 DOI: 10.1111/j.1539-6924.2010.01390.x

# Petroleum and Hazardous Material Releases from Industrial Facilities Associated with Hurricane Katrina

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Hurricane Katrina struck an area dense with industry, causing numerous releases of petroleum and hazardous materials. This study integrates information from a number of sources to describe the frequency, causes, and effects of these releases in order to inform analysis of risk from future hurricanes. Over 200 onshore releases of hazardous chemicals, petroleum, or natural gas were reported. Storm surge was responsible for the majority of petroleum releases and failure of storage tanks was the most common mechanism of release. Of the smaller number of hazardous chemical releases reported, many were associated with flaring from plant startup, shutdown, or process upset. In areas impacted by storm surge, 10% of the facilities within the Risk Management Plan (RMP) and Toxic Release Inventory (TRI) databases and 28% of SIC 1311 facilities experienced accidental releases. In areas subject only to hurricane strength winds, a lower fraction (1% of RMP and TRI and 10% of SIC 1311 facilities) experienced a release while 1% of all facility types reported a release in areas that experienced tropical storm strength winds. Of industrial facilities surveyed, more experienced indirect disruptions such as displacement of workers, loss of electricity and communication systems, and difficulty acquiring supplies and contractors for operations or reconstruction (55%), than experienced releases. To reduce the risk of hazardous material releases and speed the return to normal operations under these difficult conditions, greater attention should be devoted to risk-based facility design and improved prevention and response planning.

**KEY WORDS:** Hazardous material; hurricane; storm surge

## 1. INTRODUCTION

Hurricane Katrina subjected an area of 55,600 sq miles to hurricane strength winds and buffeted hundreds of miles of shoreline with storm surge. The hurricane made landfall on August 29, 2005 on the Louisiana coast between Grand Isle and the mouth of the Mississippi River.(1) As has been well reported, this is an area where a significant fraction of the energy infrastructure of the United States lies, including refineries, oil terminals, offshore platforms, oil and gas wells, and pipelines.(2) The area also has a high density of chemical and petrochemical industries, particularly along the banks of the Mississippi River.

The damage caused by Hurricane Katrina to onshore industrial facilities has been reported in a number of studies. One important study analyzed damage to 21 storage tanks during Hurricanes Katrina and Rita and found storm surge was responsible for the most serious effects.(3) Another described

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damage to the DuPont DeLisle plant caused by Hurricane Katrina, primarily due to storm surge and flooding.[4] The National Institute of Standards and Technology also conducted inspections of several industrial facilities damaged by Hurricanes Katrina and Rita[5] and Bailey and Levitan[6] in a review of hurricane-induced wind damage to industrial facilities, including the effects of Hurricane Katrina. Three years later, similar events were observed when Hurricanes Gustav and Ike affected a number of energy infrastructure sites, causing damage that shut several for over a month[7] and resulting in many hazardous material releases from industrial facilities.[8]

The literature also contains a number of published analyses of releases resulting from Hurricane Katrina. Pine[9] provides an overview of major oil spills resulting from Hurricane Katrina, the largest of which were caused by storm surge damage. Ruckart *et al.*[10] analyzed releases of hazardous materials resulting from Hurricanes Katrina and Rita at industrial facilities in Louisiana and Texas but excluded petroleum releases. They observed that a large percentage (72%) of events reported to the Hazardous Substances Emergency Events Surveillance System (HSEES) were related to system shutdown or startup. Offshore releases resulting from Hurricanes Katrina and Rita and response efforts have been analyzed by Cruz and Krausmann.[11] A large number of studies have investigated levels of wide-scale environmental contamination resulting from Hurricane Katrina and generally found limited potential for ecological or human health impacts.[12–16]

This article fills a gap in the analyses of releases caused by Hurricane Katrina by looking comprehensively at the incidence and causes of releases from all types of onshore industrial facilities. Hazardous materials and petroleum products are treated separately as the two are distinct in terms of reporting requirements and regulations. The Comprehensive Environmental Response, Compensation, and Liability Act requires reporting for hazardous materials above thresholds ranging from 1 to 5,000 pounds. The Oil Pollution Act of 1990 (which amended the Clean Water Act) requires reporting of releases of oil and petroleum products that affect a water body. These regulations have implications for the type and amount of data collected for each material category. It is also important to distinguish between the two types of materials as they have different dominant release causes and release scenarios. Also, rather than being limited by political boundaries as was Ruckart *et al.*[10] due to the state-specific nature of the HSEES database, the geographic scope of this investigation is determined by the region subjected to hurricane-strength winds and/or storm surge. In order to provide a comprehensive overview of the releases due to Hurricane Katrina, data were collected from numerous sources, including government databases, published accounts of particular incidents, interviews with involved parties, and a small industry survey. Some of the data used in this investigation were not available earlier owing to late reporting of the releases.

## 2. DATA AND THE METHODOLOGY

The primary data source for this study was the National Response Center (NRC)'s Incident Reporting Information System (IRIS) database. The NRC is administered by the U.S. Coast Guard (USCG) and is responsible for receiving reports of hazmat releases and oil spills. As such, the IRIS database contains reports of chemical releases and oil spills from a variety of sources, including onshore facilities, offshore platforms, pipelines, vessels, and mobile sources (http://www.nrc.uscg.mil/download.html). Releases caused by Hurricane Katrina were extracted for 2005 by querying the "incident cause" field for "hurricane" or "natural phenomena." Then, using location, date, and incident description, events resulting from Hurricane Katrina were identified. For 2006 to 2008, events were identified by the appearance of "Katrina" within the event description field. Duplicate reports of the same event were removed based on incident date and location. The locations of onshore releases were geocoded by street address to provide an approximate location for plotting. Releases were categorized, based on the "material released" fields in the IRIS database, as "chemical," "natural gas," or "petroleum," with the majority of releases consisting of materials of only one type. An exception was a small number (3) of releases of PCB-contaminated transformer oil, which were classified as petroleum due to the trace amounts of PCBs involved and for consistency with the larger number of releases of uncontaminated oil from transformers.

To collect information about releases and remediation, interviews were conducted in November 2005 at the USCG Incident Command Post (ICP) with personnel from the Louisiana Department of Environmental Quality (LADEQ), USCG, Minerals Management Service (MMS), and Louisiana Oil Spill

Coordinator's Office (LOSCO). Representatives of the Louisiana Mid-Continent Oil and Gas Association (LMOGA) were also interviewed in 2005. In 2008, additional in-person and telephone interviews were conducted with personnel from EPA region 6, LADEQ, Mississippi Department of Environmental Quality, MMS, USCG, the Louisiana Chemical Association (LCA), and LMOGA. Data on oil spill response were also collected from records of the USCG, which was the lead agency for management of oil spills caused by Hurricane Katrina. However, some USCG records relating to investigation of major oil spills were not available because as of 2009 a number of lawsuits and government investigations are ongoing. Additional information was collected from news reports, government documents, and company press releases.

Regulatory agency databases were used to identify industrial facilities in the region impacted by Hurricane Katrina. The EPA's Risk Management Plan (RMP) database was used to identify industrial facilities that handle large quantities of hazardous substances in the region (http://data.rtknet.org/rmp). EPA's Facility Registry System (FRS) database contained information to identify facilities with the SIC industry code 1311, which is the code for petroleum and natural gas extraction (http://www.epa.gov/enviro/html/facility.html). The Toxic Release Inventory database (TRI) was used to identify manufacturing facilities that handle hazardous materials, as well as federally owned sites and petroleum bulk storage facilities (some facilities included in the RMP database also report to the TRI program, http://www.epa.gov/tri/). The National Pipeline Mapping System was used to identify companies that operated pipelines in affected areas (http://www.npms.phmsa.dot.gov).

Areas impacted by the storm surge and wind-driven flooding from Hurricane Katrina were defined based on the Federal Emergency Management Association's (FEMA) storm surge GIS data for Louisiana and Mississippi, and storm surge in Alabama was delineated based on maps from FEMA's wind-water-level reports.[17] Storm surge data for the New Orleans area could not be extracted from the FEMA report because its storm surge delineation only extends to areas outside of levees. Instead, flooded zones inside levees in New Orleans were identified through the use of NOAA flood maps. Limited coastal flooding was also experienced in Lafourche and Terrebonne parishes in Louisiana (to the west of New Orleans) but is not delineated in this study. The area impacted by hurricane winds was taken to be that which had a >74 mph sustained speed (category 1 hurricane) based on maps of sustained wind speed available through the USGS, while areas of tropical storm winds were delineated using NOAA H*Wind data.[18]

Significant efforts were also made to collect information about Hurricane Katrina's impacts and hurricane preparedness directly from industrial facilities. Over a dozen facilities that experienced significant accidental releases of material during Hurricane Katrina were contacted seeking additional information on these events. The majority declined to respond, often citing fear of legal liability or ongoing lawsuits. However, several were willing to provide general information about the practice of hurricane preparedness within their industry. In order to collect additional information about hurricane preparedness prior to Hurricane Katrina, the hurricane's impacts, and how facilities learned and adapted after the hurricane, a random survey of industries in the area affected by Hurricane Katrina was conducted in the spring of 2008. The RMP database, the National Pipeline Mapping System, and the EPA's Permit Compliance System were used to identify facilities handling hazardous materials, pipeline operators, and petroleum storage facilities in counties impacted by hurricane winds and storm surge. From this population, 180 facilities were selected randomly and were contacted by phone using the contact numbers provided in the respective databases. If a knowledgeable individual was identified and gave consent, a survey was sent, primarily through email.

Only 11 surveys were successfully completed (6% response rate). Approximately 30% could not be contacted because of disconnected phone numbers or failure to reach an appropriate person. Initially, or after the survey was sent, 9% declined to respond. The remainder (55%) did not respond to three successive attempts to contact an appropriate individual. Of the 11 responding companies, three were processors of natural gas and three were chemical manufacturers, while the others were waste water treatment, drinking water treatment, fertilizer retail, logistics (truck), hazardous waste treatment, and electrical generation facilities. Responding facilities were well distributed over the area impacted by Hurricane Katrina (Fig. 1) and ranged from 12 to 1,500 employees (median of 30). While this small responding sample cannot be considered representative, useful qualitative information was collected

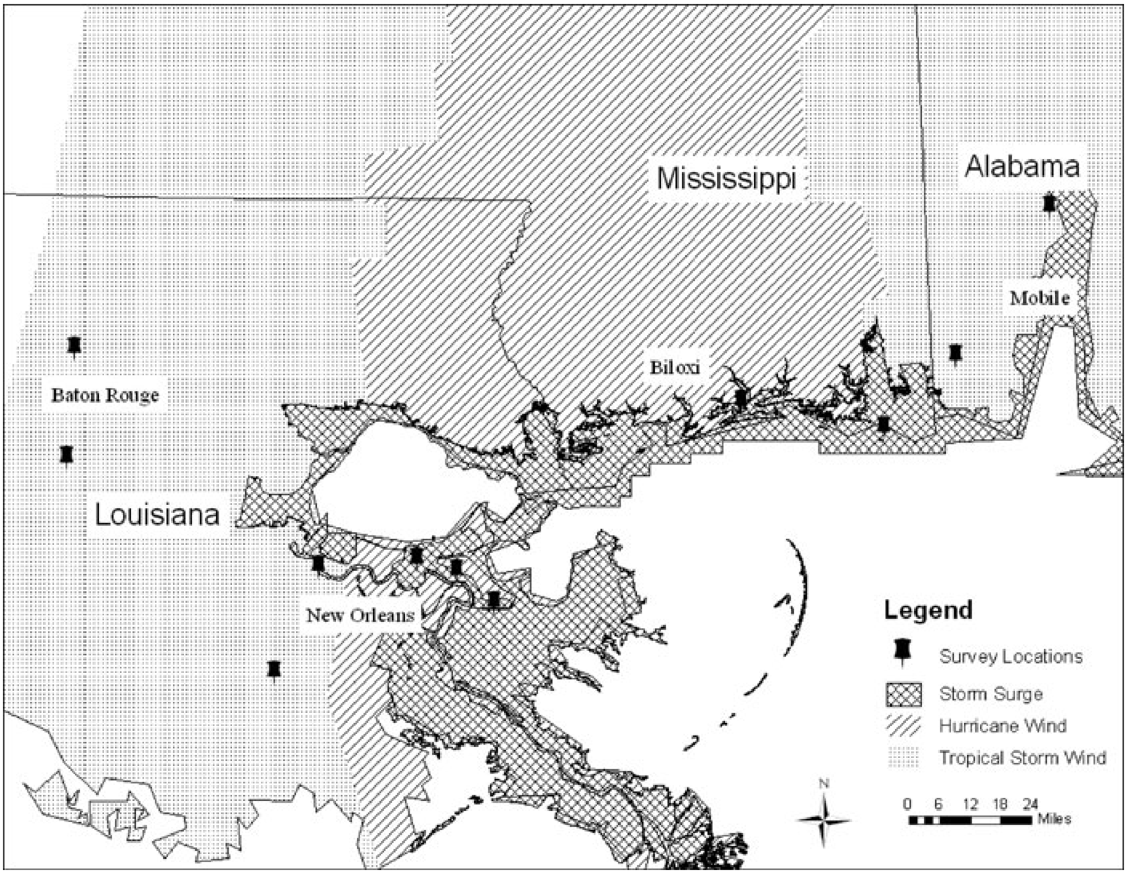


**Fig. 1.** Location of industrial sites responding to survey.

describing industry experiences during and after Hurricane Katrina.

## 3. RESULTS AND DISCUSSION

In the discussion below, we detail the releases of environmentally hazardous materials from industrial facilities during Hurricane Katrina. Discussion is divided into sections on (1) the oil and gas industry and (2) other industries handling hazardous materials. These results are then brought together in a geographic analysis of releases and discussion of lessons learned.

### 3.1. Hurricane Katrina's Impacts on the Oil and Gas Industry

The releases of petroleum products caused by Hurricane Katrina were extraordinarily large. There were 10 onshore releases that were greater than 10,000 gallons each. In sum, these 10 releases totaled approximately 8 million gallons, nearly 75% of the Exxon Valdez oil spill.[19] According to USGS reports and files, damage to storage tanks at processing terminals and at a refinery along the Mississippi River was the cause of nine of these releases.[20] Of these, five were major according to the Coast Guard terminology (more than 100,000 gallons), and four were medium (between 10,000 and 100,000 gallons). The characteristics of these releases are summarized in Table I.

Large releases were generally of crude oil that leaked from tanks damaged by storm surge. Secondary containment around the tanks was flooded, allowing the oil to spread into surrounding areas. These sites were difficult to access except by boat until the flood waters receded, and much of the oil was lost before containment and recovery was initiated. In some cases, such as Chevron Empire, storage tanks were so heavily damaged that their

**Table I.** Releases from Storage Tanks

| Facility | Location | Description of Release | Hurricane Effects Storm Surge Wind Speed | Quantity (gallons) Spilled Recovered |
|---|---|---|---|---|
| Bass Enterprises South | Cox Bay, LA | Two tanks shifted and damaged by storm surge, secondary containment breached. | ~4.9 m<br>100 mph | 3,800,000<br>1,900,000 |
| Shell Pilot Town | Pilot Town, LA | Tank shifted and damaged by storm surge. | ~2 m<br>100 mph | 1,100,000<br>950,000 |
| Murphy Oil | Meraux, LA | Tank shifted and damaged by storm surge, major impact to residential area. | 3.7 m<br>90 mph | 1,050,000<br>755,000 |
| Chevron Empire Facility | Buras, LA | Tank damaged, most of oil dispersed, small release from cleanup due to Rita. In-situ burn of >4,200 gal oil in adjacent marsh. | ~2 m<br>100 mph | 991,000<br>4,000 |
| Bass Enterprises North | Point a la Hache, LA | Seven tanks of various sizes leaked, most oil lost from two tanks shifted by storm surge. Some oil reached offsite. | ~4.9 m<br>100 mph | 460,000<br>116,000 |
| Chevron Port Fourchon Terminal | Port Fourchon, LA | Valves and pipelines damaged when struck by displaced potable water tank. | 2 m<br>75 mph | 54,000<br>45,000 (diesel / water mix) |
| Sundown East | Potash, LA | Discharge from ruptured tanks and piping. | 2 m<br>90 mph | 52,000<br>16,000 |
| Dynergy Venice | Venice, LA | Two tanks damaged by storm surge. | ~2 m<br>100 mph | 25,000<br>19,000 |
| Sundown West | Potash, LA | Discharge from ruptured tanks and piping caused by levee breach, some impact to residential area. | 2 m<br>90 mph | 13,000<br>8,000 |

contents were almost entirely dispersed to the environment before response teams could reach them.[4]

Under the National Response Plan (Emergency Service Function 10) the EPA would normally be the lead agency responding to these releases as they primarily affected inland waterways. However, because the spills were so extensive, the USCG led the response with EPA, USCG, LADEQ, and NOAA conducting joint operations. Due to the widespread and long lasting flooding, much of the initial surveillance of industrial faculties was performed by air.

Remediation was conducted by contractors with agency oversight, as would be the case in normal spill remediation. However, due to the scale of the response, government agencies also provided direct assistance. Spill response was inhibited by the fact that many responders were themselves displaced or otherwise impacted by the hurricane. At the peak of the oil spill response, there were approximately 150 government workers and 2,000 contractors paid by the responsible parties involved. Triage was performed so that more serious spills were given priority. For minor spills in relatively inaccessible areas, government agency response often took the form of sighting sheen during an overflight, notifying the owner of the facility, and monitoring the situation through additional flights until the situation was remedied. EPA and state agencies conducted follow-up environmental sampling at some sites.[(21)] The last remediation case files were closed early in 2008.

Hurricane Katrina also affected a number of refineries, which generally begin shutting down three days ahead of the hurricane to minimize damage and prevent process upsets.[(22)] Nine refineries in the area (one in MS, eight in LA) were shut down completely and four refineries reduced runs before the hurricane.[(23)] Although shutdowns are required for safety purposes, they have the disadvantage of potentially causing large emissions of volatile organic compounds, particulate matter, and other chemicals. Eight of these types of releases were reported in the NRC database, three of which were from refineries. Impacts on the nine refineries shut down by Hurricane Katrina are summarized in Table II, with information on releases based on IRIS and USCG reports. During the hurricane, four refineries in the area experienced damage, which kept them shut down for some time.[(24)] The most significant of these events,

[4]It should also be noted that releases from storage tanks within the petroleum industry were not limited to petroleum products. For example, BJ Services in Venice, LA lost 2 tanks containing 759 gallons of zinc bromide solution to storm surge and Halliburton reported loss of 8,250 gallons of calcium bromide solution in Venice, LA from a damaged storage tank.

**Table II.** Damage and Releases from Refineries Shut Down by Hurricane Katrina

| Facility | Location | Volume and Material Released | Details |
|---|---|---|---|
| Chalmette Refinery | Chalmette, LA | Unknown quantity process water | Release during shutdown, water damage prevented restart till November 2005.[31] |
| Chevron | Pascagoula, MS | Unknown quantity of flaring and chlorine gas | Flaring during shutdown, chlorine released from damaged tank car. |
| ConocoPhillips | Belle Chasse, LA | None reported | Major flooding damage and limited access due to flooding and infrastructure damage.[32] |
| Exxon Mobil | East Baton Rouge, LA | 0.5 gal oil | Small quantity of oil released from outfall. |
| Marathon Ashland Petroleum | Garyville, LA | None reported | Minor impacts, restarted quickly. |
| Motiva Convent Refinery | Convent, LA | Sulfur dioxide 500 lb, nitrogen oxide 10 lb | Flaring during shutdown, minor damage. |
| Murphy Oil | Meraux, LA | 1,050,000 gal oil | Storm surge damage to storage tank, major impacts on residential community. |
| Placid Oil | Port Allen, LA | None reported | No damage, plant restarted quickly. |
| Shell Chemical/Motiva Norco | Norco, LA | Unknown quantity of flaring | Flaring during shutdown, minor flooding, and some wind damage. |

because of its size and because it contaminated a residential neighborhood, was the oil spill from Murphy Oil refinery in St. Bernard Parish (Meraux). The refinery was inundated with 12 feet of water [25] and a partially filled 250,000-barrel above ground storage tank was dislodged and ruptured, releasing 25,100 barrels (1.05 million gallons) of mixed crude oil. Dikes surrounding the oil tanks at the refinery were flooded and breached and oil from the spill covered a residential area of approximately one square mile affecting approximately 1,800 homes.[26] Initial response efforts were hampered by limited accessibility due to flooding.[27] Ultimately, front-end loaders were needed to remove the oily sediments from the area and the refinery was not able to resume operation until mid 2006.[28] A class action lawsuit resulted from the spill, ending in a $330 million settlement with a buyout of properties closest to the spill and graded compensation in a larger zone.[29,30]

Also notable, because of previous history, were the impacts on Chevron's Pascagoula, MS refinery, one of the largest petroleum refineries in the United States (325,000 barrels/day). Located close to the hurricane's path, the refinery experienced severe winds (gust speeds up to 93 mph) and storm surge flooding (approximately 20 feet), resulting in damage to its marine terminal, cooling towers, and other equipment. The plant was shut down for more than a month.[33] The refinery had suffered significant damage due to Hurricane Georges (1998), causing a large release of oil and gasoline additives from damaged storage tanks[22] and a shutdown of almost three months. In response, the company had built a 5-mile-long dike 20 feet above sea level, which, though damaged during Hurricane Katrina, was credited with preventing worse flooding and damage.[34]

Vast networks of onshore and offshore transmission and distribution pipelines lay within the area hit by Hurricane Katrina. However, only six onshore releases from petroleum and natural gas pipelines were reported to the NRC. The largest release was a 139,000-gallon crude oil leak from a 20-inch pipeline at Shell Nairn Pipeline Company in Port Sulphur, Louisiana.[20] Approximately 10,500 gallons of the spill reached the shoreline and coastal marshes[9] and only 10,700 gallons were recovered. This release resulted in a $5.5 million class action settlement to nearby property owners (www.nairnclaims.com). Enbridge Offshore Gas Transmission also reported damage to onshore facilities located near the Dynegy gas processing plant at Venice.[35] There was also potential for a significant transportation-related release when a moored dry dock broke loose on the Mississippi River, striking a tanker (the Stone Buccaneer) containing 58,000 gallons of fuel oil. An unknown but apparently minor quantity was spilled when one of the tanker's storage tanks was breached.[36]

Like petroleum storage facilities, natural gas processing plants tend to be near the coast to facilitate transfer of raw product from offshore wells. One gas plant, which was undamaged by Hurricane Katrina, Duke Energy in Mobile AL, reported release of 1,382,000 cf natural gas and 169 lb nitrogen oxides from flaring during shutdown prior to the hurricane. Three gas facilities were damaged as a result of Hurricane Katrina: Dynegy plants at Yschoskey and Venice, LA and the BP plant at Pascagoula, MS,[37] but no releases were reported to the NRC from these facilities. Disruptions continued during restoration. Two weeks after Hurricane Katrina, the BP gas plant at Moss Point, MS reported a release of 1,460 pounds of nitrogen oxide due to flaring necessitated by pipeline damage.

### 3.2. Hurricane Katrina's Impact on Hazardous Material Handling Industries

Fewer and smaller releases were reported from chemical and manufacturing industries handling hazardous materials than from oil and gas industries. This is in large part due to the greater vulnerability of oil and gas industries to Hurricane Katrina's storm surge. Only one nonpetroleum hazmat event received significant media attention: a series of explosions and fires that occurred along the New Orleans waterfront on September 2 and 3 near downtown and was initially reportedly as originating from a chemical facility.[38] Subsequent reports indicate that the fires originated from a warehouse containing propane tanks that exploded and spread the flames. Fire trucks responded but were unable to pump water so several fire boats and other vessels were called in to contain the fires.[39] EPAs Airborne Spectral imagery of Environmental Contaminants Technology aircraft also provided screening of the site for hazardous materials during and after the fire.[40]

Releases greater than 100 gallons or pounds of hazardous substances recorded in the IRIS database from chemical and other industries are summarized in Table III. The number of chemical releases within the IRIS database is likely to be a significant underestimate as many smaller releases would not have been required to be reported. One indication of this underreporting is the larger number (25) of reports of chemical releases occurring due to Hurricane Katrina within LA in the HSEES database compared to those within IRIS (17); IRIS underrepresents the number of chemical releases by at least 30%. This is probably the case because smaller releases not legally required to be reported to the NRC are often reported to the state and hence to HSEES. In addition, many releases of chemicals occurred in the form of orphaned containers, the discoveries of which were only occasionally recorded within IRIS. In total, 3.3 million orphaned containers of various sizes were recovered and processed by EPA and LADEQ after Hurricane Katrina.[41]

Less information is readily available about the damage and other impacts experienced by industries handling hazardous materials due to Hurricane Katrina than for the petroleum industry, in part because impacts were less severe. Harris and Wilson[4] describe damage, indirect impacts, and steps

**Table III.** Chemical Releases Resulting from Hurricane Katrina

| Facility | Location | Description of Release | Material | Quantity |
|---|---|---|---|---|
| Crompton (chemical production) | Geismar, LA | Flaring during shutdown | n-hexane | 12,800 lb |
| Aqua Pool Co (pool supply) | Waveland, MS | Released from a warehouse because of flooding | Calcium hypochlorite, dichlor and trichlor (stabilized chlorine), hydrochloric acid | 3,000 lb, 2,500 lb, unknown amount |
| Entergy New Orleans Inc. (power generation) | New Orleans, LA | Asbestos released from piping and duct work | Asbestos insulation | 1,010 cubic feet |
| Lone Star Industries Inc. (slag cement plant) | New Orleans, LA | Five small storage tanks were overturned | Lubricating oil and grease, gasoline and diesel fuel | 1,220 gal total |
| Tomah Reserve Inc. (chemical production) | Reserve, LA | Piping at shut down plant was heated by the sun after the hurricane | Ethylene oxide | 316 lb |
| Weyerhaeuser Co. (pulp and paper) | Columbus, MS | Released due to power loss | Hydrogen sulfide, methyl mercaptan | 100, 120 lb |
| Mississippi Phosphate (fertilizer production) | Pascagoula, MS | Released from storage tanks due to flooding | Anhydrous ammonia, sulfuric acid | Unknown amount, 100 gal |

taken to meet these challenges by one chemical plant impacted by Hurricane Katrina. The survey conducted as part of this investigation provides additional useful information on this topic as nine of the survey responses were from chemical industry facilities or those handling hazardous materials. Most reported physical damage, with storm surge and flooding being the most common and most damaging mechanism. Three of the facilities experienced flooding damage when levees in the New Orleans area failed. Damage experienced was significant, totaling over $160 million for all nine companies with a median value of $900,000. Lost revenue during the period when operations were shut down was also large, totaling $41 million for the nine companies with a median value of $250,000. Six of these companies reported that part of the cost of damage or lost revenue was recovered from insurance coverage. However, only three of the facilities reported releases, all of which were relatively small amounts of oil and petroleum products and due to storm surge-related flooding. Significantly, seven companies reported that displacement of workers due to evacuation, worker home loss, and gasoline shortages reduced available manpower and disrupted their operations. Three facilities also reported loss of communication systems as a hindrance, while two reported difficulty acquiring supplies and contractors for reconstruction or operation.

### 3.3. Analysis of Hazmat Releases from the IRIS Database

Although not complete, the IRIS database contains the single most comprehensive record of petroleum and hazardous material releases caused by Hurricane Katrina. As such, it is the best source of data available to analyze the mechanism and nature of hazmat releases as a whole. Over 1,070 releases attributed to Hurricane Katrina were reported between 2005 and 2008 and are summarized in Table IV. Louisiana was the hardest hit (87% of reports), with smaller fractions in Mississippi (7%), Alabama (4%), and Florida (1%). The majority of releases originated from offshore platforms but large numbers also came from fixed facilities and storage tanks. Unusual in the context of the IRIS record were the large number of releases from Hurricane Katrina reported from 2006 to 2008, that is, 5 to 36 months *after* the hurricane. A majority of these were leaks from offshore platforms, as well as from pipelines and vessels damaged or sunk during the hurricane.

**Table IV.** Releases by Reporting Year and Location Type

| Location Type | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|
| Fixed facility | 135 | 13 | 3 | — |
| Mobile | 2 | 1 | — | — |
| Onshore/offshore pipeline | 53 | 21 | 3 | 5 |
| Offshore platform | 165 | 210 | 174 | 90 |
| Railroad | 6 | — | — | — |
| Storage tank | 81 | 9 | 1 | 1 |
| Unknown sheen | 23 | 3 | 1 | 2 |
| Vessel | 52 | 13 | 3 | 4 |
| Total | 517 | 270 | 185 | 102 |

Only a small number of releases reported late were from fixed facilities (e.g., five releases of oil from flooded transformers) or storage tanks discovered during cleanup and recovery. The large oil spills resulting from Hurricane Katrina, discussed above, are all recorded in the IRIS database, but since reports are often preliminary, incomplete, and are not updated most do not accurately report the quantity of oil released. For example, the NRC database contains reports of the release of only 1.6 million gallons of petroleum, largely crude oil, as a result of Hurricane Katrina compared to estimates of 8 million from large spills alone. Therefore, while the NRC database may accurately portray the number of significant releases, the *quantity* of material released can only be considered (at least in the case of a catastrophic event like Hurricane Katrina) a first-order estimate.

Looking at only onshore fixed facilities and storage tanks, which are the focus of this study, it is evident that a majority of releases were of petroleum (76%) with smaller amounts of chemicals (18%) and natural gas (6%). These events, classified by type of material released and by location type, are mapped in Fig. 2. Releases are concentrated within the area of the storm surge with the highest concentration of releases in Plaquemines Parish, which was both in the direct path of Hurricane Katrina and has numerous oil storage and transfer facilities along the Mississippi River. Concentrations of releases are also observed around New Orleans, LA, Pascagoula, MS, and Mobile, AL.

These records were further characterized by the damage mechanism and cause of the release if they could be reconstructed from the event description within the database. Reports on petroleum released from fixed facilities and storage tanks only contained enough information that 23% of releases could be

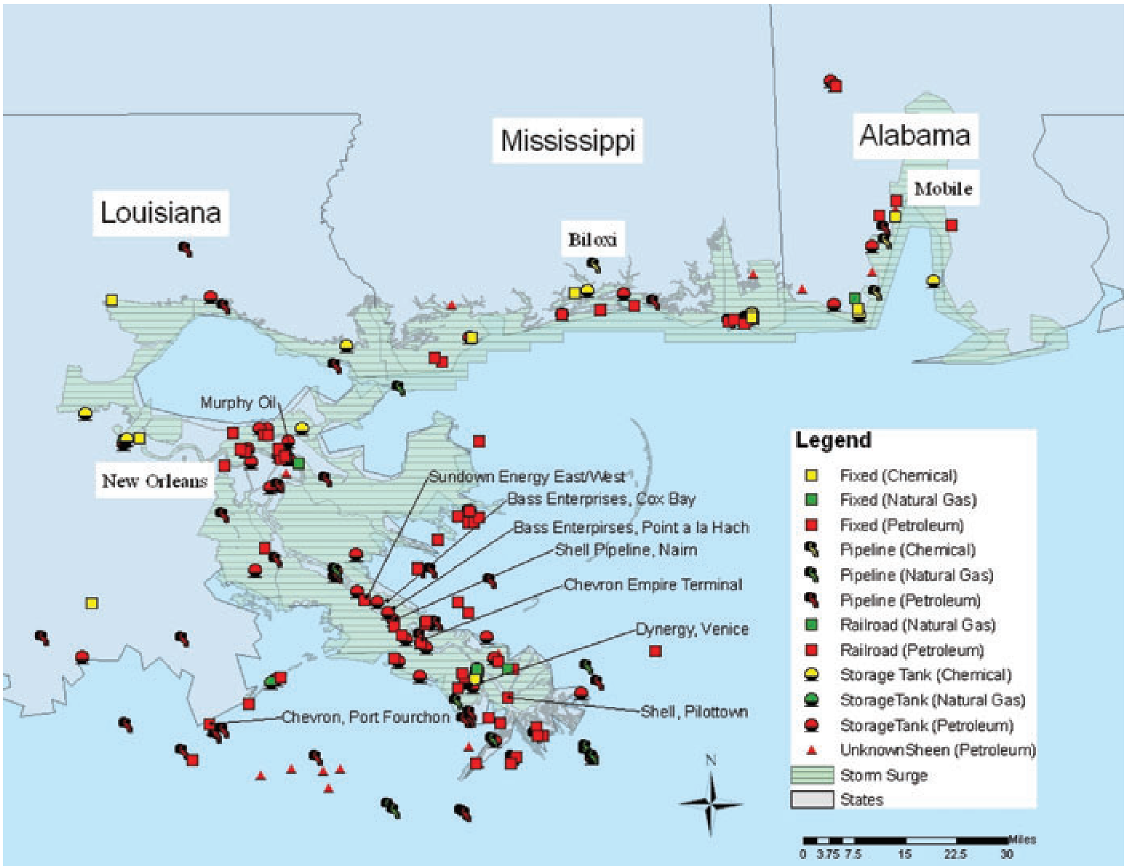


**Fig. 2.** Releases caused by Hurricane Katrina, excluding platforms and vessels, classified by facility type and material released.

classified by damage mechanism and 74% by release mechanism. Of those that could be characterized, 21 (64%) were damaged by storm surge, 6 (18%) by wind, and 3 facilities had no physical damage. The most common mechanism of release was storage tank failure, which occurred in 62 cases (64%). These are largely composed of releases from the petroleum extraction industry near the coast and reflect its vulnerability to storm surge.

The NRC database also records the medium (air, water, or soil) to which material is released: 13% of releases were to land and 80% to water with the rest unknown, reflecting the regulatory structure that mandates reporting of even small quantities of petroleum released to water, and the location of petroleum facilities near the coast. Typically, water releases are harder to remediate since petroleum spreads quickly in the water and, depending on the oil product, may eventually become entrained in the water body's sediment. Oil dispersed to land will spread to soils and groundwater, both of which are difficult and costly to remediate.

Event descriptions of chemical releases (not including petroleum) at fixed facilities and storage tanks contained enough information that 63% could be classified by the damage mechanism and 94% could be classified by release mechanism. Of those events that could be classified, 3 (15%) resulted from storm surge or flooding, 4 (20%) from wind, and 13 (65%) experienced no physical damage. The three most common release mechanisms were unspecified equipment damage, plant startup and shutdown with eight releases (26%) each, and storage tank failure with seven releases (22%). A significant difference is observed between the receiving medium for chemical compared to petroleum releases. For chemical releases from fixed facilities and storage tanks, 52% were releases to air, 17% to land, and 19% to water, with the rest unknown. The prevalence of chemical release to air reflects the fact that many of these releases are due to flaring. Unlike releases to land or water, hazmat released to the air cannot be recovered or remediated.

Ruckart *et al.*[10] observed that 72% of chemical releases from Hurricanes Katrina and Rita were related to system shutdown or startup. The larger proportion of chemical releases caused by startup and shutdown observed by Ruckart *et al.*[10] is due to the large number of releases in their data set (114) caused by shut down or start up of industrial facilities related to Hurricane Rita, which are not included in our analysis. In addition, all events analyzed by Ruckart *et al.*[10] were from LA or TX, while half of the chemical releases reported to the NRC as a result of Hurricane Katrina are from MS (which does not report to the HSEES system) where no releases were reported resulting from start up or shut down.

### *3.3.1. Risk Assessment of Hazmat Releases*

To understand the level of risk faced by industrial facilities during a major hurricane, it is necessary to compare those facilities that experienced releases to the total population of facilities exposed. The probability of a release resulting from Hurricane Katrina was calculated for two broad classes of industrial facilities: those within the TRI and RMP programs and those of industries with an SIC code of 1311, which represents oil and gas extraction. Releases were analyzed with respect to these broad industry types without regard for the material released. We proceeded in this manner because both chemical and petroleum releases often occur at the same facility and because determining vulnerability for widely recognized classes of facilities allows for a more straightforward use of these results in future risk analysis. With additional data the same technique could be applied to more specific classes of facilities (e.g., large storage tanks).

As storm surge appeared to be the dominant cause of releases, the region affected by storm surge and that affected by hurricane speed winds without storm surge were analyzed separately. Spills from RMP and TRI facilities were identified based on matching location address and company name from the IRIS database to those from the TRI and RMP databases. Spills that appeared to originate from crude oil and gas extraction facilities (SIC 1311) were identified both by matching address and company name to specific 1311 facilities and also based on the description and location of the event. While this may result in a small number of events that did not occur at a 1311 facility being listed as such, this approach was necessary due to incomplete address and company information for many petroleum releases originating from Plaquemines parish. For both the RMP and TRI and SIC 1311 facilities, the number of releases in each zone was divided by the number of facilities, yielding an estimate of the fraction of facilities that experience a release although in reality multiple releases were sometimes reported for the same facility.

This analysis is shown in Figs. 3A and 3B and the results are summarized in Table V. It can be seen that for the area affected by storm surge, there was a higher percentage of facilities that experienced releases than in the area affected by hurricane or tropical storm strength winds. SIC 1311 facilities were considerably more likely to experience releases than TRI and RMP facilities. This observation probably reflects the exposure of SIC 1311 facilities to more severe storm surge and winds due to being located in low-lying areas close to the coast. Approximately half of the releases in the storm surge zone were over 1,000 gallons for liquid releases, which were primarily petroleum, or over 1,000 pounds for chemicals, while only one in four releases in the two wind zones were above these sizes. It should be noted that a small number of releases from facilities, generally due to indirect effects such as shutdown, startup, or power loss, occurred outside the direct influence of the hurricane and so are not tabulated. These results are consistent with the analysis of offshore releases during Hurricanes Katrina and Rita by Cruz and Krausmann,[11] who observed that more releases occurred in areas of greater wind speed and storm surge height.

## 3.4. Lessons Learned by Industrial Facilities

The region impacted by Hurricane Katrina has a long history of hurricane impacts. Many facilities severely affected by Hurricane Katrina had been operating for decades and were aware of the risks posed by hurricanes. As an example, most of the facilities responding to our survey had hurricane plans and reported having considered the risk of hazardous material releases caused by hurricanes. Nine of the facilities were regulated under the RMP program and seven of those list hurricanes as a major risk to their process under the prevention program portion of their RMP. In general, it is observed that the majority of RMP facilities in the areas impacted by Hurricane Katrina's storm surge (not limited to those in our

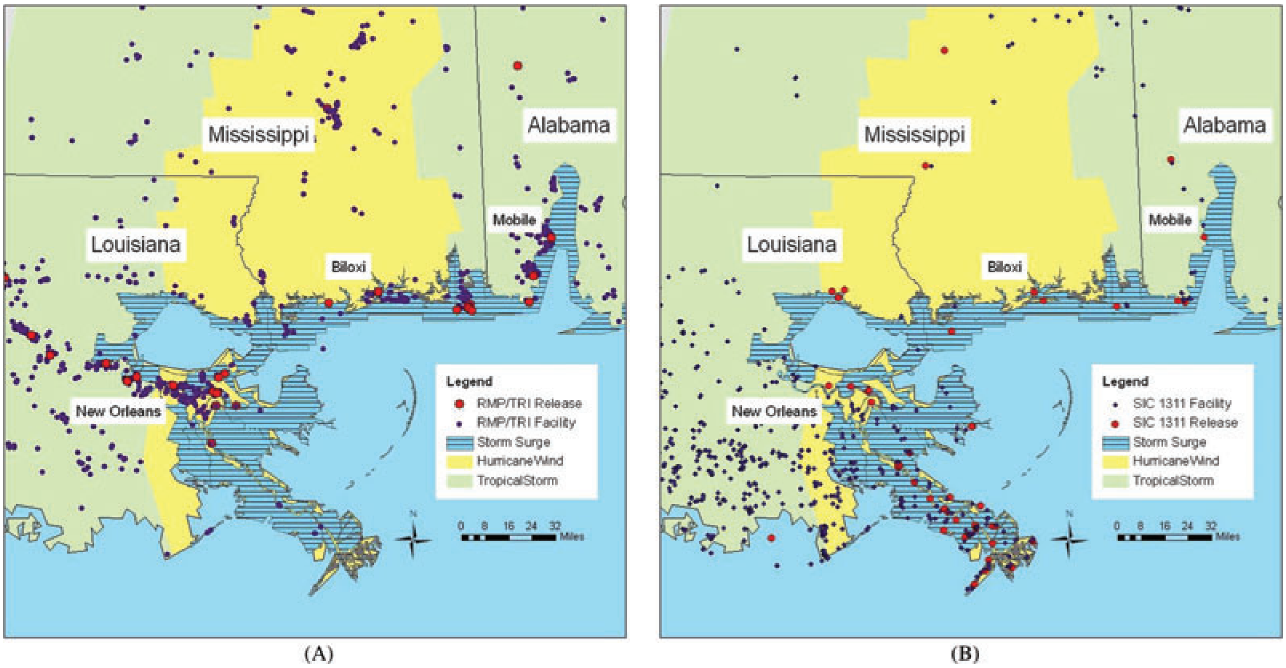


**Fig. 3.** A and B: Location of risk management plan and toxic release inventory, and SIC 1311 facilities and associated releases.

**Table V.** Number of Facilities and Releases in Storm Surge and Wind Zones

| Category | TRI + RMP Facilities | TRI + RMP Releases | Facilities with Releases % | SIC 1311 Facilities | SIC 1311 Releases | Facilities with Releases% |
|---|---|---|---|---|---|---|
| Storm surge region | 170 | 17 | 10% | 158 | 38 | 28% |
| Hurricane wind | 284 | 3 | 1% | 60 | 6 | 10% |
| Tropical storm wind | 1,047 | 12 | 1% | 457 | 6 | 1% |
| Entire hurricane region | 1,501 | 31 | 2% | 675 | 50 | 7% |

survey) identified hurricanes as a risk in their RMP filings prior to Hurricane Katrina. Notable exceptions to this are several facilities within levees in the vicinity of New Orleans. However, RMP filings do not give any indication if mitigation of this identified risk was undertaken. Mitigation depends in part on the type of process; risk from manufacturing processes might be mitigated, as is often the case, by shutting down the facility in a controlled fashion ahead of the hurricane, although this raises the risk of releases associated with shutdown and startup. Risk from storage might be much more difficult to control, with tradeoffs existing between deinventorying material stocks versus having material on hand to rapidly resume operation, as well as the tradeoff between the vulnerability of full verses empty storage tanks to damage and spills.

A number of mitigation activities, undertaken prior to Hurricane Katrina, which helped to prevent releases were reported through our survey. Many of these are standard industry practice and are among those recommended post Hurricane Katrina. These activities included shut down of normal operations prior to hurricane (practiced at 5 sites), securing small tanks, containers and other mobile equipment (3), use of ride out crews (2), use of emergency generators to provide backup power (2), high-quality construction of containment walls and storage tanks, and tie downs on chemical tanks. Many of these correspond to hurricane preparation activities and precautions recommended to industrial facilities by the EPA[42] and Chemical Safety Board.[43]

Despite these preparations, the severity and scale of the impacts of Hurricane Katrina took many industries as well as responding agencies by surprise. These experiences point to various measures that can be taken to prevent releases of hazardous materials and offer insight into what is necessary to mount an effective response to releases when they occur. With the exception of one, all companies responding to the survey reported some organized effort to compile lessons learned, primarily through internal discussion (9), and by consulting with local, state, or federal government representatives (7), as well as exchanging ideas with neighboring facilities (7). In the same vein, the LCA has published a series of lessons learned from the experiences of a small number of their member companies during Hurricanes Katrina and Rita[44] and DuPont has described the experiences of its DeLisle Plant in MS.[4] Many of the issues and adaptations brought up by respondents to the survey parallel those covered by the LCA and DuPont, including difficulties in plant operations, communication, dependence on external infrastructure, and employee support issues. All emphasized that limited access, displacement of workers, and widespread loss of outside infrastructure (particularly electrical power and communications) hinders the ability to respond to damage and return to normal business. Several companies reported workers having to be brought in from a significant distance each day at some locations, or even quartered on barges.[45] These obstacles to effective response parallel those observed from other major natural disasters.[46]

Although the lessons learned described in our survey, as well as by the LCA, may not be universal, encouraging the types of practices that more proactive companies already employ may be a useful approach to mitigate the impact of future hurricanes on industry. Six survey respondents related additional preparative actions taken post Hurricane Katrina. This was generally a joint decision by corporate and facility staff with the decision being aided by a cost-benefit analysis in three cases. Facilities reported physical improvements such as construction of flood walls, purchase of hurricane shelters and hardening of buildings, purchase of backup generators, purchase of backup communication systems, and storage of emergency supplies of gasoline. Additional preparations included making plans for transportation of workers and support of families, regular review of hurricane plans, decreasing inventory of hazardous material, arranging for personnel assistance from outside the impacted area before a hurricane, and filling storage tanks with water to minimize chances of damage from wind or storm surge.

Interestingly, five facilities indicated that existing plans and equipment were adequate despite, in two of these cases, significant damage ($9 and $12 million). Of these two, one indicated that such events are too unpredictable to make mitigation worthwhile while the other was exposed to flood damage through levee failure and is assumed to be relying primarily on reconstructed levee systems for future protection.

## 4. CONCLUSION AND RECOMMENDATIONS

Hurricane Katrina resulted in over 200 onshore releases of hazardous chemicals, petroleum, or natural gas. In addition, there were over 800 releases of these materials from offshore platforms, vessels, and pipelines in the Gulf of Mexico. Failures of storage tanks were a major cause of petroleum releases (64%). The total size of petroleum releases was quite large, rivaling the *Exxon Valdez* spill in volume, and remediation and compensation to impacted homeowners was expensive. While petroleum releases were largely due to tank failure, causes of hazardous material releases were approximately equally divided between flaring events from chemical facilities during startup and shutdown (26%), other equipment damage (26%), and damage to chemical storage tanks (22%). Given these observations, a number of recommendations can be made. Because of the severe impacts associated with storage tank damage, tanks should be emptied and filled with water (as is standard procedure for some companies) or, if this is not practical, completely filled with product, and properly secured (especially in the case of small tanks) in the face of an oncoming hurricane to minimize the chance of damage and spills. In addition, more attention should be given to planning for shutdowns, including coordination with government entities responsible for evacuation, and to plant startup after an emergency shutdown in order to minimize flaring and other releases.

Our analysis indicates that in areas that experienced storm surge due to Hurricane Katrina, 10% of RMP and TRI facilities and 28% of SIC 1311 facilities experienced releases. In areas subject only to hurricane strength winds, a lower fraction, 1% and 10% of RMP/TRI and SIC 1311 facilities, respectively, experienced a release. Half of releases in the storm surge zone were liquid releases greater than 1,000 gallons (primarily petroleum releases) or other hazardous compounds released in quantities greater that 1,000 lb, while only a quarter of releases were over these sizes in the hurricane wind zones. Preliminary work by the authors indicates similar frequency of releases from other hurricanes in the continental United States. Although only a small fraction of these releases had serious consequences, their high frequency should give facility managers and agencies responsible for hazardous material response cause for reflection. Including estimates of the frequency and size of hazmat releases in the assessment of risk associated with hurricanes would aid hazmat response planning and prevent responding agencies from being overwhelmed by unexpectedly large numbers of releases as was the case after Hurricane Katrina.

In many cases, significant damage to industrial facilities occurred but no releases of hazardous material were reported. Most of the severe damage, like the worst releases, resulted from flooding and storm surge, rather than from winds (for which engineering standards exist). In some cases, changes in construction standards (as have been implemented for offshore facilities), or improvements to engineered defenses (such as facility levees, or elevation of equipment) can mitigate the risk associated with flooding and storm surge; in other cases the only way to truly mitigate risk may be to relocate the facility. The fact that not all damaged facilities experienced releases indicates that improved procedures, design, and planning can reduce the probability of hazardous material releases despite the presence of physical risk. Chemical accident prevention and emergency response regulations in the United States and elsewhere generally do not address the threat of natural hazards directly.[47] While many companies are proactive in taking steps to mitigate natural hazard risk, others may make only the minimum effort required by statute.

Facilities have taken a number of steps to address hurricane risk. For example, a number of facilities have built or expanded levees for storm surge protection. Where these mitigation measures are employed, an in-depth analysis of storm surge likelihood should be undertaken and used to determine risk-based criteria for plant design. Harris and Wilson[4] presented an example of this, where analysis of storm surge risk was made to confirm the design of an improved levee system. This type of risk-based design would also be well applied to design of critical plant equipment. The risk analysis should include not only cost to repair the facility, but also potential downtime, liability, and environmental damage. Hurricane winds also need to be considered, although they were responsible for fewer of the serious events associated with Hurricane Katrina. Availability of hurricane probability analysis for all hurricane-prone regions of the United States, similar to the probabilistic analyses performed by the Interagency Performance Evaluation Task Force that analyzed the failures of the New Orleans levee system,[48] would help industrial facilities and local communities better understand hurricane risk and would encourage a more realistic approach to hurricane protection for industrial facilities. When large releases do occur, in-depth analysis by each plant of mechanism of failure and contributing factors should be required.

Industrial facilities also experienced many indirect disruptions during Hurricane Katrina of types that are common to large natural disasters. Common difficulties included displacement of workers due to evacuation or home loss, loss of electricity and communication systems, and difficulty acquiring supplies and contractors for reconstruction or operation. Facility hurricane plans should recognize, as more have post Hurricane Katrina, that access to the facility may be difficult or restricted, power and communications may be out, back-up personnel may need to be called in, and the area around the facility may be in a severely damaged state.

While the threat posed by hurricane-induced hazmat releases is considerable, and damage to industrial facilities is not unlikely, implementation of these recommendations could contribute substantially to the minimization of risk faced by industry as well as the general public.


## ACKNOWLEDGMENTS

The support for this research was provided by NSF under Grant #0814506 and Grant #0302194. We thank Tony Lamanna, Rae Zimmerman, Justin Smith, Ana Maria Cruz, Kyle Parks, Christie Chermak, and Hamideh Etemadnia for their contributions to this project. We also thank those companies and agencies that provided information on their experiences during Hurricane Katrina.


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