KINSTON DUST EXPLOSION

Quentin A. Baker, P.E.
Massimiliano Kolbe

Baker Engineering and Risk Consultants, Inc.
3330 Oakwell Court, Suite 100, San Antonio, TX 78218-3024
210-824-5960

ABSTRACT

An explosion occurred at the West Pharmaceutical Services plant in Kinston, NC, USA on January 29, 2003. The facility manufactured rubber components for pharmaceutical delivery devices. The explosion occurred in the rubber compounding section of the plant, which suffered extensive damage. The explosion resulted in six fatalities and a number of injuries.

An in-depth investigation by West Pharmaceutical revealed that the explosion involved a polyethylene dust. Unlike typical dust explosion events, no residual combustible dust accumulations were found in the facility. The polyethylene dust that fueled the explosion originated from an aqueous slurry used to coat rubber strips, and not from a dry powder. The investigation revealed that combustible fugitive dust from dried slurry had accumulated above a suspended ceiling along with other non-combustible dusts. The damage from the explosion was not uniform throughout the facility; the greatest damage was well removed from the location of initiation.

BACKGROUND

West Pharmaceutical Services Inc., founded in 1923, is one of the largest manufacturers of closure systems and components for sealing drug vials and pre-filled syringes. The closure systems and components are made of rubber compounds and other materials, and were developed by West. Headquartered in Lionville, Pennsylvania, West has eight manufacturing facilities in North America and ten facilities in Europe and Asia.

West’s plant in Kinston, North Carolina, started operation in 1975 and underwent a substantial expansion in the mid-1980s. The plant conducts two types of operations: rubber compounding and product finishing. The plant building consisted of a single story structure, except for the portion of the building that contained the rubber compounding operation (known as the automated compounding system (ACS) or “the Tower” section) that was approximately 60 feet tall with multiple levels. The total plant area was approximately 150,000 square feet. The rubber compounding process operated 24 hours a day, five or six days a week, producing sequential batches of rubber compounds. In January 2003, the workforce at West’s Kinston plant included 264 West employees and 35 full-time contract employees.

The ACS had two separate rubber compounding lines, each with a mixer, a mill, and batchoff equipment. Mixer 1, Mill 1, and Batchoff 1 were located at the southern part of the ACS. Mixer 2, Mill 2, and Batchoff 2 were in the northern part of the ACS.

In the rubber compounding process, raw materials were prepared in a separate area known as “the kitchen” on the first floor of the ACS. The materials for each separate batch were placed into a tote and transported by an elevator and a series of conveyors to the mixers located on the second floor of the structure. Other bulk ingredients, such as clay and mineral oil, were fed directly to each of the mixers. The mixers performed the actual compounding process, converting the raw materials through a series of steps into a rubber compound batch.
Once a rubber compound batch was completed in a mixer, the batch was dropped through a chute to the first (or ground) floor of the ACS, where a rolling mill smoothed the batch into a sheet. The sheet of rubber was then trimmed into a narrower strip and conveyed to a batch off machine where the strip was dipped through a vat containing a slurry of very fine polyethylene powder and water. The strip was then air dried, folded, and packaged in containers either for shipment to other West plants or for use in the finishing area of West’s Kinston plant.

A suspended ceiling comprised of acoustic tiles hung 10½ feet above the first floor of the ACS. The suspended ceiling covered the entire area where the rubber compounds were rolled, dipped, cooled, folded, and packaged. There were two separate dust collection systems in the ACS, one for the kitchen area and one for the mixers. The extraction ducts from the kitchen and mixer systems terminated at dust collector units located outdoors. Because West manufactured products for use in the pharmaceutical industry, the cleanliness of the facility was a very high priority. A cleaning staff worked around the clock vacuuming and wiping up any visible dust accumulations in the visible work areas.

THE INCIDENT

On the day of the incident, operations in the plant were typical and described by some workers as “very smooth.” According to witness accounts, there were no sights, sounds, or odors that would have indicated a problem. At 1:28 p.m. on January 29, 2003, an explosion occurred abruptly in West’s Kinston plant. Workers throughout the plant heard the explosion or, as some described it, a sound like “rolling thunder.” Some workers closer to, but outside of the rubber milling area, saw a bright flash and felt a pressure wave that knocked them off their feet. Workers inside the rubber milling area saw flames and were also knocked off their feet.

The explosion started a fire that engulfed part of the plant. The entire plant was affected to some extent by the explosion and fire, though the damage was most severe in the ACS or rubber compounding part of the plant, which was essentially destroyed. There were six fatalities and a number of injuries as a result of the explosion and fire.

ABSENCE OF RESIDUAL DUST FROM THE DUST EXPLOSION

The West investigation team ultimately proved that the explosion was a dust explosion involving polyethylene dust. Not until several months after the incident, however, was conclusive forensic proof found. Unlike most dust explosions, there were no residual accumulations of combustible dust, even in protected locations like flanges of I-beams supporting the second floor. Moreover, housekeeping in the facility was extremely good with dedicated cleaning crews working on all shifts, every day. All witness interviews plus pre-incident photographs verified that work areas were kept very clean to meet stringent customer and FDA requirements for the pharmaceutical industry.

Because the area above the suspended ceiling in the ACS was not a work area, however, it was not viewed as requiring a similar cleaning regimen. Some deposits were known to be above the suspended ceiling due to negative building pressure resulting from the separation of a pneumatic conveying line for a non-combustible raw material and the migration of clay dust from outdoor storage silos. The plant was continually working to improve dust control and had replaced the original dust collection system about a year before the incident. The belief of plant personnel was that the material above the suspended ceiling was non-combustible. Post-incident tests of solids collected in the dust collectors supported this belief, as the mixture of dusts in the dust collectors were, in fact, non-combustible.

Some investigators drew the conclusion just days after the incident that the explosion was a dust explosion based on the assumption that the dust above the suspended ceiling was a combustible dust. In the ensuing months, however, they found no combustible dust above the suspended ceiling in
the ACS. Not until West’s investigation team found a coating of melted, resolidified polyethylene on structural beams supporting the second floor of the ACS, was actual presence of combustible dust above the ceiling positively identified. Polyethylene dust that had not been consumed in the explosion had melted and was deposited on various surfaces as a solid coating with a light tan appearance. The coating was unremarkable, easily mistaken for a dirty surface caused by concrete dust, soot from the nearby fires, stains from fire water and rain, or other contamination sources.

DIRECTION OF PROPAGATION

The directions of flame and blast wave propagation were investigated to understand damage patterns and provide insight into initiation of the explosion. The Kinston incident posed challenges because the location of highest damage was near the opposite end of the room from the initiation source, and most investigators focused their efforts in the zone of highest damage. As the discussion below points out, it is incorrect to assume that the location of highest damage is where the event initiated.

Observations at the site were used to assess the direction of the blast forces. It is important to note that blast forces on building surfaces are applied perpendicular to the surface of the component, which may not be in the direction of the blast propagation. Therefore, it is necessary to consider several damage indicators to determine the direction of the significant explosion or explosions. Indicators include structural deformations, debris throw and equipment movement.

Figure 1 shows lateral bracing and a floor beam east of Mixer 1 that was deformed eastward. It is interesting to note that none of the other mezzanine floor beams in the ACS and none of the mezzanine columns were deformed along this column line. The apparently localized damage to the bracing and floor beam led some investigators to early conclusions that the explosion was “seated” just to the west of the bracing. Once drawings were reviewed and plant personnel interviewed, it was determined that there was a concrete block wall along this column line and it was subsequently driven into the bracing by the blast. The presence of the wall increased the out-of-plane loads carried by the bracing, which were then transferred to the floor beam, causing larger deformations in this area. Thus, the localized damage was caused by the structural configuration, not an adjacent localized explosion.

Figure 1. Out-of-Plane Displacement of Steel Bracing

Figure 2 shows an interior wall north of Mill 1 that was deformed to the north. In the area to the south and east of Mill 1, there was evidence that a significant amount of debris was moved during the emergency response operations and initial investigation by ATF. Therefore, the investigation team could not use the location of the debris in certain areas as evidence of the blast direction. However, items that were supported at higher elevations could be used as reasonable directional indicators.
Figure 2. Deflection of Interior Wall Northward

Figure 3 shows a second level floor slab that uplifted significantly and separated from the floor framing. The mixer floor slabs immediately adjacent to this area suffered no damage. It is important to determine the actual structural conditions before drawing any conclusions from this type of evidence. Most floor slabs are not designed for upward loads; there may be no reinforcement for uplift and there may be little or no attachment of the floor deck to the floor framing. A static load of only about one-half psi would have lifted the second floor slab. The floor slabs at the mixers were heavily reinforced due to the heavy equipment loads. Without proper analysis, one could inaccurately determine the explosion source and magnitude.

Figure 3. Uplift of Second Level Floor Slab

Building debris can also be used as an indicator of the blast direction and magnitude. An interior wall panel found in Mill 1 (see Figure 4) shows that blast forces in this area were directed northward. Locating or determining the origin of pertinent pieces of debris can sometimes be a challenge. Figure 5 shows the area west of the mills, where a significant amount of debris was found. The doorframe shown in this figure originated from a wall along the west side of the mixers.
Debris Thrown

Figure 4. Debris Thrown into Mill 1

Door Frame

Figure 5. Building Debris West of Mixer 1 (note doorframe)
Use of the information discussed above and many additional damage indicators allowed the West investigation team to develop a vector diagram (Figure 6) showing the direction of the blast forces throughout the building. As shown, the center of the explosion might seem to be in the area just south of Mill 1. An early witness report indicated that the event originated in this area as well. However, the investigation team was unable to identify critical evidence that would support the hypothesis that the initiating event took place in this area. Later witness reports indicated that the explosion originated north of Mill 2, at the opposite end of the room from Mill 1. In addition, all personnel working in the first floor mill area were knocked down or thrown towards the south as shown in the personnel vector diagram in Figure 7, before major damage occurred.

All of these witnesses reported an initial sighting of flame to the north of their positions. Detailed inspection of the equipment and ductwork in the area north of Mill 2 confirmed these accounts. Therefore, it was shown that the event initiated in the area north of Mill 2 and the explosion propagated to the south, where the highest blast pressure and most significant damage occurred south of Mill 1.
Figure 6. Vector Diagram Showing Direction of Deformation and Debris Throw Around ACS
DUST EXPLOSIONS

According to Eckhoff[1], a dust explosion is defined in the following terms: “Any solid material that can burn in air will do so with violence and speed that increases with increasing degree of sub-division of the material.” However, just as in flammable vapor clouds, there are many factors that are necessary in order for a dust cloud to be flammable. In addition to fuel-air concentration (dust cloud concentration) another very important factor in dust cloud explosions is the particle size. Dust combustion is highly dependent on oxygen diffusivity. In gas combustion, oxygen molecules and fuel molecules are within similar size and the mechanism is rate determining at a molecular level. In dust clouds, although the fuel is still molecular, it generally exists as a particle (massive agglomeration or clumps molecules). The surface area of these particles determines how fast the oxygen molecules can react with the particle and combust. The finer the particle, the smaller the surface area, and the faster the reaction between oxygen molecules and fuel molecules.

In order to determine the reactivity or sensitivity of certain types of dusts, we subject the dusts to several industrially accepted methods of testing. The factors that are typically tested for in dust flammability tests consist of, but are not limited to, the following:

**Minimum Ignition Energy (MIE):** This is defined typically in units of mJ (milli Joules) as the lowest quantity of electrical energy stored in a capacitor that when discharged is just sufficient to ignite a
given dust concentration in air. This test is usually carried out at atmospheric temperature and pressure.

**Minimum Autoignition Temperature (MAIT):** This is defined in temperature units (degrees Celsius) and is the lowest temperature at which a given dust cloud concentration will ignite at atmospheric pressure.

**20 Liter Apparatus:** This device is used to measure $P_{\text{max}}$ (maximum pressure rise), $K_{\text{max}}$ (maximum explosion constant), LEL (Lower Explosion Level) and LOC (Limiting Oxygen Concentration). The device is a sphere of 20 liters in volume that conducts constant volume testing.

- The $P_{\text{max}}$ is defined in units of pressure (bar) and as the maximum pressure rise that the given dust concentration, when dispersed internally and subjected to a chemical igniter of short duration, will yield during the combustion of the dust cloud.
- $K_{\text{st}}$ is defined in units of pressure – distance over time (bar-m/s) and as the dust explosion severity of a given dust. $K_{\text{st}}$ is calculated as the maximum rate of pressure rise multiplied by the cube root of the volume in which it was combusted in. There are four $K_{\text{st}}$ classes and they are, in order of severity, 0 through 3, with 3 having the most severe explosibility. They are classified in groups of $K_{\text{st}}$ values as follows:
  - Class 0: $K_{\text{st}}$ values of 0
  - Class 1: $K_{\text{st}}$ values less than 200 bar-m/s
  - Class 2: $K_{\text{st}}$ values between 300 and 200 bar-m/s
  - Class 3: $K_{\text{st}}$ values greater than 300 bar-m/s
- LEL is defined in concentration terms of fuel (for dusts it is in mass over volume or g/m³. It is known as the lowest fuel concentration that is required in order for a flame to propagate in a self-sustained manner.
- LOC is defined as the maximum oxygen concentration which does not allow combustion of a given fuel-air mixture. This is typically determined by the addition of an inert gas into the fuel-air mixture. Combustion can begin to take place where oxygen concentrations are above the LOC.

**DUST FOUND AT THE WEST PHARMACEUTICALS INTERNAL BUILDING SURFACES**

In the remains of the facility of West Pharmaceuticals in Kinston, North Carolina, there appeared to be a layer of material that covered many of the structural beams of the building. The material resembled an opaque, plastic-like covering that was tan in color and very adherent to the beams and walls. Scraped samples were taken in several locations and all appeared the same to the naked eye. In the same locations, white powder was also found inside the process equipment of the plants. The samples of white powder were subsequently sent to testing laboratories for dust combustion tests and analyzed. Table 1 below summarizes the test results.

The white powder consisted of polyethylene dust where 100% of the dust was less than 63 microns in particle diameter. The analysis showed that the white powder consisted of melted and burned polyethylene dust, that once combusted, had resolidified to the surfaces where it was found.
Table 1. Dust Combustion Results from White Powder Scraping Samples

The safety information is summarized in the following table.

<table>
<thead>
<tr>
<th>Minimum Ignition Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Inductance</td>
</tr>
<tr>
<td>Powder Resistivity</td>
</tr>
<tr>
<td>30% humidity</td>
</tr>
<tr>
<td>60% humidity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle size information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Received as:</td>
</tr>
<tr>
<td>Tested as:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum Auto Ignition Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kamin BAM Oven</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Explosion Indices by ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Explosion Conc.</td>
</tr>
<tr>
<td>Limiting Oxygen Conc.</td>
</tr>
<tr>
<td>Dust Explosion Class</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Emax</td>
</tr>
<tr>
<td>Prax</td>
</tr>
</tbody>
</table>

EXPLOSION ENERGY ESTIMATES

During the course of the West Pharmaceutical accident investigation, members of the BakerRisk team documented onsite and offsite damage indicators. Damage indicators were used to estimate explosion energy. Deformation of each damage indicator was used to determine pressure–impulse (P-I) combinations that could cause the observed damage. Iterative calculations were then performed, varying explosion source conditions until the best fit was obtained for blast loads applied to the population of damage indicators.

The dust explosion was modeled like another type of fuel-air explosion - a vapor cloud explosion (VCE). High explosive and bursting pressure vessel blast estimates were inappropriate for a dust explosion. Use of vapor cloud explosion blast curves is the best approach since a dust explosion is a distributed energy explosion and has a variable combustion rate, analogous to a VCE. BakerRisk’s VCloud software automates reading of the published Baker-Strehlow-Tang[2],[3] (BST) blast curves. BST uses various inputs such as confinement, congestion, and reactivity of fuel and energy content to generate maps and data of pressure and impulse.

Through several iterations of energy content, an energy of approximately 5x10^10 in-lbf (5,600 MJ) with a flame speed of Mach 0.5 yielded pressure contours nearly identical to the ones documented in the damage indicator map.

Figure 8 presents the pressure contours obtained through VCloud. Tabulated results show the comparison with on-site damage indicators and calculated VCloud pressures in Table 2.

The amount of polyethylene needed to produce the energy value of E=5x10^10 in-lbf is approximately 280 lbm (127 kg). The thickness of a uniform layer of polyethylene spread over 1000, 5000, and 10,000 ft^2 is 0.13 inch (3.3 mm), 0.027 inch (0.7 mm) and 0.013 inch (0.3 mm), respectively.
DETERMINING INITIATION OF THE EXPLOSION

Initiation of a dust explosion requires that combustible dust be in suspension in air at a concentration above minimum explosive concentration (MEC) and be exposed to an ignition source with sufficient energy to exceed minimum ignition energy (MIE). A systematic approach was taken to search for initiation sources that satisfied these concurrent requirements. In addition, forensic evidence was sought to provide proof of initiation. For the sake of brevity, discussion is limited to the final result.

Table 2. Comparison of Results Between Damage Indicators and Energy Estimate using VCloud

<table>
<thead>
<tr>
<th>Distance from center</th>
<th>Overpressures Based on Damage Indicators</th>
<th>Calculated Explosion Pressures from Best-Fit Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 ft</td>
<td>3 PSI</td>
<td>2.97 PSI</td>
</tr>
<tr>
<td>208 ft</td>
<td>2 PSI</td>
<td>1.91 PSI</td>
</tr>
<tr>
<td>435 ft</td>
<td>1 PSI</td>
<td>0.84 PSI</td>
</tr>
<tr>
<td>625 ft</td>
<td>0.7 PSI</td>
<td>0.57 PSI</td>
</tr>
<tr>
<td>870 ft</td>
<td>0.5 PSI</td>
<td>0.39 PSI</td>
</tr>
<tr>
<td>1450 ft</td>
<td>0.3 PSI</td>
<td>0.22 PSI</td>
</tr>
<tr>
<td>2100 ft</td>
<td>0.2 PSI</td>
<td>0.14 PSI</td>
</tr>
<tr>
<td>3900 ft</td>
<td>0.1 PSI</td>
<td>0.07 PSI</td>
</tr>
</tbody>
</table>
Initiation occurred inside the ducts that provided cooling air to electric motors driving Mill 2. The ducts were located at the north end of the room, consistent with the location discussed above based on vector diagrams and witness accounts. The physical evidence that identified the initiation source included outward bulging of the cooling air inlet header, and the presence of melted and resolidified combustible dust deposits inside the inlet header and smaller ducts leading to the motors. Additionally, these melted and resolidified combustible dust deposits were found inside the motors, on the commutators and brushes. The ducts and motors are shown in Figure 9.

The headers were located above the suspended ceiling, the location where dusts had been found to accumulate, including some polyethylene dust. Careful inspection of the inlet air header revealed that it had split open in a number of locations from internal pressure and discharged material through these splits. Analysis of the motors determined that normal arcing at the brushes exceeded MIE.

![Figure 9. Cooling Air Ducts for Mill 2 Motors with an Internal View of the Bulged and Split Inlet Header](image)

The sequence of events was determined to be as follows: Fugitive combustible dusts accumulated in the cooling air inlet header and ducts. The dusts ignited at the brushes of a Mill 2 motor, and the flame propagated upstream in the riser to the header. The deflagration over-pressured the inlet header, discharging pressure and burning material above the suspended ceiling, thereby initiating the dust explosion in the room.

**CONCLUSIONS**

The following conclusions are made concerning the dust explosion at the West Pharmaceutical Services Kinston plant:

- The location of greatest damage may not be where an explosion initiated. Moreover, the apparent direction of blast wave propagation may not be indicative of the direction of flame propagation in a dust explosion. Evidence of the early stages of the event is needed to identify the location of initiation.

- Interpretation of damage patterns requires knowledge of dynamic response and information concerning the original structural configuration. Some damage that appears to be the result of localized blast phenomena may simply be due to the structural
configuration. Misinterpretation of such indicators can lead to incorrect conclusions about the location and nature of an explosion.

- Witness accounts, particularly from injured persons, may, and frequently do, contain inaccuracies. These witnesses may convey a high degree of confidence in their recollection, but the physical evidence is often at odds with their recollection. Other segments of their account may be accurate. While witness accounts must be considered, independent corroboration by other witnesses and, in particular, from physical evidence is needed to confirm or discount their recollection.

- Based on the damage indicators and given energy estimates, using the VCE model was a reasonable representation of a dust explosion because the apparent flame acceleration and increase in blast loads within the building could be considered similar to a VCE event.

---