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Investigation and Analysis of an Explosion at the GOEX Black Powder Manufacturing Facility

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An accidental explosion at the GOEX powder manufacturing facility in Minden, Louisiana destroyed a section of the plant on June 7, 2011. The plant is the last black powder manufacturing facility in North America, producing product for a wide range of customers. The explosion originated in the corning mill where pressed black powder cakes were fed through an aluminium worm screw into a feed hopper and then moved along four sets of rolls and sieved shakers to reduce the size to the desired granular dimensions. The explosion fragmented the screw worm and hopper and destroyed the corning mill structure. Subsequent examination of recovered fragments of the screw worm suggested that the incident was likely triggered when a piece of quartz that had contaminated the batch impacted the aluminium worm. The friction generated enough heat to initiate the explosion. An alternate mechanism that could not be ruled out was frictional heating due to a fragmentation failure of the aluminium worm. Due to the nature of this product, it might not be possible to eliminate such events during the corning operation. However, based on our findings from this investigation, the authors have developed recommendations on how to minimize the frequency of such incidents.

1. Introduction

An accidental explosion at the Goex powder manufacturing operation in Minden, Louisiana destroyed the corning mill within the plant on June 7, 2011. This is the last remaining black powder manufacturing facility in North America, producing product for a wide range of customers. Given the extreme ignition sensitivity of black powder, explosions in black powder plants are a regular occurrence, especially within corning mills. Due to the nature of this product, it might not be possible to eliminate such events. However, understanding the hazards of black powder and evaluating the manufacturing process in the context of this latest incident is relevant to the explosives industry and will help minimize future accidents. Exponent investigated the explosion site, examined fragments of the screw worm and feed hopper, and conducted interviews with facility personnel. We also reviewed records of the incident batch and facility operation to verify compliance with applicable codes, including National Fire Protection Association Explosives Materials Code (NFPA 495), and applicable portions of United States requirements for commerce in explosives and Occupational Safety and Health Administration Process Safety Management. Based on the findings from this investigation, the authors offer certain preventative recommendations to operators of black powder and other explosive manufacturing plants.

2. The Properties of Black Powder

Black powder has historically been used extensively as an explosive, propellant and blasting agent (Davis, 1943). Although it is no longer as pervasive in the construction industry, it remains indispensable to hunters and sportsmen and for certain defence applications, including fuses and as an initiator for other explosives (Maltitz, 2001). Once ignited, black powder burns very vigorously, with a high flame spread and specific impulse. Other propellants typically burn much more slowly at low pressures, rendering them unsuitable for many applications (White and Sasse, 1982). The product can be simply described as an intimate mixture of potassium nitrate (between 70-76 %, depending on intended application), charcoal (8-18 %), and sulphur (9-20 %). Glazed black powder also contains a trace amount of graphite that coats (glazes) product granules (Goex, 2009). Depending on customer requirements, granulated powder is available in a range of sizes. Typically, larger grains are used for muskets or shotguns, and the finest grains are reserved for rifles smaller than 50 calibre, pistols and revolvers. Black powder is classified as a Class 1.1 explosive by the United States Department of Transportation and a Class 1.1D explosive by the United States Department of Defence. It is very sensitive to all ignition sources, including flames, sparks, friction and impact.

Black powder is generally considered a deflagrating explosive. Although the unconfined product burns violently, the reaction velocity is less than the speed of sound (Mach 1.0, 343 meters per second). However, detonations have been reported with fine grained product in heavily confined steel pipe with propagation rates exceeding 630 m/s (Mach 1.9). Auto-ignition of black powder can occur at long term exposure to temperatures above 200 °C, and ignition occurs within 5 s at 427 °C. The United States Bureau of Mines reports that confined powder can be ignited by electrostatic discharge energy of 0.8 J, whereas 12.5 J are required for unconfined powder. Dahn and Reyes (1994) have reported that, under certain conditions, black powder can be ignited by a 0.04 J spark. The product snaps under a steel shoe in the standard friction test and ignites at a drop height of 40 cm under the impact test. Hahn et al.(1980) report similar results, but note that the impact energy under the Bureau of Mines apparatus can range between 10 and 40 Nm, depending on the temperature, grain size and glazing.

3. The Black Powder Manufacturing Process at Goex and Existing Precautions

At the Goex Minden plant, black powder is manufactured following a process of 1) pulverizing/mixing, 2) milling/incorporating, 3) pressing, 4) corning/granulating, and 5) glazing/finishing (Figure 1, Goex, 2008). The raw materials are received in truck quantities and stored in super sacks. Batches of charcoal and sulphur (1,300 to 2,960 kg) are ground or pulverized in large ball mills and packaged into 13 to 16.5 kg bags. Although there is no explosion hazard during this step, the charcoal-sulphur mixture is combustible, and the high heat of hydration of charcoal creates the potential hazard of a hot spot causing subsequent ignition if the mixture gets wet at this stage. The prilled potassium nitrate is packed in 25 or 28 kg bags and stored separately. In the next step, all ingredients are further ground in remotely operated 250t (approximately 225,000 kg) wheel mills that incorporate (or mill) these ingredients together. A controlled amount of water is introduced to prevent accidental ignition of the explosive mixture during the milling process. The operators rely upon experience and their observations of the appearance and consistency of the mix to ensure that the product is not too wet for the next step and yet does not present ignition hazard. In this context, a prolonged loss of electrical power is especially hazardous because it can dry out the mix and create a hazard during the restart operation. After the milling is complete, the operators use conductive plastic shovels to transfer the wet product into bags. Goex pays particular attention to preventing stray ignition sources (including static sparks and frictional heating) at this stage, and employees are protected by appropriate Personal Protective Equipment (PPE).

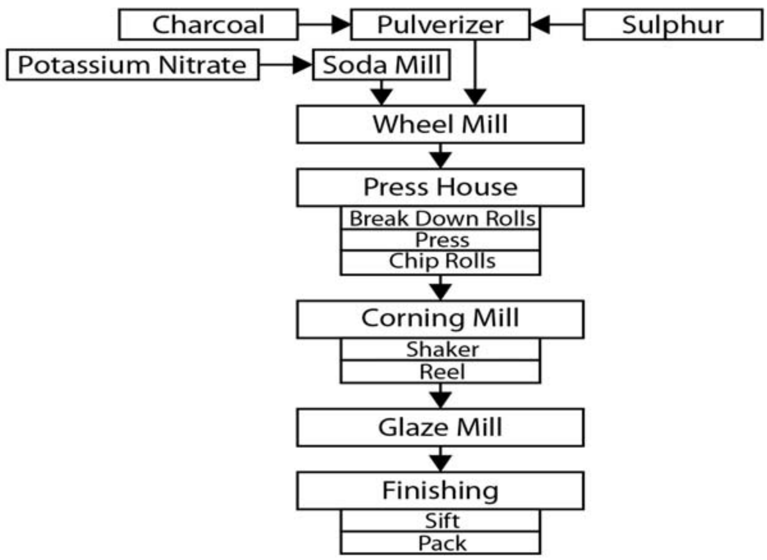

Figure 1: Goex manufacturing process

After the black powder cake from the wheel mill is run through bronze rollers that break up the cake, a manually operated hydraulic press is used to compact the product to the desired density. Excessive pressure is prevented by a mechanical safety device in the hydraulic pump that limits the maximum applied pressure. The pressed material is chipped up in another set of bronze rollers in preparation for processing in the corning mill (Figure 2a). The coarse product chips are transported to the corning mill in transfer cars (with wooden wheels) where they are fed into a feed hopper that incorporates an aluminium worm screw. The product moves along four sets of adjustable bronze rollers and sieved shakers (spool and reel) that reduce the size to the desired granular dimensions (Figure 2b and c). The product grains that are suitable for the glazing operation are irregular in shape and can range in effective diameter from 0.05 mm up to several mm. The corning operation is inherently dangerous because relatively dry powder is crushed, transported and sieved, which exposes the explosive product to mechanical energy. Accordingly, operators start and operate the mill remotely. Although product inspections are regularly required during the corning process, the operator turns off the mill before he enters the bay.

The screened grains are transported to the glaze mill where they are finished in rotating drums. The glazing mill is operated remotely, and close attention is paid to the tumbling time to prevent hot spot formation. Finally, the graphite-coated black powder granules are sifted into specific granulation sizes, weighed and packaged. The presence of the graphite glaze on most black powder grades reduces the static hazard, since graphite is a relatively good conductor and allows charge transfer over the grain surface through the grounding without ignition. However, care is exercised by Goex to prevent accidental impact, especially during the movement of carts. All packers also wear appropriate PPE to prevent static charge build-up, especially if they are working with unglazed powder.

The formulation and processing technology for black powder have changed very little over the last thousand years. The manufacturing process is inherently dangerous, and there have been significant life and property losses in black powder manufacturing plants over the years (Jasinkiewicz et al., 2004). Although there has been some innovation in the pulverizing, screening and conveying operations, the manufacturing process in the subject plant is very similar to what was first developed by DuPont in the early 1900s. Goex purchased this plant from DuPont and, in the late 1990s, moved the corning mill and sift/pack equipment from Moosic, Pennsylvania to Minden, Louisiana after railroad service to the existing plant was discontinued. Plant buildings and equipment are predominantly of wood construction and appropriate anti-static coatings are used on all floors. In the event of a fire, operators are instructed to evacuate the area immediately. All buildings are sprinklered, and automated loss-in-weight feeders prevent batch overloading in all manufacturing steps. Consistent with the requirements of NFPA 495 (2006), significant attention is paid to the training of personnel, housekeeping and collection of spilled materials, and the control of ignition sources. For example, spilled or contaminated materials are collected promptly, and all electrical equipment meets appropriate electrical classification requirements. Spark-generating materials and equipment are not permitted in the plant, and regular preventative maintenance is conducted on all moving or rotating machinery parts to minimize ignition sources associated with frictional heat. All plant buildings are constructed with appropriate stand-off distances and earthen berm protection to prevent propagation in the event of an accidental ignition.

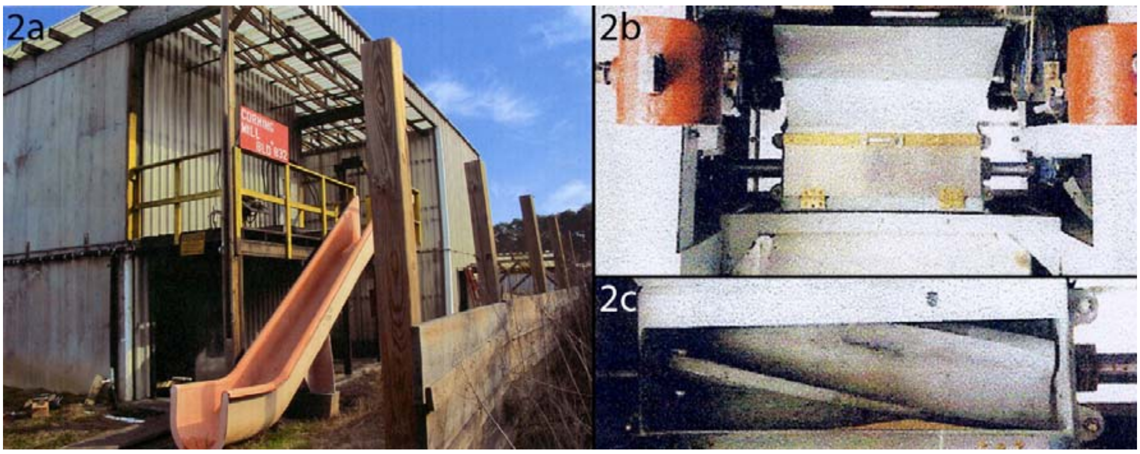

Figure 2: Corning mill (a), hopper (b) and aluminium worm (c)

4. Explosion Investigation

The explosion originated in the corning mill (also known as the shaker room), which was originally put into service in 1998. At that time, Goex modified an existing slab-on-grade concrete building by adding a two-story wood framed structure that incorporated fiberglass-reinforced plastic siding. The footprint of the corning mill consisted of an approximately 13 m by 12.2 m reinforced concrete slab, with the hopper, shaker and rollers housed within the old section of the building that had 1-foot reinforced concrete walls. The reel box and other ancillary equipment were incorporated into the new section of the building. The mill was rated for a maximum 1,180 kg (3,000 lb.) of explosives. According to Goex, a typical batch of product from the press room is processed in three cuts, each of which requires 30 minutes inside the corning mill. Witnesses stated that, at the time of the explosion, there were approximately 550 kg (1,400 lb.) of product in the corning mill building. The first cut from a new batch of press bay product had been loaded into the mill at approximately 5:30 AM, and the mill had tripped at approximately 6:00 AM because some hard material (either solidified black powder from the press machine or a contaminant) was detected between the rolls at the very end of the run. The material that caused the trip was removed and discarded, a product sample was retained for analysis, and the mill was put back into service with the second cut of material from the same press bay batch. The explosion, which occurred shortly thereafter at approximately 6:10 AM, completely fragmented the hopper, caused significant damage to one end of the screw worm, partially fragmenting two of the blades (Figure 3a), and destroyed the corning mill structure (Figure 3b). Consistent with the requirements of NFPA 495, all employees correctly evacuated the plant instead of attempting to fight the fire after the explosion. There were no fatalities and only one minor injury to an employee who fell during the evacuation.

Figure 3: Fragmented worm (a), destroyed corning mill (b) and crater under hopper and worm (c)

Damage indicators documented by Exponent included the condition of the concrete floor slab and walls and recovered fragments of the cast aluminium hopper and the screw worm. Investigation confirmed that the origin of the primary explosion was inside the hopper directly above the worm at the head of the corning mill screens and rollers. The primary explosion fragmented the hopper and the aluminium worm

and propagated through the exposed material in the screens and conveyors. Subsequently, there was a second large explosion around the reel.
Careful examination of the floor confirmed that the only evidence of localized cratering in the concrete occurred directly under the hopper, which confirmed that the primary explosion occurred within this equipment (Figure 3c). The lower portions of the surrounding concrete walls were also fragmented and had collapsed outward onto the floor slab immediately around the hopper. Multiple fragments of the aluminium hopper and worm recovered after the explosion ranged in size from 1 inch to 9 inches, indicating a relatively high degree of brisance, particularly within the hopper (Figure 4a). Many fragments also exhibited surface cracks characteristic of high strain rates (Cook, 1958) that would be expected at the seat of the explosion (Figure 4b). Basco et al. (2010) indicate that the heat of explosion of black powder is approximately 60 % of TNT. Since the mill had operated for approximately 10 min prior to the explosion, the quantity of black powder within the hopper at the time of the explosion was approximately 158 kg (400 lb.), or a TNT equivalent quantity of 95 kg. Assuming a 1 m standoff distance between the hopper and the concrete slab, a detonation within this quantity of explosives is sufficient to cause the localized cratering observed.

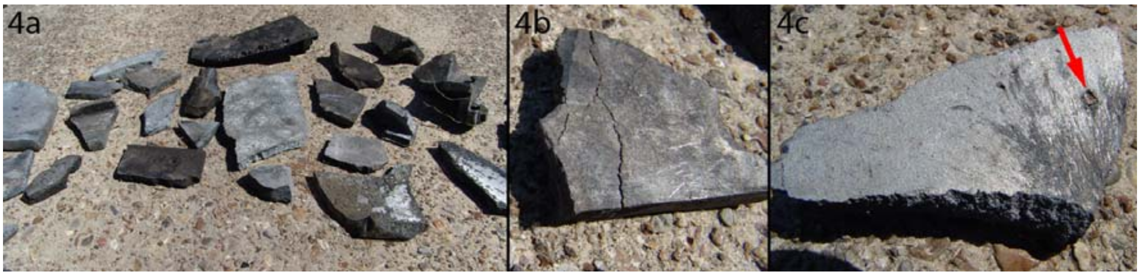

Figure 4. Recovered hopper fragments (a), cracks on hopper fragment (b) and embedded quartz (c)

There was a second large explosion under the reel as evidenced by the reel components ejected from the corning mill. These were found partially burned, in a field approximately 50 feet away. The wood frame structure surrounding this equipment was completely destroyed, and the upper portions of the concrete walls, which were originally adjacent to the reel and surrounded the corning mill rollers and conveyors, were pushed away from the seat of the second explosion and discovered partially collapsed over the conveyor.

5. Conclusions

Examination of recovered fragments of the hopper and screw worm confirmed that the primary explosion was triggered by one of two possible mechanisms.

5.1 Scenario 1

A piece of quartz that had contaminated the chipped black powder from the press bay batch impacted the sides of the hopper. The friction generated sufficient heat to initiate the explosion. One of the recovered fragments from the hopper exhibited a distinct starburst pattern that is very characteristic of a surface initiation of explosives. A quartz pebble was also discovered embedded within this fragment, directly below the starburst pattern. Surface melting was observed on the aluminium surrounding and below the pebble (Figure 4c). Goex confirmed that, due to the design of the mill, a significant amount of material from each batch would spill on the ground during the corning operation. Operators would sweep the floor and incorporate this material into the subsequent batch as it was introduced into the hopper. Accordingly, accidental introduction of rocks or quartz into the mill (for example, materials being tracked into the mill by an employee) was quite possible.

5.2 Scenario 2

An alternate mechanism for the explosion that could not be ruled out was a pre-existing defect or void in the cast aluminium worm that caused premature fracture within one of the worm blades as it turned. It is possible that a fragment of aluminium broke off and rubbed against the black powder, creating sufficient frictional heat to ignite the material. The subsequent ignition then propagated back into the hopper. Goex confirmed that they had last replaced the worm and hopper in 2006, and their procedures did not include any non-destructive testing or evaluation of rotating components to verify that there were no pre-existing defects or fractures in their equipment. However, Exponent was not able to recover any fragments that

exhibited localized melting on their fracture faces that would confirm this accident mechanism. We note that, despite extensive searches in the surrounding forest and swamp by Goex personnel, less than half of the hopper fragments could be recovered.
The second explosion likely propagated within the product fines due to fragments or flames that were generated by the primary explosion.

6. Recommendations

The plant had recently re-qualified a very detailed Process Safety Management plan, which included a hazards review as required by industry standards. Goex also maintained a strict series of Standard Operating Procedures designed to regulate step-by-step activities during the manufacturing process. However, the results of this investigation have highlighted certain structural shortcomings in their procedures that have since been corrected. Due to the obvious risk of foreign contaminants, floor sweepings should not be incorporated back into the manufacturing process. In addition, any equipment that rotates or otherwise imparts mechanical energy to explosives should be x-rayed or otherwise tested in a non-destructive manner to confirm that there are no occlusions, voids or other latent defects before it is placed into service. A regular non-destructive examination and requalification of the equipment should also be incorporated as part of the preventive maintenance program. The Process Safety Management plan and Hazards Review should include a What-if analysis to explore the effects of equipment failure in operations where energy is imparted to explosive materials.
The authors also reiterate certain NFPA 495 requirements that, in their experience, have not been consistently followed by industry and have caused explosions at other facilities. All explosives manufacturing and process areas should be regularly swept and kept clean, dry and free of grit, paper, empty packages and other assorted rubbish. Non-sparking tools should be used during all aspects of the manufacturing process, including housekeeping, and any floor sweepings should be disposed of in a manner approved for the explosive product itself. All collection systems should be cleaned at a frequency that eliminates hazardous concentration of explosives dusts or powder from accumulating in pipes, tubing and ducts or within hidden compartments. Finally, any explosive materials or residue should be removed from process equipment and the immediate surroundings before hot work or repairs that might produce heat sparks or flame is performed in the area.

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