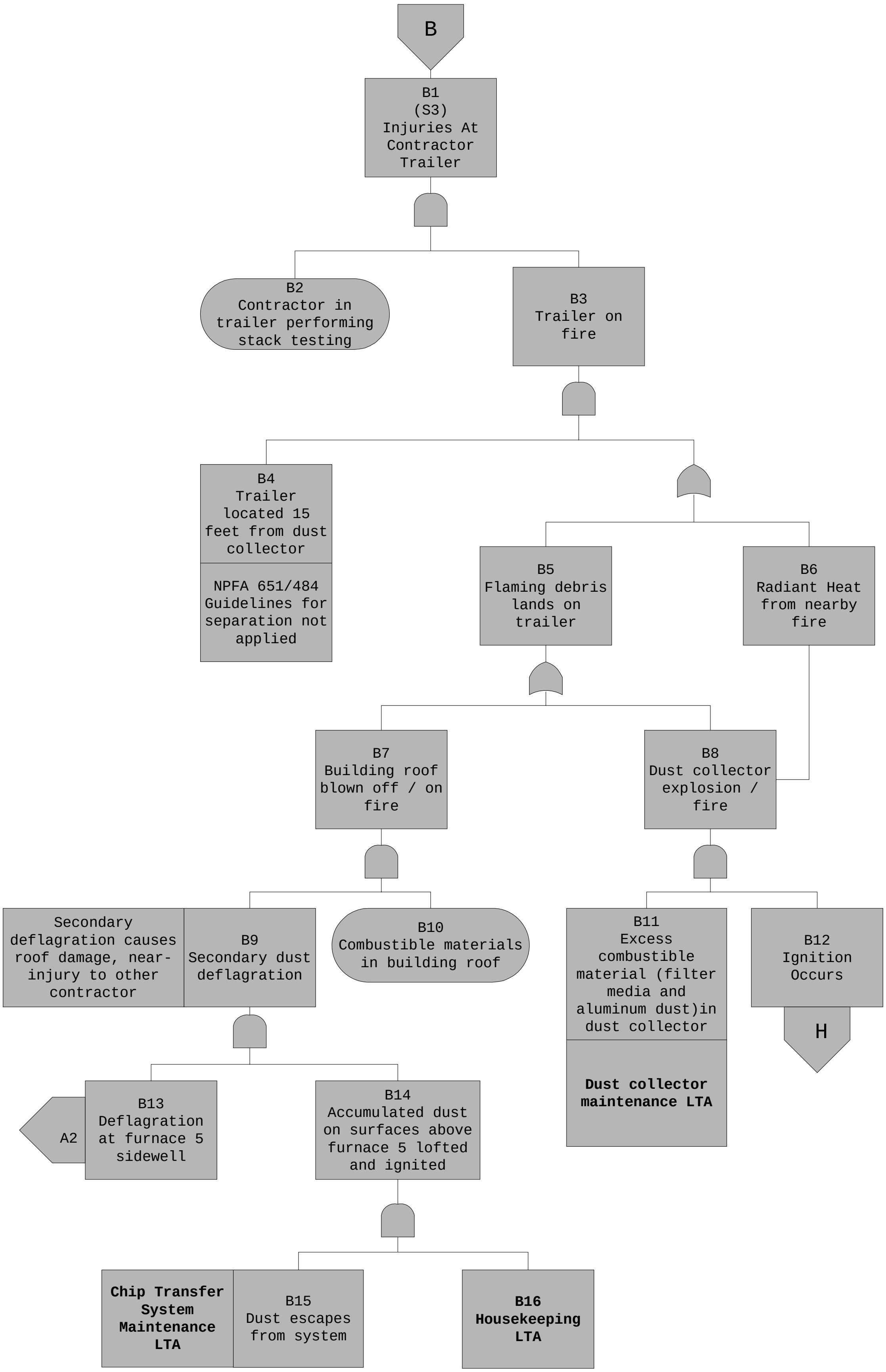
Index

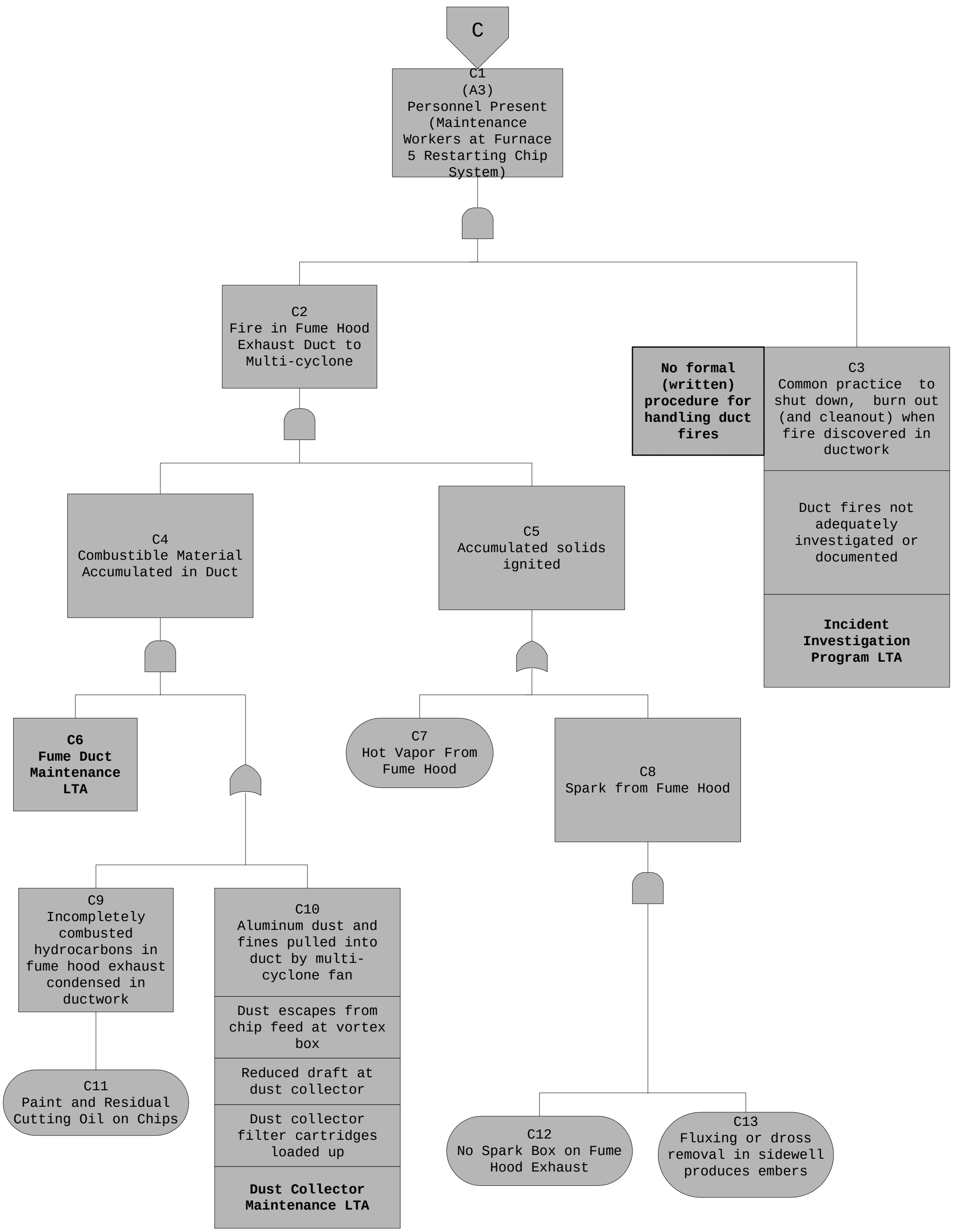
Page	Index	Event
1	Start	1 Fatality, Multiple Injuries
2	A	Injuries in melt area at furnace 5
3	B	Injuries at contractor trailer
4	C	Maintenance workers restarting chip system
5	D	Flame Front from Chip Feed System
6	E	Explosion in Dust Collector System
7	F	Explosion Originated in Drop Box
8	G	Flame Front from Vortex Sidewell
9	H	Ignition Occurs

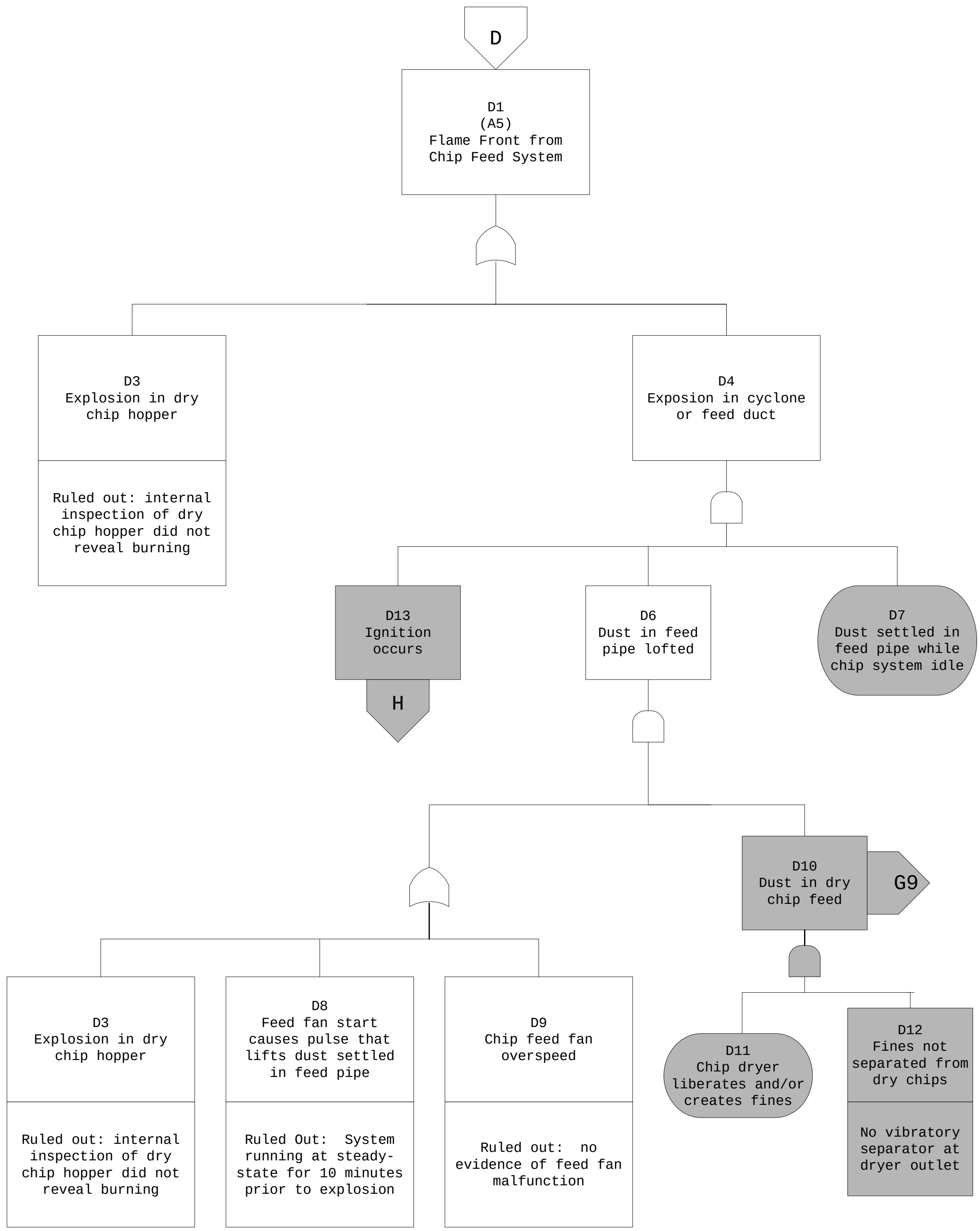
Legend

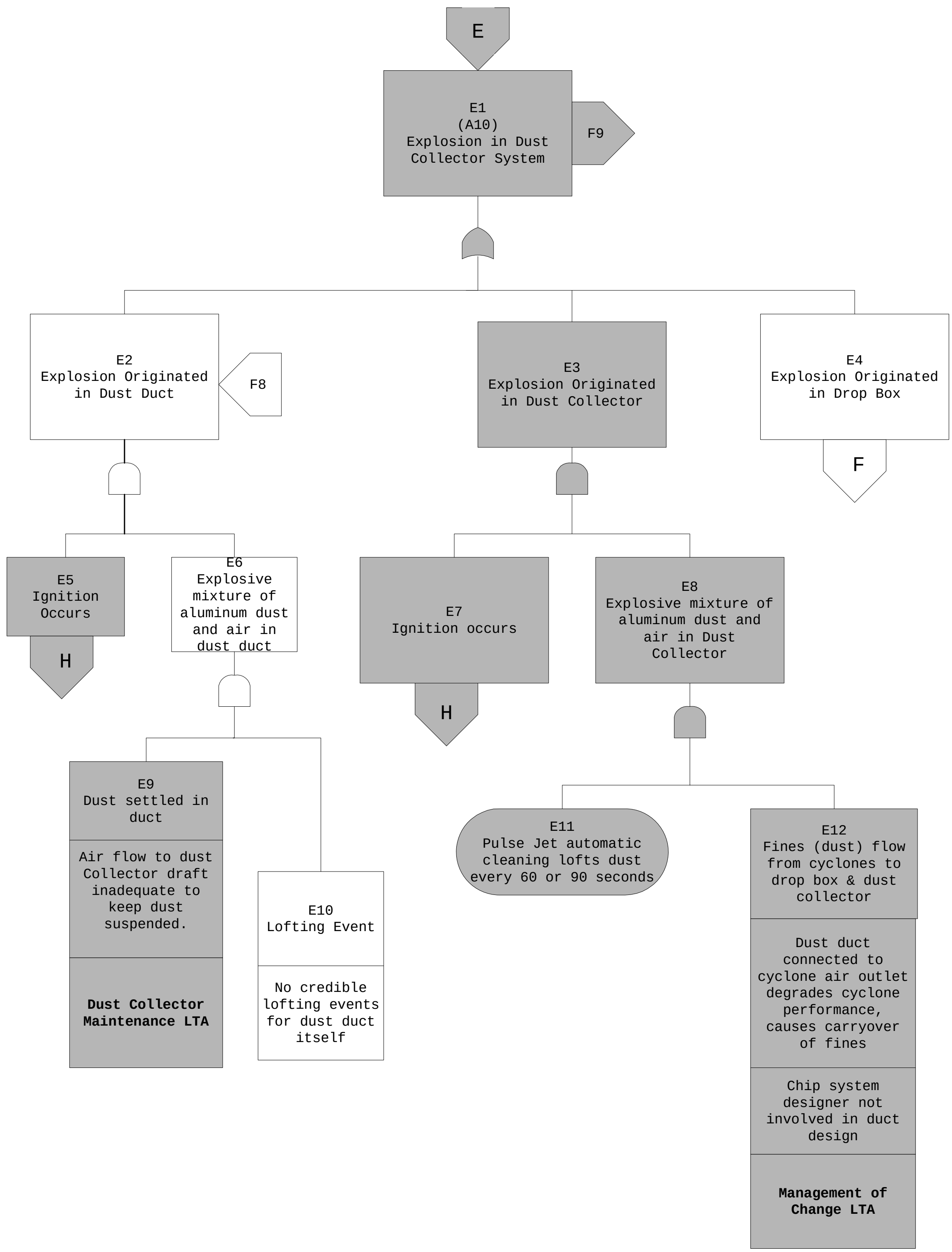


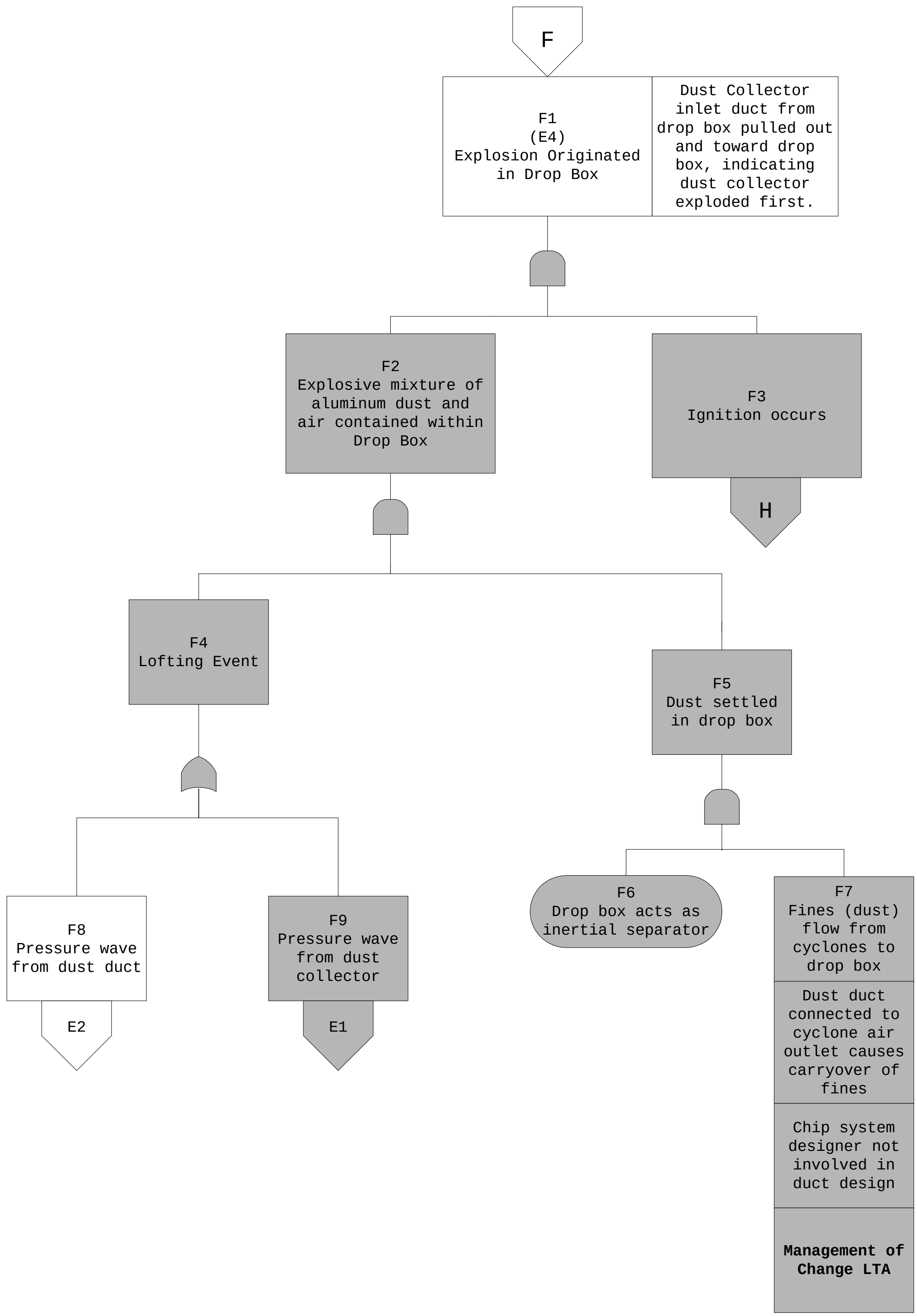

A
A1
(S2)
Injuries In Melt Area At Furnace 5
AND Gate
OR Gate
B13
A2
Deflagration at Furnace 5 sidewell
A3
Personnel Present (maintenance workers at Furnace 5 restarting chip feed)
C
A4
Flame front from fume system
A5
Flame front from chip feed system
D
A6
Flame front from vortex sidewell
G
A7
Flame front from dust collection system
A8
Deflagration in Fume System
A9
Flow path exists from fume system to sidewell
E
A10
Explosion in dust collection System
A11
No functioning explosion isolation valve in dust collector duct
Design LTA
A12
Dust Collector Explosion Protection LTA
A13
Deflagration in Multi-Cyclone
A14
Deflagration in Fume Duct
Ruled Out. Ducting fuel-depleted during fire earlier in the day
A15
Deflagration in Fume Hood
Ruled out: eyewitnesses reported no evidence of fume hood fire just prior to event
A16
Dust collector maintenance LTA (Excessive fuel in dust collector)
A17
Dust collector location LTA. Dust collector <50 m from building
A18
Explosion venting LTA (none on dirty air side of dust collector housing)
A19
NFPA 651/484 guidance not applied
Management of Change LTA
A20
explosive dust in multi-cyclone
Ruled out. No credible source for explosive dust in multi-cyclone
A21
Ignition in multi-cyclone

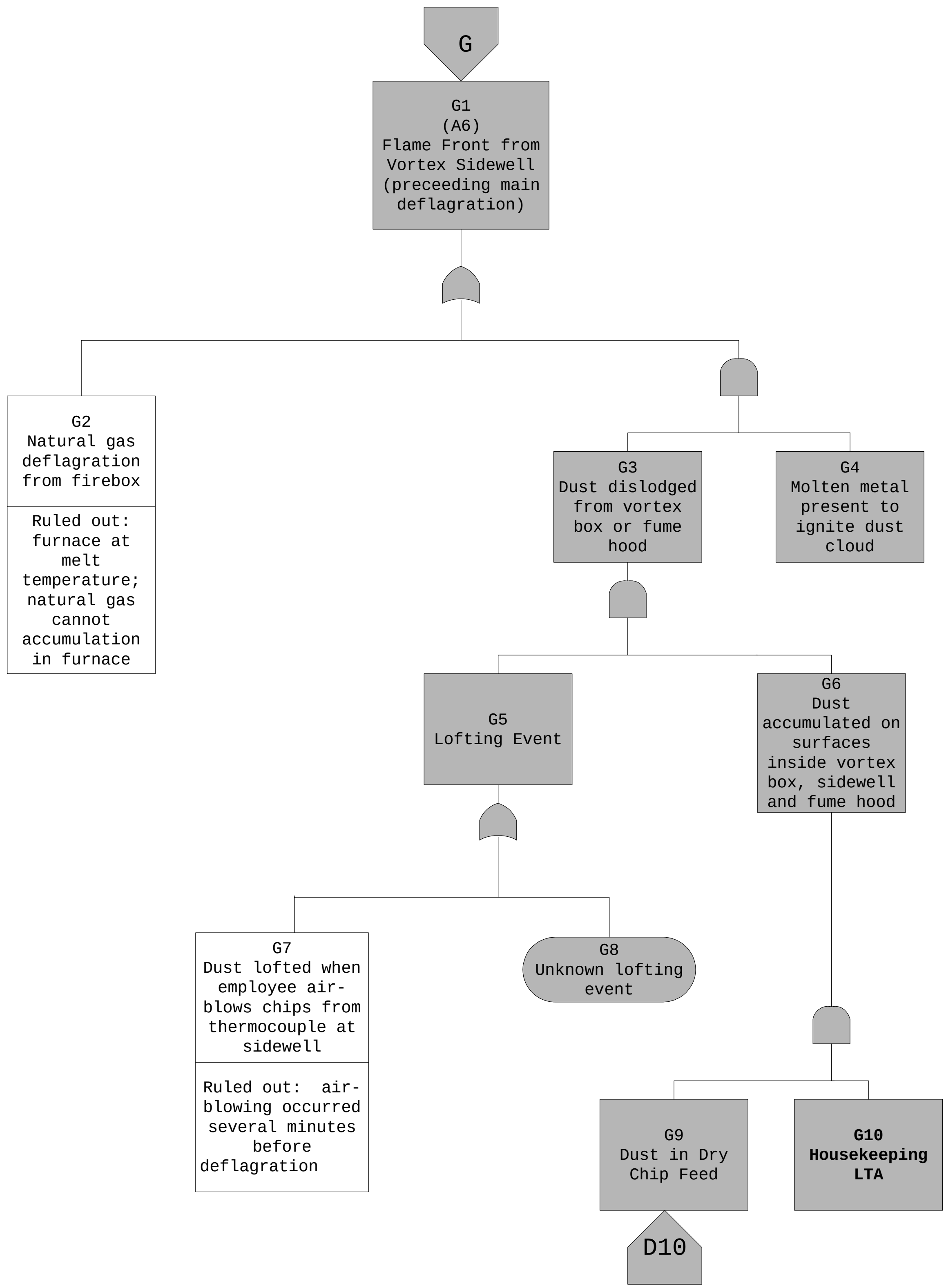

B
B1
(S3)
Injuries At Contractor Trailer
B2
Contractor in trailer performing stack testing
B3
Trailer on fire
B4
Trailer located 15 feet from dust collector
NPFA 651/484 Guidelines for separation not applied
B5
Flaming debris lands on trailer
B6
Radiant Heat from nearby fire
B7
Building roof blown off / on fire
B8
Dust collector explosion / fire
Secondary deflagration causes roof damage, near-injury to other contractor
B9
Secondary dust deflagration
B10
Combustible materials in building roof
B11
Excess combustible material (filter media and aluminum dust)in dust collector
Dust collector maintenance LTA
B12
Ignition Occurs
H
A2
B13
Deflagration at furnace 5 sidewell
B14
Accumulated dust on surfaces above furnace 5 lofted and ignited
Chip Transfer System Maintenance LTA
B15
Dust escapes from system
B16
Housekeeping LTA

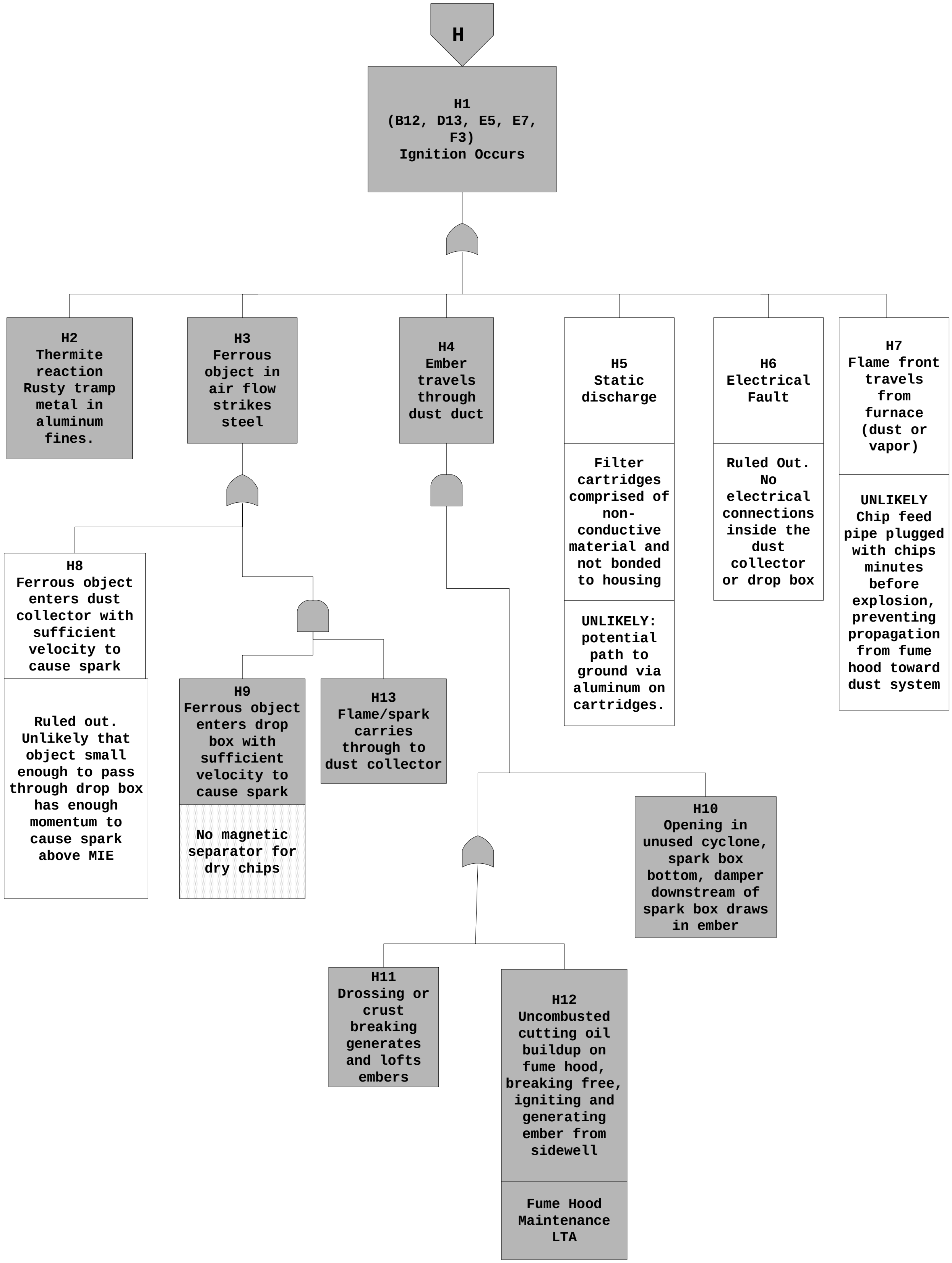

C
C1
(A3)
Personnel Present (Maintenance Workers at Furnace 5 Restarting Chip System)
C2
Fire in Fume Hood Exhaust Duct to Multi-cyclone
No formal (written) procedure for handling duct fires
C3
Common practice to shut down, burn out (and cleanout) when fire discovered in ductwork
Duct fires not adequately investigated or documented
Incident Investigation Program LTA
C4
Combustible Material Accumulated in Duct
C5
Accumulated solids ignited
C6
Fume Duct Maintenance LTA
C7
Hot Vapor From Fume Hood
C8
Spark from Fume Hood
C9
Incompletely combusted hydrocarbons in fume hood exhaust condensed in ductwork
C10
Aluminum dust and fines pulled into duct by multi-cyclone fan
Dust escapes from chip feed at vortex box
Reduced draft at dust collector
Dust collector filter cartridges loaded up
Dust Collector Maintenance LTA
C11
Paint and Residual Cutting Oil on Chips
C12
No Spark Box on Fume Hood Exhaust
C13
Fluxing or dross removal in sidewell produces embers


D
D1
(A5)
Flame Front from
Chip Feed System
D3
Explosion in dry
chip hopper
Ruled out: internal
inspection of dry
chip hopper did not
reveal burning
D4
Exposion in cyclone
or feed duct
D13
Ignition
occurs
H
D6
Dust in feed
pipe lofted
D7
Dust settled in
feed pipe while
chip system idle
D10
Dust in dry
chip feed
G9
D3
Explosion in dry
chip hopper
Ruled out: internal
inspection of dry
chip hopper did not
reveal burning
D8
Feed fan start
causes pulse that
lifts dust settled
in feed pipe
Ruled Out: System
running at steady-
state for 10 minutes
prior to explosion
D9
Chip feed fan
overspeed
Ruled out: no
evidence of feed fan
malfunction
D11
Chip dryer
liberates and/or
creates fines
D12
Fines not
separated from
dry chips
No vibratory
separator at
dryer outlet


E
E1
(A10)
Explosion in Dust Collector System
F9
E2
Explosion Originated in Dust Duct
F8
E3
Explosion Originated in Dust Collector
E4
Explosion Originated in Drop Box
F
E5
Ignition Occurs
H
E6
Explosive mixture of aluminum dust and air in dust duct
E7
Ignition occurs
H
E8
Explosive mixture of aluminum dust and air in Dust Collector
E9
Dust settled in duct
Air flow to dust Collector draft inadequate to keep dust suspended.
Dust Collector Maintenance LTA
E10
Lofting Event
No credible lofting events for dust duct itself
E11
Pulse Jet automatic cleaning lofts dust every 60 or 90 seconds
E12
Fines (dust) flow from cyclones to drop box & dust collector
Dust duct connected to cyclone air outlet degrades cyclone performance, causes carryover of fines
Chip system designer not involved in duct design
Management of Change LTA


F
F1
(E4)
Explosion Originated in Drop Box
Dust Collector inlet duct from drop box pulled out and toward drop box, indicating dust collector exploded first.
F2
Explosive mixture of aluminum dust and air contained within Drop Box
F3
Ignition occurs
H
F4
Lofting Event
F5
Dust settled in drop box
F8
Pressure wave from dust duct
E2
F9
Pressure wave from dust collector
E1
F6
Drop box acts as inertial separator
F7
Fines (dust) flow from cyclones to drop box
Dust duct connected to cyclone air outlet causes carryover of fines
Chip system designer not involved in duct design
Management of Change LTA


G
G1
(A6)
Flame Front from Vortex Sidewell (preceeding main deflagration)
G2
Natural gas deflagration from firebox
Ruled out: furnace at melt temperature; natural gas cannot accumulation in furnace
G3
Dust dislodged from vortex box or fume hood
G4
Molten metal present to ignite dust cloud
G5
Lofting Event
G6
Dust accumulated on surfaces inside vortex box, sidewell and fume hood
G7
Dust lofted when employee air-blows chips from thermocouple at sidewell
Ruled out: air-blowing occurred several minutes before deflagration
G8
Unknown lofting event
G9
Dust in Dry Chip Feed
G10
Housekeeping LTA
D10


H
H1
(B12, D13, E5, E7, F3)
Ignition Occurs
H2
Thermite reaction
Rusty tramp metal in aluminum fines.
H3
Ferrous object in air flow strikes steel
H4
Ember travels through dust duct
H5
Static discharge
Filter cartridges comprised of non-conductive material and not bonded to housing
UNLIKELY: potential path to ground via aluminum on cartridges.
H6
Electrical Fault
Ruled Out. No electrical connections inside the dust collector or drop box
H7
Flame front travels from furnace (dust or vapor)
UNLIKELY
Chip feed pipe plugged with chips minutes before explosion, preventing propagation from fume hood toward dust system
H8
Ferrous object enters dust collector with sufficient velocity to cause spark
Ruled out. Unlikely that object small enough to pass through drop box has enough momentum to cause spark above MIE
H9
Ferrous object enters drop box with sufficient velocity to cause spark
No magnetic separator for dry chips
H13
Flame/spark carries through to dust collector
H10
Opening in unused cyclone, spark box bottom, damper downstream of spark box draws in ember
H11
Drossing or crust breaking generates and lofts embers
H12
Uncombusted cutting oil buildup on fume hood, breaking free, igniting and generating ember from sidewell
Fume Hood Maintenance LTA