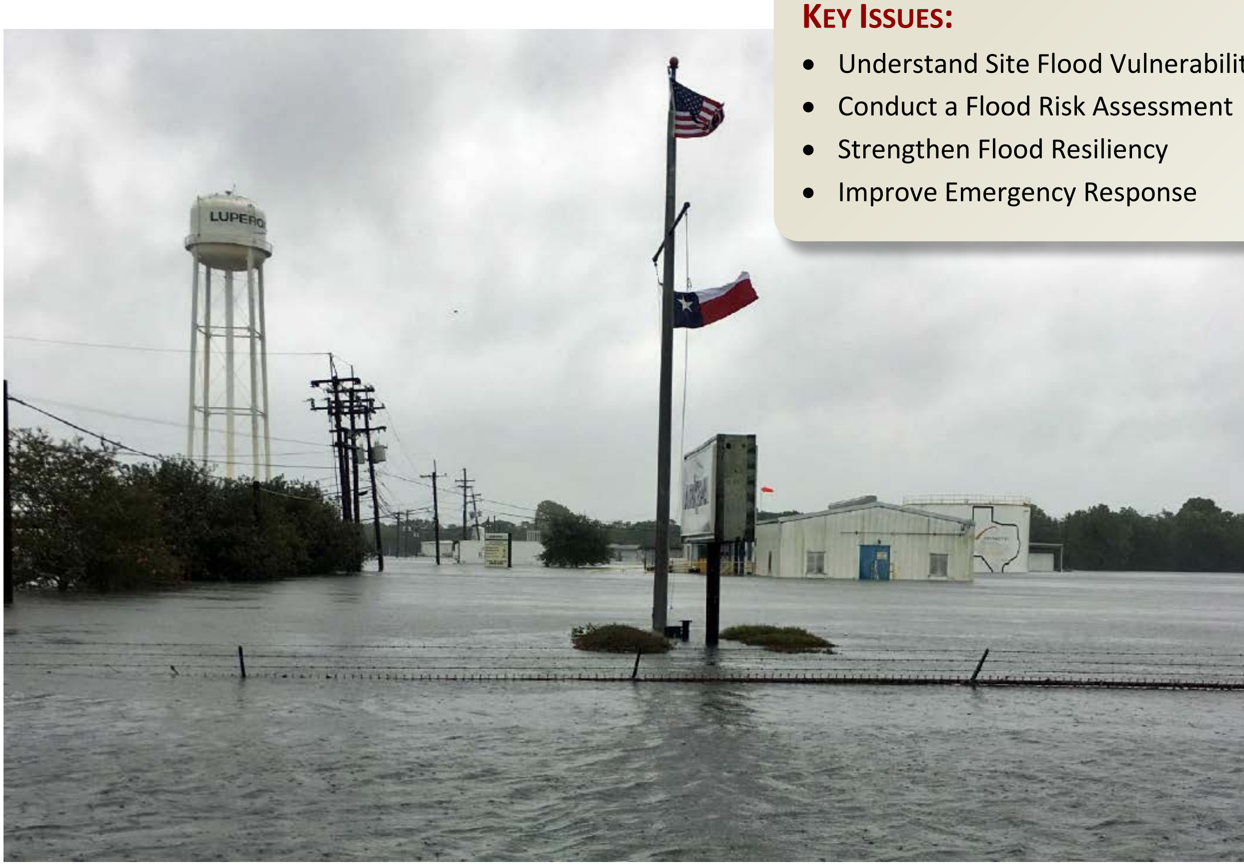
Organic Peroxide Decomposition, Release, and Fire at Arkema Crosby Following Hurricane Harvey Flooding

Crosby, Texas

Incident Date: August 31, 2017
Exposures to Emergency Responders, Community Evacuation, and Property Damage

KEY ISSUES:

- Understand Site Flood Vulnerability
- Conduct a Flood Risk Assessment
- Strengthen Flood Resiliency
- Improve Emergency Response



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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

ACC	American Chemistry Council
AEGL	Acute Exposure Guideline Level
AEP	Annual Exceedance Probability
ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
API	American Petroleum Institute
AQI	Air Quality Index
ASCE	American Society of Civil Engineers
ASPECT	Airborne Spectral Photometric Environment Collection Technology
BFE	Base Flood Elevation
BOC	Bottom of Channel
CCPS	Center for Chemical Process Safety
CDL	Commercial Driver License
CFR	Code of Federal Regulations
COMAH	Control of Major Accident Hazards
CSB	U.S. Chemical Safety and Hazard Investigation Board
CVFD	Crosby Volunteer Fire Department
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
EPR	Environmental Permitting Regulations
EU-JRC	European Commission's Joint Research Centre
FEMA	Federal Emergency Management Agency
FIA	Federal Insurance Administration
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
HCFCD	Harris County Flood Control District
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
KOP	King of Prussia
LOPA	Layer of Protection Analysis
NFPA	National Fire Protection Association
NIMS	National Incident Management System
NOAA	National Oceanic and Atmospheric Administration
NTSB	National Transportation Safety Board
OSHA	Occupational Safety and Health Administration
PHA	Process Hazard Analysis
PSM	Process Safety Management
PVC	Polyvinyl Chloride
RAGAGEP	Recognized and Generally Accepted Good Engineering Practice
RMP	Risk Management Plan
RP	Recommended Practice
SDS	Safety Data Sheet

SADT	Self-Accelerating Decomposition Temperature
SCBA	Self-Contained Breathing Apparatus
SDS	Safety Data Sheet
TCEQ	Texas Commission on Environmental Quality
TEPCO	Tokyo Electric Power Company
TOB	Top of Bank
TVA	Tennessee Valley Authority
U.K.	United Kingdom
UN	United Nations
U.S.	United States of America
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey

1. SUMMARY

1.1. OVERVIEW OF INCIDENT EVENTS AND ACTIVITIES

1. On August 24, 2017, Hurricane Harvey, a Category 4 hurricane, made landfall in southeast Texas. Over the next several days, the storm produced unprecedented amounts of rainfall over southeast Texas and southwest Louisiana, causing significant flooding. Hurricane Harvey turned out to be the most significant tropical cyclone rainfall event and the second most costly hurricane in U.S. history, after Hurricane Katrina. Over the course of the storm, Hurricane Harvey killed 68 people and flooded over 300,000 structures, forcing roughly 40,000 people to evacuate their homes. Hurricane Harvey required a large emergency response effort supported by local, state, and Federal officials.

2. The Arkema Crosby facility is located within the 100-year and 500-year flood plain.[a] Extensive flooding caused by heavy rainfall from Hurricane Harvey exceeded the equipment design elevations and caused the plant to lose power, backup power, and critical organic peroxide refrigeration systems. Consequently, Arkema used its standby refrigerated trailers to keep the organic peroxide products cool. This flooding also eventually forced all Arkema's employees to evacuate from the facility. A Unified Command established a 1.5-mile evacuation zone around the Arkema facility and helped transport residents out of this zone for their safety.

3. On August 31, 2017, organic peroxide products stored inside a refrigerated trailer decomposed, causing the peroxides and the trailer to burn. Twenty-one people sought medical attention from exposure to fumes generated by the decomposing products when the vapor travelled across a public highway adjacent to the plant. Emergency response officials initially decided to keep this highway open, despite the fact that it ran through the established evacuation zone around the Arkema facility, because this road served as an important route for hurricane recovery efforts. Over the next several days, a second fire and a controlled burn conducted by the Unified Command consumed eight more trailers holding Arkema's remaining organic peroxide products that required low-temperature storage. 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 who had evacuated the area could not return home for a week. Figure 1 provides a timeline for the incident events and activities that unfolded at the Arkema Crosby facility as Hurricane Harvey moved through southeast Texas and flooded the site.

[a] A 100-year flood plain, also called the base flood elevation, is an area that has a one percent risk for flooding in any given year. A 500-year flood plain is an area with a 0.2 percent risk for flooding in any given year.

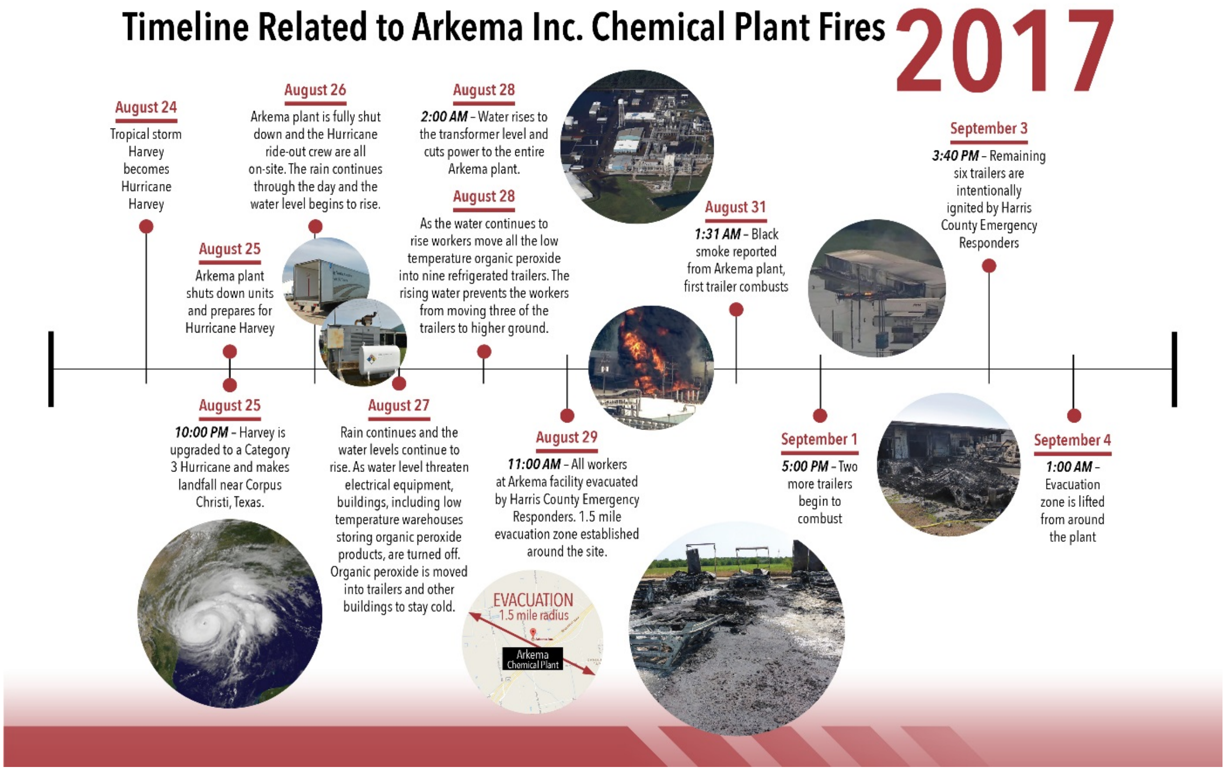

Figure 1. Overview Timeline for the Incident Events and Activities at the Arkema Crosby Facility.

1.1.1. PREPARING FOR HURRICANE HARVEY

4. After Hurricane Harvey had traveled through the Gulf of Mexico for over 10 days, on Wednesday, August 24, 2017, it became clear that the storm would impact the middle and upper Texas coast and likely stall over Texas [1]. Meteorologists projected that 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 predicted to receive as much as 30 inches over the duration of the storm [2]. In anticipation of Hurricane Harvey, personnel at the Arkema Crosby facility began to prepare even though they were not projected to be in the direct path of the storm.

5. 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 would likely flood surrounding roads and necessitate activating a “ride-out crew.” The ride-out crew would remain onsite 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, or the potential for catastrophic damage that could result. Employees with decades of plant experience expected light flooding at the facility, but not enough to impair any safety systems.

6. Following its hurricane preparedness 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 expected winds; elevating portable equipment to keep it out of floodwater; acquiring a boat and a forklift that could operate in floodwater; staging sandbags and other equipment; and ensuring adequate reserve fuel levels. In addition, the Arkema Crosby facility activated its ride-out crew and Arkema later initiated its corporate "crisis team" to help manage the potential effects of the hurricane on all of the Arkema facilities in the Gulf area.

1.1.2. Relocation of Organic Peroxides

7. All of 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). Some of the organic peroxide products at the Crosby facility had SADTs low enough that they required continuous refrigeration to prevent decomposition. This meant that organic peroxide products located in the refrigerated organic peroxide cold storage buildings ("Low Temperature Warehouses"), which were maintained at temperatures as low as -20 °F (degrees Fahrenheit), would need to be moved to other refrigerated areas to be kept cold if the warehouses lost electrical power and could not provide the required refrigeration.

8. As Hurricane Harvey stalled over Houston and began to pour unprecedented amounts of rain in the area, the ride-out crew monitored the conditions of the plant as floodwater rose at the Arkema Crosby facility. As the storm progressed, it became apparent that if the water level continued to rise, the ride-out crew would need to de-energize electrical equipment proactively to prevent short-circuiting. Based on their experience, however, the ride-out crew members still believed that the event would be manageable and that the hurricane would only minimally affect safety at the facility. Throughout the storm, the ride-out crew thought the water levels would stop rising, and if they could just manage the next few hours, the water would begin to drop.

9. On Sunday, August 27, 2017, the National Hurricane Center stated, "Harvey continues to meander over southeastern Texas, where it is producing catastrophic and life-threatening flooding rainfall [3]." Significant flooding occurred at the facility early on Sunday and the ride-out crew preemptively shut down power to several of the Low Temperature Warehouses before the rising water reached any of the electrical equipment.

10. By Sunday afternoon, parts of the Crosby facility had approximately four feet of standing water. As the water level rose, it threatened the continued operation of the Low Temperature Warehouse's refrigeration systems, so workers began moving the organic peroxide products into refrigerated truck trailers which were located onsite. Even when half of the Low Temperature Warehouses were manually powered off due to the rising floodwater level, the ride-out crew still believed sufficient storage space remained because the crew members did not believe that they would lose another warehouse. When the trailers were filled with product from Low Temperature Warehouses, they were then moved to a high location on the facility's grounds, referred to as the laydown area, where these refrigerated trailers could operate and continue to cool the organic peroxide products.

11. Heavy rainfall continued in the area, and the water level at the Arkema Crosby site kept rising. Workers continued to turn off power to additional Low Temperature Warehouses, which required them to move the organic peroxide products to other locations. By Sunday night, confronted by the rising floodwater, workers shut off power to all but one of the seven Low Temperature Warehouses and moved the organic peroxide products to refrigerated trailers. By the end of the day on Monday, there were six refrigerated trailers sitting on the high ground at the facility.

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

13. Throughout the day on Monday, the equipment that workers used to move the refrigerated trailers and pallets of organic peroxide began to fail as the high level of floodwater affected electrical components in the forklifts and the semi-tractor trucks used at the facility. At this point, the ride-out crew found itself unable to move the refrigerated trailers to higher elevation in the facility, and was no longer able to lift the pallets of organic peroxide product. Moreover, the water level in the plant around the Low Temperature Warehouses was now about chest-high, making it difficult for the ride-out crew members to move about the site.

14. By the end of the day on Monday, the workers were manually transferring the remaining small organic peroxide containers, about 2,160 in all, into the final remaining refrigerated trailer from the last Low Temperature Warehouse, which had lost power. By this time, the workers had moved nearly 10,500 containers (over 350,000 pounds) of products into nine refrigerated trailers. Three of those trailers, containing more than 4,000 containers, however, could not be taken to the higher elevation area due to the floodwater and were now in danger of losing refrigeration as the floodwater began to overflow into their fuel tanks.

15. Arkema corporate personnel determined that if the refrigerated trailers lost power, the organic peroxide products inside would reach their SADT within a few days and combust. Arkema personnel then alerted local emergency responders about this evolving situation. Arkema also provided the Unified Command with refrigerated trailer telemetry data and estimated SADTs of the organic peroxides for six of the refrigerated trailers beginning midday on Wednesday August 30, 2017.

16. 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. Arkema warned the Unified Command about the hazards of organic peroxide decomposition and alerted them that emergency responders who may be exposed to this material should wear personal protective equipment and self-contained breathing apparatus.

1.1.3. Emergency Response Activities

17. While it was becoming apparent that a reactive chemical incident would occur at the Arkema Crosby facility—and while emergency responders were dealing with that eventuality—the massive emergency response to Hurricane Harvey remained underway. As the hurricane and subsequent flooding advanced from the Houston area eastward into the Beaumont region, emergency responders needed to move as well. 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 for transporting hurricane relief and rescue resources.

18. Due to this constraint and the importance of transporting personnel and equipment to where they were needed, Harris County officials kept eastbound Highway 90 open to traffic even while enforcing the remainder of the evacuation zone. Emergency responders were also staged to block the road if the contents of one of the refrigerated trailers began to combust.

19. On Wednesday, August 30, 2017, just before midnight, two of the police officers assigned to monitor the exclusion zone perimeter reported that they drove through a cloud of white smoke coming from the Arkema Crosby facility as they drove west on Highway 90 to respond to a call related to flooding in the area. After they reported the white smoke cloud, the Unified Command closed Highway 90.

20. Following the report of the white smoke cloud, two members of the Crosby Volunteer Fire Department were sent to the Arkema facility to assess the scene. Upon arrival at the site, these responders did not see a white cloud or other signs of organic peroxide decomposition. The 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. Three of the nine refrigerated trailers, however, could not provide this data. Furthermore, those trailers sending data only measured the air temperature inside of the trailer and not the temperature of the organic peroxide products so the readings did not necessarily mean that the organic peroxide contents were decomposing. Based on the need to keep eastbound Highway 90 open as long as possible and the visual confirmation that there was no decomposition occurring, emergency responders reopened the highway.

21. The police officers who drove through the white smoke cloud reported to other police officers that their vehicle's dash cam recorded the white cloud and that some type of release was occurring at the facility. Three other police officers then drove their vehicles east on Highway 90 to check on the officers and to review the dash cam footage. As these officers passed by the Arkema facility, they also reported driving through a white cloud of smoke coming from the facility.

22. Shortly thereafter, all five police officers recognized they might have been exposed to chemicals by driving through the cloud of white smoke coming from the Arkema Crosby facility. The combination of their symptoms, and their desire to get prompt medical attention led the police officers to drive west on Highway 90 toward the command post and medical aid to obtain treatment.

23. In all, five police officers in four police vehicles drove west down Highway 90 toward the command post. The officers called to request medical assistance when they reached the southwestern end of the exclusion zone. During this trip, the officers reported being exposed to a black smoke cloud coming from the Arkema Crosby facility. By the time they reached the southwestern end of the exclusion zone, the officers reported experiencing nausea, headaches, sore throats, and itchy watering eyes. Other emergency responders examined the police officers, who were complaining of exposure to the smoke, and flushed the officers' exposed skin with water.

24. When the officers reached the forward command post they told the emergency responders what they had experienced. Harris County emergency response officials then shut down travel in both directions on Highway 90. Highway 90 was not reopened until the all-clear was sounded days later. As the night progressed, organic peroxide products in one of the nine refrigerated trailers continued to decompose and then caught on fire.

25. 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 to the high ground in the laydown area due to the high waters had all burned and the remaining six refrigerated trailers located on higher ground had still not combusted. It is likely that the refrigeration units on these trailers were still operating, but with no way to check on the contents inside of the trailers and only relying on telemetry data, the Unified Command could not safely remove the organic peroxide contents.

26. Residents who had been evacuated were still not allowed to reenter the 1.5-mile perimeter because the six refrigerated trailers still had not combusted. Around this time many evacuees began to express concern over their inability to check on their homes and gather their belongings. As it became clear that days or weeks might pass before the remaining trailers burned, the emergency responders developed a plan to conduct a controlled burn of those trailers.

27. On Sunday, September 3, 2017, emergency responders entered the Arkema Crosby site and conducted a controlled burn of the remaining six refrigerated trailers in order to end the evacuation and incident. Once the fires burned out, the emergency responders lifted the evacuation zone, allowing residents to return to their homes. Finally, on September 4, 2017, the Unified Command announced the all-clear and opened Highway 90 to traffic.

1.2. Key Findings and Lessons

28. Organic peroxides are reactive chemicals that are inherently unstable. Because of this instability, these reactive chemicals require special storage and handling precautions to prevent the organic peroxides from decomposing and producing heat and byproducts. Organic peroxides continually decompose at a rate based on the temperature of the product. An important organic peroxide safety property is the Self-Accelerating Decomposition Temperature or SADT. All of the organic peroxides produced by Arkema must be stored at a temperature below their SADT to limit the rate of decomposition to a safe level. The first three refrigerated trailers burned in two separate fires at the Arkema Crosby facility when the trailers lost refrigeration and the organic peroxide products inside, which required low-temperature storage, decomposed and combusted. Companies need to

ensure they have sufficient safeguards in place to maintain organic peroxide products below their SADTs.

29. Arkema had multiple safety systems in place to ensure that organic peroxide products were kept cold and would not reach their SADTs. In Arkema's process hazard analysis (PHA), the PHA team members identified the following layers of protection: redundant 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. All of these layers of protection failed during Hurricane Harvey because of flooding which was a common mode of failure. None of Arkema's safeguards used to address electrical power failure met company or industry standards for analyzing independent protection layers for Harvey-level flooding. The same floodwater 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 store and cool the organic peroxide products. Companies need to ensure there are not common modes of failure in their layers of protection.

30. Federal Emergency Management Agency (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 developed. The first flood map for the area encompassing the Arkema Crosby facility, found by the CSB investigation, was issued in 1985. This map showed minimal flood risk for the facility. FEMA issued a significant revision to the relevant flood insurance rate map in 2007. This revision established that the entire Arkema Crosby facility sits 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 risks to the Crosby facility, including these floodplain designations, Arkema Crosby facility employees, other than a past facility manager, appeared to be unaware of this information. Although Federal process safety regulations require companies to compile relevant process safety information, the regulations do not specifically identify flood insurance maps and related studies as required process safety information. The CSB investigation revealed that other companies also might be unaware of the potential for flood risks to create process safety hazards at their facilities if flood-related information is not typically compiled or assessed in required safety analyses.

31. The Arkema team that performed the Low Temperature Warehouse PHA for the Crosby facility did not document any flooding risk. Had the Arkema PHA assessed flooding, the limited industry guidance on flooding would likely have been insufficient to provide specific or sufficiently conservative level of action to protect against the hazards posed by the flooding during Hurricane Harvey. Even without this assessment, however, the Crosby facility appears to have had sufficient safeguards in place to prevent loss of refrigeration in the Low Temperature Warehouses for a 100-year flooding event.

32. Industry safety guidance for companies on how to address flood hazards was available from several different sources, including the Center for Chemical Process Safety (CCPS) and FEMA. This guidance, however, is either too generic or does not require sufficiently conservative precautions to have helped Arkema prevent this incident. For example, this guidance does not require elevating

critical equipment to heights that would have prevented Hurricane Harvey-level floodwater from disabling safety systems at the Arkema Crosby facility. Given this type of shortcoming, more robust industry guidance is needed to help hazardous chemical facilities better prepare for extreme weather events, such as flooding, hurricanes, snowstorms, tornadoes, or droughts.

33. Although the Arkema Crosby facility had a history of flooding over the past 40 years, long-term employees could not recall floodwater occurring higher than two feet before Hurricane Harvey. As a result, Arkema did not consider flooding of its safety systems to be a credible risk. When determining the risk of 100-year or 500-year flooding events, however, relying on the experience of individual employees is insufficient to determine the risk level. For example, long-term employees at the Arkema Crosby facility recalled Tropical Storm Allison in 2001 as the previous high-water benchmark for flooding at the site. In contrast, flood records suggest that rainfall from Hurricane Rosa in 1994, and even rainfall from an unnamed storm in 2015, produced more significant flooding at the Crosby site than did Allison. Hurricane Harvey produced over five feet of flooding in some areas of the Arkema Crosby facility. Companies should develop systems to retain key incident summary information that better document facility risks based on historical external events. These external events, such as flooding, have a low probability of occurrence but can threaten severe health and safety consequences.

34. Flooding from Hurricane Harvey extended above the 500-year flood plain elevation. Although this flood level was unprecedented in the area, extreme flooding had been occurring with regularity. Since 1994, the water gauge closest to the Arkema Crosby facility recorded three 100-year flooding events, one of which came close to the 500-year flood criteria. In recent years, flooding from extreme rainfall events has increased and according to a 2015 EPA report, this trend is projected to continue, increasing the flood risk in many parts of the U.S. This EPA report also provides future projections that show Texas as leading the nation in the potential for flood-related damage.

35. Highway 90, which bisected the evacuation zone, remained open to eastbound traffic even after emergency response officials established the evacuation zone. Although admittedly a difficult decision for the Unified Command, keeping Highway 90 open for use in moving people and resources in relation to the eastward trajectory of Hurricane Harvey allowed emergency responders to travel within close proximity to the plant even after the first fire began. But once a report came in that the situation at the Crosby facility became less stable and that decomposition might be occurring, emergency response officials should have closed Highway 90 and established alternative routes. As a result of this decision, at least 21 people were exposed to decomposition products and smoke from the burning refrigerated trailer and organic peroxides. Hurricane Harvey emergency responders had limited options available to facilitate critical transportation other than Highway 90. The telemetry data coming from the trailers containing the organic peroxide products showed no signs of combustion; however, the police officers reported a chemical release after driving into the white smoke cloud, smelling the vapor, and experiencing exposure symptoms. In an emergency, data are frequently incomplete and can even be contradictory, so emergency responders must be as conservative as practicable so that they can protect both themselves and the public.

36. In the United Kingdom, the Environment Agency published guidance to help regulated facilities conduct flood planning. This flood preparation guidance recommends that companies should be

aware of their flood risks at all facilities, obtain flood modeling results, prepare a flood plan, and improve their flood resilience. The guidance also recommends that companies should be able to implement their flood plan before flooding and that each plan include steps to protect workers, safeguard hazardous processes, and secure hazardous materials. Of relevance to the Arkema Crosby incident, the Environment Agency flood preparation guidance specifically discusses safeguarding chemical products that are vulnerable to risks posed by floodwater and proactively protecting key utilities, such as electrical power and liquid nitrogen.

1.3. Guidance to Industry

37. In response to the incident, Arkema commissioned a site elevation survey for its Crosby facility to understand the elevation for all relevant points at the facility as well as a hydrological study to understand the likely flooding conditions during extreme weather events, such as hurricanes. Arkema will be able to use this data to evaluate the risks for a number of floodwater severity levels to help prevent future loss of refrigeration leading to organic peroxide product decomposition.

38. Reflecting the positive actions taken by Arkema post-incident, the CSB provides guidance to companies with chemical manufacturing, handling, or storage facilities in areas that are susceptible to extreme weather events, such as flooding.

- Such facilities should perform an analysis to determine their susceptibility to extreme weather events. Companies should compile key safety information such as flood maps within their process safety information programs. This important safety information should be evaluated to determine whether any portions of their facilities are located within the 100-year or 500-year flood plain. In addition, companies should assess seismic hazard maps to determine the risk of earthquakes and consider the risk of other extreme weather such as high-wind events.

- Companies should evaluate risk assessments and the adequacy of relevant safeguards by applying facility process safety management programs, such as process hazard analyses or facility siting programs. Facilities should strive to apply a sufficiently conservative risk management approach when evaluating and mitigating the potential effects of extreme weather scenarios.

- Facilities should ensure that critical safeguards and equipment are not susceptible to common mode failures. For flooding scenarios, independent layers of protection should be available if floodwater heights reach the facility.

1.4. Summary of Recommendations

39. This report provides details of the incident and its causes, provides key safety lessons, and communicates industry safety guidance with the goal of preventing a similar incident. 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.

2. Background Information On Arkema Crosby Operations

40. The Arkema Group is a global chemical manufacturer reporting annual sales of $9 billion, operating in nearly 50 countries with about 20,000 employees world-wide [4].[a] The company was formed during the reorganization of Total's chemicals branch in 2004 [5].

41. In North America, the Arkema Group operates under its subsidiary Arkema Inc. ("Arkema") with headquarters in King of Prussia (KOP), Pennsylvania [6]. This regional subsidiary employs about 6,000 people and operates 48 sites in the United States, Canada, Mexico, and Brazil [6].

42. Arkema produces numerous chemicals, including a variety of organic peroxide products that the company refers to as Luperox® organic peroxides.[b] Shipping regulations prohibit transporting many of these organic peroxide products by air. As a result, the global Arkema Group manufactures these organic peroxide products locally in nine different countries [7].[c] Arkema Inc., a subsidiary, manufactures organic peroxide products in three different countries, the United States, Mexico, and Brazil.

43. In the United States, Arkema manufactures organic peroxide products at the following three locations:

- Crosby, Texas ("Arkema Crosby") [8];
- Franklin, Virginia [9]; and
- Geneseo, New York [10].

2.1. Organic Peroxides

44. The Arkema facility in Crosby, Texas employs about 50 people and produces about 30 different types of organic peroxide products that the company markets to polymer manufacturers [11, p. 2]. The organic peroxide products are used to develop a variety of consumer products such as solid surface countertops, polystyrene cups and plates, polyvinyl chloride (PVC) plates and cups, and in automotive components such as hoses, gaskets, and headlight assemblies [12]. Arkema's

[a] Sales figure based on the €7.5 billion figure reported by Arkema and the September 2017 exchange rate of $1.2 per euro [4].

[b] "Organic peroxides are initiators used in a variety of fields including commodity polymers (reaction initiators for low-density polyethylene, PVC and polystyrene), acrylic polymers, unsaturated polyesters and rubber crosslinking. [Arkema Group internal estimates show] that it ranks number two worldwide in this sector. Its main competitors are AkzoNobel and United Initiators [214, p. 24]."

[c] Arkema manufactures Luperox organic peroxide products in the United States, Mexico, Brazil, Germany, Italy, India, China, Korea, and Japan (joint venture) [7].

predecessor purchased the Crosby plant property in 1960 and constructed its chemical manufacturing processes in the 1960s.[a, b]

45. Organic peroxides are unstable chemicals, making them commercially important as polymerization initiators and curing agents [13, p. 219]. Because of this instability, organic peroxides require special storage and handling precautions [13, p. 219]. The inherent instability of organic peroxides stems from their oxygen-oxygen (-O-O-) bond, known as a peroxy functional group [14, p. 3].[c] This peroxy functional group decomposes with heat producing commercially desirable chemical reactions, in addition to heat and byproducts [14, p. 3].[d]

46. Organic peroxides continually decompose at a rate that depends on their temperature [13, p. 219]. Each organic peroxide decomposes at a different rate, and some of them need to remain at a low temperature in cold storage for quality or safety reasons [14, p. 3], [11, p. 2], [15, p. 71].[e]

47. When an organic peroxide decomposes it generates heat and when the heat gained exceeds the rate of heat loss to the surroundings, the temperature of the organic peroxide increases and can accelerate the decomposition of the remaining peroxide [13, p. 219]. As the temperature increases, this reaction can result in a self-accelerating decomposition runaway reaction [13, p. 219], [16, p. 4].[f]

48. An important organic peroxide safety property is the Self-Accelerating Decomposition Temperature (SADT) – the lowest temperature at which an organic peroxide product (in its transport packaging) exhibits self-accelerating decomposition [17, p. 7].[g, h] Organic peroxides still decompose at temperatures below the SADT, but this decomposition is slow enough that it does not lead to self-acceleration [17, p. 8]. Figure 2 shows an Arkema safety video image excerpt of an organic peroxide violently reacting from self-reactive decomposition [18].[i]

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[a] Arkema expanded its chemical production and warehouse facilities over the years.

[b] Arkema records show the Crosby site was originally owned by Wallace & Tiernan. In 1969 Wallace & Tiernan merged with Pennsalt, becoming Pennwalt. The Crosby facility remained with Pennwalt until it was acquired by Elf Aquitaine in 1990. In 2004, when Arkema was formed, the site became part of Arkema Inc.

[c] A functional group is a group of atoms that give molecules similar properties. *The Functional Group Explained* [215].

[d] AkzoNobel published several videos showing how industry uses its organic peroxides, including *Crosslinking Polymers with Organic Peroxides* [175], *Free Radical Polymerization* [174], and *Unsaturated Polyester Resin Curing* [173].

[e] Organic peroxide decomposition includes the production of vapor (gas). Some of this vapor may be flammable, but unlike hydrogen peroxide decomposition, organic peroxides do not generally release oxygen [14, p. 17].

[f] A thermal runaway is "An exothermic reaction can lead to thermal runaway, which begins when the heat produced by the reaction exceeds the heat removed. The surplus heat raises the temperature of the reaction mass, which causes the rate of reaction to increase. This in turn accelerates the rate of heat production [176, p. 1]."

[g] The SADT is the lowest temperature at which a tested organic peroxide in its packaging will exhibit self-accelerating decomposition within one week. Thus, the SADT depends on both the organic peroxide formulation and its packaging [14, p. 16].

[h] "The SADT is the lowest temperature at which product in a typical package will undergo a self-accelerating decomposition. The reaction can be violent, usually rupturing the package, dispersing peroxide, liquid and gaseous decomposition products considerable distances. The heat generated might autoignite flammable vapors. There is generally a period of time after the SADT is reached and before the decomposition becomes violent. The length of time depends upon how much the SADT is exceeded, which can greatly accelerate the decomposition [153, p. 1]."

[i] The original video is available on the Arkema website [236].

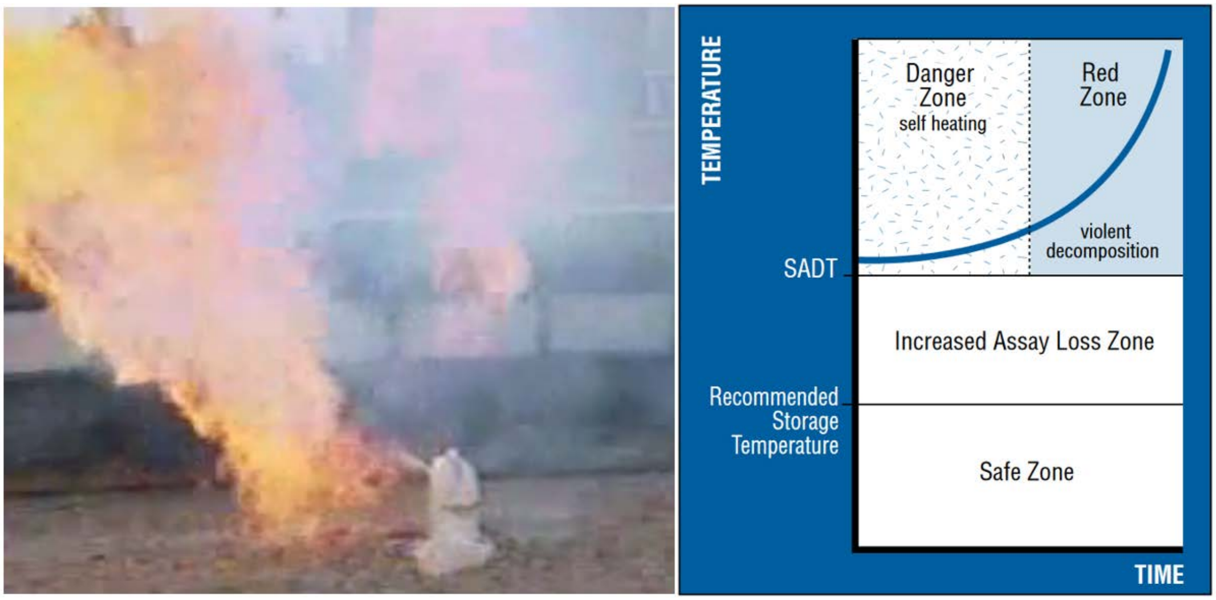

Figure 2. Organic Peroxide Decomposition. The image on the left is from a video showing an organic peroxide container under self-accelerating decomposition conditions [18]. The graphic on the right is an Arkema illustration showing that organic peroxide products are safe below the "Recommended Storage Temperature" and that the uncontrolled decomposition reaction that occurs above the SADT [11, p. 3].

49. At the time of the incident, the Arkema Crosby facility stored about 367,000 pounds of organic peroxide products that required refrigeration in the Low Temperature Warehouses. These products included 11 organic peroxide products requiring refrigeration because their SADT's ranged from 23 to 113 °F.[a] These organic peroxide products are hazardous, but not the most hazardous class of organic peroxides based on U.S. Department of Transportation (DOT) regulations.[b] Although an explosion of these organic peroxide products is possible, in their final product packaging a fire is the more probable hazard in a potential heating scenario, such as prolonged loss of refrigeration [19].[c] Additional organic peroxide information is provided in Appendix B.

2.2. ORGANIC PEROXIDE STORAGE BUILDINGS

50. The Arkema Crosby facility has nine organic peroxide storage buildings. Seven of these are cold storage buildings, referred to as Low Temperature Warehouses that Arkema maintains between -20 °F and 0 °F depending on the requirements of organic peroxide(s) stored inside (Figure 3). One organic peroxide product storage building operates at ambient temperature. The final organic peroxide storage building is the largest at the Arkema Crosby facility and has several internal compartments that the company maintains between 40 °F and ambient temperature.

[a] Arkema's required storage temperature for each organic peroxide product is well below the SADT.

[b] 49 C.F.R. § 173.128 (b) (2004).

[c] Safety Data Sheets for organic peroxide Types C through F use a flame pictogram and hazard statement that "heating may cause fire." Type A and B organic peroxides have potential explosion hazards [19].

Figure 3. Crosby Low Temperature Warehouses. Three of the seven Low Temperature Warehouses at the Arkema Crosby facility are shown in this photograph. (Source: CSB Photo)

2.3. Refrigeration

51. Each of the seven Low Temperature Warehouses is cooled using an electrically-powered refrigeration system (Figure 4). Each Low Temperature Warehouse is equipped with at least two refrigeration systems, with one serving as a backup. Because refrigeration is needed to maintain some of Arkema's organic peroxide below the self-accelerating decomposition temperature, the company's procedures stress the importance of taking prompt action when refrigeration equipment problems arise.

Figure 4. Typical Refrigeration Equipment Used to Keep the Low Temperature Warehouses Cold at the Arkema Crosby Facility. The photo on the left shows refrigeration evaporator equipment used to remove heat from the inside of a Low Temperature Warehouse. The photo on the right shows refrigeration condensing equipment, that removes heat from the refrigerant and also shows electrical equipment for the refrigeration system and other electrically powered equipment for the building, such as lighting.[a] (Source: CSB Photo)

52. Arkema's procedures detail actions to take in response to a variety of scenarios that might elevate the temperature in one of the Low Temperature Warehouses. Identified actions include:

- Expediting maintenance for refrigeration equipment issues;
- Relocating the organic peroxide products to another Low Temperature Warehouse;
- Starting up the emergency generators to supply backup electrical power;
- Using liquid nitrogen as an alternative source of refrigeration; and
- Moving the organic peroxide products to refrigerated truck trailers.

2.4. Emergency Generators

53. Seven diesel-powered emergency generators supply a backup source of electricity to buildings and equipment at the Arkema Crosby facility (Figure 5). Two of the seven emergency generators provide backup power to Arkema's Low Temperature Warehouses.

[a] See *HOW IT WORKS: Refrigerators* for a basic explanation of refrigeration [208].

Figure 5. One of Seven Emergency Generators at the Arkema Crosby Facility. Generator 21-GN-1 is one of the two generators providing emergency electrical power to Arkema's seven Low Temperature Warehouses. The bottom of the generator (top of the concrete foundation) is about two feet above the ground. (Source: CSB Photo)

2.5. LIQUID NITROGEN SYSTEM

54. The Arkema Crosby facility uses a liquid nitrogen system to deliver a backup source of emergency cooling for its Low Temperature Warehouses (Figure 6). If a significant refrigeration problem occurs, such as loss of power and backup power, workers can connect short hoses and then open valves to inject liquid nitrogen into any one of the organic peroxide Low Temperature Warehouses to supply a source of refrigeration that is independent of electricity. Each of the Low Temperature Warehouses is equipped with dedicated piping for liquid nitrogen. Normally this piping is capped and the system is locked out to prevent inadvertent use. In addition to being extremely cold, injected liquid nitrogen will dilute the oxygen concentration, creating an asphyxiation hazard to workers.

Figure 6. Liquid Nitrogen Tank at the Arkema Crosby Facility. Among other uses, this tank holds up to 40,000 pounds of liquid nitrogen that can be injected into each of the organic peroxide Low Temperature Warehouses to provide a backup refrigeration source. (Source: CSB Photo)

2.6. REFRIGERATED TRAILERS

55. As a final backup for scenarios causing elevated temperature in one of the Low Temperature Warehouses, organic peroxide products can be relocated to one or more portable refrigerated truck trailers (Figure 7). Arkema uses these refrigerated trailers primarily for shipping organic peroxide products to customers; however, Arkema procedures allow the use of these trailers in emergency situations or while making repairs to Low Temperature Warehouse refrigeration systems. The fuel tank for these refrigerated trailers is located under the container that powers the refrigeration unit. With a full tank, the refrigerated trailers can normally maintain appropriate cold conditions for more than a week.

Figure 7. Refrigerated Truck Trailer. Arkema used about a dozen refrigerated truck trailers like this one used to ship organic peroxide products to customers and to provide a temporary storage location if the refrigeration at one or more of the Low Temperature Warehouses could not be maintained. (Source: CSB Photo)

2.7. PRODUCT TOTES

56. Organic peroxide products that require low-temperature storage are generally packaged in either one or five-gallon plastic containers, or totes. Customers frequently use small quantities of organic peroxides so such totes are convenient for customers. These organic peroxide totes are stacked onto pallets and shrink-wrapped, enabling workers to move the products more easily around the facility and providing stability during shipping (Figure 8).

Figure 8. Stacked Organic Peroxide Totes. This example shows shrink-wrapped five-gallon containers on pallets. (Source: Arkema Photo)

3. Incident Description

57. The National Hurricane Center produced a report summarizing Hurricane Harvey[a] and the heavy rainfall it produced. Hurricane Harvey was a Category 4 storm before making landfall along the middle Texas coast [20, p. 1]. The storm stalled, "dropping historic amounts of rainfall of more than 60 inches over southeastern Texas [20, p. 1]." The path of the hurricane is shown in Figure 9 below. As can be seen the hurricane made landfall twice and stayed in the vicinity of southeast Texas for an extended duration, contributing to the large amount of rainfall in the area.

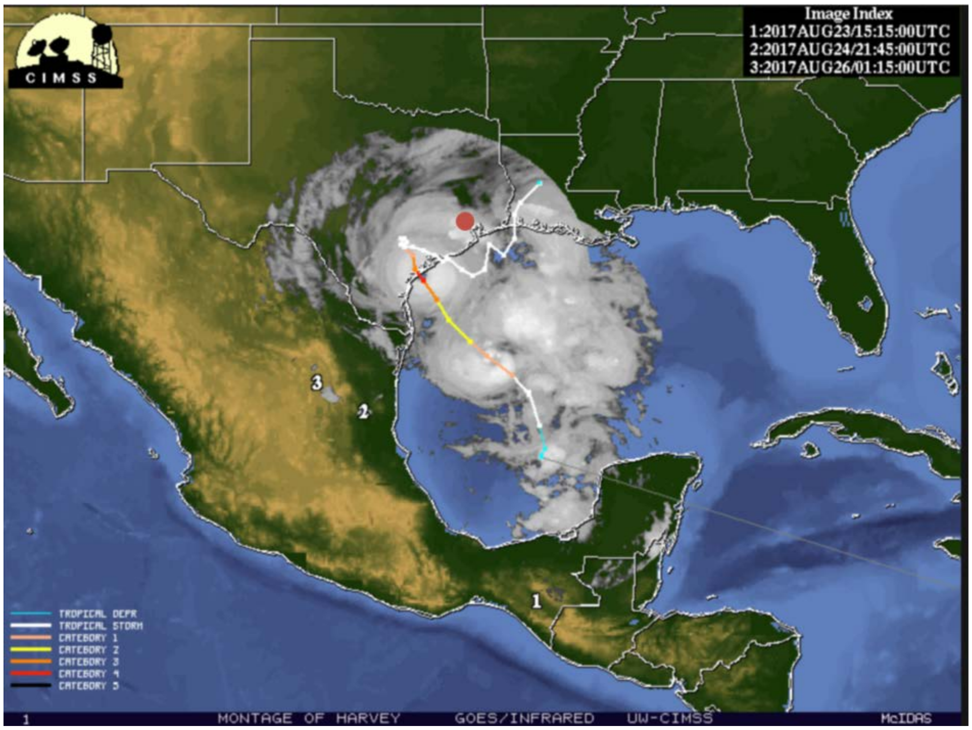

Figure 9. Path of Hurricane Harvey. The approximate location of the Arkema Crosby facility is shown by the red circle. (Source: Cooperative Institute for Meteorological Satellite Studies [21].) (Image Modified by CSB)

58. The National Hurricane Center Tropical Cyclone Report on Hurricane Harvey described the damage as follows:

> These rains caused catastrophic flooding, and Harvey is the second-most costly hurricane in U.S. history [$125 billion],[b] after accounting for inflation, behind only Katrina (2005). At least 68 people died from the

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[a] In April 2018, the World Meteorological Organization retired Harvey from its list of storm names. Storm names are retired when they are so destructive that future use of the name would be insensitive. Since 1953, 86 storm names have been retired [234].

[b] The National Hurricane Center report used damage estimates developed by the National Oceanic and Atmospheric Administration (NOAA) [20, p. 9]. See Billion - Dollar Weather and Climate Disasters: Table of Events [224].

direct effects of the storm in Texas, the largest number of direct deaths from a tropical cyclone in that state since 1919. [20, p. 1].

59. With respect to rainfall, the report observed, "Harvey was the most significant tropical cyclone rainfall event in United States history, both in scope and peak rainfall amounts, since reliable rainfall records began around the 1880s [20, p. 6]." The report also identified the storm as forcing 40,000 people to evacuate or seek refuge in shelters; flooded over 300,000 structures; and damaged about 500,000 cars [20, p. 9]. Figure 10 and Figure 11 show the areas that were most affected by the precipitation from the hurricane.

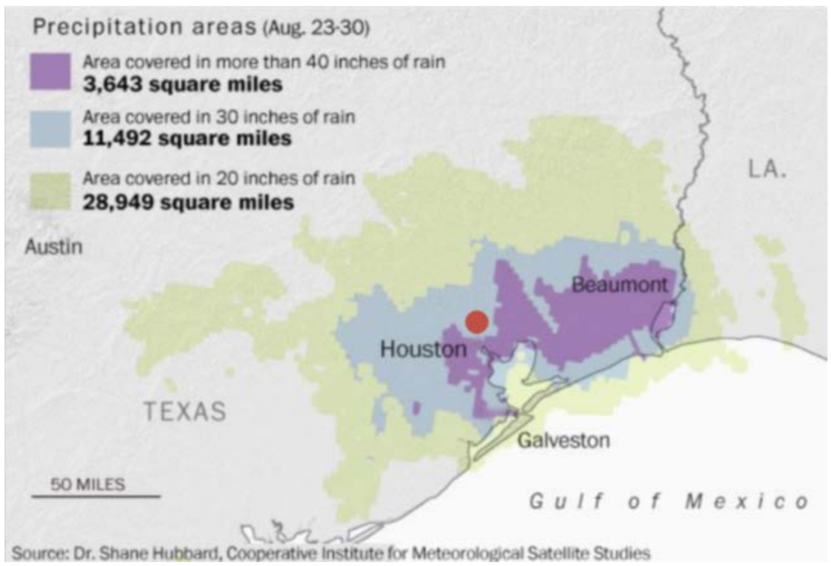

Figure 10. Total Precipitation from Hurricane Harvey in the Southeast Texas Region. The Arkema Crosby facility approximate location is shown by the red circle [22]. (Image Modified by CSB)

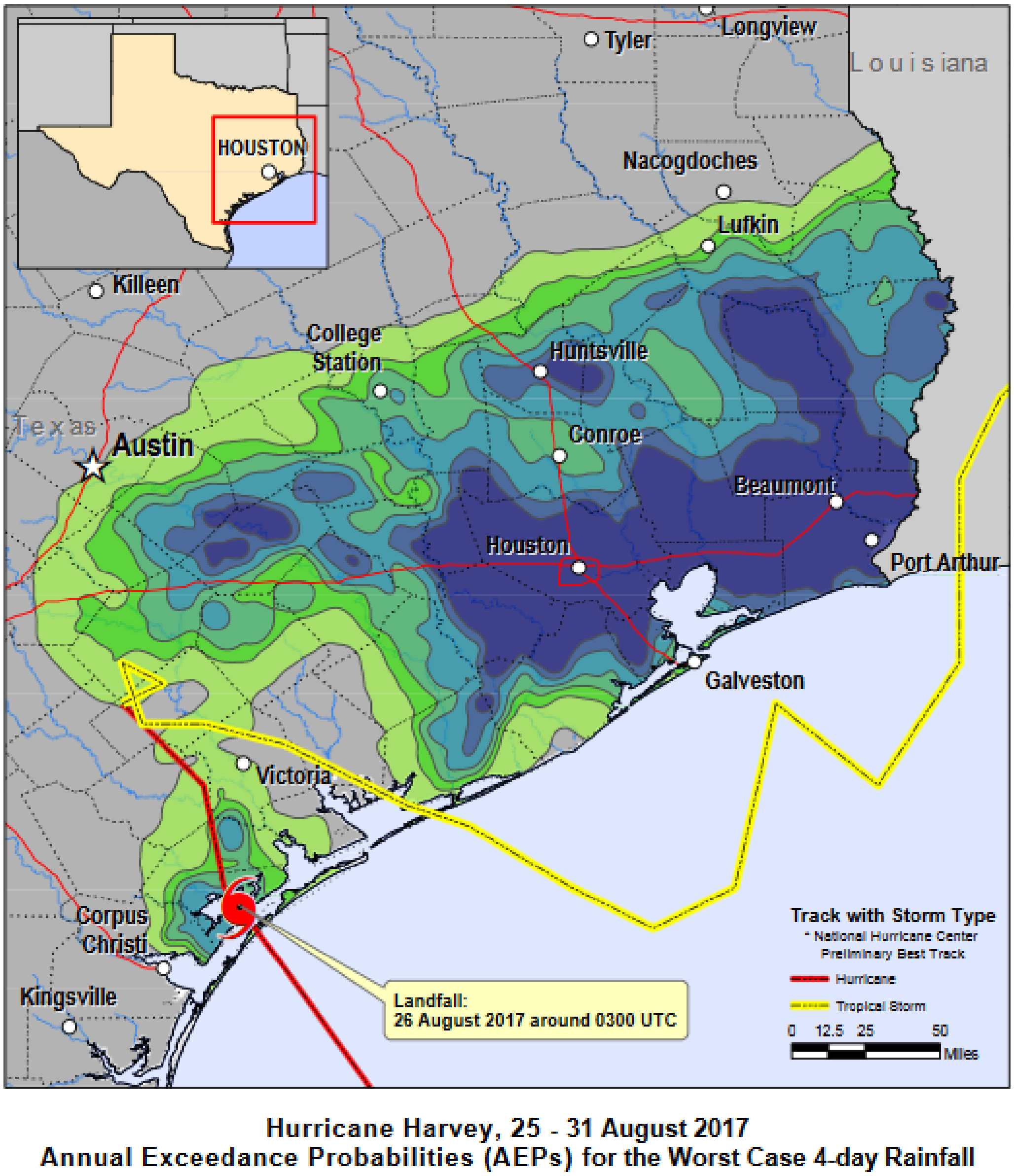

Figure 11. NOAA's National Weather Service Map Showing Rainfall Exceedance Annual Probabilities During Hurricane Harvey in Southeast Texas. The different colors show the probability in a year for the area to experience the amount of rain demonstrated by Harvey [23], [24].

60. As shown in Table 1, in the days leading up to Hurricane Harvey, the rainfall predictions increased even after the storm made landfall.

Table 1. Predicted Rainfall for the Houston Area During Hurricane Harvey.

Date	Southeast Texas Total Predicted Rainfall
Thursday, August 24	12-30 inches
Friday, August 25	15-35 inches
Saturday, August 26	15-40 inches
Sunday, August 27	15-50 inches

61. Ultimately, a rain gauge at the Arkema Crosby facility recorded more than 39 inches of rainfall during Hurricane Harvey (Figure 12).

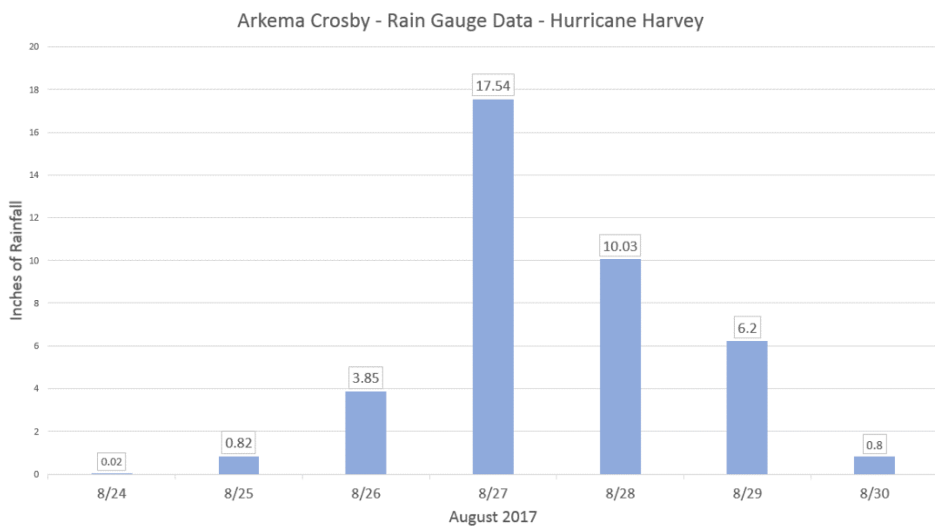

Figure 12. Arkema Crosby Facility Rain Gauge Data. The Arkema site recorded more than 39 inches of rainfall during the days when Hurricane Harvey affected the area.

3.1. Thursday, August 24, 2017

62. After traveling through the Gulf of Mexico for over 10 days, it became clear that Hurricane Harvey would affect the middle and upper Texas coast and likely stall over the southeast Texas region [1]. At 10:00 am central daylight time on August 24, 2017, the National Hurricane Center update warned that Hurricane Harvey was strengthening and predicted extreme flooding from the storm. The update stated:

> Harvey has intensified quickly this morning, and is now forecast to be a major hurricane at landfall, bringing life-threatening storm surge, rainfall, and wind hazards to portions of the Texas coast. Preparations to protect life and property should be completed by tonight, as tropical-storm-force winds will first arrive in the hurricane and storm surge warning areas on Friday [2].

> Life-threatening flooding is expected across much of the Texas coast from heavy rainfall of 12 to 20 inches, with isolated amounts as high as 30 inches, from Friday through early next week [2].

63. Anticipating that Hurricane Harvey would make landfall the next day (Friday, August 25, 2017), personnel at the Arkema Crosby facility began to prepare for the storm. The Arkema Crosby facility had a hurricane plan detailing how the site planned to protect workers and property before, during, and after a hurricane. The team assigned to implement the plan started meeting at the beginning of the hurricane season (June 1) and monitored storms forming in, or moving into, the Gulf of Mexico. The Arkema Crosby facility communicated and worked with corporate staff about potential storms to determine when to activate the ride-out crew, which is composed of staff members assigned to remain at the facility for the duration of a hurricane. The ride-out crew is responsible for the safety of the plant during the hurricane and for monitoring for changing conditions. The crew is composed of the following facility personnel:

- Management (two);
- Operators (four);
- Refrigeration specialist (one);
- Maintenance (three); and
- Mechanic/Electrician (two).

64. On Thursday, Arkema personnel decided that they needed to ready the plant in case the hurricane would affect the Crosby facility. The facility personnel had been monitoring the progress of Hurricane Harvey for a few days and were prepared to implement the Hurricane Preparedness Plan. Based on local weather forecasts, Arkema facility management personnel expected the hurricane would pass south of the Crosby facility and anticipated 10 to 15 inches of rain at the facility over the duration of the hurricane. The facility leadership team met to discuss the best way to shut down the facility and prepare for the hurricane in case the facility was seriously affected.

65. By 10:00 pm central daylight time on Thursday, August 24, 2017, the National Hurricane Center projected "devastating and life-threatening flooding across the middle and upper Texas coast from heavy rainfall of 15 to 25 inches, with isolated amounts as high as 35 inches [25]." By the end of that same day, the weather forecast was calling for 15 to 18 inches of rain at Crosby, leading the Arkema Crosby management team to initiate its operational moves to prepare for the event.

66. On the basis of their previous experience, Arkema Crosby facility employees knew that this level of rain was enough to flood roads and likely would necessitate activating the ride-out crew because workers would have difficulty getting to or leaving the facility. The Crosby facility personnel anticipated that 40 inches of rainfall would generate one to two feet of floodwater, which would make it difficult to move between locations at the facility but would not affect the safety systems. The Arkema logistics group called suppliers and customers to let them know that the facility would not need raw materials and production would likely be interrupted.

3.2. FRIDAY, AUGUST 25, 2017

67. By the morning of Friday, August 25, 2017, the weather forecast for the Crosby facility projected 15 to 25 inches of rain accumulation, with isolated amounts as high as 35 inches over the duration of the hurricane [26]. The Federal Emergency Management Agency (FEMA) worked with the Texas Division of Emergency Management and other agencies to pre-position supplies and personnel in place to manage the hurricane's effects [27]. By the end of the day, FEMA formally declared the situation a "major disaster" [28].

68. The forecast calling for increased rainfall made it clear that flooding of local roads was likely and that the 12-member ride-out crew should be activated. There was little concern, however, about the facility losing power or any potential effects on the refrigerated organic peroxide products.

69. At 2:00 pm on Friday, August 25, 2017, Hurricane Harvey became a Category 3 hurricane, and then early Friday evening evolved to a Category 4 hurricane with sustained winds reaching 130 miles per hour [1]. Throughout the day, the outer bands of the storm began to produce rainfall at the Crosby facility as Harvey approached the coast (Figure 13).

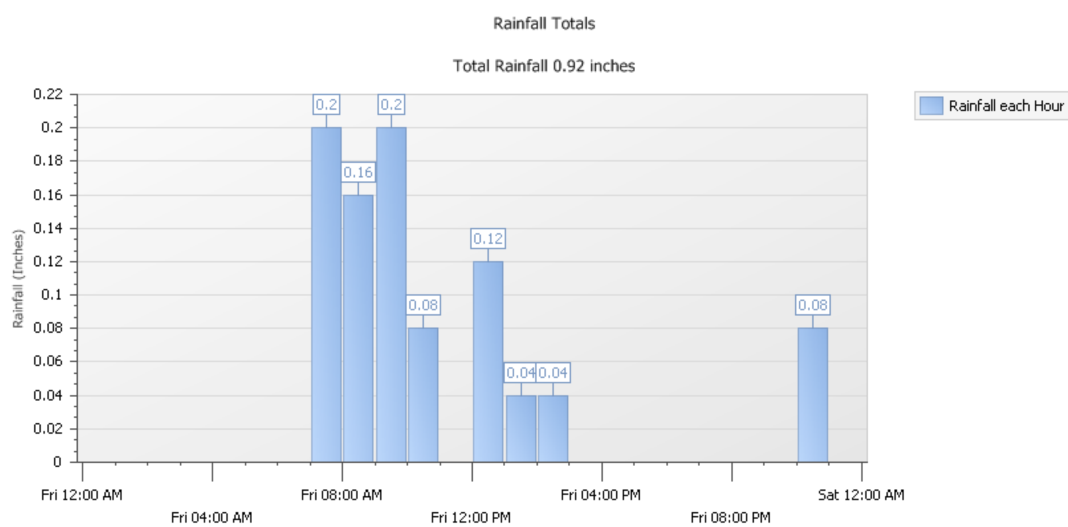

Figure 13. Hourly Rainfall on Friday, August 25, 2017 During Hurricane Harvey. Cedar Bayou gauge station 1740, which is about 2.5 miles northeast of the Arkema Crosby facility, measured hourly rainfall during Hurricane Harvey as shown in this graph for August 25 [29].

70. Arkema halted production at the Crosby facility due to the impending arrival of Hurricane Harvey. Plant personnel started hurricane preparations, including:

- Securing loose materials, such as scaffolding and empty product totes, so that they could not blow or float away in the storm;
- Elevating portable equipment such as compressors to keep them out of floodwater;
- Completing process shutdown including emptying and washing process equipment;

- Bringing storm equipment onsite, including an off-road forklift and a boat;
- Staging equipment, such as pumps, hoses, and sandbags;
- Filling diesel tanks for backup generators and refrigerated trailers;
- Ensuring that the liquid nitrogen tank was full;
- Reviewing storm scenarios and corrective actions with members of the ride-out crew; and
- Reducing the level in waste water treatment equipment in preparation for the heavy rain.

71. On Friday, only about an inch of rain fell on the Arkema Crosby facility but the storm was beginning to worsen (Figure 13) [29]. At around 10:00 pm, the eye of Hurricane Harvey made landfall about 30 miles northeast of Corpus Christi, Texas on the southern Texas Gulf Coast [1]. As the storm progressed into Texas, the National Hurricane Center forecasted “catastrophic and life-threatening flooding” across the middle and upper Texas coast and from 15 to 30 inches of heavy rain, with isolated totals as high as 40 inches [30].

3.3. Saturday, August 26, 2017

72. At 10:00 am, the forecast from the National Hurricane Center remained unchanged, with a prediction of heavy rainfall of 15 to 30 inches, and isolated amounts as high as 40 inches [31]. As the rain continued to fall in the Houston area, flooding began at the Crosby facility and the water level rose in the Cedar Bayou watershed (where the Crosby facility is located) by about 13 feet (Figure 14).

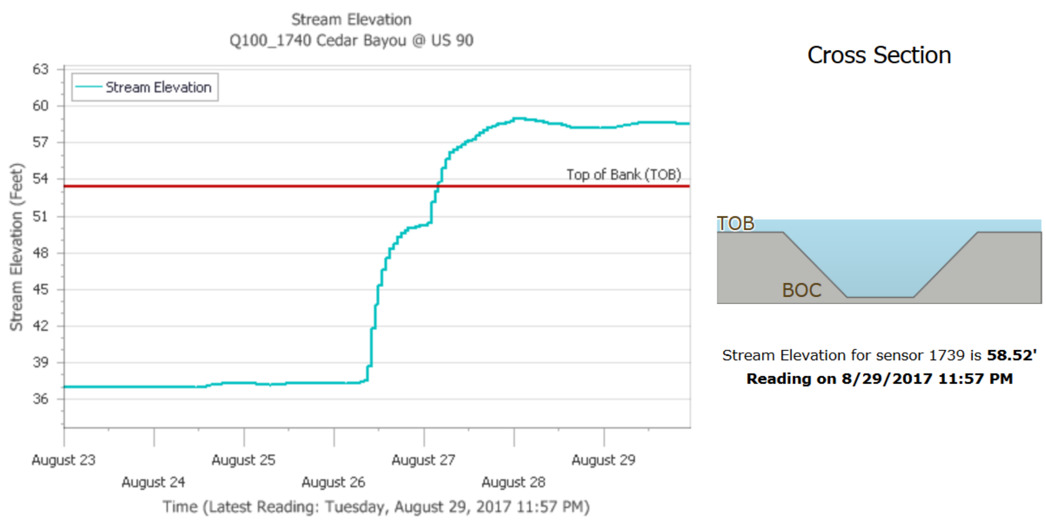

Figure 14. Gauge Station 1740 Graphic Showing Cedar Bayou Stream Elevation During Hurricane Harvey. The water level steadily rose for most of the day on Saturday, August 26, 2017 [29].[a, b]

73. Once Arkema shut down the facility and activated the ride-out crew, the 12 members of the Crosby ride-out crew remained at the Arkema site for the duration of the storm. The incident then evolved into the next phase with the ride-out crew attempting to move the organic peroxide products to safe locations at the Crosby facility. As the waters rose at the Arkema facility, the ride-out crew monitored the condition of the plant, focusing on the plant utilities and the wastewater treatment system to ensure that they could handle the increased demand. The ride-out crew performed surveillance trips around the facility to ensure that no loose items remained that could blow or float away and to check on the condition of the facility. As the day progressed, it became apparent that if the water continued to rise, the ride-out crew would need to proactively de-energize electrical equipment, including transformers for individual building power, so that nothing short-circuited.

74. The ride-out crew analyzed the susceptibility to flooding of the electrical equipment within the facility primarily by determining how close to the ground the electrical equipment was located. Water reaching the 480-volt transformers on the Low Temperature Warehouses was a primary concern as failure of these devices could either damage property or electrocute nearby workers. Once the ride-out crew members decided that a Low Temperature Warehouse (or any building) was at risk of rising floodwater reaching susceptible electrical equipment, they manually switched off the power to the entire building before the water could reach the electrical equipment.

75. On Saturday evening, the storm knocked out the plant's phone system, but the ride-out crew still had cell phone service. Steady rainfall throughout the day increased flooding at the facility causing standing water in the area around the Low Temperature Warehouses. The ride-out crew members recognized that if the floodwater continued to rise, they would need to move the organic peroxide

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[a] Bottom of channel (BOC) is the elevation at a bayou's lowest point. Top of bank (TOB) refers to the height of the banks of a bayou at the location where water could overflow during a heavy rain event. To determine the depth of a particular waterway, subtract the bottom of channel from the top of bank measurement [139].

[b] For Cedar Bayou at Highway 90, top of bank is 53.4 feet and bottom of channel is 36.09 feet [29].

products from some of the Low Temperature Warehouses as the buildings lost power and consequently their refrigeration capability. The ride-out crew, however, still thought that the event would be manageable and that the hurricane would only minimally affect facility operations.

76. Arkema corporate personnel activated the corporate crisis team to help with the response to the heavy rainfall at Arkema Texas sites in the path of the storm. The crisis team provides support and coordinates communications during any type of crisis event. Although the crisis team members were meeting at this point, they still anticipated that the ride-out crew at Crosby (as well as ride-out crews at the other Arkema facilities in the region) could prevent any type of release or incident at their facility as long as the floodwater stopped rising, which the corporate crisis team anticipated happening at any time.

77. The National Hurricane Center update at 10:00 pm called for an additional 15 to 25 inches of rainfall, with isolated totals of 40 inches through August 31, 2017 [32]. The key message included a warning that "life-threatening" flood hazards would continue over much of southeastern Texas [32]. By the end of Saturday, August 26, 2017, about five inches of rain fell near the Arkema Crosby facility (Figure 15) [29].

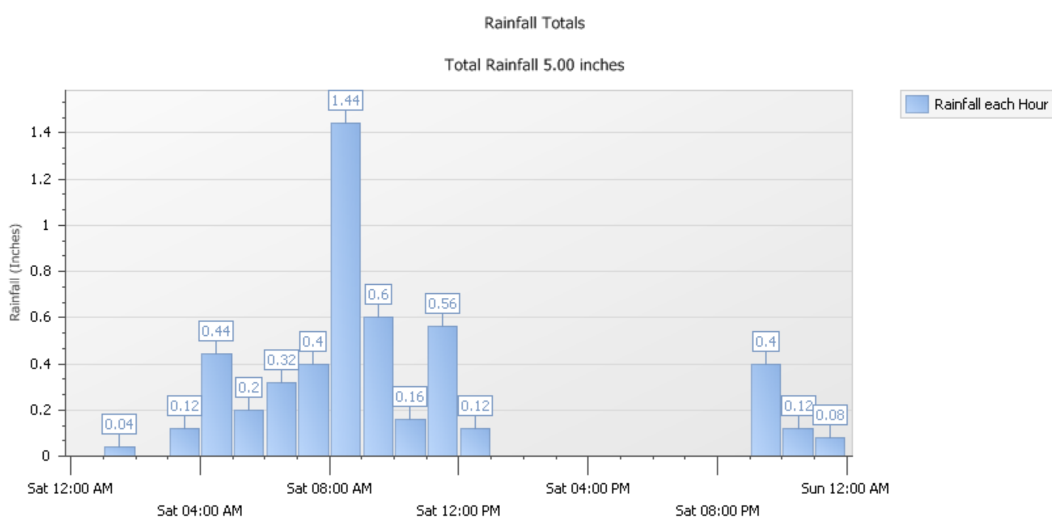

Figure 15. Hourly Rainfall on Saturday, August 26, 2017 During Hurricane Harvey. The Cedar Bayou gauge station 1740 measured hourly rainfall during Hurricane Harvey, as shown in this graph for August 26 [29].

78. Rain continued to fall, and the floodwater level at the Arkema Crosby facility continued to rise as Hurricane Harvey stalled over southeastern Texas. The rate of increase in the water level began to accelerate at the facility as Harvey continued to pour unprecedented amounts of rain in southeastern Texas and as the downstream system water level continued to rise (Figure 14). The ride-out crew members, however, monitored weather forecasts that predicted up to 30 inches of rainfall, which the ride-out crew perceived to be manageable and not likely to be a threat to the facility, including the Low Temperature Warehouses. In fact, the ride-out crew management sent an email around noon that day to discuss a plan to deactivate the ride-out crew and begin normal staffing and operation over the coming days. By Saturday night the storm did not end as expected, and with

continually rising floodwater, the management team shifted its operational decision-making strategy by adopting a day-to-day approach.

3.4. SUNDAY, AUGUST 27, 2017

79. The National Hurricane Center's update at 10:00 am reported, "Harvey continues to meander over southeastern Texas, where it is producing catastrophic and life-threatening flooding rainfall [3]." The update also predicted an additional 15 to 25 inches of rain over the next several days, with isolated storm totals of 50 inches [3]. The key message warned people not to travel unless necessary for their safety [3].

80. Significant flooding occurred early on Sunday and the ride-out crew members preemptively shut down power to several of the Low Temperature Warehouses before the rising water reached electrical equipment. Figure 16 shows a Google Earth overview image of the Crosby facility. In general, the bottom left (southwest) corner of the overview is lower ground, and higher ground is towards the top right (northeast). By 2:00 pm, parts of the facility had four feet of standing water. As the water rose, it affected operation of the Low Temperature Warehouses (labeled 1 through 7 in Figure 16) from left to right in the figure, which is largely the order in which the ride-out crew shut down the power to the warehouses and moved the organic peroxide products from the warehouses to the refrigerated trailers.

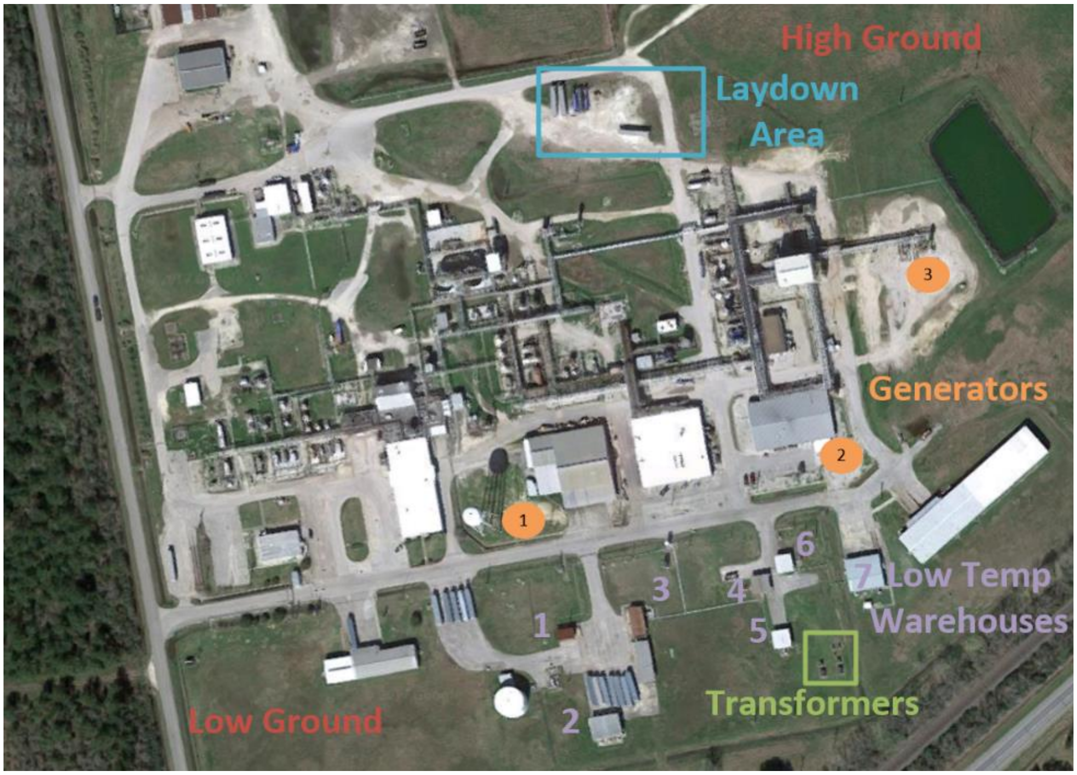

Figure 16. Pre-Hurricane Harvey Google Earth Overview of the Arkema Crosby Facility. This layout shows the location of the main facility components (but the numbering of the buildings and the generators is not representative of the actual building or equipment numbers). (Image Modified by CSB)

81. The Arkema Crosby facility served as a local distribution center by providing low-temperature organic peroxide storage for a number of other Arkema organic peroxide manufacturing facilities. As a central distribution hub, the site housed 11 refrigerated trailers that could serve as backup storage containers. A number of the refrigerated trailers can be seen in Figure 16 next to Low Temperature Warehouse 2.

82. As workers turned off power to the Low Temperature Warehouses due to the rising water level (Figure 17), the ride-out crew moved organic peroxide products from six of the seven Low Temperature Warehouses to other Low Temperature Warehouses, or to one of the 11 refrigerated trailers located onsite. By early Sunday afternoon, workers had shut down three of the Low Temperature Warehouses. Low Temperature Warehouse 1 was the first to be manually shut down when floodwater threatened to reach its electrical components. Workers next manually shut down Low Temperature Warehouse 2 and Low Temperature Warehouse 3 and moved their organic peroxide inventories to other locations. The ride-out crew used forklifts (Figure 18) to move approximately 20 pallets of organic peroxide products from these three Low Temperature Warehouses into two refrigerated trailers, which were then moved to the laydown area.[a] After these initial three Low Temperature Warehouses were emptied, the ride-out crew sent an update stating,

[a] The Crosby site had two semi-trailer trucks (referred to as “yard mules”) that workers used to move the refrigerated trailers within the facility.

“Site does not think it is likely to lose cooling on another warehouse, but if that were to happen they may not have enough [refrigerated trailers] to store [organic peroxide].” The ride-out crew believed that the floodwater level would soon begin to recede, but it kept rising. More Low Temperature Warehouses lost power and workers continued moving the organic peroxide products to other locations.

Figure 17. Air Conditioning Units Behind One of the Low Temperature Warehouses. The final floodwater level is approximated by the red lines on the air conditioning equipment at the Arkema Crosby facility. (Source: CSB Photo)

Figure 18. Forklift Used by the Ride-out Crew. Ride-out crew members used the forklift shown in this image to move organic peroxide pallets from the storage buildings after they turned off power to the buildings because of the rising floodwater. (Source: Arkema Photo)

83. The ride-out crew shut off power not only to the Low Temperature Warehouses but also to other buildings at the plant as the floodwater level rose. As they cut power to these additional buildings, the ride-out crew members lost their capability to remotely monitor some systems, such as the wastewater treatment facility. As a result, the ride-out crew began manually recording critical plant data every hour, increasing their exposure to the hazardous weather and the overall workload on the 12-member crew.

84. The rising floodwater level soon prompted workers to turn off power to the plant's water supply and fire water suppression pumps. The rising floodwater level also reached some of the backup generators causing the ride-out crew to take them offline, including the generator (Figure 19) that provided backup power to Low Temperature Warehouses 1, 2, and 3 in Figure 16, to ensure crew member safety. The Low Temperature Warehouses that had already been manually powered down by the ride-out crew no longer needed these backup generators.

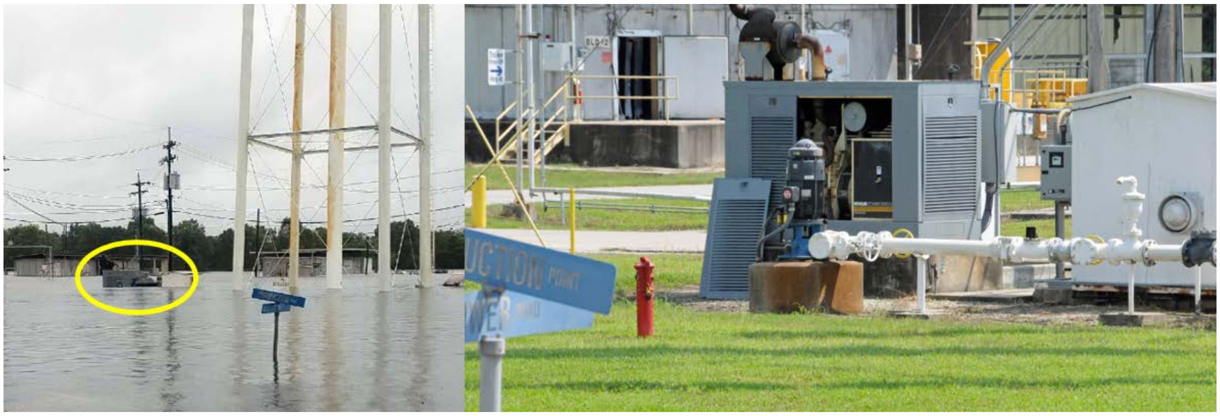

Figure 19. One of the Emergency Generators Providing Backup Electricity to the Low Temperature Warehouses. The photo on the left shows floodwater covering the bottom half of the generator (yellow oval) on Tuesday August 29, 2017. The post-incident photo on the right shows the same generator. (Source: Arkema Photo (left) Modified by CSB, CSB Photo (right))

85. As the rising floodwater level began making it difficult for vehicles to move around the facility, the ride-out crew members drove their personal vehicles to high ground to avoid the flooding.

86. As discussed previously, a tank of liquid nitrogen served as one of Arkema's safeguards for loss of refrigeration or loss of electrical power to the Low Temperature Warehouse. Workers can inject liquid nitrogen directly into a cold storage building to reduce its temperature. On Sunday, when the real threat of losing all power plantwide became clear, the ride-out crew decided to ensure the availability of the nitrogen system. The liquid nitrogen piping system allowed nitrogen to be injected into each Low Temperature Warehouse, one at a time if needed. The rising floodwater compromised this system, however, by beginning to submerge the piping system. A member of the ride-out crew called in a plant supervisor whose personal vehicle had a lifted chassis and large tires that could still travel onto the Arkema Crosby site. The plant supervisor arrived onsite and added a foot-long extension (Figure 20) to the nitrogen piping system so that it could still be accessed if the floodwater level rose higher. Before leaving the site, the supervisor also helped transfer more organic peroxide products into refrigerated trailers.

Figure 20. Liquid Nitrogen Piping Extensions. A supervisor modified the liquid nitrogen piping, extending it to ensure that the connection point would be above the floodwater if the ride-out crew needed to inject liquid nitrogen into one of the Low Temperature Warehouses that still contained organic peroxide products. These elevated (extended) connections, however, were not high enough; the rising floodwater eventually submerged them. (Source: CSB Photo)

87. As ride-out crew members cut power to Low Temperature Warehouses, the organic peroxide products in those warehouses were moved either to other Low Temperature Warehouses that still had power, or into refrigerated trailers that then were moved to the laydown area at the north end of the facility (Figure 21). By Sunday night, the ride-out crew had manually cut the power to all of the Low Temperature Warehouses except Low Temperature Warehouse 7. Additionally, the crew had transferred the contents of those six Low Temperature Warehouses into six refrigerated trailers that were operating in the laydown area at the north end of the plant.

Figure 21. Refrigerated Trailers in the Laydown Area. Six refrigerated trailers loaded with organic peroxide products are shown at the Arkema Crosby facility. Two empty tanker trailers are also shown at the top of the photo. (Source: Photo provided by Arkema)

88. Throughout the chain of events during Hurricane Harvey, the ride-out crew management continually communicated with the Arkema corporate crisis team so that it was aware of the situation at the plant. The Arkema Crosby plant manager sent a daily e-mail to corporate personnel detailing conditions at the plant and called them on his cell phone when key events occurred, such as losing a Low Temperature Warehouse. The ride-out crew informed the Arkema corporate office about the site conditions and sought advice about the best means of dealing with the failure of the Low Temperature Warehouse refrigeration systems.

89. The heavy rainfall event continued to unfold throughout Sunday over much of southeastern Texas. Hurricane Harvey had been moving slowly east-southeast during the past few hours, with heavy rain bands continuing to form over the northwestern Gulf and tracking inland over much of the upper Texas coast and southwestern Louisiana. Rainfall in the range of 20 to 27 inches had fallen across much of the Greater Houston area, and additional rainfall of 15 to 25 inches was projected over the next several days. Rainfall totals in some locations were predicted to reach 50 inches, historic for that area. As shown on Figure 22, this day had the largest daily rainfall (about 23 inches) near the Arkema Crosby facility from Hurricane Harvey [29].

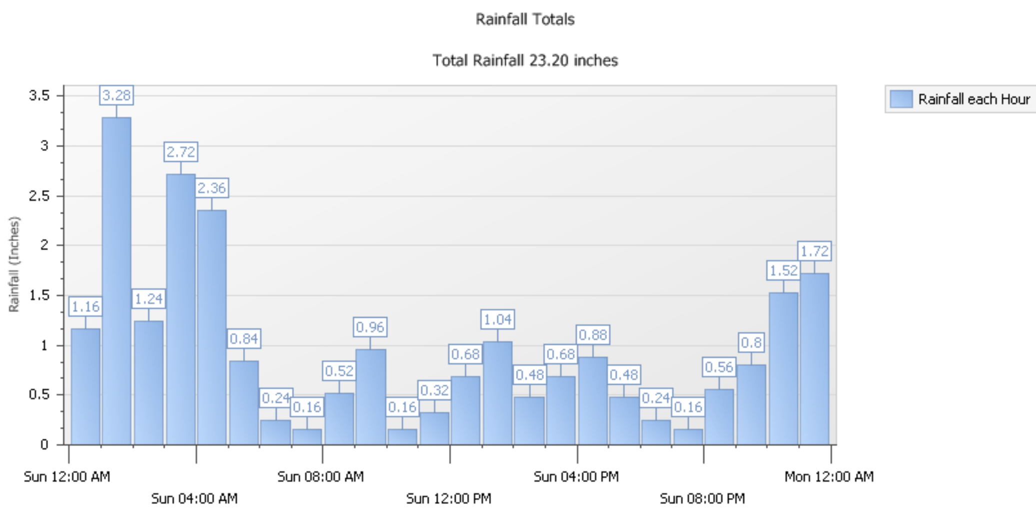

Figure 22. Hourly Rainfall on Sunday, August 27, 2017, During Hurricane Harvey. Cedar Bayou gauge station 1740 measured hourly rainfall during Hurricane Harvey, as shown in this graph for August 27 [29].

3.5. Monday, August 28, 2017

90. Rain from Hurricane Harvey continued to fall in the area and floodwater at the facility continued to rise throughout the day. At the Arkema Crosby facility, long periods of time passed with no rainfall, but the surrounding area had accumulated so much water that the floodwater heights continued to rise at the plant (Figure 23).

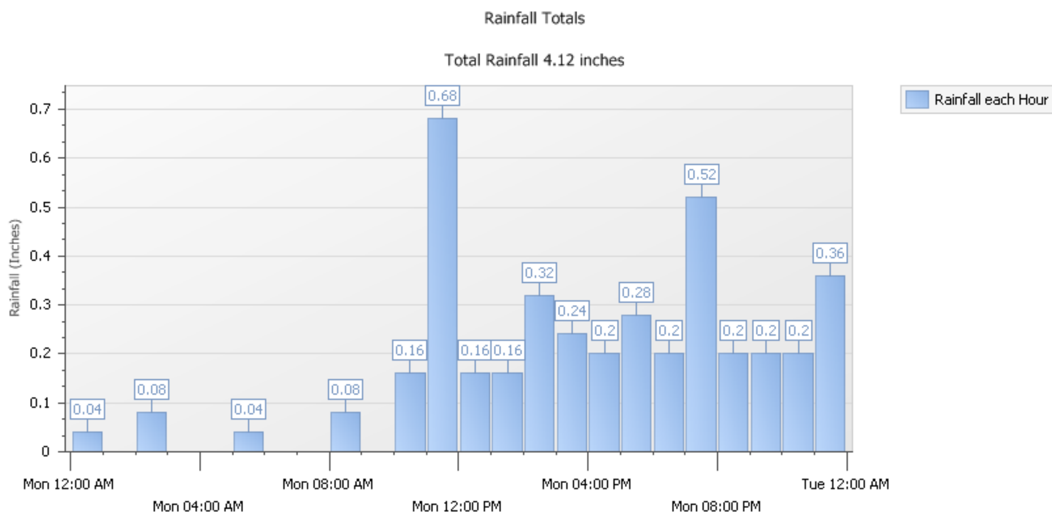

Figure 23. Hourly Rainfall on Monday, August 28, 2017 During Hurricane Harvey. Cedar Bayou gauge station 1740 measured hourly rainfall during Hurricane Harvey, as shown in this graph for August 28 [29].

91. Around 2:00 am, the main CenterPoint[a] power transformers (Figure 24) failed due to the rising floodwater. Two remaining generators (Figure 16, Generators 2 and 3) turned on at this point, supplying power to Low Temperature Warehouse 7, the last remaining low-temperature organic peroxide storage building (Figure 25). One of the generators then failed due to the floodwater, but the other generator remained on, supplying power to Low Temperature Warehouse 7. Realizing that the facility had no primary power supply and the generators might not last long, around 3:00 am, the ride-out crew went to move organic peroxide products out of Low Temperature Warehouse 7 and into two refrigerated trailers parked outside of the building. That remaining Low Temperature Warehouse contained over 100,000 pounds of organic peroxide products and the ride-out crew recognized the need to remove the products to the refrigerated trailers, where they stood a better chance of staying cold.

[a] CenterPoint is the company that provided electrical power to the Arkema Crosby facility.

Figure 24. CenterPoint Transformers at the Arkema Crosby Facility. These are the main CenterPoint power transformers onsite at the Arkema Crosby facility. (Source: CSB Photo)

Figure 25. Emergency Generator. This is one of the emergency generators that automatically turned on when the power failed at the Arkema Crosby facility. (Source: CSB Photo)

92. Around 4:00 am, the wastewater treatment pumps failed because of a loss of power. Consequently, the facility could no longer pump out the dikes surrounding the process equipment and the wastewater tanks. The wastewater treatment dikes began to fill with no way to drain them. While this situation had no direct impact on the loss of refrigeration for the low-temperature organic peroxide products, it increased the ride-out crew's workload, further complicating their responsibilities.

93. Around 5:00 am on Monday morning, as the floodwater continued to rise, the ride-out crew proactively shut down the last generator (Figure 25) before the floodwater affected the electrical equipment, leaving no power to any of the Low Temperature Warehouses.

94. On Monday morning, the ride-out crew checked the liquid nitrogen cooling system. The foot-long piping extension that the plant supervisor had added the day before was now completely submerged by the floodwater, rendering the system inoperable. Based on the plant supervisor's experience of almost 40 years at the Crosby facility, he believed that enough height was added to put the nitrogen piping connection well above any anticipated floodwater level. Despite this effort, the floodwater height continued to rise, submerging the piping extension.

95. During the morning, the equipment that the workers used to move the refrigerated trailers and pallets of organic peroxide products began to fail as the high floodwater affected electrical equipment in the forklifts and semi-tractor trucks. From this point forward, the ride-out crew could not lift the pallets of organic peroxide products or move the refrigerated trailers to the laydown area and the remaining three refrigerated trailers stood by the storage buildings (Figure 26). Moreover, the water level around the Low Temperature Warehouses was about chest-high, making it even more difficult for ride-out crew members to move and take action. In addition, empty refrigerated trailers, which workers had not yet filled with organic peroxide products and moved to the laydown area, began to fail as their fuel tanks filled with water. As a result, only 9 of the 11 refrigerated trailers stored organic peroxide products during the incident.

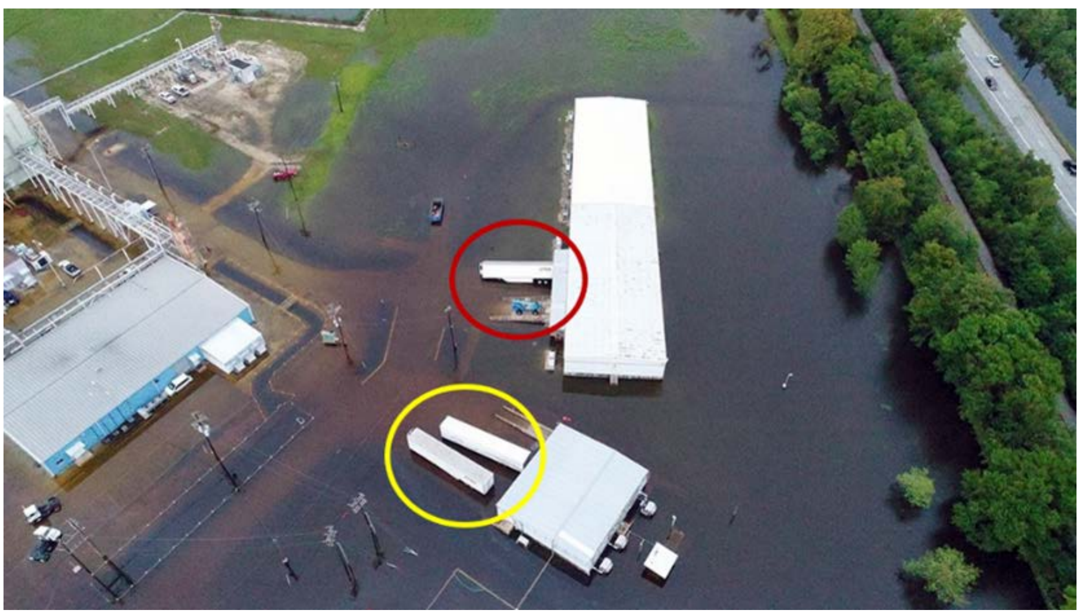

Figure 26. Three Refrigerated Trailers Not Moved to Higher Ground [33]. This aerial view shows three refrigerated trailers (yellow and red circles) filled with organic peroxide containers near two of the organic peroxide product warehouses after the Arkema ride-out crew evacuated the site. (Photo Modified by CSB)

96. On Monday morning, the Arkema corporate crisis team addressed possible scenarios for safely managing the organic peroxide products that required low-temperature storage. The team's top priority was ensuring that the organic peroxide products did not combust. This priority necessarily included confirming that the refrigerated trailers contained enough fuel to run the refrigeration system, maintaining cooling, and accommodating potential options for moving the trailers offsite to another Arkema facility or another organic peroxide company that could provide low-temperature storage. Although the corporate crisis team members did consider possible offsite storage, they determined that neither drivers nor vehicles could get to the Crosby facility.

97. If Arkema had wanted to move the organic peroxide products offsite, however, such a decision needed to have been made very early on, potentially even before Hurricane Harvey made landfall. The Department of Transportation requires a driver who transports hazardous materials to have a commercial driver license (CDL) with a hazardous materials endorsement [34]. Because organic peroxides are considered hazardous materials, Arkema would have had to find drivers that met this requirement. This requirement, in addition to obtaining additional drivers, especially before an emergency situation like a hurricane, could have taken days or weeks to fully coordinate the logistics.

98. About 50 pallets of organic peroxide products remained in Low Temperature Warehouse 7 in Figure 16. The workers needed to move these pallets because the building had lost all power and refrigeration capability. The ride-out crew members broke down the pallets in Low Temperature Warehouse 7 and transferred the organic peroxide containers by hand to a refrigerated trailer parked at a nearby building. All told, the ride-out crew moved about 2,160 organic peroxide containers by hand from Low Temperature Warehouse 7 to the last refrigerated trailer. This task finally ended around midnight with ride-out crew members using flashlights to guide their way through the darkened warehouse.

99. By the end of Monday, workers had moved 11 different organic peroxide products—which required low-temperature storage, were held in about 10,500 individual containers, and totaled more than 350,000 pounds—into 9 refrigerated trailers. Figure 27 and Figure 28 show the final location of the nine refrigerated trailers. The three refrigerated trailers near the south end of the facility, which held more than 4,000 containers, were still sitting in floodwater, and the ride-out crew members were concerned that these trailers would not be able to continue operating and refrigerating the organic peroxide products they held.

Figure 27. Location of the Nine Refrigerated Trailers Containing Organic Peroxide Products. (Source: Google Earth Image Modified by CSB)

Figure 28. Photo Identifying the Nine Refrigerated Trailers of Organic Peroxide Products. (Source: Photos Provided by Arkema and Modified by CSB)

100. As shown in Figure 29, the floodwater eventually rose above the floor level of some of the Low Temperature Warehouses. By that time, the ride-out crew members had emptied those Low Temperature Warehouses of any organic peroxide products. If the organic peroxide products were still housed there, regardless of the backup safety systems, the warm water would have quickly heated the organic peroxide products, which likely would have combusted.

Figure 29. Low Temperature Warehouse at the Crosby facility. The red line shows the high-water mark, just over five feet above the ground. (Source: CSB Photo)

101. By Monday evening, the most practical and safest way to move around the facility was by boat (Figure 30). Two boats were onsite. The first was a smaller boat, which was onsite as part of the Arkema site's Hurricane Preparedness Plan. As the floodwater heights increased, a relative brought a ride-out crew member's larger 16-foot boat to the site.

Figure 30. Boat Used by Ride-out Crew to Move Around the Arkema Crosby Facility. This photo shows two members of the ride-out crew in the 16-foot boat used to travel around the site during the flood. (Source: Arkema Photo)

102. After the ride-out crew communicated the dire nature of the situation to the Arkema corporate crisis team, the crisis team alerted the Harris County emergency responders to the possibility of a release or a fire at the Crosby facility. The Arkema corporate crisis team also began to prepare for the eventuality that when the refrigerated trailers not located in the laydown area lost power, the organic peroxide products in those trailers would combust. The corporate crisis team performed an analysis and found that if the refrigerated trailers failed, the products inside would likely reach its Self-Accelerating Decomposition Temperature (SADT) and begin to combust within a few days.

3.6. TUESDAY, AUGUST 29, 2017

103. Around midnight, Harris Country emergency responders evacuated one member of the ride-out crew after a concerned family member called local authorities. The remainder of the crew stayed behind to check on the site and to assess the condition of the refrigerated trailers one more time in the daylight before being evacuated.

104. On Tuesday morning, the ride-out crew saw that one of the refrigerated trailers had partially tipped over during the night and was leaning against the building (Figure 31). That tilting likely happened either because the floodwater current was strong enough to knock out the supports, or the trailer was overloaded with organic peroxide products, or a combination of both circumstances. When the

corporate crisis team members received the picture in Figure 31 from the ride-out crew, they reasoned that there likely was going to be at least one fire at the Crosby facility caused by the decomposition of organic peroxide products. At least some of the refrigerated trailers—those not in the laydown area—would not be able to maintain power and ultimately would lose cooling. The Arkema corporate crisis team decided to request Harris County emergency responders to evacuate the ride-out crew.

Figure 31. Condition of the Crosby Facility on the Morning of Tuesday, August 29, 2017. The ride-out crew sent this photograph to the corporate crisis team showing the trailer on the left had tilted. (Source: Arkema Photo Modified by CSB)

105. During the morning, the ride-out crew motored around the site by boat one last time to understand the condition of the facility to provide an update to the Arkema corporate crisis team and the emergency responders. Around midday, Harris County emergency responders evacuated the ride-out crew members by boat and transported them to a nearby fire station.

106. Figure 31 shows three of the trailers that the ride-out crew members could not move to the higher ground in the laydown area. The cooling systems of all three refrigerated trailers shown in Figure 31 likely failed due to the high floodwater level. At that time, the six trailers at the laydown area were still operating and cooling their organic peroxide products (Figure 32).

Figure 32. Refrigerated Organic Peroxide Trailers Located on High Ground. The refrigerated trailers containing organic peroxide products and resting on high ground are pictured here, located on the north side of the Arkema Crosby facility during high floodwater conditions on Tuesday August 29, 2017. All six trailers at this location were incinerated during a controlled burn on September 3, 2017. (Source: Arkema Photo)

107. During the day, the water level at the Crosby facility exceeded the top of the secondary containment around the wastewater tanks, and organic liquids overflowed into the floodwater. Two waste water tanks located in the secondary containment were open to the atmosphere and the contents had overfilled due to the excessive rainfall. Arkema reported the release of approximately 23,000 pounds of organic material into the floodwater (Table 2).

Table 2. Chemicals Released into Floodwater. The listed chemicals (and quantities) were released into Hurricane Harvey floodwater when the Arkema wastewater tanks overflowed.

Chemical	Quantity (pounds)
Tert-amyl alcohol	2,026
Tert-butyl alcohol	2,026
Di-tert-butyl peroxide	507
Di-tert-amyl peroxide	507
2,5-Dimethyl-2,5-di-(tert-butylperoxy)hexane	507
Ethylbenzene	405
Naphthalene	405
Naphtha (Heavy and Light)	6,089
Xylene	405
1,2,4-Trimethylbenzene	2,229
Mineral Spirits	8,106

108. During the afternoon, Arkema began to receive telemetry data from six of the nine refrigerated trailers. The manufacturer of the six refrigerated trailers provided these data. The other three trailers, supplied by a different manufacturer, did not have telemetry data capability. The telemetry data recorded the air temperature within the refrigerated trailers and included information about whether the refrigeration system was operating. Arkema provided these data to the emergency responders and used the data in an attempt to estimate when the refrigerated trailers would begin to combust. The estimated SADT for the refrigerated trailers was based on their organic peroxide product contents and ranged from 19 to 70 °F. It should be noted that the telemetry data did not give a temperature reading for the organic peroxide products in each trailer but rather the temperature of the air inside the trailer. Moreover, the hectic nature of the loading process during the storm prevented the ride-out crew members from definitively identifying the specific organic peroxide products in each refrigerated trailer. Consequently, although the telemetry data offered some guidance regarding when a trailer stopped cooling and how warm the inside of the trailer was, this data could not be used to determine precisely when a refrigerated trailer and its contents would combust.

109. When the ride-out crew evacuated the Crosby facility, the plant manager provided the emergency responders with an overview of the facility and the status of the refrigerated trailers, to the best of his understanding of the conditions at that time. The plant manager told the responders that a number of the refrigerated trailers had lost power and could not maintain cooling. Arkema maintained a person onsite at the emergency command center throughout the incident to relay information to the emergency responders.

110. Emergency responders handling the Arkema Crosby incident established a 1.5-mile evacuation zone around the Arkema Crosby facility (Figure 33). Emergency response agencies—including FEMA, the Environmental Protection Agency (EPA), and the Harris County Fire Department—performed analysis and modeling that assumed the combustion of the refrigerated trailers. The analysis evaluated a release from the sulfur dioxide storage tank, a release from the isobutylene storage tank, and ash fallout from the burning refrigerated trailers. Based on soot and particulate matter resulting from the refrigerated trailer combustion, a one-mile evacuation zone would be sufficient. To be conservative, provide greater safety for the surrounding residents, and efficiently allocate resources, emergency response officials extended the evacuation zone 1.5 miles. As part of this decision process, the Arkema corporate crisis team was consulted, and the crisis team agreed that 1.5 miles was sufficient given the likely scenario of organic peroxide products combusting. As a result, emergency responders initiated evacuations of residents within the evacuation zone. About 205 residents were evacuated from their homes during this process.

Figure 33. Extended Evacuation Zone. The 1.5-mile extended evacuation area around the Arkema Crosby facility is displayed within the red circle. (Source: Google Earth Image Modified by CSB)

111. At 4:50 pm, Arkema released a public statement alerting the public that the facility had been evacuated and issued a warning about the situation. The statement addressed the incident as follows:

> At this time, refrigeration on some of our backup product storage containers has been compromised due to extremely high water, rising to levels that are unprecedented in the Crosby area. Arkema is limited in what it can do to address the site conditions until the storm abates. We are

> monitoring the temperature of each refrigeration container remotely. At this time, while we do not believe there is any imminent danger, the potential for a chemical reaction leading to a fire and/or explosion within the site confines is real [35].

3.7. Wednesday, August 30, 2017

112. Emergency response personnel continued to evacuate residents and maintain the exclusion zone. A number of Federal and local agencies supplied personnel to monitor roads entering the exclusion zone. The emergency responders had been warned that an explosion was "imminent" at the Arkema Crosby facility. Some community members who were evacuated also believed that an incident at the plant could be imminent and therefore rushed to evacuate [36].

113. A Unified Command was set up to address the situation at the Crosby facility in accordance with National Incident Management System (NIMS) practice. The Unified Command consisted of Harris County Fire Marshal's Office, Crosby Volunteer Fire Department, Harris County Sheriff's Office and Constables, Harris County Pollution Control, Arkema, EPA, Texas Commission on Environmental Quality (TCEQ), and, later on in the incident, the City of Houston Bomb Squad. The Crosby Volunteer Fire Department acted as Incident Command, and the command post was set up at the Crosby Fire Station.

114. Figure 34 shows the location of emergency personnel around the evacuation perimeter. Roadblocks were set up at strategic locations so that people could not enter the evacuation zone. Air monitoring stations were established to test for combustion products on the perimeter of the evacuation zone.

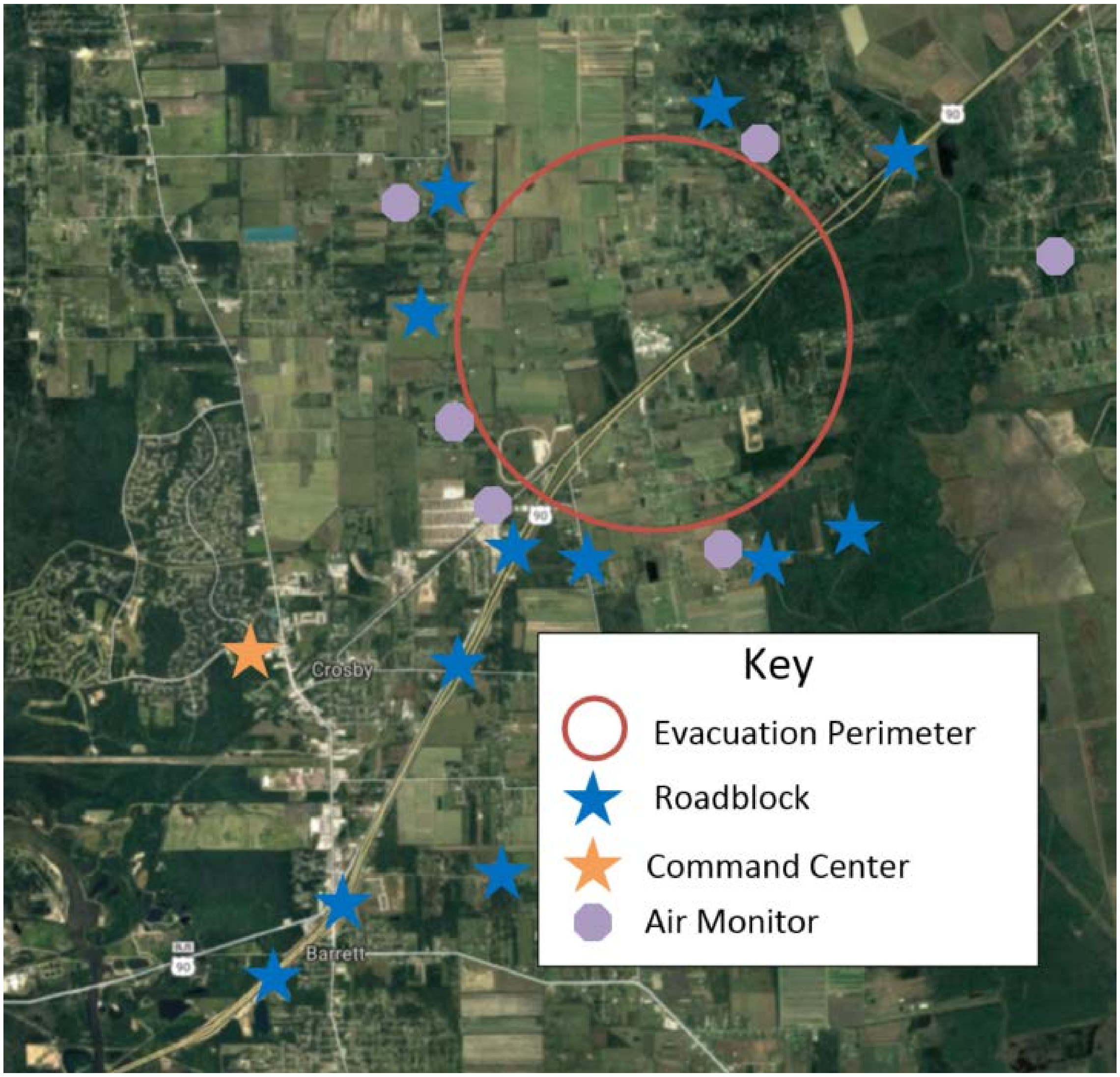

Figure 34. Evacuation Perimeter and Key Staging Locations. The evacuation zone (red circle) is surrounded by emergency response personnel staging locations, including the roadblocks, command center, and air monitoring stations. (Source: Google Earth Image Modified by CSB)

115. While it was becoming apparent to the Unified Command that an incident would occur at the Arkema Crosby facility and emergency responders were planning for that inevitability, the massive emergency response effort to Hurricane Harvey was also underway. As the hurricane advanced from the Houston area into the Beaumont region, emergency responders needed to move as well. Rainfall from the storm flooded portions of Interstate 10, leaving Highway 90, which cut through the middle of the evacuation zone for the Arkema Crosby incident, as the only viable route for transporting resources (Figure 35). Due to this constraint and the importance of transporting personnel and equipment to sites where they were needed, Highway 90 was open to such traffic even while the remainder of the evacuation zone was being enforced. The Unified Command staged emergency responders to block the road when the refrigerated trailers began to combust. Due to flooding of surrounding roads, when Highway 90 closed it would take multiple hours to detour traffic around the evacuation zone.

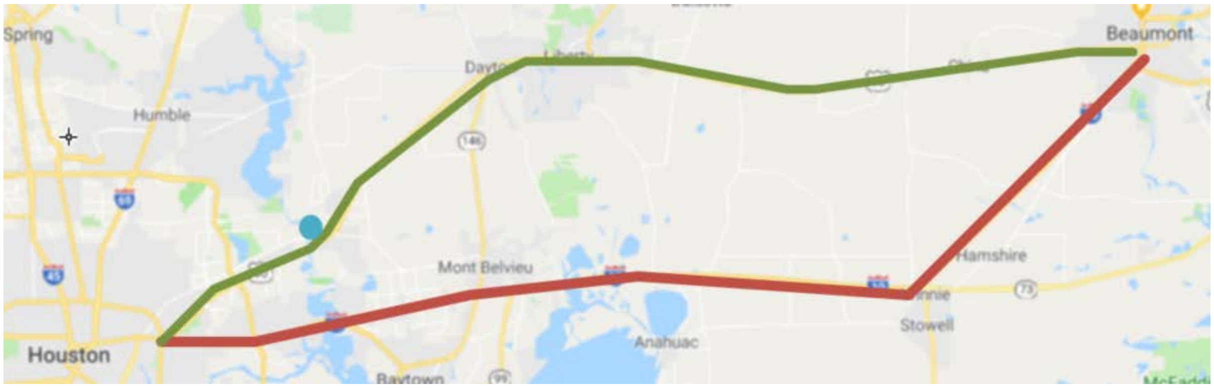

Figure 35. Major Routes Between Houston and Beaumont. As shown on this Google Map, with Interstate 10 flooded (shown with the red line), Highway 90 (shown with the green line) became an important route for hurricane relief resources between Houston and Beaumont. The Arkema Crosby location is shown by the blue circle. (Source: Google Maps Image Modified by CSB)

116. Arkema continued to provide telemetry data to the Unified Command to track the temperature in the refrigerated trailers. Arkema and the emergency responders held regular meetings during the day to discuss the site conditions and their next steps. Arkema provided a site map of the refrigerated trailers as well as an approximate list of the organic peroxide products loaded into each trailer and the SADT estimated for the products in each trailer. The Unified Command members believed that they would be able to determine when the refrigerated trailers would combust based on the temperature inside of the trailers. Three refrigerated trailers, however, could not provide telemetry data and so neither Arkema nor the emergency responders knew the temperature in these trailers. In addition, Arkema was not certain about which products were in each trailer so the SADTs were estimated.

117. Just before midnight, two of the police officers assigned to monitor the exclusion zone perimeter were asked by a supervisor to respond to a high-water call. To respond, the officers left their position located at the northeast of the Arkema Crosby facility and were traveling west on Highway 90 when they entered a "large cloud of gas," (Figure 36) which engulfed and entered their vehicle as they neared the Arkema plant (Figure 37). The officers turned their vehicle around and retreated back to their original location northeast of the Arkema Crosby facility. Because the cloud had a chemical odor and the officers experienced adverse health symptoms (eye, skin, throat, and respiratory irritation) from the exposure,[a] the officers concluded this cloud was a chemical release and they initiated a shutdown of Highway 90. The officers subsequently reported the release to the Unified Command.

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[a] Only one of the two officers had a respirator, but the exposure occurred too quickly to provide time to use it. The officer had a respirator because of his participation in the Special Response Group. The Special Response Group is a small group of officers trained to address activities such as protests. The group is equipped and prepared to handle any type of situation and to help influence a peaceful resolution [237].

Figure 36. Police Vehicle Dash Cam Image of White Smoke. The left dash cam image shows the view of the white smoke cloud adjacent[a] to the Arkema Crosby facility at about 11:52 pm on August 30, 2017. The image on the right provides a baseline of how the scene appeared on the dash cam outside of the white smoke. (Source: Harris County, Texas)

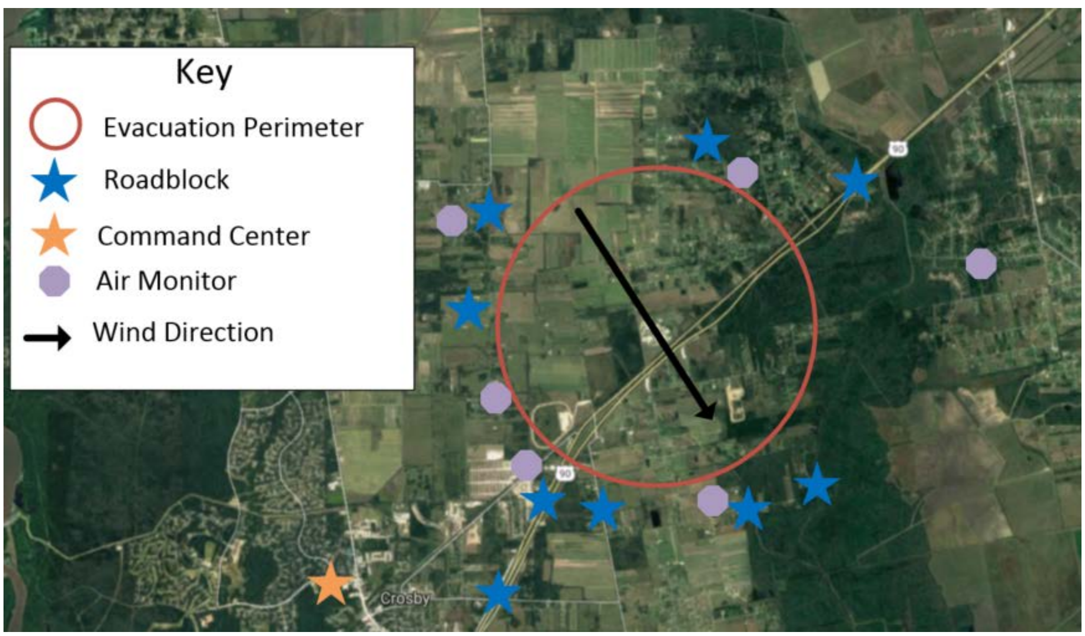

Figure 37. Approximate Wind Direction on August 30. The police officers who were first exposed to the white smoke cloud were travelling west on Highway 90 from the northeast roadblock area on Highway 90. (Source: Google Earth Image Modified by CSB)

3.8. THURSDAY, AUGUST 31, 2017

118. Around midnight, amid reports of smoke at the Arkema facility, the Unified Command conducted a safety briefing with the emergency responders at the fire station, which was serving as the base of

[a] The center of the white smoke crossed Highway 90 at approximately 29.947683N 95.018305W as measured by the police vehicle dash cam.

operations. Units were briefed on the situation at the plant and were advised to remain upwind of any potential release.

119. The available telemetry data did not show any spike in temperature within the refrigerated trailers, so the Unified Command dispatched two Crosby Volunteer Fire Department members to determine whether a fire was in progress at the Crosby facility. The firefighters did not identify anything resembling organic peroxide decomposition at the facility and reported back to the command post. At 12:30 am, with no confirmation of fire or smoke at the Arkema facility, officials concluded the initial white smoke was a “low lying weather cloud” and reopened Highway 90 to traffic. Neither telemetry data nor air monitoring data indicated any signs of combustion and, as stated previously, Highway 90 represented a vital corridor to move emergency responders toward the Beaumont area, where help was needed. The command center also relied on the telemetry data and believed that there would be some warning of any organic peroxide decomposition in the refrigerated trailers. Unknown to the Unified Command at the time, however, the refrigerated trailer that likely generated the vapor cloud did not have telemetry data capability.

120. The police officers, who first reported driving through the cloud, believed they had driven through a chemical release and they informed other police officers that the cloud was recorded on their vehicle’s dash cam, proving the release that they reported. Three other police officers then drove their vehicles on Highway 90 to check on those officers and review their dash cam footage. As they passed near the Arkema facility, the three officers also drove through a cloud originating at the Arkema facility. Even though they turned off their air conditioning, the white smoke still made its way into the vehicles.

121. When the three police officers arrived at the northeast boundary of the exclusion zone, they reviewed the dash cam footage from the first police vehicle that showed the white smoke cloud. The three police officers who had most recently driven through the cloud reported watery eyes and scratchy throats. The three police officers soon believed that they also had been exposed to chemicals from the release at the Arkema facility. From their location, the three police officers could see a black cloud coming from the Arkema facility rising above Highway 90 (Figure 38). That cloud and their symptoms combined with the flooding of all nearby roads and the officers’ desire to get prompt medical attention led the police officers to drive west down Highway 90 toward the command post and a hospital that was not flooded. In total, five police officers in four police vehicles drove down Highway 90. The officers called to request medical assistance when they reached the southern end of the exclusion zone.

Figure 38. Police Vehicle Dash Cam Image of Black Smoke. The yellow circle shows the black smoke emanating from the Arkema Crosby facility at about 1:30 am on August 31, 2017. When this image was recorded, the police vehicle was parked on Highway 90 near Shady Lane, about 2.5 miles northeast of the Arkema Crosby facility. (Source: Harris County, Texas Modified by CSB)

122. As the police vehicles drove west on Highway 90, the officers were again exposed to a cloud emanating from the Arkema facility. The health symptoms of the five officers began to worsen. By the time they reached the southern end of the exclusion zone, they were experiencing nausea and severe headaches. Other emergency responders decontaminated the police officers complaining of exposure and flushed their exposed skin with water.

123. When the officers reached the forward command post they told the emergency responders there what they had experienced and officials shut down Highway 90. From that point forward, Highway 90 remained closed to traffic until the all-clear was given on September 4.

124. Emergency medical technicians (EMTs) were called to assist with the police officers. While the EMTs were on the way to the scene, they drove through a cloud as well. By the time these EMTs arrived on scene, a number of police officers were experiencing symptoms of exposure, including vomiting. Shortly after the EMTs arrived, three of the EMTs also reported possible exposure symptoms. Ultimately, 21 emergency responders reported to the hospital for a medical evaluation related to exposure to the smoke coming from the Arkema Crosby facility.

125. At around 2:00 am, the organic peroxide products in the refrigerated trailer that had tipped on Tuesday morning decomposed to the point where they combusted and the refrigerated trailer caught fire. Figure 39 shows the burned trailer the next morning. The two refrigerated trailers outside Low Temperature Warehouse 7 are also visible in the figure. These two refrigerated trailers were the next ones that the Unified Command anticipated would decompose and burn.

Figure 39. First Refrigerated Trailer to Burn at the Arkema Crosby Facility. The first refrigerated trailer to burn is shown smoldering outside of Building 21 [37].

126. During the afternoon, the EPA conducted flyovers of the Crosby facility to perform air monitoring. The monitoring found low levels of peroxide immediately downwind of the refrigerated trailer that had burned during the night. It should be noted that the flyover was conducted at a high altitude and did not necessarily reflect conditions on the ground.

127. At 4:55 pm, Arkema released a statement to the public discussing the situation at the Crosby facility [38]. The statement read in part as follows:

> Right now, we have an unprecedented 6 feet of water at the plant. We have lost primary power and two sources of emergency backup power. As a result, we have lost critical refrigeration of the materials on site that could now explode and cause a subsequent intense fire. The high water and lack of power leave us with no way to prevent it [38].

3.9. Friday, September 1, 2017

128. Arkema held a press conference to update the community, and Harris County Pollution Control released the following statement:

> To reduce risk of exposure, residents should stay indoors and close all windows and doors along with shutting of air conditioning to close off the air intake into the home. If going outside is unavoidable, try to move out of the line of the smoke plume and minimize time outdoors for work, exercise or play [39].

129. During the day, Harris County helicopters were used to survey the condition of the Arkema Crosby facility. The helicopters flew over the refrigerated trailers to check for signs of combustion and to survey the isobutylene and sulfur dioxide feedstock tanks[a] that were the driving factor in the Crosby facility's Risk Management Plan worst-case scenario evaluation. At 10:00 am, the facility appeared to be stable with no indication of combustion from the eight remaining refrigerated trailers loaded with organic peroxide products.

130. Around 5:00 pm, two more refrigerated trailers ignited and burned. At that point, the three refrigerated trailers that could not be moved to high ground because of the floodwater on Monday had all burned, leaving the six refrigerated trailers with organic peroxide cargo in the laydown area still uncombusted. Figure 40 shows the smoke plume from the two burning trailers and Figure 41 is an image of the remains of the two refrigerated trailers after they combusted.

Figure 40. The Second and Third Refrigerated Trailers Burning. Fire and smoke are visible from two refrigerated trailers burning at the Arkema Crosby facility on September 1, 2017 [40].

[a] See additional information on these tanks in Section 11.1 and Section 11.2.

Figure 41. Remains of the Second Fire that Consumed Two Trailers Storing Organic Peroxide Products. The second fire consumed two refrigerated trailers storing organic peroxide products; the remains of those trailers are shown in this image. (Source: CSB Photo)

3.10. SATURDAY, SEPTEMBER 2, 2017

131. On Saturday, September 2, 2017, only six refrigerated organic peroxide trailers remained (Figure 42). These six remaining refrigerated trailers were also more likely to have working refrigeration units, so it was uncertain how long they would last until decomposition and combustion occurred.

Figure 42. Photo Showing the Location of the Last Six Refrigerated Organic Peroxide Trailers [41]. (Photo Modified by CSB)

132. Around 1:20 pm, the Unified Command conducted another aerial reconnaissance flight over the facility. This flyover indicated that at least one of the refrigerated trailers had lost cooling capacity. This aerial flight identified some decomposed material near the remaining trailers and smoke, but no fire. Based on infrared camera images, the material leaking out of at least one of the refrigerated trailers was at an elevated temperature. Arkema representatives were consulted to identify the substance. Although these representatives were unsure about the composition of the material, they suspected that the leaking material was a byproduct of decomposing organic peroxides.

133. As the evacuation continued, residents, who were not allowed to enter the perimeter, began to express concern over their inability to check on their homes and gather their belongings. These residents began to pressure officials to end the evacuation and remedy the situation at the Crosby facility. To facilitate an end to the evacuation, the Unified Command met around 6:00 pm with a Regional Response Team to discuss the possibility of executing a controlled burn of the remaining six refrigerated trailers. The group developed a plan to perform a controlled burn and presented it to Arkema for final approval. By 7:00 pm, all parties within the Unified Command, including Arkema, had approved the plan.

134. One concern was the isobutylene storage tank, located about 40 yards from the closest refrigerated trailer in the laydown area (Figure 43). This concern focused on the risk that the controlled burn of the six refrigerated trailers would heat the isobutylene tank, potentially causing a release or even an explosion. Emergency responders believed that the distance was great enough and that the venting on the isobutylene tank was sufficient to avoid a serious incident, but they planned the controlled burn so that the last refrigerated trailer to be burned would act as a heat shield for the isobutylene storage tank while the other five trailers combusted; the last trailer then would be burned by itself.

Figure 43. Isobutylene Storage Tank at the Arkema Crosby Facility. The isobutylene tank posed a concern because the controlled burn of the six refrigerated trailers in the laydown area would occur within about 40 yards of this storage tank. (Source: CSB Photo)

3.11. Sunday, September 3, 2017

135. The Unified Command conducted another aerial reconnaissance flight over the facility on Sunday and identified additional material leaking out of the refrigerated trailers, indicating that some type of reaction was still ongoing within the refrigerated trailers. In light of this information, emergency responders decided that it was unsafe to approach the refrigerated trailers or to try handling any of the products within the trailers.

136. The Unified Command reconvened around 10:00 am to discuss next steps. The emergency responders were concerned about the intermittent decomposition occurring in the refrigerated trailers and the lack of information about the next likely event. The responders also were concerned about not having a timeline for combusting all of the organic peroxide products. Evacuated residents were still anxious to return to their homes. Under the circumstances, a controlled burn made sense to end the incident quickly and precisely. The team decided to move forward with the controlled burn plan developed the night before.

137. Arkema provided information on the sulfur dioxide and isobutylene storage vessels to the Unified Command to help evaluate the hazards posed by the location of the tanks and the risk of a release. Using this information, the Unified Command determined that neither the sulfur dioxide nor the isobutylene tank was likely to release product during the controlled burn.

138. At 12:45 pm, the entry teams were briefed about the controlled burn plan. Before the controlled burn, a team would first conduct visual reconnaissance of the isobutylene tank to ensure that no

decomposed organic peroxides had leaked near the isobutylene tank because such leaked materials could catch fire and result in flame impingement on the isobutylene tank. If the team found evidence of leaked material near the isobutylene tank, it would reevaluate its plan and identify a way to drain the tank before performing the controlled burn. If the team did not find evidence of leaked material, the controlled burn operation would begin.

139. The visual reconnaissance team determined that it was safe to commence the controlled burn. For the controlled burn, Harris County emergency response personnel placed an incendiary device on each of the six refrigerated trailers in the laydown area that could be activated remotely. The entry members all wore a self-contained breathing apparatus because of the potential health risk posed by unknown decomposition products leaking from the refrigerated trailers.

140. Around 3:40 pm, the emergency responders commenced the controlled burn of the remaining six trailers containing organic peroxide products. The Harris County Fire Marshal's Office released a public statement warning the public about the impending controlled burn [42].

141. Around 9:00 pm, additional air monitoring was conducted within the evacuation zone and there were no readings above the baseline level. The emergency response team determined that no health threat to the community remained and that the evacuation zone could be lifted once security personnel for the Arkema Crosby facility were in place.

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142. Around 1:00 am, the Unified Command authorized lifting of the evacuation zone and allowed residents to return to their homes.

4. Flood Information

143. The Arkema Crosby facility is located in Harris County, Texas. According to the Harris County Flood Control District,[a] flooding is the primary natural disaster concern due to factors such as flat terrain, poor water-absorbing clay soils, and annual average rainfall of 48 inches [43].

144. The National Oceanic and Atmospheric Administration (NOAA) identifies inland flooding as "often the most deadly" effect from hurricanes, stating, "While storm surge is always a potential threat, more people have died from inland flooding in the last 30 years [44]." NOAA notes that some of the highest rainfall totals have occurred when weaker storms either drifted slowly or stalled over an area [44]. Hurricanes can pose a major threat to communities hundreds of miles from the coast because intense rainfall can accompany these tropical storms [44]. NOAA recommends that when residents and businesses in coastal flood hazard areas hear "hurricane," they should think inland "flooding" [44].

145. Hurricane Harvey was the strongest hurricane to strike Texas since 1961 and the first Category 4 hurricane to make landfall in the United States since 2004 [45]. The Harris County Flood Control District reported that about one trillion gallons of water fell on Harris County as a result of Hurricane Harvey rainfall over four days [46]. The rain from Harvey could cover the county's 1,800 square miles with 33 inches of water [46]. The storm flooded more than 136,000 structures [46].

146. The Harris County Flood Control District operates a flood warning system that uses 154 gauge stations with sensors that transmit data on rainfall and stream level [47]. (Figure 44). The gauge system was initiated in 1983 with 13 gauges and expanded to its current 154 gauges [47].

[a] The Texas legislature created the Harris County Flood Control District in 1937 following devastating floods in 1929 and 1935 [127]. The mission of the flood control district is to "Provide flood damage reduction projects that work, with appropriate regard for community and natural values [127]."

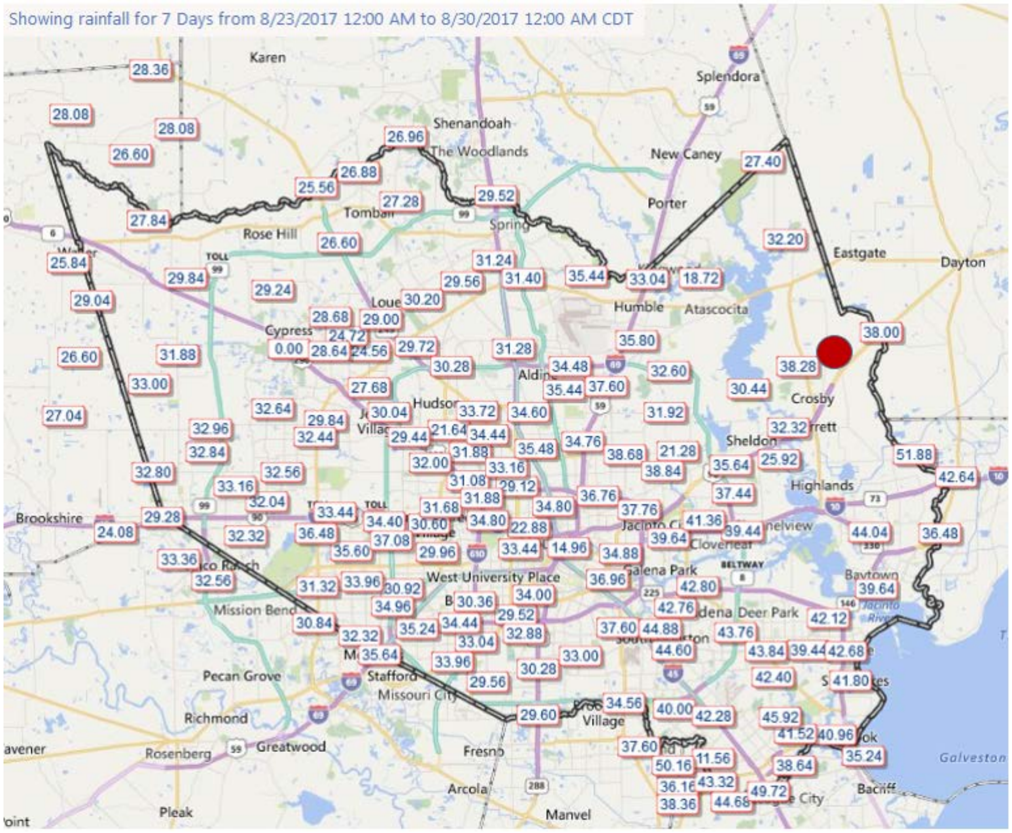

Figure 44. Harris County Flood Control District Gauge Map. This Harris County gauge map shows the 7-day rainfall totals (in inches of water) attributable to Hurricane Harvey [48]. The approximate location of the Arkema Crosby facility is shown by the red circle. (Image Modified by CSB)

147. Harris County has 22 watersheds[a] that drain into Galveston Bay [49].[b] The Arkema Crosby facility is located in the Cedar Bayou watershed (Figure 45). About 37,000 people live within the Cedar Bayou watershed, which covers an area of 202 square miles and includes 128 miles of open streams [50]. The main stream of Cedar Bayou is about 40 miles long, flows south, and discharges into Galveston Bay [50].

[a] "A watershed is a geographical region that drains to a common bayou, creek or other waterway. There are 22 major watersheds in Harris County [139]."

[b] See the section on Harris County Watersheds in the Flood Insurance Study: Harris County, Texas and Incorporated Areas: Volume 1 of 12 from January 6, 2017 [49, p. 21]. To access Volume 1 of the Flood Insurance Study (number 48201CV001E), access the FEMA Flood Map Service Center website, enter the address for the Arkema Crosby facility (18000 Crosby Eastgate Rd., 77532), and then click "Show all products for this area." Click the "Effective Products" folder, and then click "FIS Reports." Scroll down the page to map 48201CV001E under the "Product ID" column.

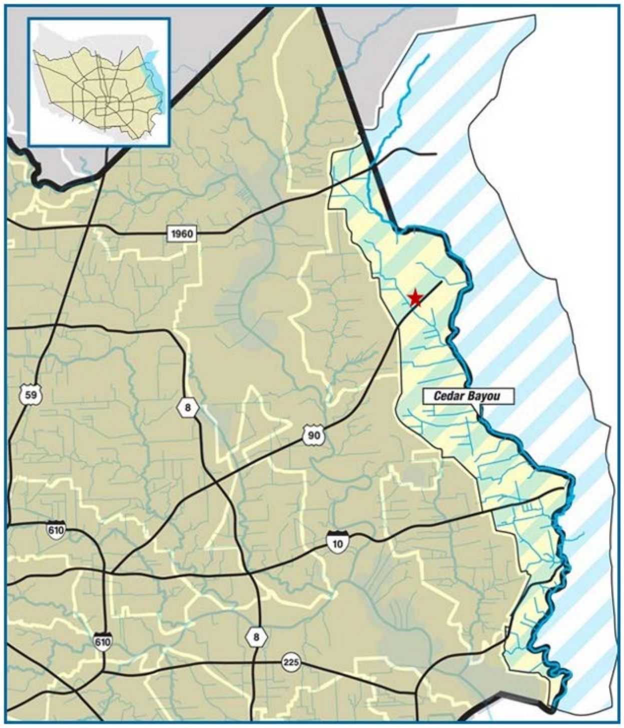

Figure 45. Map of the Cedar Bayou Watershed in Harris County, Texas. The white and blue shaded area on the right is the Cedar Bayou watershed. The red star shows the approximate location of the Arkema Crosby facility [50]. (Image Modified by CSB)

148. Congress established the National Flood Insurance Program in 1968 [51, p. 1] and the Federal Insurance Administration began to assume responsibility for flood insurance studies during the late 1970s [52, p. 1].[a] The Federal Emergency Management Agency (FEMA) now administers this program [51, p. 2]. Among its advances, the Flood Insurance Studies (FIS) group began providing maps and reports to establish a basis for flood insurance and for the regulation of floodplain development [52, p. 2]. These maps include the Flood Insurance Rate Map (FIRM) [52, p. 3]. FIRMs are used for tasks such as the following:

- Determining whether a property is in a floodplain;
- Showing the flood insurance zone of the property; and
- Establishing the approximate base flood elevation for the property [52, p. 13].[b, c]

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[a] Starting in 1954, the Tennessee Valley Authority (TVA) was the first Federal agency to prepare regional flood hazard information for communities [52, p. 1].

[b] After 1989, Flood Insurance Rate Maps began to include additional information, such as how a floodplain is divided into floodway and flood fringe, where streams are studied in detail. See Utilizing Information from Flood Hazard Studies at pages 6-15 and 6-16 [52].

[c] The Base Flood Elevation is the elevation of flooding having a one percent chance of being equaled or exceeded in any given year. The Base Flood Elevation (BFE) is also known as the "base flood" and the "100-year flood" [61, p. 1].

149. The Cedar Bayou watershed has a known history of flooding [50]. Figure 46 shows that the Arkema Crosby facility is located within a floodplain.[a] Cedar Bayou and an unnamed tributary stream are located north and east of the Crosby facility, while the Adlong Ditch sits to the west. From the Arkema facility, the Adlong Ditch flows southeast about three miles and connects into Cedar Bayou. Flooding at the Arkema Crosby facility is a function of, among other factors, rainfall within the area and the capability of the Adlong Ditch and Cedar Bayou to carry such rainfall into Galveston Bay.[b]

[a] A floodplain is the area adjacent to rivers or streams that is naturally subject to flooding [128]. "From time to time, bayous and creeks naturally come out of their banks due to heavy rainfall and inundate the adjacent land. This area that is inundated is referred to as a floodplain [139]." (Hyperlink added.) "The mapped floodplain is only an estimate of where flooding is predicted to occur from a bayou or creek, given a set of parameters including a hypothetical rainfall occurring over a watershed for an assumed amount of time. During an actual rain event, natural conditions can result in greater amounts of rainfall or runoff, resulting in flood levels deeper and wider than shown on the FEMA Flood Insurance Rate Maps [127]." (Hyperlink added.)

[b] USGS provides additional flood information including how the 100-year flood is determined, and the accuracy of the one percent annual exceedance probability (AEP) flood (also known as the 100-year flood) [216].

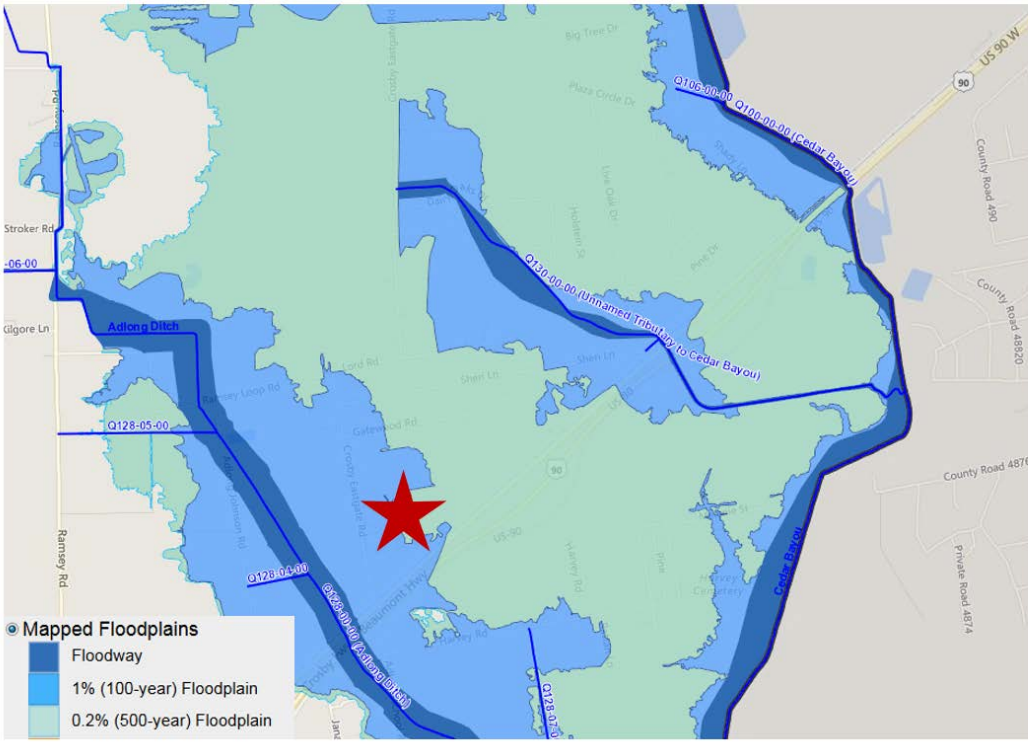

Figure 46. Approximate Floodplain Map of the Area Near the Arkema Crosby Facility. The Arkema Crosby facility (red star) is located between the Adlong Ditch and the unnamed tributary to Cedar Bayou floodways[a] and is within both the 100-year[b] and 500-year[c] floodplain [53]. (Image Modified by CSB)

150. The Harris County Flood Control District gauge station 1740 (Figure 47) is located about three miles northeast of the Arkema Crosby facility (Figure 48), where Cedar Bayou goes under Highway 90.

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[a] Floodway is the area that must be kept free of encroachments for a 100-year flood [128]. Encroachment refers to floodplain development that could obstruct flood flows [129].

[b] "A 1 percent (100-year) floodplain, also known as a Special Flood Hazard Area on a Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM or floodplain map), is an area at risk for flooding from a bayou, creek or other waterway overflowing during a 1 percent (100-year) flood. Structures located in a 1 percent (100-year) floodplain have a minimum of a 1 percent chance of flooding in any given year. Statistically, structures located in a 1 percent (100-year) floodplain have a minimum of a 26 percent chance of flooding during a 30-year period of time, which is the duration of many home mortgages. And, the risk for flooding increases the closer a structure is to a bayou or a creek, assuming the structure is not elevated. A mapped 1 percent (100-year) floodplain is an area where land development is regulated by a city or a county [139]." (Hyperlink added.)

[c] "A 0.2 percent (500-year) floodplain is an area at risk for flooding from a bayou, creek or other waterway overflowing during a 0.2 percent (500-year) flood. Structures located in a 0.2 percent (500-year) floodplain have a minimum of a 0.2 percent chance of flooding in any given year. Statistically, structures located in a 0.2 percent (500-year) floodplain have a minimum of a 6 percent chance of flooding during a 30-year period of time, which is the duration of many home mortgages. And, the risk for flooding increases the closer a structure is to a bayou or a creek, assuming the structure is not elevated [139]." (Hyperlink added.)

Figure 47. Gauge Station 1740. This gauge station uses a bubbler system to measure the Cedar Bayou water elevation at Highway 90, about three miles northeast of the Arkema Crosby facility.[a] (Source: CSB Photo)

[a] "A bubbler is one of three types of real-time, water-level measuring devices used at gage stations throughout Harris County. A bubbler system is submerged under water and uses a tube with an opening, called an orifice line, which runs from a transmitter at a gage station to the opening of the tube on the submerged part of the device to measure pressure and determine water levels. A fixed flow of air is passed through the tube, and the internal pressure of the air in the tube and the external pressure of the water outside the tube provide a water-level reading [139]." (Hyperlink added.)

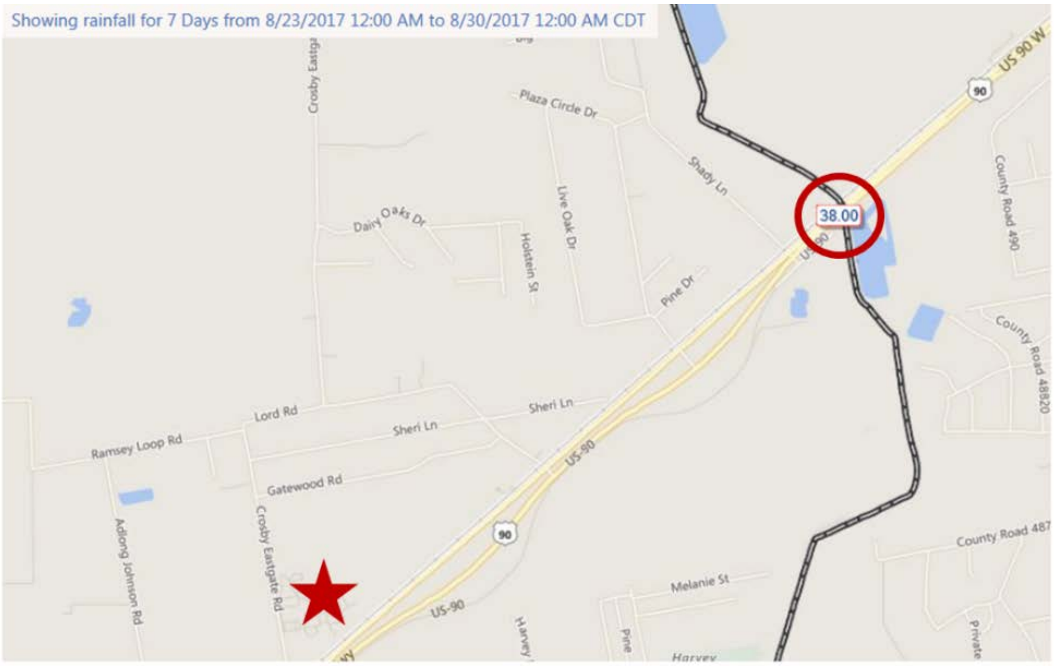

Figure 48. Arkema Crosby Facility and the Cedar Bayou Gauge Station 1740. This map shows the proximity of the Arkema Crosby facility (red star) to the nearest Cedar Bayou gauge station (red circle). Gauge station 1740 is about three miles northeast of the Crosby facility [48]. (Image Modified by CSB)

151. During Hurricane Harvey, gauge station 1740 recorded 38 inches of rain (Figure 49) raising the water level in Cedar Bayou to nearly 59 feet (Figure 50), the highest water level measured at this location since the gauge station was installed in 1984 [29].[a] This amount of rain is the equivalent of 80 percent of the average annual rainfall for the Houston area, delivered over the course of just a few days [54]. On August 27, 2017, this gauge recorded about 21.5 inches of rainfall, exceeding both the 12-hour and 24-hour 500-year rainfall criteria for Harris County by more than two inches.[b]

[a] Click on "Stream Elevation" tab for Gauge station 1740 to view historical storm elevation data [29].

[b] For Harris County, a 0.2 percent (500-year) rainfall is about 19 inches in 24 hours. A 1 percent (100-year) rainfall is just over 13 inches in 24 hours or just under 11 inches in 12 hours [217]. For the Arkema Crosby facility, which is in the Cedar Bayou region of Harris County, a 0.2 percent (500-year) is 19.3 inches in 24 hours, 20.7 inches in two days, and 22.3 inches in four days [49, p. 33]. As shown in Figure 49, Hurricane Harvey rainfall exceeded all of these benchmarks for a 500-year rainfall event.

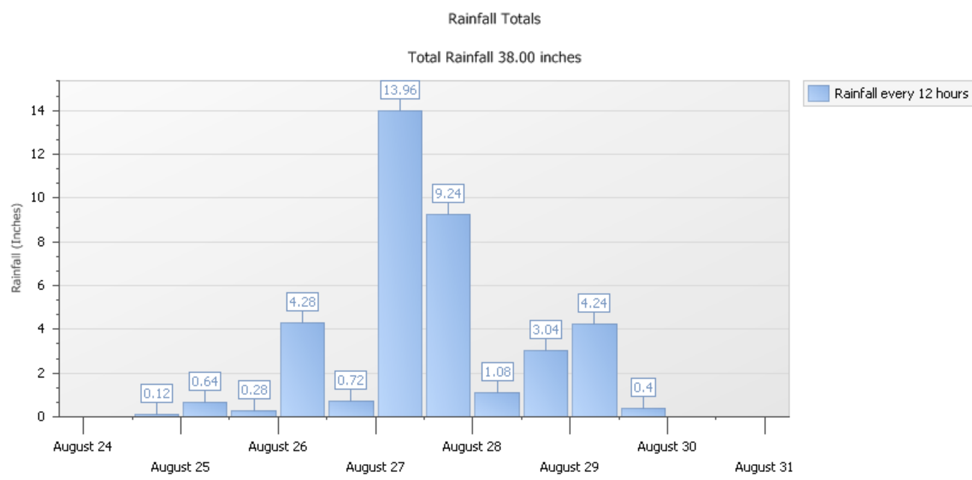

Figure 49. Rainfall Totals During Hurricane Harvey. Cedar Bayou gauge station 1740 measured rainfall totals during Hurricane Harvey [29]. The maximum 12-hour rainfall of nearly 14 inches occurred during the morning of August 27, 2017 [29].

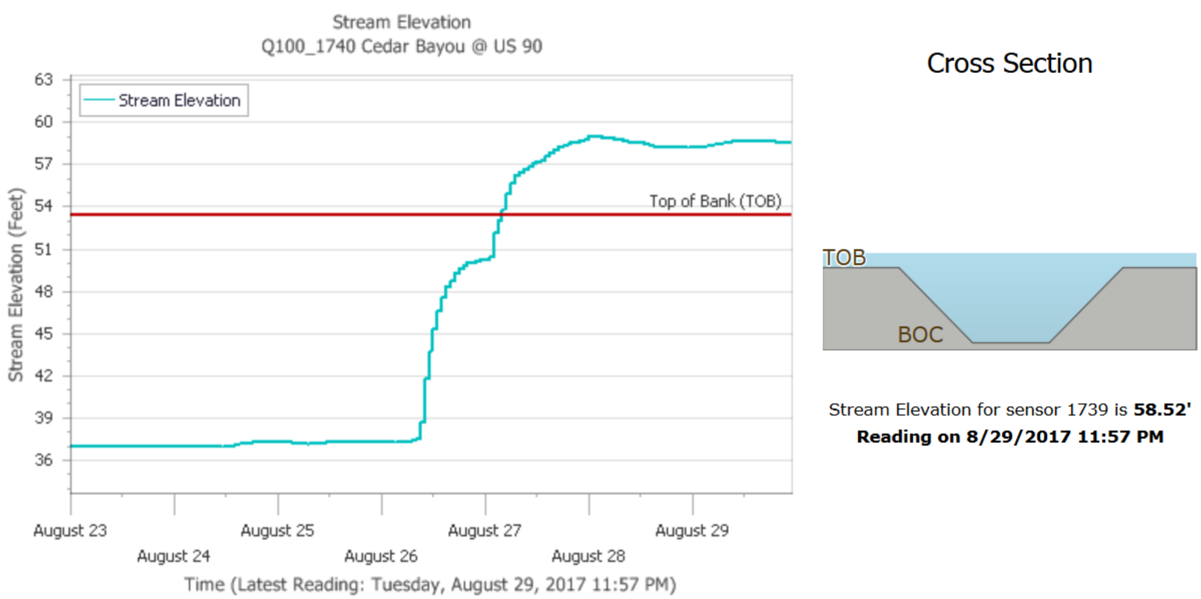

Figure 50. Gauge Station 1740 Stream Elevation Data. The graphs show Cedar Bayou stream elevation during Hurricane Harvey [29]. About 59 feet was the largest stream elevation recorded at about 1:33 am on August 28, 2017 [29].[a]

152. The 59-foot Cedar Bayou water level exceeded the nearly 57-foot predicted elevation for 0.2-percent flood frequency (Table 3) [29].[b] As a result, the flooding at the Arkema Crosby facility following Hurricane Harvey was greater than that of a 500-year flooding event. Given the

[a] For Cedar Bayou at Highway 90 (gauge station 1740), top of bank (TOB) is 53.4 feet, and bottom of channel (BOC) is 36.09 feet [29]. Click the "Stream Elevation" tab for Gauge station 1740 [29].

[b] Click the "Stream Elevation" tab for Gauge station 1740 to view historical stream elevation data [29].

floodplain where the Crosby facility is located, there is about a 10-percent chance for this level of flooding in any 50-year period [55].

Table 3. Predicted Flood Frequency Elevations. These flood frequency elevations are projected for Cedar Bayou at gauge station 1740 [29].

Flood Frequency	Elevation
10% (10-year)	52.60'
2% (50-year)	54.30'
1% (100-year)	54.90'
.2% (500-year)	56.80'

153. The Harris County Flood Control District maintains historical records for each gauge station. Before Hurricane Harvey, the previous high-water mark for Cedar Bayou at gauge station 1740 was set in 1994 with a water elevation of about 56 feet (Table 4) [29].

Table 4. Historical Storm Elevation Data. These historical storm elevations are provided for Cedar Bayou at gauge station 1740 [29]. Although not identified by the Harris County Flood Control District on its website, the 1994 event was likely Hurricane Rosa.

Historical Storm

Date	Event	Elevation
10/18/1994		56.08'
5/20/2000		50.08'
9/13/2008	Ike	53.70'
10/31/2015		55.10'
6/4/2016		50.40'
8/27/2017	Harvey	59.00'
High water mark elevations are approximate.		

4.1. History of Flood Insurance Rate Map for the Arkema Crosby Facility

154. The current and two previous versions of the Flood Insurance Rate Map for the Arkema Crosby facility are accessible on the FEMA Flood Map Service Center website. These maps show that the Crosby facility has become more susceptible to flooding over time. Available versions of these flood maps include the following:

- September 1985 – the Flood Insurance Rate Map showed that the vast majority of the Crosby facility was located in an area designated as “Zone C – Area of Minimal Flooding” [56].[a]

- November 1996 – the Flood Insurance Rate Map located the vast majority of the Crosby facility in “Other Areas – Zone X – Areas determined to be outside the 500-year floodplain” [57].[b] A small portion of the southwest corner of the facility was located in Zone A – the special flood hazard areas inundated by 100-year flood, with no base flood elevations determined [57].

- June 2007 – The current Flood Insurance Rate Map shows that the entire Crosby facility is either in the 100-year or 500-year floodplain [58].[c]

155. Of these map revisions, the June 2007 update is significant because it established that the entire Arkema Crosby facility is located within a floodplain (Figure 51). Some portions of the facility are in the 100-year floodplain and the remainder of the site is in the 500-year floodplain.

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[a] To access the September 27, 1985, Flood Insurance Map (number 4802870240D), access the FEMA Flood Map Service Center website, enter the address for the Arkema Crosby facility (18000 Crosby Eastgate Rd., 77532), and then click “Show all products for this area.” Click the “Historic Products” folder, and then click “FIRM Panels.” Scroll down the page to map 4802870240D under the “Product ID” column.

[b] To access the November 6, 1996, Flood Insurance Map (number 48201C0535J), access the FEMA Flood Map Service Center website, enter the address for the Arkema Crosby facility (18000 Crosby Eastgate Rd., 77532), and then click “Show all products for this area.” Click on the “Historic Products” folder, and then click on “FIRM Panels.” Navigate to page three to locate map 48201C0535J under the “Product ID” column.

[c] To access the June 18, 2007, Flood Insurance Map (number 48201C0535L), access the FEMA Flood Map Service Center website, enter the address for the Arkema Crosby facility (18000 Crosby Eastgate Rd., 77532), and then click to either view or download using one of the two “Map Image” icons.

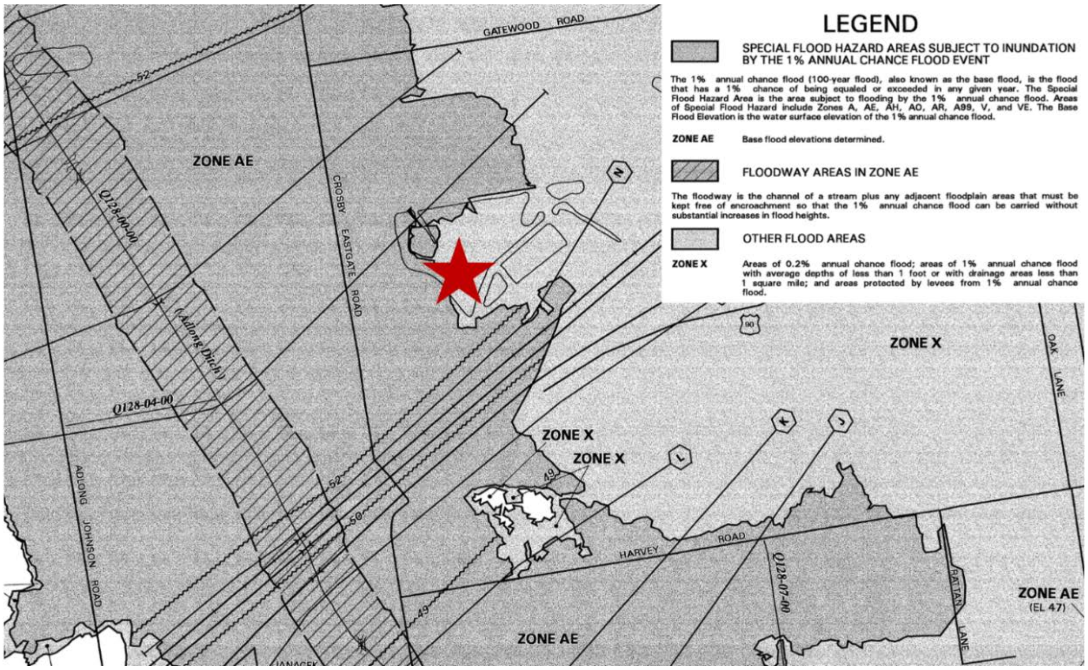

Figure 51. Excerpt from the June 2007 Flood Insurance Rate Map (FIRM). This part of the FIRM shows that the Arkema Crosby facility is located in the 100-year and 500-year floodplains [58]. (Image Modified by CSB)

156. The FEMA flood map website also offers access to digital flood map images. Figure 52 shows a digital flood map of the Arkema Crosby facility. This map places the Arkema electric utility supply and organic peroxide product Low Temperature Warehouses in the 100-year floodplain.

Figure 52. Southern Part of the Arkema Crosby Facility in the 100-Year Floodplain. This digital image shows that the southern part of the facility, where Arkema's electric utility equipment and refrigerated organic peroxide product storage facilities are located, sits in the 100-year floodplain. The blue portion of the map is Zone AE – the 100-year floodplain [58].[a]

157. In addition, a September 2016 report from Factory Mutual Insurance Company (FM Global), Arkema's insurer, shows that the Adlong Ditch represents a flood hazard to the Arkema Crosby facility. The FM Global report also confirms that some portions of the facility are in the 100-year floodplain while the remaining portions are in the 500-year floodplain.

4.2. Flood Insurance Study

158. In addition to supplying Flood Insurance Rate Maps, FEMA also provides communities with Flood Insurance Study reports that include detailed flood elevation maps called flood profiles (Figure 53) [59]. The Flood Insurance Study for Harris County, Texas includes detailed flood elevation maps for the streams near the Arkema Crosby facility including Cedar Bayou, Adlong Ditch, and the unnamed tributary northeast of the plant [59].[b]

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[a] To access the digital version of the June 18, 2007 Flood Insurance Map (number 48201C0535L), access to the FEMA Flood Map Service Center website, enter the address for the Arkema Crosby facility (18000 Crosby Eastgate Rd., 77532), and then click the icon for "View Web Map" [58].

[b] Although the Flood Insurance Study for Harris County has 12 volumes, Volume 1 and Volume 8 are the most relevant to understanding flood risks at the Arkema Crosby facility. On the FEMA Flood Map Service Center website, Volume 1 is product identification number 48201CV001E and Volume 8 is 48201CV008D [49], [60]. To access these documents navigate to the FEMA Flood Map Service Center website, enter the address for the Arkema Crosby facility (18000 Crosby Eastgate Rd., 77532), then click "Show all products for this area," then click the folder for "Effective Products," and finally click the "FIS Reports" [59].

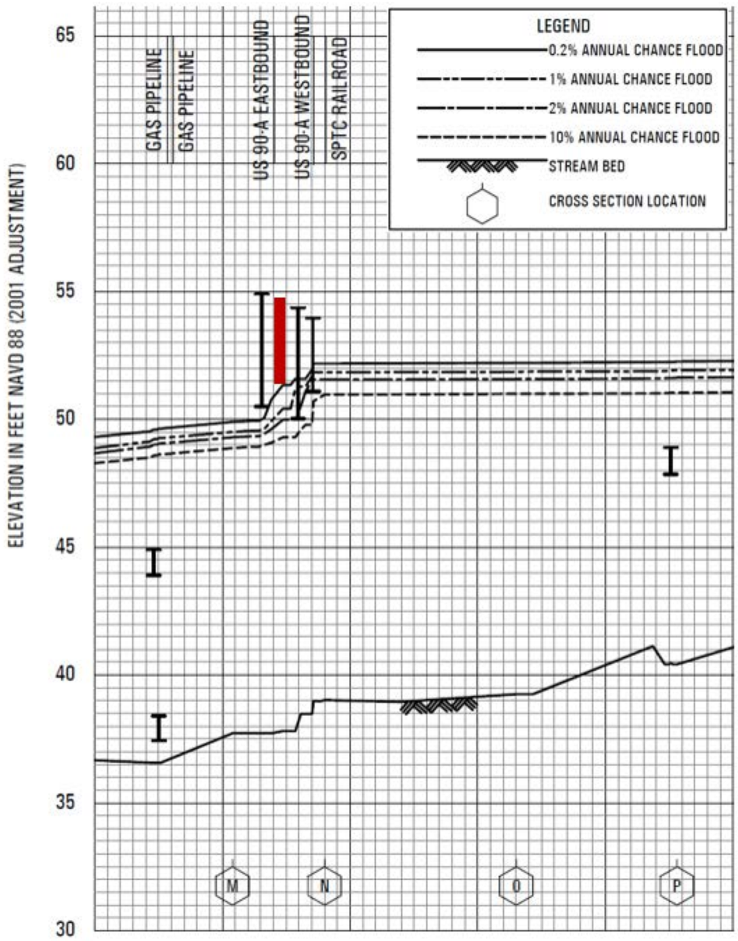

Figure 53. Excerpt from the Adlong Ditch Flood Profile. This excerpt from the Adlong Ditch flood profile shows the estimated water elevation for various flood chance scenarios adjacent to the Arkema Crosby facility [60, p. 35]. The red rectangle was placed by the CSB to show that the approximate floodwater height from Hurricane Harvey was more than two feet above the 500-year flood elevation. Exceeding the 500-year flood elevation by more than two feet is significant because the flood elevation difference between the 100-year and 500-year events is less than one foot. (Graphic Modified by CSB)

4.3. Base Flood Elevation

159. As shown in Figure 54, the Flood Insurance Rate Map indicates that for the Arkema Crosby facility, the base flood elevation, which is equivalent to the 100-year flood level, is 52 feet [58].

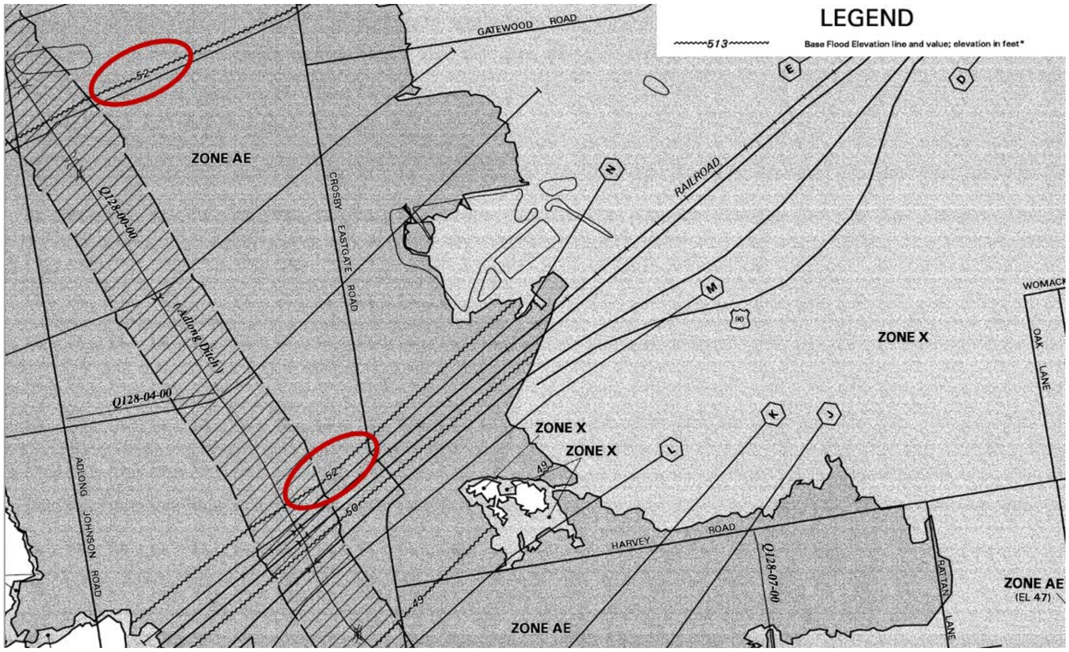

Figure 54. Base Flood Elevation for the Arkema Crosby Facility. The Flood Insurance Rate Map shows that the base flood elevation for the Crosby facility is 52 feet [58]. (Map Modified by CSB)

160. Figure 55 shows one of several elevation survey markers at the Arkema Crosby facility. The base flood elevation is six inches above the elevation of this survey marker.

Figure 55. Elevation Survey Marker Near the Liquid Nitrogen Storage Tank. The metal plate on top of the concrete block shows that the elevation is 51.5 feet, about six inches lower than the base flood elevation. During Hurricane Harvey, floodwater exceeded the height of the survey marker by more than three feet. (Source: CSB Photo)

161. According to FEMA, floods often exceed the base flood elevation. FEMA cautions that during recent storms—including Katrina, Ike, and Sandy—floodwater level exceeded the base flood elevation by several feet in some areas, and flooding extended far beyond the flood area shown on the Flood Insurance Rate Maps [61].

4.4. 2016 Insurance Report Identified and Evaluated Flood Risk

162. FM Global is a Rhode Island-based insurance company with offices worldwide that provides loss prevention insurance to large corporations. When FM Global[a] engineers visit a location for a client company, they perform a number of evaluations, including assessing whether any natural hazard loss exposures exist by reviewing flood, wind, and earthquake maps [62, p. 21].

163. A year before Hurricane Harvey, FM Global engineers visited the Arkema Crosby facility, met with the Crosby plant manager, and produced a report that identified the Crosby facility as susceptible to flooding hazards, among other insurance risks.[b] The September 2016 FM Global report specifically

[a] FM Global was the insurance provider for the Arkema Crosby facility before 2017, but Arkema switched insurance companies in 2017, so FM Global was not the insurance carrier at the time of Hurricane Harvey.

[b] The plant manager who met with FM Global representatives in September 2016 retired from Arkema in early 2017. The Arkema manager who then assumed an interim role was not aware of the FM Global report.

showed that the Adlong Ditch presented a flooding hazard to the Arkema Crosby facility. The report also found that the site was in both the 100-year and 500-year floodplains. FM Global developed property damage and business interruption loss estimates for the 100-year and 500-year flooding, which indicated that a 500-year flood could cause five times more property damage and 16 times more extensive business interruption losses than a 100-year flood event.

164. FM Global states that its engineers gather 700 data points during more than 100,000 site visits each year [63]. FM Global analyzes these data and uses them to predict the locations where insurance losses are likely to occur and the exposures most likely to result in a loss [63]. FM Global provides its clients with reports to help prioritize their risk improvement efforts [63]. Among several FM Global risk tools, the company's benchmarking tool, Risk*Mark*, measures the risk quality of evaluated sites [63]. Risk*Mark* uses a 100-point scale, with higher scores representing well managed and higher quality risks with lower risk of loss [64]. Risk*Mark* includes four components, including natural hazards, such as flooding [62, p. 21]. FM Global reports that locations with the lowest Risk*Mark* scores are seven times more likely to experience loss than those with higher Risk*Mark* scores [63]. In addition, FM Global reports that sites with low Risk*Mark* scores have losses 30 times more severe than sites with higher Risk*Mark* scores.

165. The 2016 FM Global report also provided Arkema management with a Risk*Mark* score. The score for the Crosby facility fell in the bottom quartile compared with other Arkema facilities and other FM Global client sites that manufacture hazardous chemicals. The Crosby facility received low scores for natural hazards such as flooding. Although FM Global identified the flooding risk at the Arkema Crosby facility, the FM Global report did not make any recommendations to Arkema to address its flood hazards. Furthermore, FM Global was satisfied with the changes that Arkema made based on their report. It should be noted that the FM Global report pointed out multiple issues at the Crosby facility and the facility addressed many of the issues.

5. Flood Design at the Arkema Crosby Facility

166. Although the CSB investigation found no single flood design basis for the Arkema Crosby facility, the site's hurricane plan, emergency plan, process hazard analysis (PHA), worst-case scenarios, and written statements issued by Arkema in relation to the Hurricane Harvey flooding all show how the facility viewed its susceptibility to flooding. This viewpoint is expressed by Arkema's post-incident statements, which are consistent with those made by Arkema employees to CSB investigators—the site had a history of flooding, and about two feet of water is the most employees recall onsite before the Hurricane Harvey flooding.

5.1. Hurricane Preparedness Plan

167. Among other storm preparations, the Arkema Crosby Hurricane Preparedness Plan includes the following items to address flooding:

- Fill storage tanks, where practical to prevent them from floating;
- Fill dumpsters with water to prevent them from floating;
- Acquire an off-road forklift, with large tractor-style tires that is capable of moving through a couple of feet of floodwater [65];
- Obtain a flat-bottom boat, capable of operating in shallow water [66]; and
- Stock waders as part of the personal protective raingear.

5.2. Emergency Response Plan

168. The Arkema Crosby's Emergency Response Plan discusses many potential emergency situations including:

- Organic peroxide decomposition;
- Loss of electrical power; and
- Severe weather events such as flooding.

169. The flooding and high-water section of the Emergency Response Plan does not consider the amount of flooding as seen during Hurricane Harvey. Arkema wrote its emergency plan with an unstated emphasis on a lower level of floodwater. The Emergency Response Plan says:

> Care shall be taken to be sure water is kept out of equipment, shops, control rooms, offices, etc. These areas are to be checked during severe rainstorms to prevent damage or personal injuries. Non-essential personnel are to be released when appropriate.

The following items must be checked during heavy rains:

- Monitor levels in all secondary tank containments.
- Open storm water containment gates as needed.
- Secure all containers and equipment as necessary.
- Monitor levels in sanitary sumps.

170. The Emergency Response Plan describes preparatory actions and emphasizes worker safety during severe weather. Arkema's Emergency Response Plan, however, does not identify the possibility that flooding could lead to a loss of electric power, the subsequent loss of refrigeration capability, and the resulting decomposition of organic peroxide products.

5.3. Storage Building Safety Guidelines

171. The Arkema Crosby facility had a written policy which was intended to provide guidance, limits, and process safety information for organic peroxide storage at the facility. Among other items, this policy detailed the actions operators should take to provide cooling for the organic peroxide products in the event that power is lost to the Low Temperature Warehouses. The policy was updated in 2016 to direct workers to move organic peroxide products to refrigerated trailers if the backup generators failed to operate upon loss of power to the Low Temperature Warehouses. The liquid nitrogen system was to be used in the event that there was "no other alternative available." At the 500-year flood level, if the refrigerated trailers had been loaded and placed in the laydown area, as attempted during Harvey, the organic peroxide contents would have likely maintained sufficient cooling to prevent a decomposition incident.[a]

5.4. Process Hazard Analysis

172. The Arkema team that performed the Low Temperature Warehouse PHA for the Crosby facility did not document any flooding risk.[b] Had the Arkema PHA assessed flooding, the limited industry guidance on flooding would likely have been insufficient to provide specific or sufficiently conservative level of action to protect against the hazards posed by the flooding during Hurricane Harvey. Even without this assessment, however, the Crosby facility appears to have had sufficient

[a] During Hurricane Harvey, the flood water at Adlong Ditch reached about 54.5 feet. The elevation at the laydown area is 52 feet and the fuel tank for the refrigerated trailer is 3 feet 5 inches above the ground. If all refrigerated trailers had been placed in the laydown area, they would likely not have lost refrigeration if workers could have stayed onsite to monitor them.

[b] The Arkema Low Temperature Warehouse PHA was completed in November 2013. Arkema uses as low as reasonably practicable (ALARP) in its risk assessment and risk mitigation programs. CCPS defines ALARP as follows: "The concept that efforts to reduce risk should be continued until the incremental sacrifice (in terms of cost, time, effort, or other expenditure of resources) is grossly disproportionate to the incremental risk reduction achieved. The term as low as reasonably achievable (ALARA) is often used synonymously [178]."

safeguards in place to prevent loss of refrigeration in the Low Temperature Warehouses for a 100-year flooding event.

173. Although Arkema's corporate PHA policies in place at the time of the Low Temperature Warehouse PHA included flooding as one of the possible initiating events, the Arkema Crosby PHAs did not document any risk from flooding. The Arkema PHA covering the Low Temperature Warehouses, however, identified the following three scenarios that could cause elevated temperature in the Low Temperature Warehouses, including:

- Loss of refrigeration because of a compressor failure;
- Loss of refrigeration because of a refrigerant leak; and
- Loss of power.

174. To address possible loss of power, the Crosby PHA team identified safeguards, including the following:

- Emergency generators that provide electricity to all low-temperature storage buildings;
- Liquid nitrogen supply for alternative cooling; and
- Manual temperature checks conducted every two hours and the capability to relocate organic peroxide products from an affected cold storage building to another building or to a portable refrigerated trailer that is still capable of providing the required cooling.

175. The adequacy of flood risk safeguards was not assessed for Hurricane Harvey-like flooding in the PHA process. Both Arkema's own corporate policies and industry standards call for safeguards to be independent of hazard initiating events. The flooding that caused the Crosby facility to lose electrical power during Harvey, however, also provided a common failure mode for the safeguards Arkema considered as protection layers, including:

- Emergency generators flooded and were not available;
- Liquid nitrogen piping flooded and was not available; and
- Refrigerated trailers' diesel fuel tanks flooded and were not available.

176. Lacking sufficient independent protection layers for the level of flooding it confronted during Hurricane Harvey, the Crosby site was not protected and the organic peroxide products decomposed. Appendix C provides additional analysis of the Arkema Crosby PHA.

5.5. PROCESS SAFETY WORST-CASE SCENARIOS

177. Each Arkema site develops a list of worst-case process safety scenarios to improve employee awareness of the most significant hazards. Arkema communicates these hazards to employees in safety orientation training, and in periodic safety meetings.

178. Arkema managers developed the list of worst-case process safety scenarios by evaluating each of the site PHAs. In the Crosby facility's development of its worst-case process safety scenarios, Arkema managers evaluated a variety of hazard categories including fires, explosions, chemical releases, and extreme weather events.[a] The weather events documented by Arkema managers included a range of natural disasters,[b] but did not list flooding.

5.6. ARKEMA STATEMENTS

179. In its written post-incident statements, Arkema stressed that the company's history in Crosby dates to 1960. In its 57-year history at the Crosby site, many hurricanes and tropical storms affected the facility. Arkema shared that some of its current staff members have been at the Crosby facility for 40 years and that their experience in the worst earlier floods was that pickup trucks could still drive around the site. These long-term employees identified Tropical Storm Allison [67] in 2001 as the previous high-water benchmark for flooding at the Crosby facility. Arkema also said that recent hurricanes, including Ike in 2008 [68] and Rita in 2005 [69], made landfall closer to Crosby than Harvey, and although both Ike and Rita produced significant rainfall, they did not result in similar flooding.

180. The CSB notes that none of the previous storms cited by Arkema exceeded the rainfall produced by Hurricane Harvey, but Hurricane Rosa and an unnamed storm in 2015 produced significantly more rain near the Arkema Crosby facility than either Ike or Rita. The highest two-day rainfall totals recorded near the Arkema Crosby facility were as follows:

- Hurricane Rosa (1994): 23 inches;
- Tropical Storm Allison (2001): 2.7 inches;
- Hurricane Rita (2005): 3.8 inches;
- Hurricane Ike (2008): 6.5 inches; and
- Hurricane Harvey (2017): 26.5 inches.

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[a] Extreme weather events include hurricanes, droughts, tornadoes, snowstorms, and flooding [240].

[b] These natural disasters included tornadoes, lightning, and excessive heat, among other events.

181. Before Hurricane Harvey, based on Harris County Flood Control District rainfall gauge data, the most recent comparable rainfall event at the Arkema Crosby facility was the October 2015 unnamed storm, with a two-day rainfall total of 13 inches [29].[a]

182. Arkema records indicate that the Crosby plant flooded during the October 2015 rain storm, but the Low Temperature Warehouses and emergency generators did not flood during the event. During this storm, Arkema experienced no releases or fires from the Crosby facility.

[a] Peak rainfall for the 2015 storm occurred on October 31, 2015.

6. Flood Planning Guidance

183. Several different sources offer guidance for facilities on how to address flood hazards. Nonetheless, even if Arkema had applied this guidance before Hurricane Harvey, the incident likely would not have been averted. This conclusion suggests that more robust flood hazard guidance is needed in the U.S.

6.1. American Society of Civil Engineers

184. The American Society of Civil Engineers (ASCE) published *Flood Resistant Design and Construction*, ASCE 24, as a standard for the siting, design, and construction of buildings and structures in flood hazard areas [70, p. 1].[a] ASCE 24 includes, among other building types, commercial, residential, industrial, educational, healthcare, and critical facilities [70, p. 1]. ASCE 24 establishes Flood Design Classes based on building use and the potential risk to the public or disruption to the community, as shown in Table 5 [70, p. 8].

Table 5. Flood Design Classes. Each ASCE Flood Design Class is a function of building use and potential risk to the public [70, p. 8].

Flood Design Class	Public Risk or Community Disruption	Building Example
1	Minimal	Temporary Buildings, and Vehicle Parking Structures
2	Moderate	Residential, Commercial, or Industrial Buildings
3	High	Museum, Church, or Community Centers
4	Substantial	Air Traffic Control, Police Station, or Hazardous Chemical Manufacturing or Storage

185. Flood Design Class 4 includes “buildings that pose a substantial risk to the community at large in the event of a failure, disruption of function, or damage by flooding [70, p. 8].” Flood Design Class 4 also includes facilities such as the Arkema plant in Crosby, “that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, or hazardous waste [70, p. 8].”

186. ASCE 24 specifies the required elevation and the additional height above the base flood elevation as a function of both the Flood Design Class and the nature of the flood hazard area [70, p. 4]. Flood Design Class 4 buildings and structures must be elevated or protected to the base flood elevation plus two feet or to the 500-year flood elevation [70, p. 4]. Because the base flood elevation of the Arkema Crosby facility is 52 feet, applying ASCE 24 to new construction requires using flood damage resistant materials for all buildings and structures below 54 feet and establishes that utilities and equipment must be elevated above 54 feet [70, p. 4]. On the basis of floodwater

[a] ASCE 24 states the minimum requirements and applies to buildings and structures that are subject to building code requirements. ASCE is a referenced standard in the *International Codes*® [70, p. 1].

level produced during Hurricane Harvey, this standard would have been insufficient to protect the Low Temperature Warehouses and their backup systems.

6.2. Center for Chemical Process Safety

187. The American Institute of Chemical Engineers' Center for Chemical Process Safety (CCPS) is a corporate membership organization that identifies and addresses process safety needs in the chemical, pharmaceutical, and petroleum industries. CCPS publishes a series of guidance documents that are widely used in these industries.

6.2.1. Guidelines for Safe Warehousing of Chemicals

188. In its book *Guidelines for Safe Warehousing of Chemicals*, CCPS states that chemical storage creates "the potential for hazards including injuries, illness, environmental damage, property damage, and business interruption" [71, p. 1]." CCPS also notes that natural disasters, including floods, can triggers these hazards [71, p. 1]. CCPS cautions companies to evaluate these risks, stating, "… it is paramount that the risk of chemical warehousing be fully understood and appropriate steps taken to prevent or mitigate losses [71, p. 1]."

189. CCPS identifies flooding as having the potential to release chemicals into the environment [71, p. 59]. To understand flood risk, companies are directed to FEMA resources, including Flood Insurance Studies and Flood Insurance Rate Maps. CCPS observes, "The 100-year flood interval and its associated flood elevation are the most widely used criteria for estimating flood potential" [71, p. 59].

190. CCPS emphasizes the importance of a comprehensive warehouse risk management strategy, including an emergency plan that addresses emergency scenarios [71, p. 135]. CCPS identifies decomposition reactions that create chemical releases among the potential scenarios that company emergency plans should address [71, p. 135]. In addition, CCPS recommends that emergency planning efforts consider the possibility of chemical releases caused by flooding [71, p. 136].

191. In *Guidelines for Safe Warehousing of Chemicals*, CCPS provides companies with design and emergency protection guidance to mitigate flood damage, including the following:

- Designing warehouse floors that are higher than the base flood levels;
- Building levees or flood walls with appropriate freeboard;[a]
- Providing watertight closures, flood doors, and shields over windows; and

[a] "Freeboard is a factor of safety usually expressed in feet above a certain flood level, and is often applied to critical facilities. Freeboard (commonly 1-3 additional feet) compensates for the many unknown factors that could contribute to how high floodwater can rise, such as wave action, constricted bridge openings, and the hydrological effect of urbanization in the watershed [228, p. 1]."

- Removing chemicals that require refrigeration [71, p. 106].

192. The CCPS guidance recommends building “above base flood levels” which likely would have been interpreted as higher than the 100-year flood elevation. Lacking specific criteria on how far above base flood level companies should elevate their critical equipment, however, this CCPS guidance might not have been sufficient to prevent the Arkema Crosby incident.

6.2.2. Guidelines for Safe Storage and Handling of Reactive Materials

193. In its book *Guidelines for Safe Storage and Handling of Reactive Materials*, CCPS offers guidance for reactive chemicals, which are self-reactive materials that decompose, or break down into simpler molecules [13, p. 2]. CCPS specifically addresses organic peroxides, noting that these chemicals “have particular stability problems that make them among the most hazardous of industrial chemicals [13, p. 3].” Organic peroxides “may decompose at an accelerating rate until it proceeds in an uncontrollably high rate of reaction (“runaway” decomposition reaction) [13, p. 3].”

194. CCPS recommends that equipment designers “consider the use of existing codes and standards as the starting point from which to design a safe facility” [13, p. 138]. This is because “Codes and standards embody a wealth of technical know-how and lessons learned from past experience and previous incidents [13, p. 138].” CCPS states that many codes address hazardous chemical characteristics and management systems “such as emergency planning and response” [13, p. 138].

195. CCPS describes a number of the organic peroxide decomposition hazards that are applicable to the Arkema Crosby incident, including the following:

> “The instability of organic peroxides requires special precautions in their storage and handling [13, p. 219].”
>
> “The primary hazards involved in the safe storage and handling of organic peroxides are thermal sensitivity and, in many cases, flammability or combustibility [13, p. 219].”
>
> “Most will burn vigorously once ignited, and some are susceptible to detonation if not diluted (such as dry benzoyl peroxide) or if confined when decomposition occurs [13, p. 219].”

196. CCPS also described the decomposition characteristics of organic peroxides, saying:

> Organic peroxides also all exhibit sensitivity to heat, which increases with the reactivity of the peroxide. Organic peroxides are constantly undergoing decomposition, at a rate that is dependent on the temperature of the material. When thermal energy available from the heat of decomposition exceeds the rate of heat dissipation to the surroundings, the increasing temperature accelerates the decomposition of the remaining peroxide. This may proceed out of control in a characteristic "runaway reaction" decomposition. The danger of runaways is increased for some

peroxides, such as cumene hydroperoxide, because the decomposition is autocatalytic; i.e., the decomposition products catalyze further decomposition and cause the reaction to self-accelerate [13, p. 219].

197. CCPS recommends that companies consider elevating the storage of reactive chemical containers if the possibility of flooding exists [13, p. 156], but does not give specific guidance on how high products must be raised above the anticipated level of floodwater.

6.2.3. Guidelines for Technical Planning for On-Site Emergencies

198. In its book *Guidelines for Technical Planning for On-Site Emergencies*, CCPS provides companies with guidance on developing emergency plans [72, p. 153]. Emergency planning guidance "included identifying credible incidents, evaluating resources, devising response tactics, organizing properly, and defining necessary resources" [72, p. 153]. In addition, CCPS includes guidance on developing a number of hazard-specific procedures, including procedures for both hurricanes and flooding [72, pp. 172-177].

199. CCPS recommends that companies develop a flood procedure whenever a facility lies in a floodplain, is subject to potential flooding, or has a history of flooding [72, p. 177]. CCPS directs companies to seek available flood studies that might offer insights into the level of flooding to be expected [72, p. 177].

6.3. Federal Emergency Management Agency

200. The Federal Emergency Management Agency (FEMA) recommends that emergency power systems (and the equipment they supply) within critical facilities, such as the Arkema Crosby facility, should be protected against the highest anticipated flood elevation, including the following:

- Base flood elevation plus two feet;
- Locally adopted design flood elevation plus one foot; and
- 500-year flood elevation plus one foot [73, pp. 6-12].

201. As detailed previously, the water level during Hurricane Harvey was more than two feet above the base flood elevation. On the basis of this water level, the FEMA guidance would have been insufficient to protect the Low Temperature Warehouses and their backup systems.

6.4. EPA Facility Design Practice

202. The EPA established facility design practices to enhance the resilience of its buildings against extreme weather events [74]. For critical buildings in flood hazard areas, EPA builds three feet above the 100-year flood elevation [74].

203. If Arkema had used this guidance before Hurricane Harvey, it possibly could have prevented the incident. This EPA document, however, is intended as guidance only for EPA buildings and is not intended as general industry guidance.

6.5. FM Global

204. FM Global published *Creating a Flood Emergency Response Plan* to offer flood preparation guidance to companies [75]. FM Global is convinced that being prepared for flooding can reduce flood damage and business disruption [75, p. 1]. FM Global also believes that the key to success is devoting an adequate amount of time to developing a flood plan before the flood [75, p. 1].

205. In addition to enhancing safety, flood preparations represent a good business decision. FM Global's loss history shows that "facilities with well-organized flood emergency response plans have nearly 70 percent less damage, and resume operations sooner than those locations without a flood emergency response plan, or an inadequate one, in place [75, p. 1]."

206. According to FM Global's flood preparation guidance, elevating critical equipment constitutes a key activity to reduce flood risk because relocating key equipment to higher elevations makes a "major—and permanent—impact" if flooding occurs by reducing company reliance on human intervention during a flood [75, p. 1].

207. FM Global recommends, among other flood preparation guidance, that companies take the following actions:

- Evaluate flood risk to understand potential exposure;
- Ensure that a reliable flood warning system is in place;
- Balance the flood warning time with the flood response time—balance the time available to activate flood response actions against the time needed for the staff to implement those actions;
- Identify and implement changes that permanently reduce flood risk, such as elevating critical equipment or installing permanent flood barriers to keep out floodwater;
- Establish effective emergency actions, including erecting temporary water barriers, relocating critical inventory, or moving portable high-value equipment; and
- Develop a written flood plan, train employees in its use, and periodically conduct a dry run of the entire plan [75, p. 2].

208. The FM Global guidance also identifies the following other features of a sound flood plan:

- Establishment of who has the authority to activate the plan, redirect production resources, and shut down operations;

- Written procedures to safely shut down and isolate electrical equipment, and to raise or relocate key materials and critical equipment;

- Reliable methods to prevent water from entering key buildings or areas;

- Means to take care of employees and their families if the flood is prolonged;

- Focused reliance on employees whose homes are less likely to be affected during a flood; and

- Periodic review and updating of the flood plan to address changes in equipment, people, or business activities [75, pp. 2-3].

209. The FM Global guidance is general and Arkema could not have effectively used it to prevent the incident at the Crosby facility.

6.6. United Kingdom Environment Agency

210. In the U.K., the Environment Agency published *Preparing for Flooding – A guide for sites regulated under EPR and COMAH* as guidance to help regulated facilities conduct flood planning to comply with their environmental permits and regulations [76].[a, b] Similar to Harris County, the U.K. experiences flooding as a common event. The Environment Agency flood preparation guidance recommends that regulated companies take the following actions:

- Determine whether the site is in an area at risk of flooding;

- Be aware if flooding is imminent;

- Understand flood warnings;

- Obtain site topography information and more detailed flood modeling;

- Prepare a flood plan; and

- Improve the site's flood resilience by:

  a. Taking steps to protect the operation from flooding; and

  b. Applying protective measures to stop, slow, or deflect floodwater including:

[a] EPR is an initialism for Environmental Permitting Regulations in England and Wales [147]. COMAH is an initialism for Control of Major Accident Hazards – United Kingdom chemical industry regulations [242]. The Health and Safety Executive (HSE), the Environment Agency (EA), and the Scottish Environmental Protection Agency (SEPA) are the United Kingdom's competent authorities responsible for the enforcement of these regulations [148], [149], and [150], respectively.

[b] The Environment Agency also published *Would your business stay afloat?* as a more general guide for businesses to prepare for flooding [219].

i. Using drainage systems with excess capacity;

ii. Employing drainage techniques such as retention ponds;

iii. Raising the ground or providing raised platforms; and

iv. Ensuring effective maintenance of drainage and flood management systems [76].

211. For chemical product warehouses, the Environment Agency recommends moving vulnerable products (such as organic peroxides) above the predicted floodwater elevation. In addition, the Environment Agency encourages companies to use flood resistance measures, such as removable flood barriers. The Environment Agency also directs companies to a website that lists flood defense product options and suppliers [76, pp. 1-4].

212. The Environment Agency guidance informs companies that flood planning should be part of their site accident or emergency plans [76, p. 2]. The guidance also suggests that a good flood plan will include steps to protect workers, safeguard hazardous processes, and secure materials [76, p. 2]. In addition, companies should be able to implement the plan within the time available before the site floods [76, p. 2].

213. The Environment Agency flood planning guidance cautions companies to recognize and consider that flood warnings might result in limited response time and that all flood mitigation measures may fail [76, p. 2].

214. The Environment Agency flood planning guidance states, "An effective plan will be based on a thorough understanding of the risks of flooding on specific areas of the plant and operations" [76, p. 3]. The Environment Agency guidance also recommends that companies complete a "flood Hazard and Operability (Hazop) study," especially for sites that fall under the U.K. Control of Major Accident Hazards (COMAH) regulations [76, p. 3].

215. Of relevance to the Arkema Crosby incident, the Environment Agency flood preparation guidance specifically discusses key utilities, such as electrical power and liquid nitrogen. The flood preparation guidance states:

> You should make sure that electricity (including on-site transformers and substations), gas, steam, heating, cooling, and water supply systems are above predicted flood levels, are flood resilient or can be safely isolated or switched off before flooding. As the loss of utilities may be for an extended period, you should consider the installation of backup systems for critical equipment [76, p. 5].

216. Also pertinent to the Arkema Crosby incident, the Environment Agency flood preparation guidance recommends that companies move vulnerable products in warehouses above the height of the predicted floodwater [76, p. 4].

217. When a company is developing a flood plan, the Environment Agency guidance recommends considering the following factors:

- Hazards created by floodwater inundating equipment;
- Both short-term and long-term loss of utilities, such as the electric power supply;
- Loss of critical safety equipment;
- Capability of performing manual operations, taking into account hardware, operating procedures, competence, and training; and
- Required time to safely shut down operations, relocate personnel, and secure chemicals [76, p. 3].

218. The Environment Agency flood plan guidance also stresses the importance of taking actions when forecasts predict flooding, including identifying proper actions and needed information. The Environment Agency states that a good flood plan will include the following components:

- Assignment of flood response tasks to trained workers;
- Identification of sources of flood warnings, weather predictions, and floodwater level;
- Development of trigger points—such as amount of rainfall, river levels, and flood warnings—that initiate predefined actions such as shutting down operations, isolating equipment, or evacuating personnel;
- Design details, including operation of flood defenses;
- Contact information and contractual arrangements for the supply of emergency resources – such as pumps, electrical power generators, and cleanup equipment; and

    a. Post-flooding activities, including removal of floodwater; verification of plant and equipment integrity; and physical inventory checks to identify any loss of polluting, hazardous, or radioactive material [76, p. 3].

219. The Environment Agency flood planning guidance also recommends periodic training and reviews to prepare staff members for their responsibilities and to ensure that required actions are realistic given the likely time limitations and few resources that might be available during extreme weather [76, p. 3].

6.7. Chemical Industries Association

220. In its report *Safeguarding Chemical Businesses in a Changing Climate – How to Prepare a Climate Change Adaptation Plan*, the Chemical Industries Association, a United Kingdom (U.K.) chemical

industry trade association,[a] acknowledged that climate projections show U.K. chemical facilities facing an increased risk of more frequent and severe flooding because of heavy rainfall [77, p. 4].[b]

221. The report states that preparing for extreme weather events makes good business sense by enabling continued operations as weather risks increase [77, p. 7]. Similar to weather events in the U.S., flooding is the most frequently occurring natural disaster in the U.K. [77, p. 7]. Unlike the U.S., however, the U.K. specifically requires chemical facilities in the U.K. to prepare for flooding as part of their environmental protection systems [77, p. 7].

222. As an initial step in assessing flood risk, the Chemical Industries Association recommends that companies consider the following questions:

- Is the site susceptible to flooding?
- Has the site flooded before?
- Will climate change affect the risk of future flooding [77, p. 7]?

223. The report reviewed a 2013 flooding event that affected three facilities. Key lessons from the event included a recognition that flood defenses can fail and that putting a flood plan in place is essential [77, pp. 12-13].

6.8. United Nations Disaster Risk Reduction

224. In March 2015, the United Nations (UN) issued a document dealing with global disaster risk management to assist in reducing existing risks and to strengthen resilience[c] in the face of both natural and human induced hazards [78].

225. Among other conclusions, the UN report states:

> [From 2005 to 2015], disasters have continued to exact a heavy toll and, as a result, the well-being and safety of persons, communities and countries as a whole have been affected. Over 700 thousand people have lost their lives, over 1.4 million have been injured and approximately 23 million have been made homeless as a result of disasters. Overall, more than 1.5 billion people have been affected by disasters in various ways, with women, children, and people in vulnerable situations

[a] Chemical Industries Association [192]. The Chemical Industries Association runs a Responsible Care program in the U.K. covering issues of health, safety, environment, and security [77, p. 10]. In the U.S., the American Chemistry Council (ACC) requires its member companies, such as Arkema [232], to adhere to Responsible Care [233].

[b] The report was prepared by a partnership between the Chemical Business Association [193], the Chemical Industries Association [192], the Non-Ferrous Alliance [194], and the Environment Agency's Climate Ready Support Service [196], [77]. Note – the Environment Agency ended its Climate Ready program in March 2016 [195].

[c] The United Nations defines resilience as follows: "The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management [220]."

> disproportionately affected. The total economic loss was more than $1.4 trillion. In addition, between 2008 and 2012, 144 million people were displaced by disasters [78, p. 10].
>
> It is urgent and critical to anticipate, plan for and reduce disaster risk in order to more effectively protect persons, communities, and countries, their livelihoods, health, cultural, heritage, socioeconomic assets and ecosystems, and thus strengthen their resilience [78, p. 10].

226. The UN report found that the drivers for disaster risk have a local, national, or global scope, but the risks with local characteristics must be understood to reduce disaster risk [78, p. 13]. The report found that mitigating disaster risk before an incident is more cost-effective than reliance on post-disaster response and recovery [78, p. 13]. To reduce risk before a disaster, relevant data should be collected and analyzed. These data, including risk maps, should be disseminated to appropriate decision-makers, the public, and communities at risk of exposure to the disaster [78, p. 15]. Baselines should be periodically assessed to evaluate disaster risks [78, p. 14]. The report noted that during post-disaster recovery, however, it is critical to reduce future disaster risk by "Building Back Better" and increasing disaster risk education and awareness [78, p. 14].

227. The UN recommended that local and national governments adopt risk reduction strategies and plans aimed at preventing incidents, reducing existing risk, and strengthening resilience [78, p. 16]. Governments should also "encourage" the establishment of mechanisms and incentives to ensure compliance with existing regulations and to update regulations so that they promote an adequate focus on disaster risk management [78, p. 17].

228. This UN document offers only general guidance and does not provide any prescriptive requirements that Arkema could have used before Hurricane Harvey to prevent the incident.

7. Regulatory Analysis

7.1. Flood Hazards

229. As the previous section has shown, there is a lack of robust flood risk guidance available to industry to help prepare companies such as Arkema for extreme weather events. The CSB recommendation to CCPS is intended to help close this gap.

7.1.1. United States Approach

230. Similar to weaknesses in existing industry guidance, Federal safety regulations also lack specific requirements or detailed guidance on how companies should evaluate and address extreme weather events, such as flooding.

7.1.1.1. OSHA Process Safety Management Standard

231. Arkema considers its organic peroxide manufacturing process at the Crosby facility as covered by the OSHA PSM standard[a] because of the chemical quantities used or stored.[b] In addition, Arkema views one of its organic peroxide storage buildings as meeting the chemical quantity requirements for coverage under the OSHA PSM standard. Arkema did not consider its seven Low Temperature Warehouses as covered by the PSM standard. As a stated "best practice," however, Arkema applies its PSM program to all areas of the facility.

232. The Clean Air Act Amendments of 1990 required OSHA to promulgate the PSM standard, along with the concurrent requirement for the EPA to issue its Risk Management Plan regulations [79]. OSHA implemented the PSM standard with the primary objective of preventing unwanted releases of highly hazardous substances at locations storing such substances in quantities above the established threshold, with special emphasis on protecting locations where workers could be exposed to the serious hazards posed by such chemicals. PSM and its 14 elements focused on trying to bring a systematic approach to managing process safety [79].[c] PSM uses bedrock process safety principles designed to make entire chemical processes safe, as formalized in the regulatory requirements, such as the requirements to perform a process hazard analysis, establish sound operating procedures, ensure adequate employee training and involvement, maintain the mechanical integrity of all process equipment, and ensure a satisfactory level of emergency preparedness in the event of an unwanted release.[d]

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[a] 29 C.F.R. § 1910.119.

[b] The PSM standard covers chemicals that have been deemed hazardous either because of their chemical composition and quantity (listed in Appendix A) or because of their flammability characteristics (flash point below 100 °F). The Arkema Crosby facility had PSM-covered (sufficient quantities of) chemicals that were either listed in Appendix A or had a flash point below 100 °F.

[c] 29 C.F.R. § 1910.119.

[d] 29 C.F.R. § 1910.119.

233. OSHA considers a strength of its PSM standard to be its performance-based nature [80]. For example, OSHA asserts that it provides many examples of process safety information through guidance that is not specifically called out in the PSM standard [80]. Furthermore, although flood-related documents such as FEMA flood maps and Flood Insurance Studies are not specifically identified as process safety information, OSHA contends that for facilities at risk of flooding, this information could be considered process safety information, prompting the need for a management-of-change review [80]. In addition, OSHA maintains that although the PSM standard does not define facility siting requirements by design, that does not mean that consideration of flood risk or flood hazards are not required as part of a company's facility siting review [80]. The PSM standard does not, however, contain an express regulatory requirement for companies to consider flood insurance maps and related studies as process safety information or to consider flood risk or flood hazards in their PHAs or facility siting reviews. In addition, the CSB investigation did not identify any current and applicable OSHA guidance on flood risk or flood hazards.

234. OSHA PSM guidance provided to industry on PHAs states that a PHA should analyze "external factors that might affect the process [81]." While companies may analyze flood risk in their PHA as part of external factors, this limited guidance may not prompt a PHA team to have a specific discussion or evaluation of flooding or flood risk.

7.1.1.2. EPA Risk Management Program

235. Arkema considers two of the chemicals at the Crosby facility as covered by EPA's Risk Management Plan (RMP) rule[a]—sulfur dioxide and isobutylene. Arkema does not consider the Low Temperature Warehouses to be covered by the RMP rule. The Arkema Crosby facility submitted its most recent RMP to the EPA in 2014.

236. The EPA RMP rule constituted EPA's efforts aimed at chemical accident prevention. The RMP rule requires a facility to estimate not only the potential impacts of a worst-case release but also alternative, more likely scenarios that could impact the public. Depending on the type of facility, the rule requires a facility to: analyze potential hazards of its covered processes; train employees; document operating procedures; maintain mechanical integrity of covered processes; investigate accidental release and other events; and periodically reassess its accident prevention program.[b] Facilities must coordinate with emergency responders on steps to take in the event of an accident, and summarize all compliance steps in the facility's RMP.[c] The RMP rule also requires owners and operators of stationary sources with threshold quantities of regulated substances onsite to register and provide the government with certain information. Specifically, companies must provide their own worst-case offsite consequence analysis of an accidental release of those regulated substances. Companies also must document a number of data points about both the nature and extent of the chemicals on site, as well as accident history data, pertinent company programs intended to keep

[a] 40 C.F.R. §§ 68.150-68.195.
[b] 40 C.F.R. Part 68.
[c] 40 C.F.R. Part 68.

those chemicals safe from release, and emergency response information in the event of an accidental release.[a]

237. When the EPA promulgated the RMP rule, the agency intended for the PHA requirement to parallel the requirements found in the OSHA PSM rule. The EPA, in response to comments about the new RMP rule in 1996, provided the following guidance on the RMP PHA requirement: "As part of a properly conducted PHA, sources would normally consider whether a process is vulnerable to damage caused by external events, such as earthquakes, floods, high winds, and evaluate the potential consequences [if] such events damaged the integrity of the process [82]." The EPA general RMP guidance for Program 2[b] facilities states that facilities should consider "reasonably anticipated external events as well as internal failures. If you are in an area subject to earthquakes, hurricanes, or floods, you should examine whether your process would survive these natural events without releasing the substance [83, pp. 6: 10-11]."

238. To avoid conflicting regulations, EPA noted: "To ensure consistency with OSHA PSM, EPA has adopted OSHA's language on PHAs. Therefore, EPA has not added language on consideration of external events to the rule. EPA agrees, however, that sources must consider the hazards created by external events in any appropriate risk management program. As part of a properly conducted PHA, sources would normally consider whether a process is vulnerable to damage caused by external events, such as earthquakes, floods, high winds, and evaluate the potential consequences if such events damaged the integrity of the process. (1996 RMP RTC, 9-23) [82] and [84]."

239. EPA further explained: "you should consider reasonably anticipated external events as well as internal failures. If you are in an area subject to earthquakes, hurricanes, or floods, you should examine whether your process would survive these natural events without releasing the substance. RMP General Guidance, pages 6-10 to 6-11 [83] and [84]."

240. EPA also notes that in examining a company's processes, "considerations are chemical and process dependent and site-specific in nature, and therefore the regulations require facilities to determine the measures needed to address such hazards at their facility, using good industry practices and recognized and generally accepted good engineering practices (RAGAGEP), such as consensus

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[a] 40 C.F.R. §§ 68.150-68.195.

[b] Under RMP, Arkema is a Program 3 facility. Under the RMP rule, Program 2 facilities are those that do not meet the eligibility requirements for Program 1 and Program 3 facilities. 40 C.F.R. § 68.10(c). Program 1 facilities are those that meet the following requirements: "For the five years prior to the submission of an RMP, the process has not had an accidental release of a regulated substance where exposure to the substance, its reaction products, overpressure generated by an explosion involving the substance, or radiant heat generated by a fire involving the substance led to any of the following offsite: (i) Death; (ii) Injury; or (iii) Response or restoration activities for an exposure of an environmental receptor; (2) The distance to a toxic or flammable endpoint for a worst-case release assessment conducted under subpart B and §68.25 is less than the distance to any public receptor, as defined in §68.30; and (3) Emergency response procedures have been coordinated between the stationary source and local emergency planning and response organizations." 40 C.F.R. § 68.10(b). Program 3 facilities are those that meet the following requirements: "A covered process is subject to Program 3 if the process does not meet the requirements of paragraph (b) of this section, and if either of the following conditions is met: (1) The process is in NAICS code 32211, 32411, 32511, 325181, 325188, 325192, 325199, 325211, 325311, or 32532; or (2) The process is subject to the OSHA process safety management standard, 29 CFR 1910.119. (e) If at any time a covered process no longer meets the eligibility criteria of its Program level, the owner or operator shall comply with the requirements of the new Program level that applies to the process and update the RMP as provided in §68.190. (f) The provisions of this part shall not apply to an Outer Continental Shelf ("OCS") source, as defined in 40 CFR 55.2." 40 C.F.R. § 68.10(d).

industry codes and standards [84]." As noted above, however, effective guidance from consensus industry codes and standards is lacking with respect to flood risk. As such, guidance must be developed to meet the thrust of EPA's original position on this topic, which rested on limited OSHA guidance and weak or non-existent industry standards.

241. Despite Federal safety requirements covering the hazardous substances specified in both regulatory frameworks and despite the potential for flood risk to be analyzed under existing terms within the existing regulatory structure, no clear and specific regulatory requirement calls for flood risk to be assessed in relation to process safety under the regulation language in either the PSM standard or the RMP rule.

7.1.2. European Union Approach

242. In contrast to the U.S. approach, in the European Union, major chemical incident risks are regulated by the Seveso Directive, which applies to industrial activities that use, handle, or store specific hazardous substances [85, p. 53]. The Seveso Directive requires some facilities that manufacture or store large quantities of hazardous chemicals to generate a safety report demonstrating the facility has a major-accident prevention policy and that the incident scenarios have been identified and the risks mitigated [85, p. 53]. The Seveso Directive requires facilities to address increased risk arising from the geographical location of a plant. If a facility that manufactured organic peroxides, such as Arkema's Crosby facility, was physically located in the European Union and was therefore covered by Seveso, the safety report that would be required under the Seveso Directive could have included risks attributable to flooding from hurricanes.

243. After a number of incidents, the European Union updated the Seveso Directive in 2012 to address extreme weather risks more explicitly. The Seveso Directive now requires that companies regularly identify and evaluate environmental hazards, such as floods and earthquakes in the facility's safety report [85, p. 54].

7.2. Reactive Hazards

244. The August 2017 incident at the Arkema Crosby facility was a reactive incident. As defined, a reactive incident is a sudden event involving an uncontrolled chemical reaction—with significant increases in temperature, pressure, or gas evolution—with the potential to cause serious harm to people, property, or the environment [86, p. 103]. In September 2002, the CSB completed its major hazard investigation, entitled *Improving Reactive Hazard Management* [86]. The CSB concluded that better management of reactive hazards is necessary to prevent reactive incidents [86] and [87, p. 4].

245. In *Improving Reactive Hazard Management*, the CSB notes:

> When developing the list of substances, EPA considered only the inherent characteristics of a chemical that indicate a severe threat due to exposure. Well-defined criteria were used for toxicity and flammability. However,

> because of the complexities of site-specific factors and process conditions, EPA was unable to determine any inherent characteristic as an indicator of reactivity. EPA concluded that there was "insufficient technical information for developing criteria for identifying reactive substances." Consequently, the January 1994 RMP list of 130 chemicals does not contain any substances listed due to reactive hazards [86, p. 60].

246. As the CSB's 2002 *Improving Reactive Hazard Management* study found, "More than half of the accidents involved chemicals that [similar to organic peroxides] are exempt from OSHA and EPA process safety rules."[a] The study concluded that "the EPA Accidental Release Prevention Regulations (40 CFR 68) have significant gaps in coverage of reactive hazards [86, p. 87]."

247. As a result, the CSB issued Recommendation Number 2001-1-H-R3 to the EPA to improve coverage and regulation of reactives. It states: "Revise the Accidental Release Prevention Requirements, 40 CFR 68, to explicitly cover catastrophic reactive hazards that have the potential to seriously impact the public, including those resulting from self-reactive chemicals and combinations of chemicals and process-specific conditions. Take into account the recommendations of this report to OSHA on reactive hazard coverage. Seek congressional authority if necessary to amend the regulation [86]."

248. EPA did not act on the CSB's recommendation, as presented. Instead, EPA took a number of other steps that it believed helped to strengthen the management of reactive hazards, which included participating in a 2003 roundtable meeting, revising the agency's accident reporting system to improve collection of reactives data, collaborating with CCPS in producing a 2003 publication on managing chemical reactivity hazards, and publishing two safety alerts on reactives in 2004 and 2005. EPA also informed the CSB that it would continue to use its authority under the Clean Air Act's General Duty Clause to apply RMP requirements to facilities producing, processing, handling or storing "an extremely hazardous substance." The CSB, however, found these alternative measures inadequate, believing the regulatory changes as proposed in Recommendation 2001-1-H-R3 remained necessary, and voted to designate the recommendation as "Open – Unacceptable Response [88]." The CSB is now reiterating this recommendation to EPA to help prevent future reactive chemical incidents. First and foremost, the CSB continues to believe that reactives should be covered by RMP in the manner originally recommended. Second, and more germane to the Arkema incident, if reactives had been covered by RMP, and Arkema had conducted its required off-site consequence analyses (both worst-case and alternative scenarios) in accordance with RMP requirements, the company may have identified the hazards associated with the Crosby site's flood vulnerabilities, and the follow-on threats to the company's organic peroxides stored onsite, through that additional level of risk-based thought process.

[a] Although OSHA or EPA rules might not have covered the specific chemical involved in these accidents, other chemicals used in the process might have resulted in the process being covered by these Federal safety regulations.

8. How Companies Can Evaluate Flood Risk at Their Facilities

249. Given the lack of flood risk guidance from OSHA, EPA, or existing chemical industry standards, companies might not have a good practice approach for evaluating the flood risk at their facilities.

250. In response to the incident, Arkema commissioned a site elevation survey for its Crosby facility to understand the elevation for all relevant points at the facility as well as a hydrological study to understand the likely flooding conditions during extreme weather events, such as hurricanes. Arkema will be able to use this data to evaluate the risks for a number of floodwater severity levels to help prevent future loss of refrigeration leading to organic peroxide product decomposition.

251. In 2007, FEMA updated flood documents for the region containing the Arkema Crosby facility. FEMA changed the flood designation map covering the area where the Low Temperature Warehouses containing organic peroxides are located; the warehouses are no longer outside of the 500-year flood zone but rather sit inside the 100-year zone. FEMA also established the base flood elevation at 52 feet. Arkema did not incorporate this new information into its process safety management systems and it did not evaluate the potential flood risks.

252. Process safety information broadly describes all of the information necessary for companies to identify and understand the process safety hazards at their facilities.[a] Although OSHA identified minimum process safety information requirements—including data such as "design codes and standards employed"—OSHA did not specifically identify FEMA flood maps or Flood Insurance Studies as process safety information.[b] Furthermore, no other subheading is listed for process safety information that could fairly be read to capture the inclusion of flood risk for consideration. Despite this, OSHA's position is that the agency could consider FEMA flood maps or Flood Insurance Studies as required process safety information, especially for facilities at risk of flooding [80].

253. If companies do not view flood maps or Flood Insurance Studies as process safety information, these documents might not be reviewed as part of process hazard analyses or during facility siting reviews. Changes to these important flood information documents might not prompt companies to consider the need for a management-of-change review. As a result, company process safety management systems might not be including important flood risk information. In this case, the Arkema checklist used for collecting process safety information did not include flood maps or Flood Insurance Studies.

254. Assessing flood risk during facility siting reviews represents one approach that companies might consider when evaluating the potential for flooding to initiate process safety hazards. Chemical manufacturing facilities covered by either the OSHA PSM standard or the EPA RMP rule are

[a] 29 C.F.R. § 1910.119(d).
[b] 29 C.F.R. § 1910.119(d).

required to evaluate facility siting (stationary source siting) as part of the process hazard analysis component within their process safety management systems.[a]

255. Neither regulatory agency, however, defined the specific requirements that companies must complete when evaluating facility siting hazards. As such, CSB's investigation was unable to identify any existing requirements for companies to evaluate flood risk during facility siting reviews, and no such evaluations were ever documented for the Crosby site. OSHA's position is that the PSM standard does not define facility siting requirements by design, but that does not mean that consideration of flood risk or flood hazards are not required as part of a company's facility siting review [80].

256. Industry guidance on facility siting generally focuses on assessing and managing explosion, fire, and toxic chemical release hazards that could threaten people occupying buildings in close proximity to the process plants [89]. This focus stems from incidents such as the 2005 explosion at the BP refinery in Texas City, Texas that killed 15 workers in or around trailers located near the isomerization unit [90]. In response to CSB's findings regarding the BP Texas City incident, industry groups like the American Petroleum Institute (API) and the Center for Chemical Process Safety (CCPS) have developed guidance documents to help assess facility siting hazards [89].

257. API Recommended Practice 752 (API RP 752), *Management of Hazards Associated with Location of Process Plant Permanent Buildings*, updated in the pertinent part in 2009, provided additional guidance to companies operating facilities covered by the OSHA PSM standard "for managing the risk from explosions, fires and toxic material releases to on-site personnel located in new and existing buildings intended for occupancy [91, p. 1]." API RP 752 offered a systematic process for siting evaluations of both new and existing buildings [91, p. 5]. API RP 752 excluded storage facilities, such as the Arkema Low Temperature Warehouses for organic peroxides products, however, because such warehouses primarily store materials and are only intermittently occupied [91, p. 5].

258. In its book *Guidelines for Hazard Evaluation Procedures*, CCPS identified the following three overlapping aspects of facility siting:

- Facility location with respect to its surroundings;
- Facility layout and spacing of equipment and buildings; and
- Personnel protection in occupied buildings [92, p. 288].

259. Although the *Guidelines for Hazard Evaluation Procedures* book did not exclude the potential evaluation of flood hazards, it did not offer specific guidance on how companies can evaluate flood risk [92]. CCPS did describe a conceptual facility hazard analysis where the hazard review team identified potential equipment damage attributable to flooding by including a specific flood risk

[a] 29 C.F.R. § 1910.119 and 40 C.F.R. §§ 68.150-68.195.

question to the hypothetical facility in the illustrative analysis, based on its proximity to a river [92, pp. 330-336].

260. The CCPS guidelines noted the importance of severe weather events:

> Frequently, causal events initiated outside the fenceline are discussed almost as an afterthought. Floods, power loss, high winds, earth movement, and other forces of nature, while unpredictable in timing and force, can have a more or less predictable impact on the process. Predictable effects such as these can be addressed and controlled to protect people, property, and the environment [92, p. 202].

261. In its book *Guidelines for Facility Siting and Layout*, CCPS noted that many states and local areas have enacted zoning restrictions designed to minimize potential damage from flooding [93, p. 32]. These regulations might limit a company's ability to construct a facility in a flood-prone area or might restrict the type of equipment installed at certain elevations [93, p. 32]. CCPS identified flood information such as the following that companies should review and consider when selecting a new site:

- Obtaining flood history information—including dates, total rainfall, and flood depth;
- Identifying whether a flood control organization for the area is in place and who is responsible for the operation and maintenance of flood control equipment; and
- Determining whether any flood models have been developed for the area [93, p. 157].

262. To evaluate facility siting[a] hazards, Arkema technical PHA team members, including at least one operator, reviewed a facility siting checklist for "qualitatively identifying types and magnitudes of releases that impact people in the workplace and in the community … ." This checklist, however, did not include any prompts or guidewords about flooding or flood risks.

263. Companies might decide that the PHA process is an appropriate venue for evaluating facility flood risks; however, PHA teams often do not include personnel with expertise in evaluating flood risks. Civil engineers represent one group of professionals with relatively more flood risk expertise, so consideration should be given to adding this skill to the team for flood risk identification and evaluation [94].

264. Industry guidance should include evaluations of potential flood risks, and if a PHA team identifies the potential for a flood risk at its facility, the team should be expanded to include at least one member with flood risk expertise.

265. In the PSM standard, OSHA defined the following requirements for a PHA team:

[a] Arkema defines facility siting as "the spatial relationship between the hazards of the covered process and the location(s) of humans in the plant, the identification of hazards that may affect adjacent process plant buildings and management of risks related to those hazards."

- A team with expertise in engineering and process operations;
- At least one employee with experience and knowledge specific to the process being evaluated; and
- One person knowledgeable in the specific PHA methodology being used.[a]

266. Although OSHA does not define specific engineering discipline(s) that should be represented in a PHA, chemical engineers are most often involved. Although some chemical engineers might be knowledgeable about flood risks, companies might need to provide training to its chemical engineers or secure outside professional engineering assistance, such as civil engineers or other professionals with relevant flood evaluation experience, to assist with a comprehensive flood risk assessment.

[a] 29 C.F.R. § 1910.119(e)(4).

9. Other Flooding Incidents

267. A number of flooding incidents have impacted industrial facilities over the years. This section includes a brief discussion of two relevant incidents, the Fukushima nuclear reactor incident and the San Jacinto pipeline incident. Although the consequences of the Fukushima incident were much more severe than those of the Crosby incident, industry can still apply the lessons learned from both incidents to help prevent losses from extreme weather in the future.

9.1. Fukushima Daiichi Accident Report

268. The Great East Japan Earthquake struck on March 11, 2011, registering a magnitude of 9.0 and causing a tsunami that struck the northeastern coast of Japan, where waves reached a height of more than 30 feet [95, p. 1]. The earthquake and tsunami resulted in more than 15,000 deaths and more than 6,000 injured victims. Buildings and infrastructure along Japan's northeastern coast suffered considerable damage [95, p. 1].

269. The earthquake and tsunami resulted in a nuclear incident at the Fukushima Daiichi nuclear power plant operated by the Tokyo Electric Power Company [95, p. 1]. The incident ranked as the worst nuclear power plant incident since the Chernobyl disaster in 1986. The release of radionuclides at the Fukushima power plant forced the evacuation of more than 100,000 people within a radius of 20 kilometers (12.5 miles) [95].

270. As a result of the Fukushima incident, the International Atomic Energy Agency (IAEA) conducted an investigation with the stated purpose of considering "human, organizational, and technical factors, and aims to provide an understanding of what happened and why, so that necessary lessons learned can be acted upon [95]." The report found weaknesses in the plant design, emergency preparedness, planning for severe incidents, and response arrangements [95]. The investigation also found that "there was an assumption that there never [would] be a loss of all electrical power at a nuclear power plant for more than a short period" and that "insufficient provision was made for the possibility of a nuclear accident occurring at the same time as a major natural disaster [95]." Despite the major difference in consequences between the Fukushima and Arkema Crosby incidents, there are similarities in the lessons learned from both incidents.

271. The Great East Japan Earthquake damaged the electric power supply at the Fukushima facility and the associated tsunami caused substantial damage to the site's infrastructure. These combined failures led to the total loss of offsite and onsite electrical power which resulted in the loss of the cooling function at the three operating reactor units as well as at the spent fuel pools [95]. Despite the efforts of workers at the facility, three reactor cores overheated; the nuclear fuel melted; and three containment vessels were breached. Moreover, a hydrogen release led to an explosion that injured workers and released radionuclides into the environment [95]. Figure 56 shows the water height at the Fukushima facility as a result of the tsunami. The water level exceeded the height of both the primary electrical equipment (switchgears) and the backup systems (diesel generators).

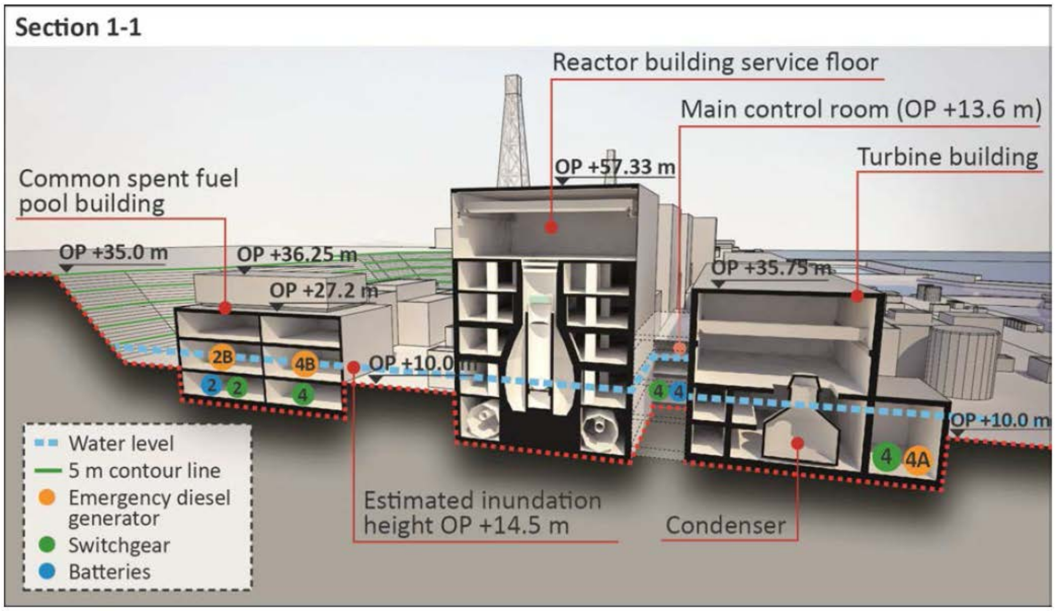

Figure 56. Water Level at the Fukushima Plant. This IAEA figure shows the water level at the Fukushima plant as a result of the tsunami caused by the Great East Japan Earthquake [95].

272. Like the flooding caused by Hurricane Harvey, the earthquake and tsunami significantly exceeded the hazard assumptions made when the Fukushima plant was originally designed [95, p. 3]. The seismic hazard and wave height considered in the original design were evaluated mainly on the basis of historical weather and seismic data [95, p. 3]. In addition, before the incident, the area was categorized as having the potential for a magnitude 8 class earthquake, but a magnitude 9 earthquake was deemed not to be credible [95, p. 3].

273. The IAEA report made the following findings, which also could be implemented at hazardous chemical facilities preparing for extreme weather events:

> The assessment of natural hazards needs to be sufficiently conservative. The consideration of mainly historical data in the establishment of the design basis of nuclear power plants is not sufficient to characterize the risks of extreme natural hazards. Even when comprehensive data are available, due to the relatively short observation periods, large uncertainties remain in the prediction of natural hazards [95, p. 4].
>
> The assessment of natural hazards needs to consider the potential for their occurrence in combination, either simultaneously or sequentially, and their combined effects on a nuclear power plant. The assessment of natural hazards also needs to consider their effects on multiple units at a nuclear power plant [95, p. 4].

274. Like hazardous chemical facilities, nuclear power plants mitigate risks by implementing multiple independent layers of protection. The Fukushima power plant relied on four layers of protection to prevent the release of radionuclides into the environment. These layers were created to protect

against a wide range of potential hazards, but external hazards such as flooding caused by tsunamis were not fully addressed [95, p. 5]. As a result, the flooding simultaneously disabled three layers of protection, which failed because of a single common cause. The IAEA report concluded:

> The common cause of failures of multiple safety systems resulted in plant conditions that were not envisaged in the design. Consequently, the means of protection intended to provide the fourth level of defence in depth, that is, prevention of the progression of severe accidents and mitigation of their consequences, were not available to restore the reactor cooling and to maintain the integrity of the containment. The complete loss of power, the lack of information on relevant safety parameters due to the unavailability of the necessary instruments, the loss of control devices and the insufficiency of operating procedure made it impossible to arrest the progression of the accident and to limit its consequences [95, p. 5].

275. In the 1960s and 1970s, when the Fukushima facility was originally designed and constructed, the nuclear industry practice was to use historical weather and seismic data to estimate external hazards such as earthquakes and flooding [95, p. 50]. Operators would add a conservative safety factor to the analysis by assuming that any event would happen at the closest possible location to the facility and then would increase the maximum recorded event by some level [95, p. 50]. The Fukushima plant used official sources to obtain a "conservative" estimate for maximum earthquake intensity and tsunami wave height, but these values were less than those of the actual events on March 11, 2011. For example, the maximum wave height estimate was based on a 1960 earthquake in Chile that resulted in wave heights around 10 feet above sea level, a third of what Fukushima actually experienced [95, p. 50]. In 2009, the wave heights were reassessed at about 20 feet above sea level, which prompted the facility to raise the motors on certain pumps [95, p. 51]. This elevation level still proved insufficient, however, because the facility had not elevated the backup generators following this reassessment [95, p. 51].

9.2. San Jacinto Pipeline Flooding Incident

276. In October 1994, atmospheric moisture from Hurricane Rosa contributed to major flooding of the San Jacinto River watershed near Houston, Texas [96] and [97]. The San Jacinto watershed is a few miles to the west of the Arkema Crosby facility and is adjacent to the Cedar Bayou watershed where the Arkema facility sits [97]. The flooding resulted in ruptures in eight pipelines and damage to 29 others [98, p. v]. More than 35,000 barrels of petroleum and petroleum products were released into the river [98, p. v]. The ignition of hydrocarbons released into the river resulted in burn and inhalation injuries for 547 people [98, p. v].[a] (Figure 57).

[a] Video showing local news coverage of San Jacinto River fire [222].

Figure 57. San Jacinto River Fire, 1994. This local news photo shows the San Jacinto River fire in October 1994 after pipeline ruptures resulted in the release of petroleum products [99].

277. During one week in October 1994, 15 to 20 inches of rain fell on the San Jacinto River near Houston as the remnants of Hurricane Rosa stalled over southeast Texas [98, p. 2]. This rainfall produced flooding that was "an extreme and dangerous event [96]."[a] The floodwater forced 14,000 people to evacuate their homes and resulted in 20 deaths [98, p. v]. The pipeline spill response costs exceeded $7 million, and estimated property damage losses were around $16 million [98, p. v].

278. On October 19, 1994, flooding caused the first pipeline, a liquefied petroleum gas pipeline eight inches in diameter, to fail [98, p. 4]. By the following day, October 20, 1994, a number of other pipelines failed, including a 40-inch pipeline and a 36-inch pipeline that transported gasoline [98, pp. 4-6]. On October 20, 1994, the released gasoline ignited, producing five distinct explosions [98, p. 6]. A nine-mile evacuation radius was established around the pipeline releases [98, p. 7]. On October 23, 1994, the emergency response group conducted a controlled burn of the remaining uncombusted released petroleum products [98, pp. 13-17].

279. The National Transportation Safety Board (NTSB) investigated the incident and released a report in 1996 [98]. In its investigation, the NTSB reviewed pipeline failures in the U.S. attributable to flooding over a three-year period (1991–1993) [98, p. 35]. The investigation found that during this time period, 21 pipelines ruptured during floods, including 13 natural gas pipelines and 3

[a] The National Transportation Safety Board (NTSB) report details the historical flooding near Houston, showing the area that was known to flood, and had flooded 17 times between 1907 and 1996 [98, p. 4].

containing “highly volatile liquids” [98, pp. 35-36]. As a result of this investigation, the NTSB issued nine safety recommendations to prevent recurrence of such an incident [98, p. v].

280. The NTSB investigation report drew 11 conclusions, and at least the following two apply to the Arkema Crosby flooding incident:

1. The design bases of most pipelines undermined or ruptured during the flood did not include study of the flood plain to identify potential threats; rather, operators used only general design criteria applicable at the time the pipelines were installed [98, p. 47].

2. Standards for designing pipelines across flood plains are needed to define the multiple threats posed to pipelines and to address the research, study, and future considerations that must be used for designing pipelines and periodically reevaluating the integrity of their designs during their operating life [98, p. 47].

10. Emergency Response Activities

281. Even before the Arkema Crosby incident began, the emergency response community was fully occupied with Hurricane Harvey, which prompted the largest disaster response in Texas history [27]. Emergency responders performed more than 120,000 rescues, using 82 aircraft and more than 100 boats [27]. More than three million meals and bottles of water were distributed to those in need, and over 24,000 displaced residents were housed in hotels [27]. More than 21,000 Federal staff members were deployed in support of Hurricane Harvey relief, and 53,000 pounds of medical equipment and supplies were dispatched to Texas and Louisiana [100]. The Federal staff included more than 6,300 active-duty military personnel who were deployed [100].

282. When Hurricane Harvey reached the Texas coast, a Unified Command was established between the EPA, TCEQ, U.S. Coast Guard, and Texas General Land Office to oversee all emergency response activities [101]. The National Guard and Federal Urban Search and Rescue supported this Unified Command [101]. The Unified Command organized itself into three operational branches in Corpus Christi, Houston, and Beaumont [101]. In the Houston region, Harris County aided the Unified Command by providing its emergency response assets, including the Harris County Fire Marshal's office and the Harris County Fire Department.

283. The U.S. Army Corps of Engineers assigned more than 150 personnel to engage in flood mitigation and infrastructure recovery tasks throughout the response [100].

284. EPA deployed its Airborne Spectral Photometric Environment Collection Technology (ASPECT) surveillance aircraft during the incident to monitor for airborne toxic chemicals [101]. ASPECT testing did not identify any levels of chemicals above baseline concentration when the organic peroxide refrigerated trailers burned [101]. During the chain of events around the decomposition of the organic peroxide products in the refrigerated trailers, EPA monitored smoke and air quality, checked the potential for additional fires in the area, and collected downstream surface water samples at four locations to test for organic chemicals likely to come from the Crosby facility [101]. Despite the reported releases at the Arkema Crosby facility, including the burning of the nine organic peroxide trailers, none of these samples detected any organic peroxides or their likely decomposition products.

11. Evacuation Zone

285. In setting up the 1.5-mile evacuation zone, emergency response officials considered several factors, including staffing requirements to maintain the evacuation perimeter, air quality from the potential burning of refrigerated trailers temporarily storing organic peroxide products, and potential releases of sulfur dioxide or isobutylene, the EPA regulated chemicals identified in the Arkema Risk Management Plan. Arkema stores and uses sulfur dioxide and isobutylene to manufacture organic peroxides.

11.1. Sulfur Dioxide

286. The Arkema Crosby sulfur dioxide storage tank (Figure 58) was located more than 300 feet from the isobutylene storage tank and about 400 feet from the nearest refrigerated trailer storing organic peroxide products. Despite the unlikely nature of a release, emergency response officials modeled a sulfur dioxide release of 16,000 pounds per hour, based on a scenario where a pressure-relief device on the tank opened and remained stuck in the open position. It should be noted that no sulfur dioxide was released during the incident.

Figure 58. Crosby Sulfur Dioxide Storage Tank. The sulfur dioxide storage tank at the Arkema Crosby facility was roughly 300 feet from the isobutylene tank and 400 feet from the nearest refrigerated trailer storing organic peroxide products during the incident. (Source: CSB Photo)

287. The modeling evaluated the potential downwind distance for sulfur dioxide concentrations meeting the Acute Exposure Guideline Levels (AEGLs), AEGL-3 and AEGL-2. AEGL values are described as follows:

- AEGL-3: **Death Possible** – the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death [102, p. 394].

- AEGL-2: **Injury Possible** – the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious and long-lasting adverse health effects or an impaired capability to escape [102, p. 394].

288. The models used the AEGL values for a four-hour exposure to sulfur dioxide, 0.75 parts per million (AEGL-2) and 19 parts per million (AEGL-3) [102, p. 397].

289. The modeling results showed that no AEGL-3 or life-threating concentrations of sulfur dioxide extended beyond about one mile from the Arkema Crosby facility. Injuries to members of the public from AEGL-2 concentrations of sulfur dioxide could, however, extend several miles from the Arkema site. Because emergency response officials did not consider this scenario as credible, the evacuation zone was not extended to account for this possibility.

11.2. ISOBUTYLENE

290. The Arkema isobutylene storage tank (Figure 59) was more than 100 feet from the nearest refrigerated trailer of organic peroxide products. To evaluate the potential isobutylene hazard, emergency response officials modeled an explosion of the isobutylene storage tank. The modeling results showed that the predicted blast pressure effects were concentrated within the Arkema Crosby facility.

Figure 59. Arkema Crosby Isobutylene Storage Tank. The isobutylene storage tank at the Arkema Crosby facility was located more than 100 feet from the nearest refrigerated trailer containing organic peroxide products. (Source: CSB Photo)

11.3. Still-Unknown Potential Health Effects From the Release and Burning of Organic Peroxides at the Arkema Facility

291. The CSB is not aware of whether there are long-term health effects that could arise from the type of exposure first responders and Crosby area residents may have had to either the vapor cloud or the smoke caused by the decomposition of the various organic peroxides products, or the combustion of the peroxides packaging materials and trailers. The CSB cannot make a statement regarding the toxicity or potential health effects of the airborne threat presented by this incident. Some emergency responders and members of the local community were concerned about potential health effects from the vapor cloud emitted by decomposing organic peroxides and from the smoke caused by the burning organic peroxides and combusting refrigerated tractor trailers where Arkema temporarily stored those products. The CSB has reviewed relevant Safety Data Sheet (SDS) information provided by Arkema, but no existing SDS covers the unknown quantity and composition of substances in the vapor cloud, as well as the trailers used to contain the organic peroxide products after they were moved from the Low Temperature Warehouses.

292. As noted previously, the EPA deployed personnel and equipment to this incident to monitor the impact of any releases on the air and water quality. Through its airborne ASPECT testing and surface groundwater testing, EPA detected no evidence of organic peroxides. In addition, the EPA applied its Air Quality Index (AQI) metric and the accompanying methodology, trying to determine potential health effects that could be experienced by those breathing unhealthy air. For example, breathing soot particles from the incomplete combustion of burning organic peroxide products and the refrigerated trailers, or inhaling any associated particulate matter, could cause negative health effects.

293. AQI is a metric used to represent the health effects that people might experience within a few hours or days after breathing unhealthy air [103, p. 2]. EPA officials evaluated potential soot particles that they anticipated after incomplete combustion of the organic peroxide products and the refrigerated trailers; such particle pollution or particulate matter is one of the established AQI pollutants.[a] The EPA brochure *Air Quality Index: A Guide to Air Quality and Your Health* notes that "people with heart or lung disease, older adults,[b] and children are considered sensitive and therefore at greater risk [103, p. 3]." To evaluate possibly unhealthy air conditions from the Crosby incident, these same officials developed models using EPA's AQI levels of health concern for unhealthy, very unhealthy, and hazardous air. The EPA explanations for these air quality categories are as follows:

- Unhealthy: Everyone might begin to experience health effects when AQI values fall between 151 and 200. Members of sensitive groups might experience more serious health effects.
- Very Unhealthy: AQI values between 201 and 300 trigger a health alert. Everyone might experience more serious health effects.
- Hazardous: AQI values exceeding 300 trigger a health warning about emergency conditions. The entire population is even more likely to be affected by serious health effects [103, p. 3].

294. EPA officials also attempted to develop models incorporating the AQI, by using the three tiered categories that would demonstrate increasing potential health threats as AQI scores rose. But because the models of anticipated dispersion for the Arkema Crosby incident did not reflect the nature of actual dispersions that occurred, among other practical difficulties, any attempts by EPA to analyze ongoing or long-term health threats based on the tiered modeling using AQI remains inconclusive. It is impossible for the CSB to draw any meaningful conclusions on the topic, in the absence of additional data based on relevant evidence in the form of air emissions from the Crosby incident, which began to disappear within a matter of hours or days as vapor and smoke dissipated following the release. As a result, this report does not seek to analyze the health effects stemming from the decomposition of the organic peroxides at the Arkema Crosby facility beyond noting the apparent short-term health effects suffered by those people who reported for medical treatment following their exposure as an important aspect of the incident.

11.4. Staffing Resources

295. On the basis of the results from evaluating the sulfur dioxide, isobutylene, and air quality scenarios, emergency response officials identified a need for a 1-mile evacuation perimeter. Emergency response personnel represented a key factor, however, because of the high demand for emergency

[a] The other three Air Quality Index pollutants are ground-level ozone, carbon monoxide, and sulfur dioxide [103, p. 2].

[b] "Due to the normal aging process, older adults may experience increased health risks from exposure to unhealthy air. Studies indicate that some people become more sensitive in their mid-60s. However, the risk of heart attacks, and thus the risk from particle pollution, may begin as early as the mid-40s for men and mid-50s for women [103, p. 3]."

responders to support Hurricane Harvey flooding relief throughout Harris County. When assessing staffing requirements to support a 1-mile perimeter, emergency response officials found that the layout of local roads required fewer personnel for a 1.5-mile evacuation perimeter. Because the extra half-mile not only provided a larger and safer perimeter, but also required fewer emergency responder resources, officials selected and established a 1.5-mile public evacuation zone.

11.5. Keeping Highway 90 Open

296. Even after the evacuation zone was enforced, Highway 90, which ran through the middle of the evacuation zone and near the Crosby facility, was left open to traffic. The Unified Command made this decision, in part, because Highway 90 was the only remaining major throughway for transporting personnel and equipment from the Houston area to the Beaumont region, where Hurricane Harvey was causing severe flooding. This situation posed a difficult decision for all emergency responders and the Unified Command. On one hand, the Unified Command had to consider the potential safety threat posed by organic peroxides which were no longer being adequately cooled and had to be decomposing at an increasing rate. On the other hand, Highway 90 served as a vital transportation corridor as Hurricane Harvey tracked east and emergency responders and other related resources needed to move with the storm. The emergency responders planned to monitor the situation at the Crosby facility and to shut down Highway 90 at the first sign of any fire in, or chemical release from, the refrigerated trailers.

297. Starting on Wednesday, August 30, 2017, Arkema provided telemetry data to the Unified Command showing that the air temperatures in six of the refrigerated trailers loaded with organic peroxide products were increasing and air temperatures inside three of these trailers were above the estimated SADTs of the organic peroxide products. The first refrigerated trailer to combust, however, did not have the capability to generate telemetry data and emergency responders could not accurately predict the time when the organic peroxide products in that trailer would begin to decompose. Moreover, although the ride-out crew gave its best approximation of the organic peroxide products in each refrigerated trailer, because of the hectic nature of the process for loading the trailers, the crew could not be completely sure that its list was accurate. Consequently, when the organic peroxide products in the refrigerated trailer (the first one to burn) reached a sufficiently high temperature to begin the rapid decomposition and combustion process, Highway 90 was still open.[a]

298. At about 11:50 pm on Wednesday, August 30, 2017, the organic peroxide products in the first refrigerated trailer were likely decomposing when two officers drove through a white smoke cloud coming from the Arkema Crosby facility. The emergency responders shut down Highway 90 after the officers reported the white smoke; however, emergency responders soon reopened it based on lack of visual confirmation of decomposition at the Crosby facility, and based on the telemetry data indicating that no decomposition should be occurring. When the white smoke cloud could not be visually confirmed at the Arkema facility, the emergency responders concluded that the cloud the

[a] It is not possible to determine the exact composition of chemicals people were exposed to from the release, because multiple organic peroxide products were stored in the refrigerated trailers and were in varying degrees of decomposition with limited oxygen when they combusted.

officer drove through had been a “low lying weather cloud” (most likely fog), based on the reported description of a white cloud. Because the initial organic peroxide decomposition was not confirmed, the emergency responders reopened Highway 90. Although an admittedly difficult decision, the choice to reopen Highway 90 allowed more emergency responders and private individuals alike to be potentially exposed to the chemical cloud. Only after the emergency responders later confirmed the organic peroxide decomposition did they shut down all lanes of Highway 90.

299. This incident demonstrates the difficulty of weighing options during an emergency response. The Arkema Crosby incident was occurring within the context of the larger emergency precipitated by Hurricane Harvey. The needs of officials who were strictly enforcing an evacuation zone conflicted with the needs of officials providing support for the response to Hurricane Harvey. Emergency officials understandably kept Highway 90 open initially. But once a report came in that the situation at the Crosby facility became less stable and that decomposition might be occurring, emergency response officials should have closed Highway 90 and established alternative routes. In an emergency, data are frequently incomplete and can even be contradictory, so emergency responders must tend towards being as conservative as might be prudent so that they can err on the side of caution and protect both themselves and the public.

12. Frequency and Cost of Flooding Natural Disasters

300. The reliability of flood-frequency estimates for large recurrence intervals (such as 100-year or 500-year floods) is uncertain [54, p. 2].

301. The European Commission Joint Research Centre published a report in 2004 that estimated the dollar losses from natural disasters in the United States had increased from $4.5 billion annually in 1970 to $6 to 10 billion annually in 1999 (all in 1970 dollars) [104, p. 2].[a] As the rate of natural disasters increases, the frequency and cost of incidents at chemical facilities affected by such natural disasters might also rise unless appropriate actions are taken to strengthen the resilience of the facilities.

302. In recent years, flooding from extreme rainfall events has escalated, and some EPA climate experts project that this trend will continue [105] and [106], resulting in an increased flood risk in many parts of the United States [106]. Future projections show Texas leading the nation in potential flood damage (Figure 60) [106].

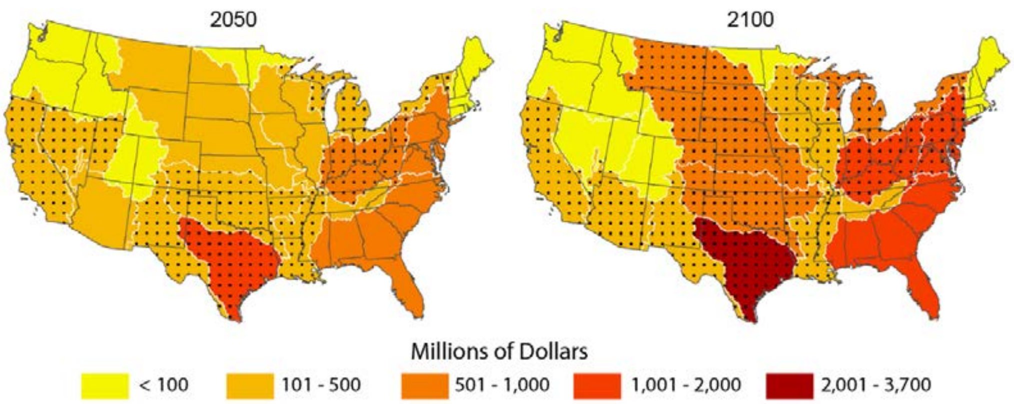

Figure 60. Future Flood Damages Attributable to Unmitigated Climate Change [106].[b, c] This projection used 2014 U.S. dollars as the basis for the future damage estimates.

303. A 2017 study by Swiss Re, an international insurer, found that worldwide insured losses from disasters[d] had fueled a surge in insurance claims in 2016 because of an increase in natural disasters including earthquakes, storms, floods and wildfires [107]. The report found that in 2016, 42 percent of insurance losses were attributable to natural disasters; in addition, in contrast to the decrease in human-induced disasters, natural disasters continued to increase (Figure 61) and (Figure 62) [108]. North America experienced the highest insured losses from disaster events in 2016, with

[a] In 2017 dollars, the losses in 1970 were $28.4 billion, and by 1999, they had increased to $63.1 billion [223].

[b] "For more information, visit EPA's Climate Change in the United States: Benefits of Global Action [182]." (Hyperlink added.)

[c] "Climate change refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among other effects, that occur over several decades or longer [229]." (Hyperlink added.)

[d] The report characterized a disaster (catastrophe) as an event producing insured losses that exceed $109 million or resulting in at least 20 deaths, 50 injured people, or 2,000 homeless victims [108, p. 2].

most of the losses stemming from hurricanes, hailstorms, thunderstorms, and severe flood events [108].

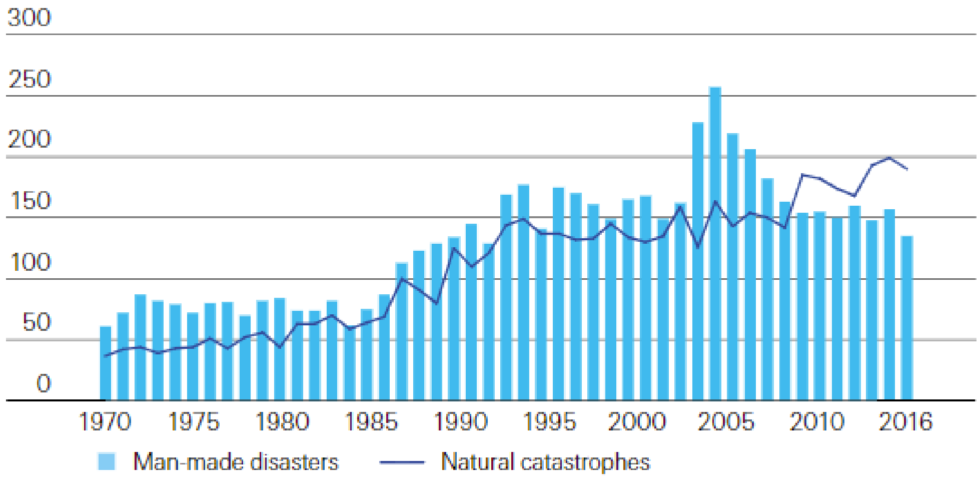

Figure 61. Swiss Re Study on Insured Losses. International insurer Swiss Re studied insurance losses attributable to disasters from 1970 to 2016 [108, p. 2].

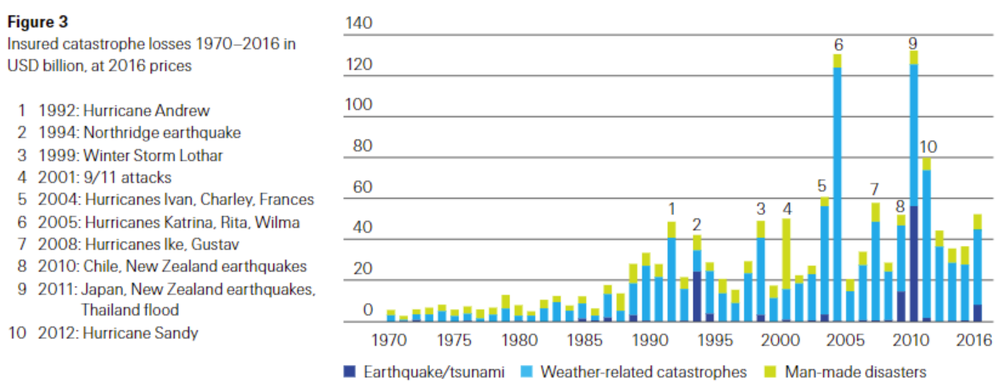

Figure 62. Insured Losses from Catastrophes, 1970 through 2016. Swiss Re studied the value of insurance losses from disasters from 1970 through 2016 (in billions of U.S. dollars and 2016 prices [108, p. 4].

304. The 2016 Swiss Re report also identified flooding as an underinsured risk in the United States [108]. This conclusion indicates that people and industry might not view the flooding risk as seriously as they should. The report stated that the United States “remains highly vulnerable to flood risk [108, p. 14].” The report specifically mentions the Houston metropolitan area as built on floodplains and prone to flooding during heavy rains, noting that “the multi-billion dollar losses that Houston suffered after two separate inland flood events in 2016 and 2015 are not entirely inexplicable [108, p. 15].”

305. Swiss Re proposes that the underinsuring of flooding in America is attributable to a "shortcoming of loss experience from a selection of individual events" that "do not necessarily reveal the true extent of underlying risk [108, p. 16]." Essentially, Swiss Re concluded that people are relying on their own memories of flooding to understand the risk, which is an insufficient basis for recognizing the full extent of the risk. This attitude was prevalent at the Arkema Crosby facility as well, with flooding expectations based on employee memories of previous rain events and how they had affected the facility. Compared to the assessment of risk based on scenarios that occur over hundreds of years, reliance on personal experience, which has a limit of several decades, is an unreliable method of risk evaluation. High-consequence but low-frequency events—such as flooding that occurs only once every several decades—might not be fully captured. Even with this realistic outlook, Swiss Re expected that flooding insurance claims in the United States would be around $15 billion annually. A few months after Swiss Re published its report, Hurricane Harvey caused more than $20 billion in flood damage.

13. NATECH RISK ASSESSMENT AND MANAGEMENT

306. Because of a number of chemical releases that occurred in the wake of extreme weather events around the world (starting with a Turkish earthquake in 1999 and floods across Europe in 2002), the European Commission, in conjunction with other groups such as the Disaster Prevention Research Institute in Kyoto, Japan, began to analyze how these incidents can be avoided in the future [104, p. 1]. This group found that little information was available on the risk of industrial incidents during extreme weather events (a type of natech[a]) [104, p. 1].

307. The latest book by the European Commission Joint Research Centre (EU-JRC) on industrial incidents caused by extreme weather notes the following:

> The past years set a record in the number of natural disasters accompanied by unprecedented damage to industrial facilities and other infrastructures. In addition to the Japan twin disasters in 2011 [earthquake and tsunami], recent major examples include Hurricane Sandy in 2012 that caused multiple hydrocarbon spills and releases of raw sewage, the damage to industrial parks during the Thai floods in 2011, or Hurricanes Katrina and Rita in 2005 that wreaked havoc on the offshore oil and gas infrastructure in the Gulf of Mexico. These events clearly demonstrated the potential for natural hazards to trigger fires, explosions, and toxic or radioactive releases at hazardous installations and other infrastructures that process, store, or transport dangerous substances. These technological "secondary effects" caused by natural hazards are also called "Natech" accidents. They are a recurring but often overlooked feature in many natural-disaster situations and have repeatedly had significant and long-term social, environmental, and economic impacts [85, p. 1].

308. Natech hazards increase the burden on a population already coping with extreme weather events and can result in multiple and simultaneous releases of hazardous chemicals over large areas [85, p. 1]. The EU-JRC points out that the risk from extreme weather is difficult to ascertain because this multidisciplinary topic cuts across traditional professional boundaries [85, p. 3]. For example, the flooding event at the Crosby facility is largely a civil engineering issue, but because the floodwater caused a loss of cooling for organic peroxide products, the civil engineering discipline intersected with the chemical and electrical engineering disciplines. Moreover, the risk from extreme weather is still considered an emerging risk and thus has received more attention in reaction to recent incidents [85, p. 3]. Further complicating an appropriate response is the conviction that existing protection measures and layers of protection to prevent "conventional" industrial incidents will also defend against extreme weather incidents [85, p. 3].

309. The EU-JRC natech report also notes that extreme weather scenario planning must assume scarce emergency response personnel and associated resources because the emergency responders likely would be dealing with many effects of the extreme weather and because the releases of hazardous

[a] A natech is defined as a technological disaster triggered by any type of natural disaster [104, p. 1].

chemicals could endanger the emergency responders themselves as well as the completion of their important tasks [85, p. 4]. Extreme weather, especially flooding, can limit access to or from a facility that is experiencing an incident. If roads are not accessible and passable, emergency responders might not be able to reach a facility, and community members might be unable to evacuate.

310. Risk mitigation planning for extreme weather pays dividends [85, p. 35]. Unsurprisingly, the EU-JRC reports that companies fare better during extreme weather events if they have implemented risk reduction measures and if they design specifically for extreme weather [85, p. 35]. The report states that industry and authorities do not generally appreciate the likelihood of significant effects from extreme weather. The EU-JRC also identified a lack of guidance on how to address extreme weather risks [85, p. 35].

311. The EU-JRC found that the largest problem area for companies was not properly preparing for natural hazards rather than experiencing the failure of safety systems [85, p. 35]. The report concluded that chemical facilities often use generic design criteria as a basis for safeguards and do not take into account the likelihood of extreme weather at each individual location [85, p. 35].

312. Flooding at a facility can lead to a variety of modes of operational failure and chemical release by a variety of methods. For example, floodwater can lift vessels, especially atmospheric storage tanks, from their footings, leading to a release of their contents. Floating vessels not only can release their contents, which can lead to a more serious incident, but also can impact other stable or floating vessels. Water can increase drag forces and cause piping connections to fail [85, p. 40]. Water can intrude into electrical equipment, as it did at the Arkema Crosby facility, causing power failure and indirectly triggering an incident. Flooding frequently affects large areas and can deposit hazardous chemicals over a wide region if they are released [85, p. 42]. This multilayered risk threatens both the communities around the facilities and the surrounding environment.

14. Hurricane Harvey Other Industrial Releases

313. As part of the response to Hurricane Harvey, 263 EPA personnel supported the relief efforts [101]. A total of 41 Superfund sites were located in the area affected by Hurricane Harvey [101]. The EPA reported on September 2, 2017, that of those 41 Superfund sites, 13 were flooded or experienced possible damage attributable to the storm [109]. Of those 13 sites, 11 were inaccessible during the hurricane because of flooding, so EPA personnel could not conduct sampling until after the floodwater had receded [109]. Once the EPA conducted the sampling, the agency determined that the contamination at all but one of the Superfund sites was consistent with the existing contamination before the hurricane [110].

314. The San Jacinto River Waste Pits Superfund site contains toxic dioxins [111]. The site is located in Harris County and consists of impoundments that were constructed in the 1960's for the disposal of paper mill wastes [112]. The impoundments are about 34 acres in size and are on the west bank of the San Jacinto River. EPA conducted testing after the hurricane and found that a protective cap (put in place to prevent the release of contaminants) had been damaged during the flooding and that underlying waste material was exposed [113]. The sample showed dioxin levels higher than 70,000 nanograms per kilogram although EPA's recommended cleanup level for the site is 30 nanograms per kilogram [113]. Subsequent analysis determined that the flooding had eroded the river bottom under the protective cap by as much as 12 feet [114].

315. During and after Hurricane Harvey, EPA performed air monitoring tests near the refineries in southeast Houston but did not identify any toxic chemicals that exceeded the normal atmospheric levels [101]. A light crude oil storage tank at the Valero Houston Refinery, however, failed as a result of Hurricane Harvey, releasing benzene and other organic compounds [101]. The tank failed when floodwater lifted the tank from its foundation and the walls separated from the bottom of the tank.

316. The U.S. Coast Guard operates the National Response Center which is the designated Federal point of contact for reporting all oil, chemical, radiological, biological, and etiological discharges into the environment in the United States [115]. When an industrial facility has a chemical release into the environment, it is required to alert the National Response Center and to give an account of the release.[a]

317. Based on National Response Center data during Hurricane Harvey, 102 reported incidents involving releases to the environment from industrial facilities were in some way caused by the hurricane [116]. Of those reported incidents, 44 releases were done in a "controlled" manner through the facility flare and were completed during shutdown operations before the arrival of the hurricane and during startup activities after the hurricane had passed [116]. The U.S. Department of Energy estimated that immediately before Hurricane Harvey made landfall, 24.5 percent of the country's oil production, 25.9 percent of the natural gas production in the Gulf of Mexico, and 43 percent of the Gulf Coast petroleum refining capacity [117] (12 percent of the U.S. refining

[a] 40 C.F.R. § 302.6

capacity) were shut-in as a precaution [118]. Large storage tanks accounted for the biggest releases to the environment because of flooding from Hurricane Harvey [116].

318. For example, the Galena Park, Texas release occurred at a Magellan Midstream Partners, L.P. facility. Shortly after midnight, September 1, 2017, Magellan alerted the National Response Center that its Galena Park facility had released an unknown quantity of a “gasoline type product” because of floodwater at the facility [116]. In an update 12 hours later, Magellan reported that it had released 1,000 barrels (42,000 gallons) of gasoline because of flooding [116]. Then, two days later, Magellan reported that the release had reached a local waterway [116]. On September 5, 2017, four days after the release, the company increased the estimated quantity released to 10,988 barrels (about 461,000 gallons) of gasoline [116].

319. The Magellan Midstream Galena Park terminal has the capability to store 7.2 million barrels of crude oil in above-ground storage tanks [119]. The terminal serves Houston and Texas City refineries, as well as other terminals and pipelines in the area [120]. Two storage tanks failed because of high floodwater level, releasing their contents during Hurricane Harvey [121]. The facility took action to recover the spilled material, capturing approximately 20 percent of the spilled gasoline, with the rest likely soaking into the ground or evaporating [121].

15. RECOMMENDATIONS

Pursuant to its authority under 42 U.S.C. §7412(r)(6)(C)(i) and (ii), and in the interest of promoting safer operations in the U.S. chemical industry, and protecting workers and communities from future accidents, the CSB makes the following safety recommendations:

15.1. REITERATED RECOMMENDATIONS FROM REACTIVES STUDY TO THE ENVIRONMENTAL PROTECTION AGENCY

2001-1-H-R3[a]

Revise the Accidental Release Prevention Requirements, 40 CFR 68 [Risk Management Plan], to explicitly cover catastrophic reactive hazards that have the potential to seriously impact the public, including those hazards resulting from self-reactive chemicals and combinations of chemicals and process-specific conditions. Take into account the recommendations of this report [*Improving Reactive Hazard Management*] to OSHA on reactive hazard coverage. Seek congressional authority if necessary to amend the regulation.

15.2. ARKEMA CROSBY FACILITY

2017-08-I-TX-R1

Reduce flood risk to as low as reasonably practicable (ALARP). Ensure that any safeguards for flooding meet independent layer of protection requirements.

15.3. ARKEMA INC.

2017-08-I-TX-R2

Within 18 months, develop a policy requiring that Arkema and its subsidiaries that manufacture organic peroxides or that have processes which involve more than the threshold quantities of highly hazardous chemicals (HHC)[b] periodically (corresponding with PHA cycle), analyze such facilities to determine whether they are at risk for extreme weather events such as hurricanes or floods.

2017-08-I-TX-R3

Establish corporate requirements for its facilities that manufacture organic peroxides or that have processes which involve more than the threshold quantities of highly hazardous chemicals (HHC)[c]

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[a] The current status of 2001-1-H-R3 is Open – Unacceptable Response [88]. See Recommendations Status Change Summary for additional detail and a summary of EPA's response to this CSB recommendation.

[b] 29 C.F.R. § 1910.119 Appendix A

[c] 29 C.F.R. § 1910.119 Appendix A

to ensure that critical safeguards, such as backup power, function as intended during extreme weather events, including hurricanes or floods.

15.4. CCPS

2017-08-I-TX-R4

Develop broad and comprehensive guidance to help companies assess their U.S. facility risk from all types of potential extreme weather events. Guidance should address the issues identified in this report and cover actions required to prepare for extreme weather, resiliency and protection of physical infrastructure and personnel during extreme weather, as well as recovery operations following an extreme weather event, where appropriate. Include guidance for each of the following:

- Addressing common mode failures of critical safeguards or equipment that could be caused by extreme weather events, including but not limited to flooding. For flooding scenarios, sufficient independent layers of protection should be available if floodwater heights reach the facility.
- Evaluating facility susceptibility to potential extreme weather events. Relevant safety information such as flood maps should be incorporated as process safety information.
- Involving relevant professional disciplines, including engineering disciplines, to help ensure risk assessments and process hazard analyses are as robust as practicable for any given facility.

15.5. Harris County

2017-08-I-TX-R5

Update your emergency operations training using lessons learned from the Arkema incident to help ensure that personnel enforcing evacuation perimeters are not harmed by exposure to hazardous chemical releases. Update existing protocols and revise training curricula to include the use of analytical tools, air monitoring, and personal protective equipment, to provide appropriate protection when emergency equipment or personnel need to be moved through an evacuation zone during a hazardous materials release. Include a process for periodic refresher training.

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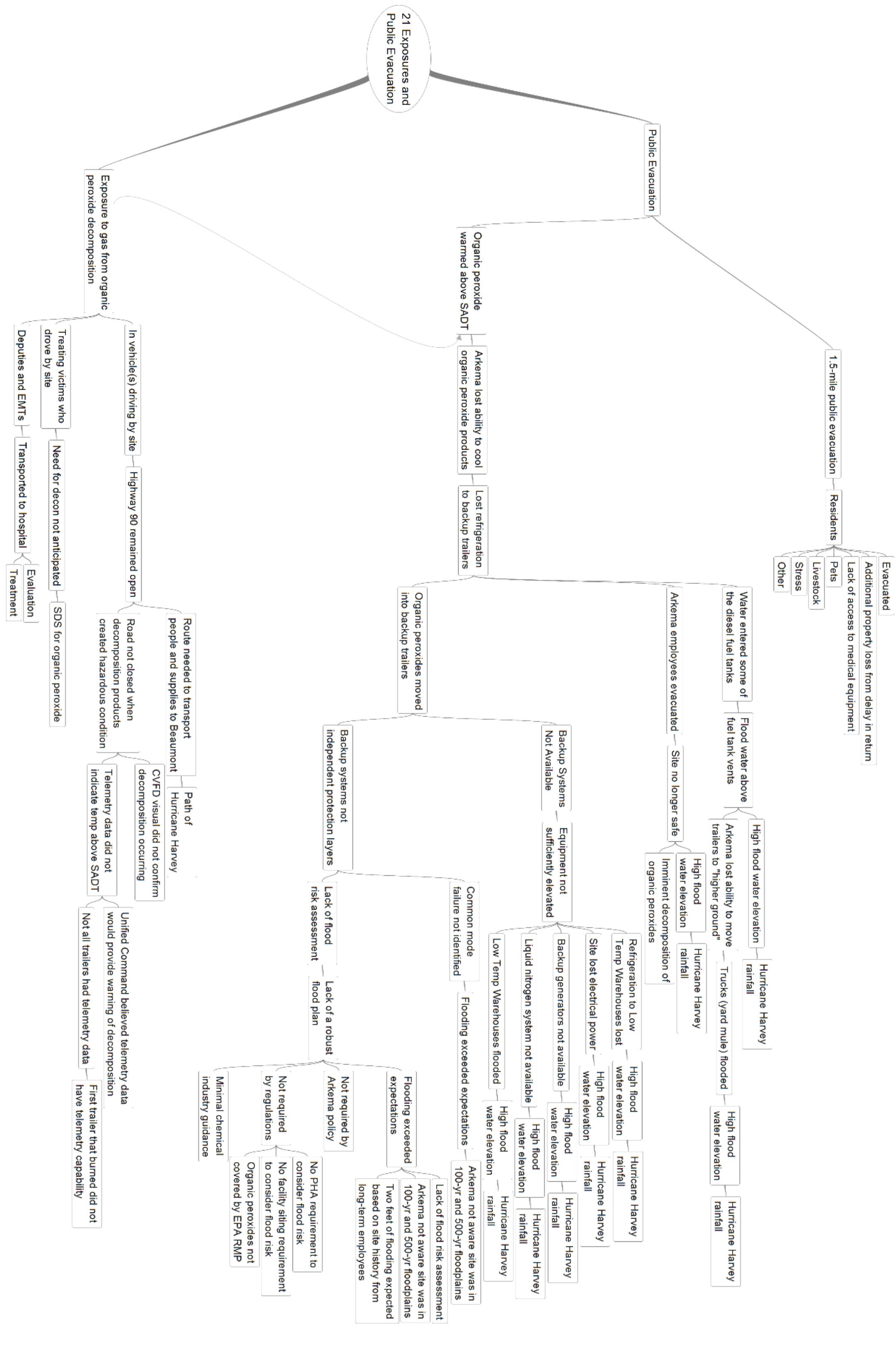
Appendix A: Causal Analysis



APPENDIX B: ADDITIONAL ORGANIC PEROXIDE INFORMATION

320. Table 6 provides information about the organic peroxides involved in the Arkema Crosby incident including product trade name, organic peroxide family, maximum storage temperature, self-accelerating decomposition temperature, and the hazard category (Type) for each product.

Table 6. Refrigerated Organic Peroxide Inventory and Properties. Organic peroxide properties are excerpted from the Safety Data Sheets (SDS) [122].[a] Luperox™ is a trade name that Arkema uses to market its organic peroxide products.

Luperox™	Peroxide Chemical Family	Maximum Storage Temperature (˚F)	SADT (˚F)	Hazard Category (Type)
10	Peroxyester	14	70	D
10M75	Peroxyester	14	81	D
11M45	Peroxyester	32	113	D
11M75	Peroxyester	32	84	C
188M75	Peroxyester	5	59	D
221	Peroxydicarbonate	-9	23	C
233M75S	Peroxydicarbonate	14	68	D
223S	Peroxydicarbonate	0	59	C
223V75	Peroxydicarbonate	14	77	D
225M60	Peroxydicarbonate	14	50	C
546M75	Peroxyester	14	77	D
	Total Inventory (Pounds)	367,000		

321. DOT regulations establish seven organic peroxide categories or "types" based on their hazard level, which is a function of both the properties of the organic peroxides and how the chemicals are packaged—including the design, style, and size of the container.[b] Organic peroxides are identified as Type A through Type G, with Type A representing the greatest hazard and Type G being the least hazardous.[c] As shown in Table 6, the organic peroxides involved in the Arkema Crosby incident are Type C and Type D. These organic peroxides are hazardous, but not the most hazardous. Although an explosion of Type C or Type D organic peroxides is possible, in their final product packaging a fire is the more probable hazard in a potential heating scenario, such as prolonged loss of refrigeration [19].[d]

[a] Note that there are temperature discrepancies between individual product Safety Data Sheets and the Arkema Organic Peroxides – Their Safe Handling and Use safety guidance document.

[b] 49 C.F.R. § 173.128 (b) (2004).

[c] 49 C.F.R. § 173.128 (b) (2004).

[d] Safety Data Sheets for organic peroxide Types C through Type F use a flame pictogram and hazard statement that "heating may cause fire." Type A and Type B organic peroxides have potential explosion hazards [19].

322. Additional information on Arkema's refrigerated organic peroxides, including National Fire Protection Association (NFPA) 432, *Code for the Storage of Organic Peroxide Formulations*, storage classes, is available on the company's website [11]. In 2007, Arkema published *Organic Peroxides – Their Safe Handling and Use* [11]. This safety guidance indicates that the refrigerated organic peroxide products involved in the Crosby incident included Class I, II, and III organic peroxides [11, pp. 6-7]. In developing this guidance document, Arkema used the 1997 edition of NFPA 432, which defines organic peroxides based on their potential hazard as follows:

- Class I – describes "those formulations that are capable of deflagration but not detonation;"[a]
- Class II – describes "those formulations that burn very rapidly and that present a severe reactivity hazard;" and
- Class III – describes "those formulations that burn rapidly and that present a moderate reactivity hazard [123]."[b]

323. Arkema safety guidance emphasizes the importance of keeping organic peroxides below their required storage temperatures shown in Table 6 [11, pp. 4-5].[c] Of the organic peroxides involved in the Crosby incident, Luperox™ 221 required the lowest storage temperature, minus (-) nine degrees Fahrenheit (°F) [124].[d] Luperox™ 221 is also a Class I organic peroxide, meaning it can deflagrate [11, pp. 6-7]. Although Luperox™ 221 represented the smallest inventory (less than 3,000 pounds) at Crosby, it still posed an elevated risk given its low SADT of 23 °F [124] and its status as the only product onsite categorized under this higher risk type.

[a] Deflagrations and detonations are types of explosions. Detonations typically create higher pressure and result in more damage than deflagrations.

[b] The definitions provided in the 2002 version of NFPA 432 are the same as those in the 1997 version. NFPA 432 was withdrawn in 2009 and incorporated into NFPA 400, *Hazardous Materials Code* [168, p. 1].

[c] Note that there are temperature discrepancies between this safety guidance document and the individual product Safety Data Sheets.

[d] The Arkema Crosby facility does not manufacture Luperox™ 221, but it is among the organic peroxides manufactured in Geneseo, New York and shipped to the Crosby facility for temporary storage until sold to customers.

APPENDIX C: LOSS OF REFRIGERATION RISK ASSESSMENT

324. Arkema completed its most recent process hazard analysis (PHA) for organic peroxide storage at the Crosby facility in November 2013. The PHA team performing the analysis consisted of a manager who served as the review leader, a safety engineer, a process engineer, an operator from the production facility, and an operator from the shipping department with experience working in the organic peroxide cold storage buildings. The PHA used a Structured What-If methodology.

325. To evaluate risk, companies often use a risk matrix. Figure 63 shows an example of a generic risk matrix.[a] Using the Arkema risk matrix, the company's PHA team evaluated the risk of each hazard for the following three cases:

- Risk with none of the existing safeguards available (potential);
- Risk with the existing available safeguards (current); and
- Risk with existing and proposed safeguards (final).

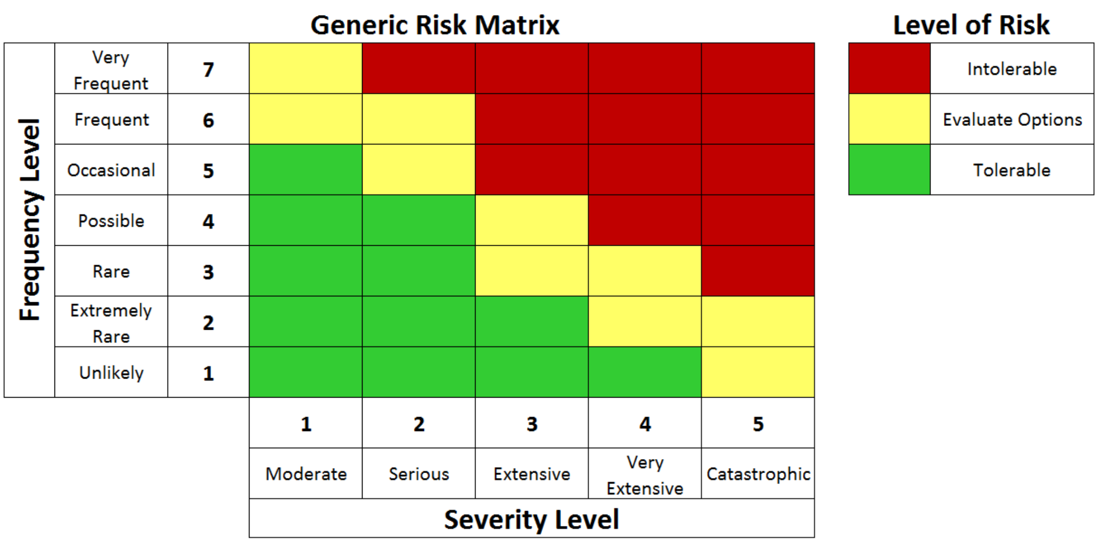


Figure 63. Generic Risk Matrix. This is a generic risk matrix shown to provide an example that a company could use to evaluate risk as a function of the frequency and the severity of a potential hazard. Similar to the Arkema risk matrix, this risk matrix uses three risk levels – tolerable (green), evaluate options (yellow), and intolerable (red).[b]

326. For the review of the Low Temperature Warehouses, the following three potential scenarios that could result in elevated temperature were evaluated:

[a] This example risk matrix is generally based on an example provided in *Layer of Protection Analysis: Simplified Process Risk Assessment* [126, p. 23].

[b] This example risk matrix is generally based on an example provided in *Layer of Protection Analysis: Simplified Process Risk Assessment* [126, p. 23].

- Loss of refrigeration because of a compressor failure;
- Loss of refrigeration because of a refrigerant leak; and
- Loss of power.

327. The Arkema PHA did not document whether the team considered flooding as a scenario.[a] At the time the Low Temperature Warehouse PHA was performed, corporate PHA requirements did not mandate that all PHA teams consider flooding scenarios. In 2014, Arkema modified its corporate PHA policy to require its PHA teams to identify and evaluate natural hazards such as flooding.

328. For a scenario based on loss of power, the Low Temperature Warehouse PHA documented both a business consequence and a safety consequence. For a scenario of power loss that results in loss of the cooling capability, the PHA team documented the safety consequence as "decomposition of product with potential fire," and the effect as "possible personnel injury." The team further documented that such an electrical outage would need to last more than four hours before building temperatures reach the SADT.

329. Following the company's process, the PHA team first evaluated the risk of this potential loss of power consequence without any safeguards. The team assigned a frequency level of six (frequent) for this consequence. The frequency of a scenario is determined by using existing Arkema corporate databases, vendor data, and plant experience. Arkema defined frequent as an "[e]vent that may happen several times over 10 years of life cycle of an installation." The team selected a severity level of three (extensive).

330. Arkema subdivides severity levels into four additional categories:

- Safety – Onsite;
- Safety – Offsite;
- Environmental; and
- Financial (dollars or euros).

331. The PHA did not detail the factors that drove the choice of severity level three (extensive). Per the Arkema PHA policy, a severity level three consequence equated to "Exposure / injury with irreversible effects" or a "public shelter in place" as an offsite impact to members of the public.

332. As shown in Figure 64, mapping this combination of frequency (six) and severity (three) on the generic risk matrix, results in an intolerable risk. Although not shown because of confidential business information concerns, the results using the Arkema risk matrix are similar.

[a] Flooding is not discussed in the PHA report.

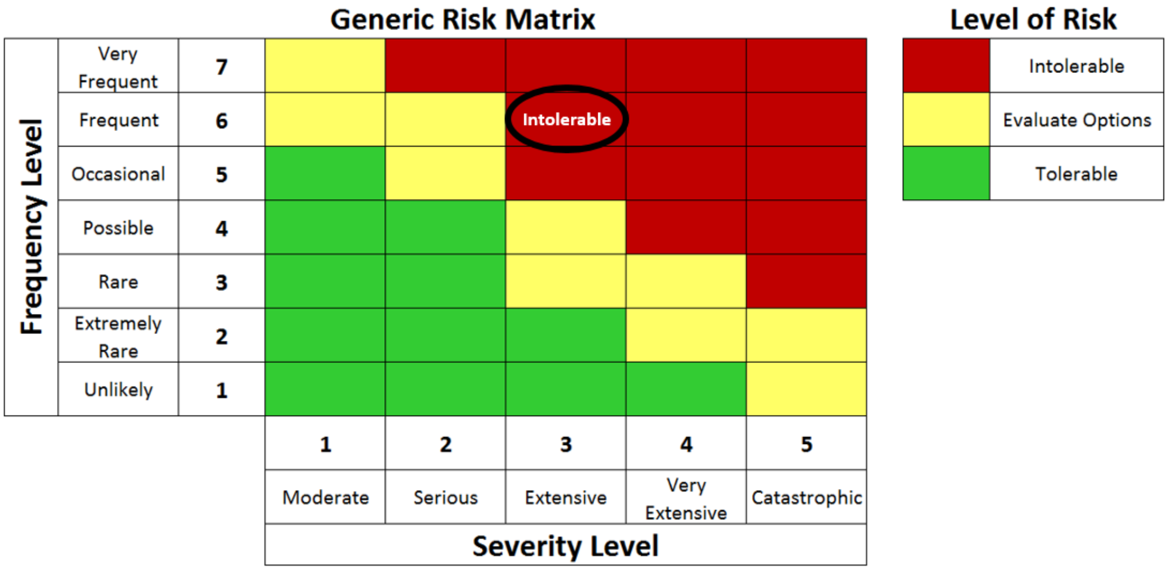


Figure 64. Example Risk Assessment for Loss of Power to Low Temperature Warehouses With No Risk Reduction Credit. This example risk assessment approximates Arkema's potential risk of power loss to the Low Temperature Warehouses, without taking any risk reduction credit for safeguards.

333. Arkema requires that a layer of protection analysis (LOPA) be performed for all scenarios that fall in the red (intolerable risk) boxes in Figure 64 as well as for higher level severity yellow (evaluate options) boxes. A LOPA is a semi-quantitative method used to analyze and assess risk. Using a LOPA, the PHA team looks at the safeguards already in place and determines how effective such safeguards will be in mitigating risk. Depending on the complexity of the scenario, the LOPA might be conducted by the PHA team or by another team at a different time.

334. The PHA team next identifies the existing safeguards and assigns to each a value for risk reduction credit. Safeguards identified by the PHA team for the power loss scenarios in the Low Temperature Warehouse PHA included the following:

- Emergency generators that provide electricity to all Low Temperature Warehouses;
- Liquid nitrogen supply for alternative cooling; and
- Manual temperature checks conducted every two hours and the capability to relocate the organic peroxides from an affected Low Temperature Warehouse to another refrigerated building or a portable refrigerated trailer.

335. The PHA team assigned two levels of risk reduction for the emergency generators, one for the liquid nitrogen system, and one for the capability to relocate the organic peroxide inventory. In all, the PHA team assigned four levels of risk reduction to these existing safeguards.

336. As shown in Figure 65, by taking four risk reduction credits for the existing safeguards the risk decreased from an unacceptable or intolerable risk to a tolerable risk. A tolerable risk represented

an acceptable long-term level of risk for Arkema, so the PHA team did not make any further risk reduction recommendations.

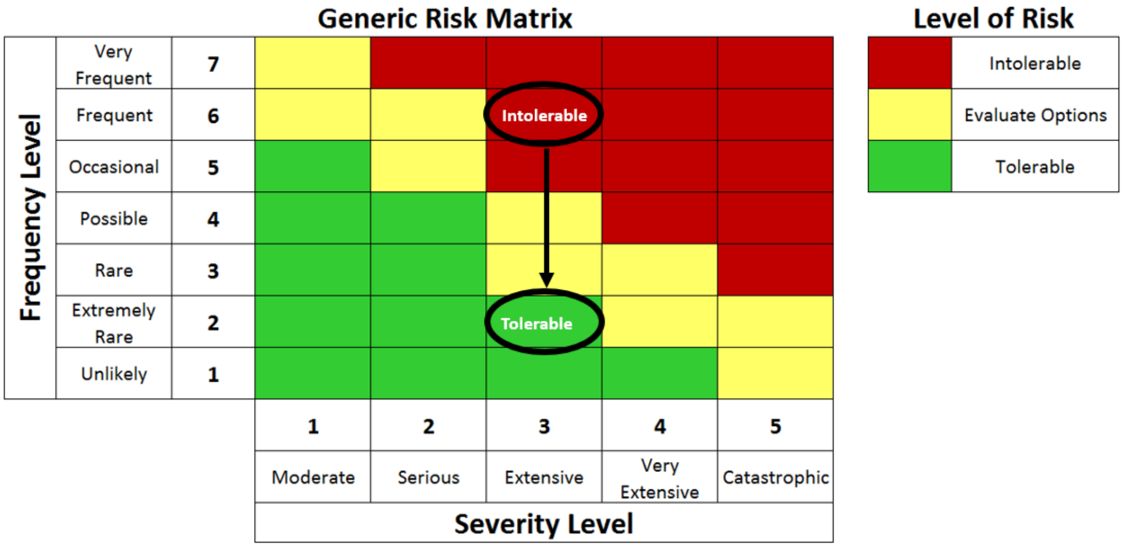


Figure 65. Example Risk Assessment for Loss of Power to Low Temperature Warehouses with Risk Reduction Credit. This example risk assessment approximates Arkema's potential risk of power loss to the Low Temperature Warehouses with four levels of risk reduction credit for the company's existing safeguards.

Harvey Flooding – Simulated Risk Assessment

337. Using hindsight knowledge of the Hurricane Harvey organic peroxide decomposition incidents, as well as Arkema's corporate requirements for performing a PHA, a simulated risk assessment of the safeguards in place for Harvey-level flooding can be conducted. This simulated risk assessment is intended to demonstrate the potential of such an extreme weather event at a chemical facility.

338. A rainfall event far exceeding the 500-year flood elevation can be evaluated as a frequency level of four (possible) or three (rare). Under the Arkema PHA policy, a "possible" frequency event is expected to occur between 1-in-100 to 1-in-1,000 years, but the lowest frequency available for floodplains is the 500-year elevation, which Harvey exceeded by over two feet. In addition, NOAA rainfall estimates show the rainfall during Harvey had less than a 1-in-1,000 year likelihood of occurring, [125] which would be a "rare" frequency event in the Arkema PHA policy. Using this information, a "rare" frequency is assumed for Harvey-level of flooding.

339. Using Arkema's more detailed severity level guidelines, severity level four (very extensive), is an appropriate severity level for the Hurricane Harvey organic peroxide decompositions, which caused evacuations. Arkema guidelines for severity level specifically identify an event that results in public evacuation as severity level four (very extensive).

340. Figure 66 shows an estimation of Arkema's risk for the Hurricane Harvey rainfall event. The combination of frequency of three (rare) for power loss due to flooding, and a severity level four

(very extensive) consequence due to public evacuation, results in a risk level of two (evaluate options) without applying any safeguards.

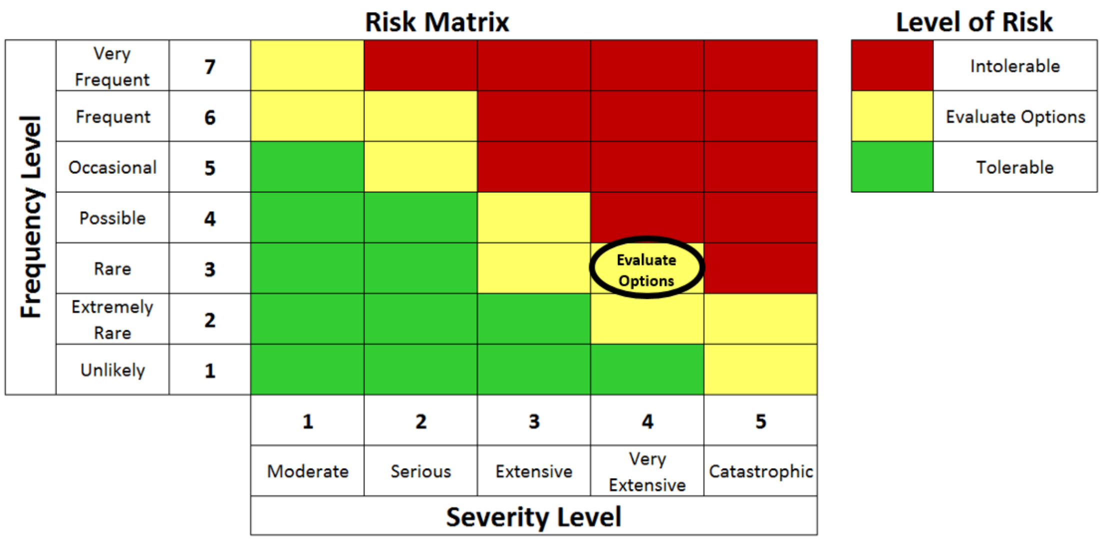


Figure 66. Example Risk Assessment Approximating Arkema's Potential Risk of Power Loss to the Low Temperature Warehouses Because of Hurricane Harvey Flooding. No safeguards were available because the flooding that caused the power loss in the Low Temperature Warehouses also disabled each of the company's backup systems.

341. Arkema thought that the following safeguards would be available in a scenario where electrical power was lost:

- Emergency generators to provide backup power;
- Liquid nitrogen to provide emergency refrigeration to the Low Temperature Warehouses; and
- Backup refrigerated trailers to serve as a redundant cold storage location.

342. The Arkema PHA includes a LOPA, a well-recognized hazard analysis method that strives to determine whether the layers of protection are sufficient to protect against a particular hazard or accident scenario. In its book *Layer of Protection Analysis: Simplified Process Risk Assessment*, CCPS explains, "Layer of protection analysis (LOPA) is a semi-quantitative tool for analyzing and assessing risk [126, p. 1]."[a]

343. In a Harvey-level flooding (significantly exceeding 500-year flood elevation) scenario, with loss of electrical power due to flooding, Arkema had insufficient safeguards to reduce the risk. The

[a] CCPS defines semi-quantitative as "Risk analysis methodology that includes some degree of quantification of consequence, likelihood, and/or risk level [178]." The CCPS quote was modified by changing semiquantitative to semi-quantitative.

flooding that caused the facility to lose electrical power also provided a common failure mode of the safeguards Arkema considered protection layers, including:

- Emergency generators flooded and were not available;
- Liquid nitrogen piping flooded and was not available; and
- Refrigerated trailers diesel fuel tanks flooded and were not available.

344. In a LOPA, risk reduction credit is only available for special safeguards that meet established criteria [126, p. 80]. CCPS calls these special safeguards "independent protection layers" or IPLs [126]. To qualify as an independent protection layer, CCPS requires that a device, system, or action (various types of safeguards) must be:

    1. Effective in preventing the consequence when it functions as designed;
    2. Independent of the initiating event and the components of any other independent protection layer already claimed for the same scenario; and
    3. Auditable – the assumed effectiveness in terms of consequence prevention and probability of failure on demand must be capable of validation in some manner, such as by documentation, review, testing, etc. [126, p. 80].

345. In a LOPA, all independent protection layers are safeguards, but not all safeguards are independent protection layers [126, p. 76].

346. Among the established CCPS requirements, a safeguard must be independent of the initiating event to serve as an independent protection layer and provide LOPA risk reduction credit [126, p. 80]. The same floodwater that caused the facility to lose electrical power also compromised the emergency generators, liquid nitrogen system, and refrigerated trailers. Ultimately, none of the Arkema safeguards met the CCPS independent protection layer requirements during Harvey-level flooding. With insufficient independent protection layers to reduce this risk, the company unknowingly had a level two (evaluate options) risk, not identified by its PHA. For this simulated example, Arkema corporate PHA policy would require that LOPA be applied to consider further risk reduction to "as low as reasonably practicable."

347. The Arkema manual detailing how to perform a layer of protection analysis describes an initiating event as "the first event in a sequence of events that leads to the undesirable consequences." Among other possibilities, the Arkema layer of protection analysis manual identifies, among other possibilities, natural phenomena including ***floods***, hurricanes, and earthquakes as potential initiating events.

348. Arkema's internal guidance on layers of protection does not allow safeguards to be considered as independent protection layers if the initiating event can prevent the safeguard from performing its safety function. The guidance notes that to be an independent protection layer, the safeguard, "shall prevent an unsafe scenario from progressing regardless of the initiating event or the performance of

another [safeguard].” Thus, the Arkema layer of protection analysis guidance prohibits safeguards such as electrical generators, liquid nitrogen injection, and portable refrigerated trailers from being designated as protection layers in Harvey-level flooding scenarios because flooding prevents these safeguards from functioning.

349. To meet the Arkema corporate risk targets for a future flooding event such as the flooding during Hurricane Harvey, the Crosby site must be better protected from high floodwater, or the facility’s safeguards must be modified so that they can perform their safety function even in high floodwater depths. Potential modifications include raising the elevation of the Low Temperature Warehouses, their electrical systems, and the backup generators, or providing a high-ground location onsite where refrigerated trailers can be staged during the hurricane preparedness phase.

Resilience from Extreme Weather Events

350. Although the flooding associated with Hurricane Harvey exceeded the design capability of Arkema’s safeguards, the CSB investigation concluded that Arkema’s safeguards could likely provide adequate protection for a 100-year flooding event.

351. A 100-year flood with a base flood elevation of 52 feet might prevent the Crosby facility’s liquid nitrogen system from being available because the valves and piping connections might be under water, but other Arkema safeguards could probably operate as intended. The emergency generators were elevated above the base flood elevation and would likely be available. In addition, 100-year floodwater levels would be unlikely to compromise the company’s capability to relocate the organic peroxide products to refrigerated trailers. Further risk reduction could be accomplished by modifying the liquid nitrogen system to ensure its availability during a 100-year flood.

352. Despite the appearance that Arkema’s safeguards can withstand a 100-year flood, as the company evaluates its options to ensure resilience from future flooding like the floodwater elevation from Hurricane Harvey or by other extreme weather events, Arkema should also perform a thorough review of its programs and ensure availability of its safeguards during more frequent flooding events.

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