

EXTREME WEATHER, EXTREME CONSEQUENCES: CSB INVESTIGATION OF THE ARKEMA CROSBY FACILITY AND HURRICANE HARVEY



U.S. Chemical Safety and Hazard Investigation Board

Executive Summary

On August 31, 2017, a fire erupted at the Arkema facility in Crosby, Texas, when refrigerated organic peroxides decomposed following the effects of Hurricane Harvey. The fire started after vapors from the facility traveled across a public highway and twenty-one emergency responders sought medical attention from exposure to fumes generated by the decomposing product. Due to hurricane relief efforts, officials decided to keep this highway open despite a 1.5-mile evacuation zone around the Arkema facility; however, it was closed after the first fire started. Over the next several days, a second fire and a controlled burn consumed eight trailers holding Arkema's remaining low-temperature organic peroxide products. Over the course of the three fires, in excess

of 350,000 pounds of organic peroxide combusted. As a result, more than 200 residents living within 1.5 miles of the facility evacuated and could not return home for a week.

Although the Arkema Crosby facility is located within the 100-year and 500-year flood plain, extensive flooding from heavy rainfall exceeded equipment design elevations and caused the plant to lose power, backup power, critical organic peroxide refrigeration systems, and standby refrigerated trailers needed to keep the organic peroxide cool. This flooding also eventually forced all of Arkema's employees to evacuate from the facility.

The incident at the Arkema Crosby facility

developed over twelve days, from August 24, 2017 through September 4, 2017. Figure 1 shows a summarized incident timeline. This incident can be separated into three primary phases:

- Arkema's Hurricane Harvey preparations before and in the initial stages of the Hurricane;
- Arkema ride-out crew's efforts to keep the organic peroxide products cold during the flooding to prevent decomposition and combustion; and
- Emergency response activities after significant flooding forces Arkema personnel to evacuate from the facility and a series of three fires consumes over 350,000 pounds of organic peroxide products.

Timeline Related to Arkema Inc. Chemical Plant Fires 2017

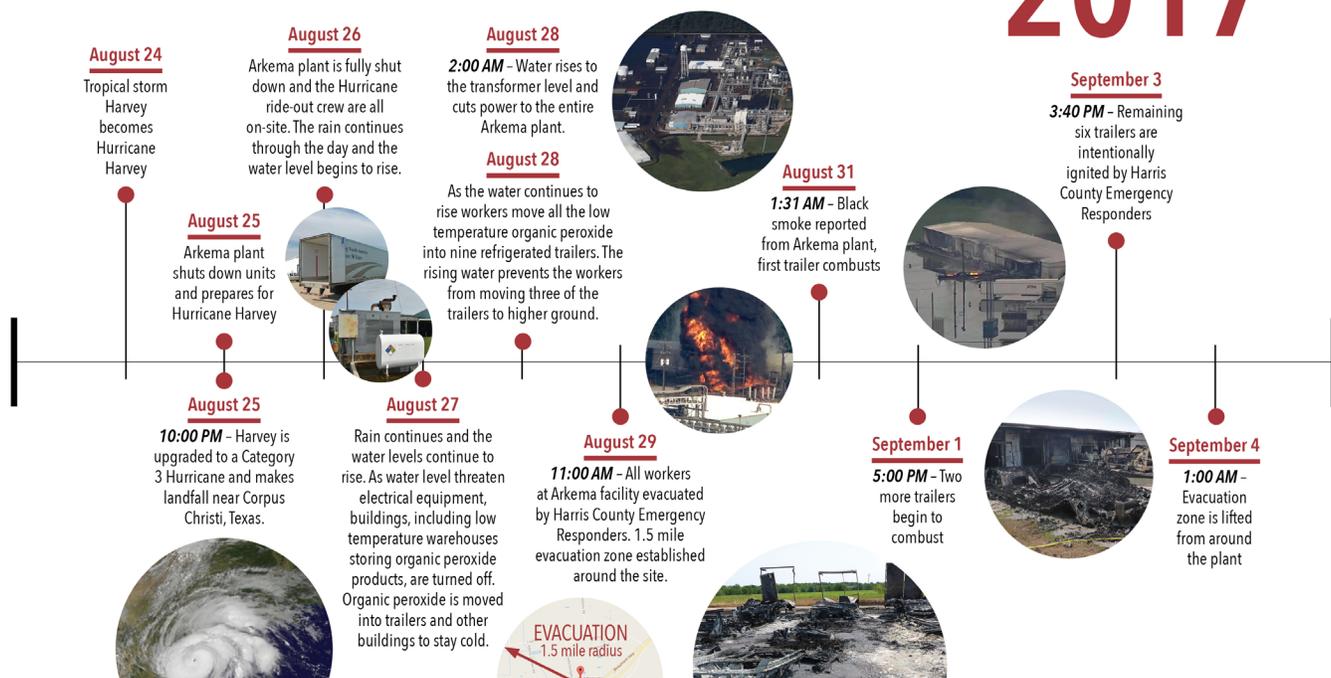


Figure 1. Overview timeline for the Incident at the Arkema Crosby facility.

EXTREME WEATHER, EXTREME CONSEQUENCES: CSB INVESTIGATION OF THE ARKEMA CROSBY FACILITY AND HURRICANE HARVEY



U.S. Chemical Safety and Hazard Investigation Board

Overview of Incident

Preparing for Hurricane Harvey

On Wednesday, August 23, 2017 it became clear that Hurricane Harvey would impact the middle and upper Texas coast and likely stall over southeast Texas. Meteorologists projected the storm would make landfall on Friday, August 25, 2017, bringing heavy rainfall of 12 to 20 inches across much of Texas, with some areas receiving up to 30 inches over the duration of the hurricane. In anticipation of Hurricane Harvey, the personnel at the Arkema Crosby facility began to prepare even though they were not expecting to be in the storm's direct path.

The Arkema Crosby facility had a written hurricane preparedness plan that detailed how the site planned to protect workers and property before, during, and after a hurricane. On Thursday, August 24, 2017, Arkema personnel decided that the plant needed to be readied in the event the hurricane affected the Crosby facility. Based on the collective experience of Arkema Crosby facility employees, the predicted amount of rain level would likely flood surrounding roads and necessitate activating a "ride-out crew." The ride-out crew would remain on-site because other workers would have difficulty getting to or leaving the facility. None of the Crosby employees, however, anticipated the amount of rain or level of flooding, nor the potential for catastrophic damage, that could result. Employees with decades of plant experience expected there to be light flooding at the facility, but not enough to impact any safety systems.



Clockwise from top: Overview of facility indicating locations of both generators and transformers. Right, bottom-left, middle-left; low temperature warehouse.

Following their hurricane plan, on Friday, August 25, 2017, Arkema halted production and took many precautions to prepare for the storm. These precautions included securing loose materials that could blow away or cause damage in the wind, elevating portable equipment to keep them out of flood waters, acquiring



EXTREME WEATHER, EXTREME CONSEQUENCES: CSB INVESTIGATION OF THE ARKEMA CROSBY FACILITY AND HURRICANE HARVEY



U.S. Chemical Safety and Hazard Investigation Board



Chemical fire at Arkema, Inc.

a boat and a forklift that could operate in flood waters, staging sandbags and other equipment, and ensuring reserve fuel levels. In addition, the Arkema Crosby facility activated its ride-out crew and Arkema later initiated its corporate "crisis team" to deal with the potential impacts of the hurricane on all the Arkema facilities in the gulf area.

Relocation of Organic Peroxides

All the organic peroxides manufactured and stored at the Arkema Crosby facility can decompose and combust if they are not kept below critical temperatures, referred to as Self Accelerating Decomposition Temperatures (SADTs). This meant that organic peroxides located in Low Temperature Warehouses, which are maintained at temperatures as low as negative twenty degrees Fahrenheit, would need to be moved to other refrigerated areas to be kept cold if electrical power was

lost and the Low Temperature Warehouses could not provide refrigeration.

As Hurricane Harvey stalled over Houston and began to pour unprecedented amounts of rain in the area, and flood waters rose at the Arkema Crosby facility, the ride-out crew monitored the condition of the plant. As the storm progressed, it became apparent that if the water continued to rise, the ride-out crew would need to de-energize electrical equipment proactively to prevent short-circuiting by the rising water. Based on their experience, however, the ride-out crew still believed that the event would be manageable and that the hurricane would only minimally affect safety at the facility.

On Sunday, August 27, 2017, the National Hurricane Center stated that "Harvey continues to meander over southeastern Texas, where it is producing catastrophic and life-threatening flooding rainfall."

Significant flooding occurred early Sunday and the ride-out crew preemptively shut down power to several of the refrigerated organic peroxide storage buildings ("Low Temperature Warehouses") before the rising water reached electrical equipment.

By Sunday afternoon, parts of the Crosby facility had four feet of standing water. As the water level rose, it affected operation of the Low Temperature Warehouse's refrigeration systems and workers began moving organic peroxides into refrigerated trailers located on-site. Even when half of the Low Temperature Warehouses were manually powered off due to rising flood levels, the ride-out crew still believed sufficient storage space remained in the Low Temperature Warehouses and refrigerated trailers to prevent combustion of the organic peroxides, because they did not believe they would lose another warehouse. When the refrigerated trailers were filled from the Low Temperature Warehouses, they were then moved to a higher location on the facility where they could operate and keep the organic peroxides cool.

Heavy rainfall continued and water levels at the site kept rising. Workers continued to turn off power to more Low Temperature Warehouses, requiring them to move the organic peroxide products to other locations. By Sunday night, driven by rising flood waters, workers shut off power to all but one of the seven Low Temperature Warehouses and moved the organic peroxides to refrigerated trailers. By the end of Monday,

EXTREME WEATHER, EXTREME CONSEQUENCES: CSB INVESTIGATION OF THE ARKEMA CROSBY FACILITY AND HURRICANE HARVEY



U.S. Chemical Safety and Hazard Investigation Board

there were six refrigerated trailers located on the "high ground" at the facility, sometimes referred to as the laydown yard.

Around 2:00 am on Monday morning, August 28, 2017, the flood waters reached the site's main power transformers and every building on-site lost power. Backup generators turned on automatically, but the rising flood waters forced workers to turn them off for their safety. As a result, the last remaining Low Temperature Warehouse lost power.

Throughout the day on Monday, the equipment used to move the refrigerated trailers and pallets of organic peroxide began to fail as high-water levels impacted electrical components in the forklifts and yard mules used at the facility. At this point, the ride-out crew found itself unable to move the refrigerated trailers to an area of higher elevation in the facility, and was no longer able to lift the pallets of organic peroxide product. The water level in the plant around the Low Temperature Warehouses was about chest height, making it difficult for the ride-out crew members to move about the site.

By the end of the day on Monday, workers were manually moving the remaining small organic peroxide containers, about 2,160 in all, into the final remaining refrigerated trailer from the last Low Temperature Warehouse that had lost power. By this time, workers had moved nearly 10,500 containers (over 350,000 pounds) of



Transformers at the facility.

product into nine refrigerated trailers. Three of those trailers, containing more than 4,000 containers, could not be taken to the higher elevation area due to the flood waters and were now in danger of losing refrigeration as the flood waters began to overflow into their fuel tanks.

Arkema corporate personnel determined that if the refrigerated trailers lost power, the products inside would reach their SADT within a few days and combust. Arkema alerted local emergency responders of this situation.

On the morning of Tuesday, August 29, 2017, Arkema requested that emergency responders evacuate the ride-out crew. After the evacuation, emergency responders implemented a 1.5-mile evacuation zone around the facility based on modeling performed that assumed the refrigerated trailers would combust.

Emergency Response Activities

While it was becoming apparent that there would be a reactive chemical incident at the Arkema Crosby facility and emergency responders were dealing with that eventuality, the massive emergency response effort addressing Hurricane

Harvey remained underway. As the hurricane and subsequent flooding moved from the Houston area eastward into the Beaumont region, responders needed to relocate. Rainfall from the storm flooded portions of Interstate 10, leaving eastbound Highway 90, which cut through the middle of the evacuation zone for the Arkema Crosby incident, as the best route to move resources.

Due to this constraint and the importance of getting personnel and equipment where it was needed, Harris County officials kept eastbound Highway 90, open to traffic even while enforcing the remainder of the evacuation zone, which included the closure of the westbound side of Highway 90 due to flooding. Emergency responders were staged to block the road in the event one of the refrigerated trailers began to combust.

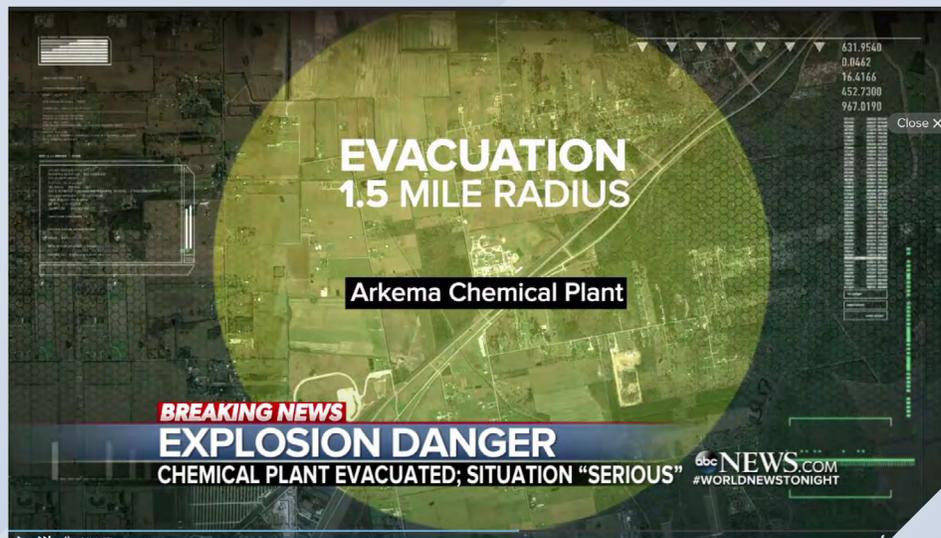
On Wednesday, August 30, 2017, just before midnight, what appeared to be white smoke was reported coming from the Arkema facility and traveling across Highway 90, directly south of the plant. Two police officers assigned to monitor the exclusion zone perimeter reported that they drove through that same cloud of smoke coming from the Arkema facility as they drove east on Highway 90 to respond to a distress call from a resident. After they reported the white smoke cloud, emergency responders closed Highway 90.

Following the report of the white smoke cloud, two members of the Crosby

EXTREME WEATHER, EXTREME CONSEQUENCES: CSB INVESTIGATION OF THE ARKEMA CROSBY FACILITY AND HURRICANE HARVEY



U.S. Chemical Safety and Hazard Investigation Board



ABC News graphic of evacuation radius.

Volunteer Fire Department were sent to the Arkema facility to assess the scene. Upon arriving at the scene, these responders did not see a white cloud or other signs of organic peroxide decomposition at the site. Unified Command also reviewed telemetry data provided by Arkema including temperature readings within some of the trailers showing that the air temperatures in three of the refrigerated trailers were above the estimated SADT. However, not all the trailers could provide this data, and those trailers sending data only measured the air temperature inside of the trailer, not the temperature of the organic peroxide products. Unified Command also reviewed telemetry data provided by Arkema, including temperature readings within some of the trailers. Based on this information and the need to keep eastbound Highway 90 open as long as possible, emergency responders reopened the highway.

One of the police officer who drove through the cloud reported to other police officers that he recorded driving through the cloud on his vehicle's dash cam. Three other police officers then drove their vehicles east on Highway 90 to check on the officer and review his dash cam footage. As they passed by the Arkema facility, the Three officers also drove through the same cloud of smoke.

The three police officers began shortly afterwards to recognize they may have been exposed to chemicals by driving through the same cloud of white smoke coming from the Arkema Crosby facility. That fact, combined with the fact that all nearby roads were flooded, and the desire to get prompt medical attention, led the police officers again to drive west on Highway 90 toward the command post.

The five police officers started driving down Highway 90. As these four police vehicles traveled down Highway 90, the five officers

inside were exposed to a new black smoke cloud coming from the Arkema Crosby facility. By the time they reached the southern end of the exclusion zone, the officers reported experiencing nausea, headaches, sore throat, and itchy watering eyes. Other emergency responders examined the police officers, who were complaining of exposure and flushed their exposed skin with water.

When the officers reached the forward command post they told the emergency responders located there what they had experienced. Harris County emergency response officials shut down travel in both directions Highway 90. As the night progressed, organic peroxides in one of the nine refrigerated trailers continued to decompose and caught on fire.

The next day, Friday, September 1, 2017, at about 5:00 pm, two more refrigerated trailers ignited and burned. At this point, the three refrigerated trailers that could not be moved due to the high waters had all burned, leaving the six refrigerated trailers located on higher ground still uncombusted.

As the evacuation continued, residents began to express concern over their inability to reach their homes to check on their houses and gather belongings.

As it became clear it might take days or weeks for the remaining trailers to combust, emergency responders developed a plan to conduct a controlled burn of the remaining

EXTREME WEATHER, EXTREME CONSEQUENCES: CSB INVESTIGATION OF THE ARKEMA CROSBY FACILITY AND HURRICANE HARVEY



U.S. Chemical Safety and Hazard Investigation Board

trailers. On Sunday, September 3, 2017, emergency responders entered the site and conducted a controlled burn of the remaining six refrigerated trailers.

Once the fires were out, emergency responders lifted the evacuation zone, allowing residents to return home. Highway 90 remained closed to traffic until the all clear was given on September 4, 2017.

Findings

The first three trailers burned in two separate fires at the Crosby facility when organic peroxides requiring low temperature storage lost refrigeration, decomposed, and combusted. Organic peroxides are reactive chemicals that are inherently unstable. This instability requires special storage and handling precautions to prevent them from decomposing and producing heat and byproducts. Organic peroxides are continually decomposing, at a rate based on the temperature of the product. An important organic peroxide safety property is the Self-Accelerating Decomposition Temperature (SADT). Some organic peroxides need to be stored at a low temperature in order to limit the rate of decomposition to a safe level. Companies need to ensure they have sufficient safeguards in place to maintain organic peroxides below their SADT.

Arkema had multiple safety systems in place to ensure that organic peroxides were kept cold and would not reach the SADT. The layers of protection were: redundant



Top: Refrigerated trailer. Right; Refrigeration machinery at front of trailer. Above: Diesel fuel tanks for refrigerated trailer, located under the trailer.

refrigeration systems in the Low Temperature Warehouses; emergency generators to provide power in case a Low Temperature Warehouse lost power; liquid nitrogen for alternative cooling; and refrigerated trailers to store organic peroxide temporarily. These layers of protection identified in Arkema's process hazard analysis (PHA) all failed during Hurricane Harvey from a common mode of failure. The same flood water that caused the facility to lose electrical power also compromised the backup emergency generators, the liquid nitrogen system, and the refrigerated trailers used to temporarily house the organic peroxide products.

Flood Awareness

FEMA flood insurance rate maps and flood insurance studies provide important flood risk information. The Arkema Crosby facility was constructed before any flood maps or studies of the area were done. The first flood map for the area encompassing the Arkema Crosby facility, found by the CSB investigation, was issued in 1985. This map showed that the facility had minimal flood risk. FEMA issued a significant revision to the relevant flood insurance rate map in 2007. This revision established that the entire Arkema Crosby facility sat within a floodplain. Some portions of the facility are in the 100-year floodplain and the remaining areas of the site are in the 500-year floodplain. Although a September 2016 report from Arkema's insurer, FM Global, identified flood risk to the Crosby facility including these floodplain designations, other than a past facility manager, Arkema Crosby facility employees appeared to be unaware of this information. In addition, although Federal process safety

EXTREME WEATHER, EXTREME CONSEQUENCES: CSB INVESTIGATION OF THE ARKEMA CROSBY FACILITY AND HURRICANE HARVEY



U.S. Chemical Safety and Hazard Investigation Board



Warehouse following explosion.

regulations require companies to compile process safety information, flood insurance maps and related studies are not specifically identified as required process safety information. The CSB investigation revealed that other companies may also not be aware of the potential for flood risks to create process safety hazards at their facilities.

Arkema's PHA Policy

The company team that performed the Low Temperature Warehouse PHA for the Crosby facility did not document any flooding risk. Additionally, none of Arkema's safeguards for electrical power failure met company or industry standards for analyzing independent protection layers for the Harvey-level flooding. Given the limited industry guidance on flooding, it is unclear whether that would have provided enough information to specify sufficiently conservative levels of action sufficient to provide specific or sufficiently conservative levels of action to protect against the hazards posed by the flooding that occurred during Hurricane Harvey.

Guidance for companies on how to address flood hazards was available from several different sources including the Center for Chemical Process Safety and Federal Emergency Management Agency. This guidance, however, is either too generic or did not require conservative enough precautions that would have helped Arkema prevent this incident. For example, this guidance did not require elevating critical equipment to levels that would have prevented flood waters from impacting safety systems at the Arkema Crosby facility. Based on this type of shortcoming, more robust industry guidance is needed to help hazardous chemical facilities better prepare for extreme weather events.

History of Flooding at Arkema

Although the Crosby facility had a history of flooding over the past 40 years, employees could not recall flood waters over two feet prior to Hurricane Harvey, which caused at least four feet of flood water at the facility. When determining the risk of 100-year or 500-year flooding

events, however, using individual employees' experience is insufficient to determine the risk level. For example, long-term employees at the Arkema Crosby facility identify tropical storm Allison in 2001 as the previous high-water benchmark for flooding at the site. Flood records, however, suggest rainfall from Hurricane Rosa in 1994 and even an unnamed storm in 2015 produced more significant flooding at the Crosby site. Given that Federal process safety regulations only require companies to retain incident data for five years, companies should develop systems to retain key incident summary information that better document their risks from historical process safety events, including flooding, which have a low probability of occurrence but threaten a high degree of potential health and safety consequences.

Extreme Flooding Events

Hurricane Harvey led to flooding above the 500-year flood plain elevation. While this flood level was unprecedented in the area, extreme flooding had been occurring with regularity. Since 1994, the water gauge closest to the Crosby facility recorded three 100-year flooding events and Hurricane Harvey, a 500-year flooding event. In recent years, flooding from extreme rainfall events has increased and according to a 2015 EPA report, this trend is projected to continue, resulting in an increased flood risk in many parts of the United States. Further, future projections show Texas leading the nation in potential for flood-related damage.

EXTREME WEATHER, EXTREME CONSEQUENCES: CSB INVESTIGATION OF THE ARKEMA CROSBY FACILITY AND HURRICANE HARVEY



U.S. Chemical Safety and Hazard Investigation Board



Remains of refrigerators in the 'Lay Down' yard.

Evacuation Efforts

Highway 90 ran adjacent to the Crosby facility and bisected the evacuation zone. It remained open to eastbound traffic even after emergency response officials established the evacuation zone. Keeping Highway 90 open allowed emergency responders to travel within close proximity to the plant even after the first fire began. This decision resulted in at least 21 people reported being exposed to decomposition products and smoke from the burning refrigerated trailer and organic peroxides. Emergency responders had limited options available to facilitate critical transportation as Highway 90 was important to the larger Hurricane Harvey response. When the first police officer reported a white cloud of smoke, however, emergency responders should not have reopened Highway 90 until they confirmed there was no combustion occurring, despite contrary indications from telemetry data coming from the trailers containing the organic peroxides which showed no sign of combustion.

Key Lessons - Industry Guidance

The CSB provides the following key lessons for companies with chemical manufacturing, handling, or storage facilities located within areas that are susceptible to extreme weather events, such as flooding.

- Facilities should perform an analysis to determine what potential extreme weather events they are susceptible to. Flood maps should be evaluated to determine if any portion lies within the 100-year or 500-year flood plain. Seismic hazard maps should be evaluated to determine the potential risk of earthquake. Risk of other extreme weather events such as lightning strikes and high wind events should also be considered.
- Risk assessment and the adequacy of safeguards should be evaluated in facility process safety management programs, such as PHAs or facility siting. Facilities should strive to apply a sufficiently

conservative risk management approach when evaluating and mitigating potential impacts from extreme weather scenarios.

- For flooding scenarios, facilities should ensure that critical safeguards and equipment is not susceptible to common mode failures and that independent layers of protection are available in the event of high water elevation at the facility.

Summary of Recommendations

As a result of its investigation, the CSB is issuing safety recommendations to management at the Arkema Crosby facility, Arkema Inc., the American Institute of Chemical Engineers Center for Chemical Process Safety, and to officials of Harris County, Texas. The CSB urges companies to review the key safety lessons and safety guidance contained in this document for application at their facilities and to evaluate their existing process safety management practices and equipment design for potential improvements.