

IDENTIFYING HURRICANE-INDUCED HAZARDOUS MATERIAL RELEASE SCENARIOS IN A PETROLEUM REFINERY

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ABSTRACT: Hurricanes and other natural disasters can induce hazardous material (hazmat) releases. However, researchers generally treat natural and technological disasters as separate entities rather than as conjoint events. This paper investigates hurricane-induced hazardous material (hurmat) releases in a petroleum refinery. The information developed in this study indicates the need to develop emergency response plans, mitigation measures, and design criteria to minimize health risks and property damage from conjoint disasters at industrial facilities. This paper identifies possible hurmat release scenarios in a refinery, and assesses the type of release that might result. Four hurricane threats are considered: high winds, tornadoes, flooding, and lightning. These hazards can lead to hazmat releases caused by damage to equipment, damage to pipes and connections, short circuits and/or power failures, punctured tanks and vessels, and structural damage to buildings and facilities. Hazmats can be released in fires and/or explosions, toxic gas emissions, and spills. The multiple consequences of each hazard scenario are analyzed, and the relationships between the different hazard types are illustrated. The present paper concludes that refineries are susceptible to all four hurricane threats and that these threats could serve as triggering mechanisms for hazardous chemical releases. For public policy application, risk quantification of the scenarios presented should be undertaken; the authors recommend that a strategy of expert elicitation be adopted for this purpose.

INTRODUCTION

Natural disasters such as hurricanes can induce hazardous material (“hazmat”) releases. However, researchers generally treat natural and technological disasters as wholly separate events. This paper considers both types of events in a study of the potential for hazardous material releases due to hurricane-induced hazards at petroleum refineries along the Louisiana Gulf Coast.

The information available on hazardous material releases caused by natural disasters is scarce. The few existing studies suggest an increase in natural disaster-induced hazardous material (“natmat”) releases over the last 20 years, whether expressed as increases in monetary damages as indicated by data from Marsh and McLennan (1997), or as increases in the total number of natmat events as documented by Showalter and Myers (1994) and Lindell and Perry (1997). Emergency management preparations to deal with natural disaster-induced hazmat releases, however, are very limited, if they exist at all. In general, facilities that use hazmats in the United States are required to perform a process hazard analysis and develop

process safety management and emergency response plans under Occupational Safety and Health Administration regulations. An emergency response plan that includes off-site response is required under the Emergency Planning and Community Right to Know Act and, under the Clean Air Act, a risk management plan for accidental chemical releases was required as of June 1999. However, none of these requirements explicitly addresses a natmat release.

The absence of regulations to address the threat of conjoint events may be due to the low probabilities associated with natural hazards coupled with the perception that natural disasters are unlikely to trigger hazardous materials releases. Hurricanes are rare events. For example, the National Oceanic and Atmospheric Administration has calculated that the probability that a particular 80-km segment of coastal area along the U.S. Gulf Coast will be hit by a major hurricane in any given year is very low, ranging from close to 0.0 to 4.0% (Petak and Atkisson 1982). Nonetheless, when a major hurricane comes ashore, the results can be devastating. The effect of the disaster on the community will be compounded if the hurricane generates a hazardous material (“hurmat”) release. Examples of such releases include release of oil and other hazardous materials during Hurricane Camille in 1969 from petroleum storage and loading facilities in Venice, La. (U.S. Army 1970) and the release of large amounts of oil during Hurricane Georges in 1998 from a sunken floating roof of a storage tank at an oil refinery in Mississippi. Simultaneously, a tank at this refinery containing hazardous gasoline additives floated off its foundations (Chevron 1998). A hazardous materials spill into the Raritan River in New Jersey was narrowly avoided when drums of hazardous chemicals were rescued after having been set adrift from an industrial facility during Hurricane Floyd in 1999 when the system was at tropical storm strength (Smothers 1999).

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Hurmat releases are particularly problematic because the hurricane may simultaneously degrade electric, water, communications, and transportation lifelines inside and outside of the plant, thus hampering on-site response to the hazardous material release. Emergency personnel normally available for hazardous material response are likely to be engaged in countering the direct effects of the hurricane, and are therefore unavailable to respond to the hazardous emission. Unusual hazards may result from hurmat releases. For example, a particularly dangerous scenario would involve the release of an acidifying gas such as hydrogen fluoride which, when dissolved in rainwater, becomes hydrofluoric acid.

NATURAL DISASTERS AND NATURAL DISASTER-INDUCED HAZARDOUS MATERIAL RELEASES

Natural disasters and losses due to these hazards have increased in the last 30 years. In a document prepared for the International Decade for Natural Disaster Reduction, Mileti (1999) showed that average annual losses per 1 million people in the United States increased from approximately \$20 million (in 1994 dollars) in 1970 to \$100 million in 1994. This increase is not surprising, Mileti notes, given the nation's dramatic increase in capital stock during these years. Furthermore, the nature of natural hazards is becoming more complex as population density and industrialization increase in disaster-prone areas. This complexity is compounded when, in addition to considering the natural disaster itself, technological disasters triggered by natural events are also considered.

One of the few existing studies on the incidence of natural disaster-induced hazardous material releases investigated how frequently these types of events occurred in the United States between 1980 and 1989. Showalter and Myers (1994) surveyed emergency management agencies in all 50 states to determine the number of hazardous chemical releases caused by natural disasters over this period. They found that the majority of natmat incidents involved interaction with earthquakes (228 reported incidents), followed by hurricanes (26), floods (16), lightning (15), winds (13), and storms (7). An important finding of their study was a clear trend toward an increasing number of natmat events during the period studied. In a case study of the Northridge earthquake of 1994, Lindell and Perry (1997) found that there were 134 natmat "problems" and 60 natmat release incidents officially reported. Their findings indicated that the number of incidents had almost tripled compared to releases during the Loma Prieta earthquake in 1989, although underreporting of the incidents in the Loma Prieta earthquake may account for some of this difference.

Additionally, a 1998 study conducted by the insurance firm Marsh and McLennan (1997) of the 100 most costly property losses in the hydrocarbon-chemical industry indicated an increase in the number and magnitude of losses over the period 1967–1997. Of the 100 incidents studied,

8% were triggered by natural disasters. Thirteen percent of all losses reviewed occurred during startup and shutdown operations. This is noteworthy because when a refinery comes under a hurricane threat, evacuation procedures typically require shutdown of the process units. According to the study, refineries suffered greater property losses than any other type of hydrocarbon-chemical facility. Vapor cloud explosions, which result from the sudden release of pressurized flammable gas, caused more damage than any other type of chemical release.

Marsh and McLennan also noted that during the last 10 years of the study period, there were several natural disasters, including Hurricane Hugo in 1989, the San Francisco earthquake in 1989, Hurricane Andrew in 1992, the Midwest floods of 1993, and the Northridge earthquake in 1994, that caused large losses. However, many of these losses were not insured, and therefore were not included in their analysis. Both Mileti (1999) and Showalter and Myers (1994) observed that there is an urgent need to record the incidence and impacts of natmat events. Only with this type of data collection will it be possible to learn from past experience and establish a baseline for comparison with future natmat events.

HURRICANES AND HAZARDOUS MATERIALS

Hurricanes

Hurricanes are tropical cyclones that originate over the warm waters of the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico; and in the Central, Eastern, and South Pacific Oceans (Williams and Duedall 1997). Hurricanes can have impact radii of as much as 500 km, although damaging winds are usually limited to a 100-km radius around the storm center (Simpson and Riehl 1981). Hurricanes are classified using the Saffir/Simpson Scale. On this scale, hurricanes are given classifications ranging from 1 to 5, based on wind speed and damage potential. Category 1 wind speeds range from 33 to 42 m·s⁻¹ while a Category 5 hurricane has wind speeds in excess of 69 m·s⁻¹. Damage potential is rated minimal, moderate, extensive, extreme, and catastrophic for the 1, 2, 3, 4, and 5 hurricane categories, respectively, based on wind speed and storm surge (Simpson and Riehl 1981). Of the 15 hurricanes to affect Louisiana between 1900 and 1998, one was a Category 5 (Camille in 1969); three were Category 4 storms (in 1915, 1947, and Andrew in 1992); six were Category 3 storms; and five were Category 1 or 2 hurricanes (Williams and Duedall 1997).

It is important to note that although the damage potential for a Category 1 or 2 hurricane is only rated minimal to moderate in terms of potential wind and storm surge damage, torrential rainfall, and associated flooding and mudslides may result in catastrophic effects. For example, in 1998 Hurricane Mitch made landfall in Honduras as a Category 2 hurricane yet it caused massive flooding and widespread mudslides. In 1998 Hurricane Irene moved

across Florida as a Category 1 hurricane, yet it caused over \$700 million of damage due to flooding.

Storm surges associated with hurricanes may also cause significant damage. Hurricane-induced storm surges routinely reach 1.2–1.6 m (Category 1 storms) and may be >5.5 m for Category 5 hurricanes. In southeastern Louisiana, storm surge levels are estimated to range from 1.8 to 2.4 m in a Category 2 or 3 hurricane and up to 3.7–7.5 m levels during a Category 5 hurricane (*Hurrevac* 2000). A catastrophic storm surge with heights as high as 7.5 m was recorded when Hurricane Camille struck the Mississippi coastline in 1969 (Simpson and Riehl 1981).

Tornadoes spawned by hurricanes can add to the overall threat. McCaul (1991) defined a major hurricane tornado outbreak as one in which more than eight tornadoes are spawned by a single hurricane; by this definition McCaul identifies 18 major hurricane tornado outbreaks in the United States between 1948 and 1986. The intensity of tornadoes is measured on the Fujita scale with values ranging from F0 (surface wind speeds of $32 \text{ m}\cdot\text{s}^{-1}$) to F5 ($142 \text{ m}\cdot\text{s}^{-1}$). In a study of tornadoes associated with Hurricane Danny in 1985, McCaul (1987) found that at least 20 tornadic storms were produced, ranging in intensity from F0 to F3 ($92 \text{ m}\cdot\text{s}^{-1}$). Hurricane Andrew in 1992 spawned much tornado activity, including sightings in the Florida counties of Glades, Collier, and Highlands (Pielke and Pielke 1997), and in southeastern Louisiana. During Hurricane Georges in 1998, a refinery on the Mississippi Gulf Coast was not only damaged by hurricane winds, but also by a tornado that caused extensive losses to one of the plant's cooling towers (Chevron 1998).

In addition to strong winds and storm surge, the lightning that often accompanies hurricanes can be quite damaging to refineries. A recent lightning strike to a floating roof storage tank containing naphtha in Indonesia resulted in a fire that ultimately ignited six additional fuel storage tanks (Marsh and McLennan 1997). A lightning strike at a refinery in Norco, La., in June 2001 set a storage tank containing 5.6 million gallons of gasoline on fire and resulted in a directive to nearby residents to remain indoors for 18 h (Swerczek 2001). Samsury and Orville (1994) analyzed lightning data from Hurricanes Hugo and Jerry in 1989. Although Jerry was a much weaker system than Hugo (Category 4), Jerry was found to be more electrically active. Samsury and Orville found that the existence of cloud-to-ground lightning in tropical cyclones is strongly dependent on the presence of intense outer rainbands, a condition that was present in tropical cyclone Jerry. Furthermore, they observed that the majority of lightning flashes are located in the front right and right rear quadrants of the hurricanes. In later studies, Cecil and Zipser (1999) obtained similar results detecting much greater lightning frequency in rainbands than in eyewalls of hurricanes.

Hazardous Materials

A hazardous material may be defined as a substance or material in a quantity, concentration, or form that has a

substantial present or potential threat to human health or the environment when improperly treated, stored, disposed of, or otherwise managed. Examples of hazardous materials include compounds which are toxic (t) or flammable (f). The hazardous materials that are of particular interest to this study are hydrogen fluoride (anhydrous)(t), ammonia (anhydrous)(t), hydrogen sulfide(t), liquefied petroleum gas (LPG)(f), and propane(f). These materials may be stored in large quantities at oil refineries. Under normal (nonhurricane) conditions, depending on its toxicity and physical/chemical characteristics, a toxic compound may travel many kilometers from the release site before the effects of atmospheric dispersion reduce the ambient concentration of the compound to levels that no longer threaten public health and safety. Hurricane winds will quickly disperse the contaminant, reducing its impact region, but these winds will not prevent the toxic compound from exposing communities adjacent to the release point to the compound. Rain will also dissolve some toxic gases. This will have the effect of reducing the concentration in the gaseous phase but, depending on the type of gas will have the ancillary effect of creating a highly acidic rain in the region around the release site.

In order for emergency management and mitigation personnel to be prepared for hurricane-induced hazardous materials releases at oil refineries, it is necessary to develop an understanding of the type of releases that might occur, and the circumstances that can precipitate these releases. In the following section, we develop several scenarios that can serve as a model for the identification of industrial hazardous materials releases that might occur under hurricane conditions. Four potential causes of hazardous chemical releases at oil refineries due to a hurricane are identified. These include high winds, tornadoes, flooding, and lightning. The potential consequences of each hazard are analyzed, and the relationships between the different hazards are described.

HURMAT RELEASE SCENARIOS IN A REFINERY

Hurricane Threat to a Refinery

Local and state emergency officials begin to monitor an incoming hurricane several days (or even weeks) in advance of its landfall in order to ensure sufficient time for evacuation of vulnerable areas. A refinery will normally monitor the storm and maintain contact with local emergency officials. If evacuation is required, shutdown procedures begin about 72 h prior to landfall of hurricane winds. Process units are “deinventoried,” meaning that all hazardous materials are sent to storage tanks within the plant at locations distant from processing units. The advantage of this procedure is that hazardous materials are removed from the more vulnerable units. However, the magnitude and possible consequences of a potential release may increase because the hazardous material is concentrated at one location.

Steam boilers, water-cooling towers, and power stations

usually remain operating during a hurricane in order to maintain temperature or pressure in storage tanks and, in some cases, to power control equipment and safety devices. A small group of workers typically remain at the refinery to carry out shutdown operations, attend to emergencies, and assure quick start-up once the threat is over. However, these workers will not respond to emergencies while severe weather conditions exist (Category 1 hurricane winds or stronger, or if there is lightning). Once the hurricane threat is over, start-up of processing units may take 2 to 3 days. If there is damage caused by the storm, more time may be required for inspection and repairs.

Impact of High Wind Speeds

High wind speed is one of the main threats of a hurricane. These winds may be generated by the hurricane itself, or by the tornadoes it spawns. Buildings and structures are designed to particular wind speeds depending on climatic characteristics of the region. In the United States, ASCE's design standard ASCE 7 (ASCE 1998), "Minimum Design Loads for Buildings and Other Structures," provides the guidelines for the design and calculation of wind loads. The major provisions of ASCE 7 have been incorporated into the Uniform Building Code, the Standard Building Code, the International Building Code, and the BOCA/National Building Code. ASCE 7 is periodically updated. Between 1960 and 1995, these codes relied on estimates of fastest mile wind speed {the highest sustained average wind speed based on the time required for a mile-long (1.61 km) sample of air to pass a fixed point [International Conference of Building Officials (ICBO) 1991]} to set the design basic wind speed on structures. These values were based on measurements of extreme

wind speeds, extrapolated to recurrence intervals using one of a number of probability distribution functions. For the New Orleans area, the design basic wind speed in 1979 was 40–45 m·s⁻¹ (Ketter et al. 1979).

Beginning in the 1980s, the approach for estimating wind speeds in hurricane-prone areas was reexamined. A Monte Carlo approach was developed in which storm occurrences were modeled using a random selection of storm statistical properties (Georgiou et al. 1983; Peterka and Mehta 1994; Vickery and Twisdale 1955). These results were incorporated in the 1995 edition of ASCE 7 (Peterka and Mehta 1994). Due primarily to changes in data availability from the National Weather Service, the 1995 wind speeds were reported as 3-s peak gust wind speeds rather than as fastest mile wind speeds. Although these speeds were significantly larger than the previously reported fastest mile wind speeds due to the effect of averaging wind speed over a shorter time period, the resulting design speeds in most geographical areas did not change substantially from the 1988 standard. For example, the new 3-s gust speed for New Orleans was 54–58 m·s⁻¹, roughly comparable to a fastest mile wind speed of 41–45 m·s⁻¹ (Peterka and Mehta 1994). In 1998, ASCE published an updated version of ASCE 7 (ASCE 1998) in which the peak gust speeds were revised to reflect recent meteorological data and the work of Vickery and colleagues, described in Vickery et al. (2000). This work was based on a Monte Carlo study of hurricane tracks over a simulated 20,000-year period. Hurricane peak wind speeds in ASCE 7 were revised as a result of this effort and in some hurricane-prone areas basic wind speeds decreased as a result of the new analysis. The New Orleans area 3-s gust value remained at 54–58 m·s⁻¹. These basic wind speeds represent 50-year recurrence intervals which,

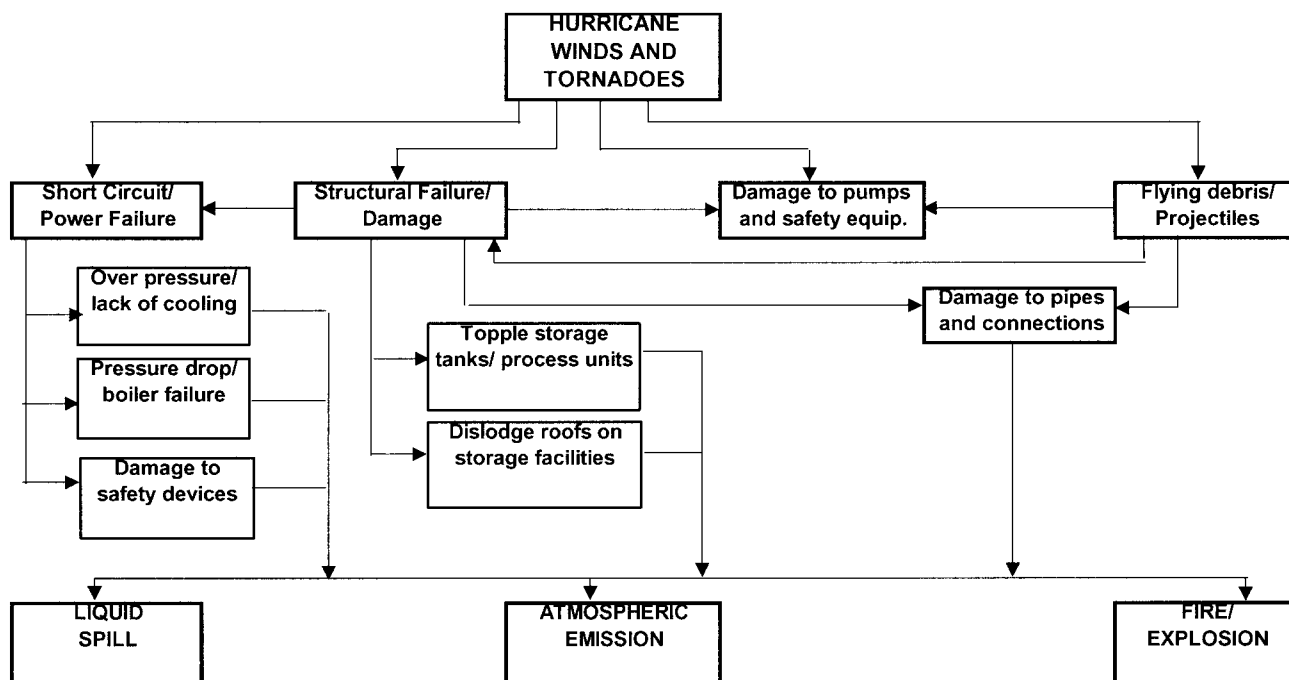


FIG. 1. Potential Effects of Hurricane Winds and Tornadoes on Refinery

when multiplied by the required safety load factor of 1.3, yield a recurrence interval on the order of 500 years (Simiu and Scanlan 1996).

Fig. 1 presents the potential effects of hurricane winds and tornadoes on an oil refinery. High wind speeds and tornado-force winds may damage buildings and structures in a refinery by toppling processing units or storage facilities, and dislodging roofs on refinery structures. Particularly vulnerable to wind-induced failure are the piping and connections between storage and process units. High wind speeds may cause power failure or short circuiting, leading to the failure of steam boilers and cooling water towers, and precipitating a hazmat release. High winds can launch objects such as tree branches, signs, and rooftops into the air. These projectiles can damage equipment, break pipes and connections, and puncture tank roofs.

Effects of Flooding

Flooding may occur due to the heavy rain associated with hurricanes or storm surge generated by hurricane

winds. Storm surge can cause an abnormal rise in water levels of canals, bayous, lakes, and rivers that are directly connected to the sea. Fig. 2 summarizes the possible effects of flooding and the hazmat releases that can result from flooding. High water hazards in a refinery include flooding of electrical equipment (e.g., electrical lines, pumps) causing short circuiting or power failure. A short circuit or power failure will effectively shut down units that are left running during the hurricane including steam boilers, cooling towers, pumps, and electrically operated safety control mechanisms. Internal plant drainage systems containing waste oil can flood, causing oil to float up and out of the drainage system. Ignition of this oil during a lightning storm or other ignition source could cause a fire or explosion. Flooding of containment dikes can cause empty, or nearly empty, storage tanks to float, potentially tearing pipe connections and resulting in a hazmat release. Heavy rains on floating tank roofs can make them sink or tip, leaving oil exposed on tank tops, and presenting a fire hazard in the presence of lightning or other ignition source. Finally, a storm surge can destroy or move building structures, wash away parked vehicles,

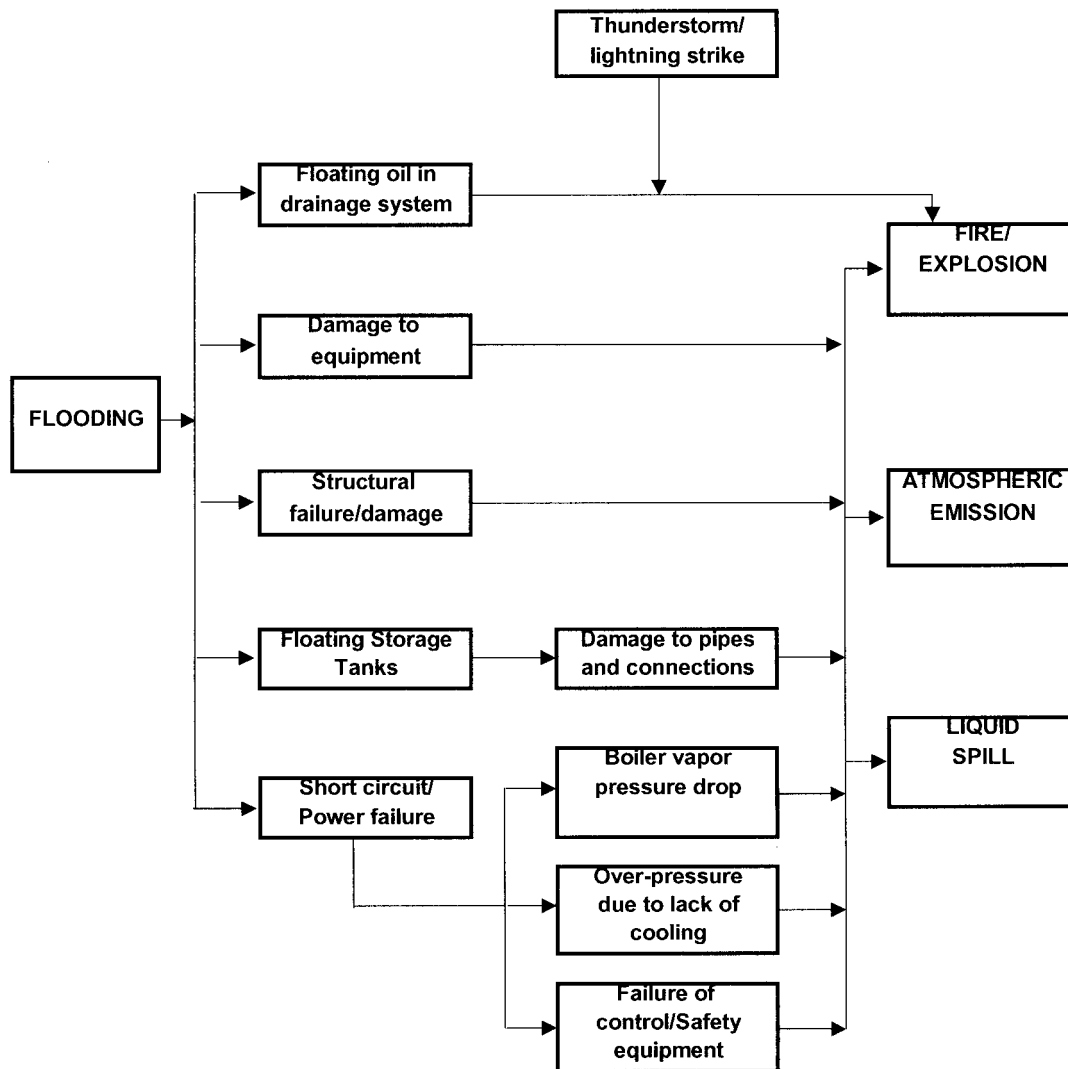


FIG. 2. Potential Effects of Flooding on Refinery

storage tanks, fences, pumps, transformers, tree limbs, and other objects it picks up as it moves through an area. Any of these objects, when pushed up against a hazardous material storage unit, may cause damage, and potentially result in a hazardous materials release.

Lightning Hazard

Lightning can accompany hurricanes whether they are weak or strong tropical cyclones. Lightning can ignite fires, cause power failures, and generate power surges at a refinery. Although steps are usually taken to minimize the likelihood of chemical accidents due to lightning strikes, there have been numerous reports of lightning strikes at refineries [Environmental Protection Agency (EPA) 1997; Marsh and McLennan 1997]. Lightning tends to strike the tallest structures or objects in its path. Projecting structures such as vents, roofs, stacks, towers, etc., are most likely to be struck. Fig. 3 shows the possible effects of lightning on a refinery. Power failure and high current surges can result in false signals, damage, or destruction of sensitive electronics that could cause an upset or release in storage units, steam boilers, pumps, safety devices, and control panels. Lightning can also directly strike structures and storage tanks containing flammable materials causing fires or explosions. Metal fragments from an exploded vessel can puncture other storage tanks, damage nearby equipment, and puncture product pipelines, resulting in hazmat releases.

HAZARDOUS CHEMICAL RELEASES

Hurricane-induced hazardous chemical releases in an oil refinery can be triggered by high winds, hurricane-

spawned tornadoes, flooding, and lightning. These hazmat releases can be in the form of liquid spills, toxic or flammable air emissions and fires/explosions. The overall threat to human populations and infrastructure in the vicinity and surrounding areas to a refinery will depend on the chemical characteristics (toxicity, flammability, density, etc.), amount present at the time of release, storage characteristics, and meteorological conditions.

Spills from nonpressurized storage tanks or pipes and connections containing flammable liquids (e.g., fuel oil, crude oil) can ignite (by lightning or other ignition source), resulting in fires and/or explosions (Fig. 4). Atmospheric emissions can occur when toxic or flammable materials are released from storage tanks or appurtenances. Toxic chemicals such as hydrogen fluoride gas can be stored at atmospheric pressure or as a pressurized gas. In both cases the toxic chemical plume can be transported through the plant and disperse into residential areas near the plant, posing a severe health risk. During a rainstorm, substances such as hydrogen fluoride, which are highly soluble in water, can dissolve and form highly corrosive rainwater.

Flammable materials may be stored in pressurized or nonpressurized storage tanks. A release from a pressurized tank can result in pooling and burning, or evaporation, of the liquid. Following evaporation, the flammable gas may be transported as a vaporous cloud and, upon contacting an ignition source, the plume may explode in a “vapor cloud explosion” capable of causing catastrophic damage (Chang et al. 1997).

The occurrence of one chemical release may trigger another. If an ignited flammable liquid, vapor cloud explosion, or other intense heat source provides sufficient thermal energy in the proximity of a pressurized storage tank

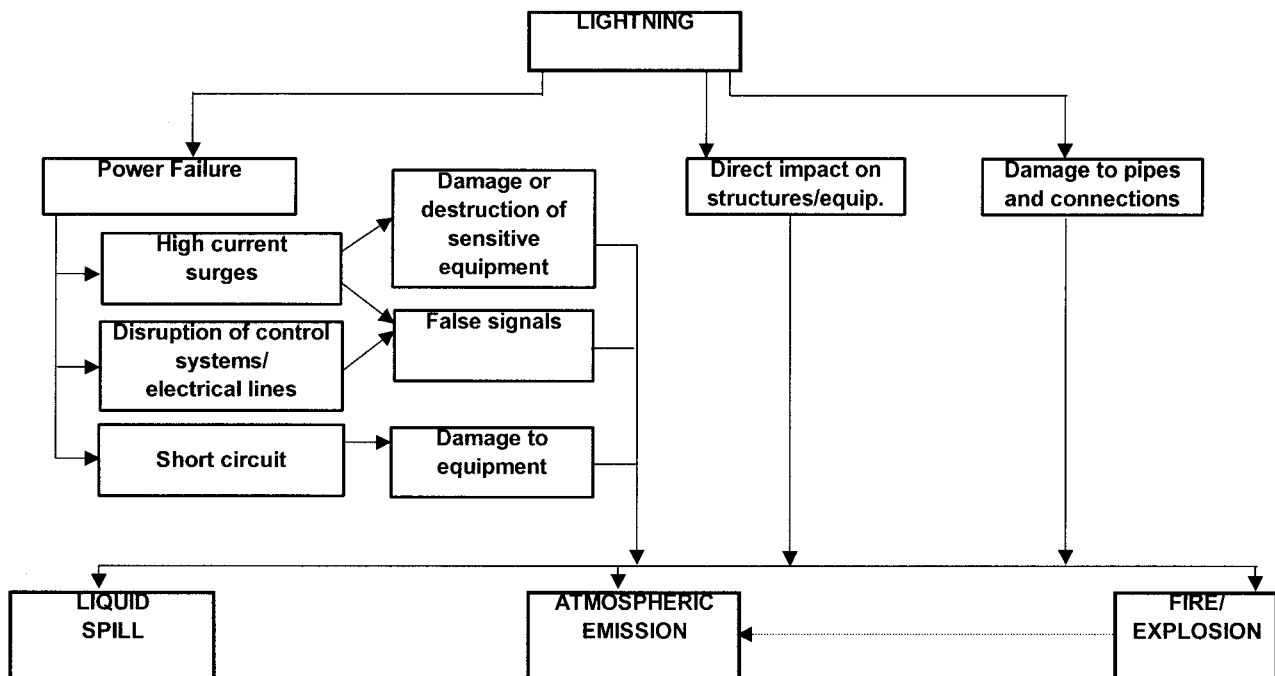


FIG. 3. Potential Effects of Lightning on Refinery

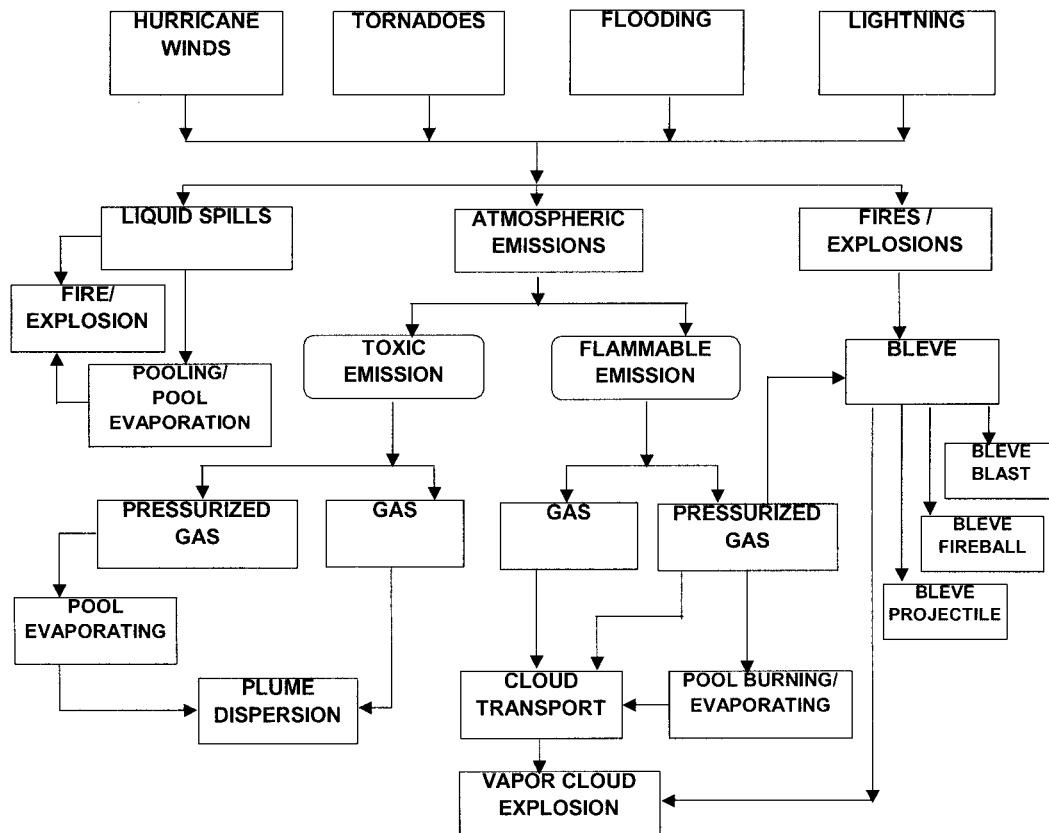


FIG. 4. Potential Hazardous Chemical Releases from Refinery due to High Winds, Tornadoes, Flooding, and Lightning

containing a flammable liquefied gas (e.g., propane), a potentially deadly boiling-liquid evaporating-vapor explosive (BLEVE) may occur (Birk 1998). A BLEVE may be followed by a blast of pressurized air resulting from the explosive release of the pressurized vapor and liquid. A fireball may result if the pressure vessel contents are ignited immediately upon release. Fireballs are sent into the air as a result of the high-momentum jet that can form after tank failure. Fireballs can travel for several hundred meters, potentially reaching into the neighboring community. A BLEVE projectile results from flying parts of the ruptured vessel and can be transported even further than a BLEVE fireball. Flammable liquefied gases that are released during the explosion but fail to ignite immediately may cause a vapor cloud explosion downwind of the release.

CONCLUSIONS

The natural hazards literature has given little consideration to the possibility of joint natural and technological disasters. This paper has addressed the potential for a technological disaster in an oil refinery triggered by a hurricane. Several scenarios have been developed under which an oil refinery might release hazardous compounds during a hurricane. Hurricane-induced flooding, high winds, tornadoes, and lightning may trigger damage to buildings, structures, and storage tanks; rupture of pipes and connections; and upset to safety, control, and service

units such as steam boilers, water cooling towers, and pumps. Stored hazardous materials may be released from the damaged infrastructure. Releases can also be induced by projectiles that act like missiles, puncturing atmospheric and pressurized storage tanks and pipelines. These releases can be in the form of liquid spills, atmospheric emissions, and fires and explosions. Wind load design codes offer protection against wind-induced releases, but winds resulting from the strongest hurricanes or tornado winds may still exceed design criteria. Since a hurricane can affect a large area, the potential for simultaneous hurricane releases, either at the same facility or at neighboring facilities, is greatly increased over ordinary accidental chemical emissions. Furthermore, one chemical release may trigger another: a BLEVE high winds may send puncture-producing projectiles through the air or lightning may ignite a contaminant plume, causing a secondary explosion downwind.

The potential for conjoint disasters at industrial facilities warrants careful attention by government officials and emergency planners. This study demonstrates that conjoint disasters at oil refineries are indeed a possibility, and outlines several scenarios that would lead to such a release. Similar studies should be undertaken at other types of industrial facilities to determine their vulnerability to conjoint disasters. In addition, quantification of the risks associated with the scenarios presented should be undertaken. The authors recommend the risk quantification be performed using a strategy of elicitation of failure prob-

abilities from a panel of experts since there is little field data from major hurricanes on which to base an empirically derived risk analysis. Studies such as these will be essential in developing industry and site-specific emergency response plans for conjoint disasters, designing mitigation measures to prevent conjoint disasters, and developing appropriate design criteria to minimize hazmat release risk and disaster damages.

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REFERENCES

- ASCE. (1998). "Minimum design loads for buildings and other structures." *ASCE 7*, Reston, Va.
- Birk, A. M. (1998). "Propane and LPG BLEVE incident simulation for plant safety analysis, emergency response planning and training." Dept. of Mech. Engrg., Queens University, Kingston, Ont, Canada.
- Cecil, D. J., and Zipser, E. J. (1999). "Relationships between tropical cyclone intensity and satellite-based indicators of inner core convection: 85-GHz ice-scattering signature and lightning." *Monthly Weather Rev.*, 127(1), 103–123.
- Chang, N. B., Wei, Y. L., Tseng, C. C., and Kao, C.-Y. J. (1997). "Design of a GIS-based decision support system for chemical emergency preparedness and response in an urban environment." *Comp., Environment, and Urban Sys.*, 21(1), 67–94.
- Chevron. (1998). "Hurricane George." *Spotlight*, 11(10).
- Environmental Protection Agency (EPA). (1997). "Lightning hazard to facilities handling flammable substances." *EPA 550-F-97*, Washington, D.C.
- Georgiou, P. N., Davenport, A. G., and Vickery, B. J. (1983). "Design wind speeds in regions dominated by tropical cyclones." *J. Wind Engrg. and Industrial Aerodynamics*, 13, 139–152.
- Hurrevac; release 2.0.0.* (2000). Federal Emergency Management Agency, Washington, D.C.
- International Conference of Building Officials (ICBO). (1991). *Uniform building code*, Pasadena, Calif.
- Ketter, R., Lee, G. C., and Powell, S. P. (1979). *Structural analysis and design*, McGraw-Hill, New York.
- Lindell, M. K., and Perry, R. W. (1997). "Hazardous materials releases in the Northridge earthquake: Implications for seismic risk assessment." *Risk Analysis*, 17(2), 147–156.
- Marsh and McLennan. (1997). *Large property damage losses in the hydrocarbon-chemical industries. A thirty-year review*, D. G. Mahoney, ed., M&M Protection Consultants, New York.
- McCaul, E. W., Jr. (1987). "Observations of Hurricane "Danny" tornado outbreaks of 16 August 1985." *Monthly Weather Rev.*, 115(6), 1206–1223.
- McCaul, E. W., Jr. (1991). "Buoyancy and shear characteristics of hurricane-tornado environments." *Monthly Weather Rev.*, 119(8), 1954–1978.
- Mileti, D. S. (1999). *Disasters by design. A reassessment of natural hazards in the United States*, Joseph Henry Press, Washington, D.C.
- Petak, W. J., and Atkisson, A. A. (1982). *Natural hazard risk assessment and public policy*, Springer, New York, 322–353.
- Peterka, J., and Mehta, K. (1994). "Proposed hurricane wind speeds for ASCE 7-95." *Proc., Struct. Congr. XII*, Vol. 1, ASCE, New York, 461–465.
- Pielke, R. A., Jr., and Pielke, R. A., Sr. (1997). *Hurricanes. Their nature and impact on society*, Wiley, New York.
- Samsury, C. E., and Orville, R. E. (1994). "Cloud-to-ground lightning in tropical cyclones: A study of Hurricanes Hugo (1989) and Jerry (1989)." *Monthly Weather Rev.*, 122(8), 1887–1896.
- Showalter, P. S., and Myers, M. F. (1994). "Natural disasters in the United States as release agents of oil, chemicals, or radiological materials between 1980–9: Analysis and recommendations." *Risk Analysis*, 14(2), 169–181.
- Simiu, E., and Scanlan, R. H. (1996). *Wind effects on structures*, Wiley, New York.
- Simpson, R. H., and Riehl, H. (1981). *The hurricane and its impact*, Louisiana State University Press, Baton Rouge, La.
- Smothers, R. (1999). "Hunting industrial hazards carried off by flood waters." *New York Times*, Sept. 24, Metro, B5.
- Stanford, J. L. (1987). *Tornado. Accounts of tornadoes in Iowa*, Iowa State University Press, Ames, Iowa.
- Swerczek, M. (2001). "Refinery blaze extinguished but neighbors are fired up." *The Times-Picayune*, June 9, Metro, B4.
- Uman, M. A. (1987). "The lightning discharge." *International Geophysics Series*, Vol. 39, Academic, San Diego.
- U.S. Army Corps of Engineers. (1970). "Report on Hurricane Camille." New Orleans.
- Vickery, B. J., and Twisdale, L. A. (1995). "Prediction of hurricane wind speeds in the United States." *J. Struct. Engrg.*, ASCE, 121(11), 1691–1699.
- Vickery, P. J., Skerlj, P. F., and Twisdale, L. A. (2000). "Simulation of hurricanes in the United States using an empirical storm track modeling technique." *J. Struct. Engrg.*, ASCE, 126(10), 1222–1237.
- Williams, J. M., and Duedall, I. (1997). *Florida hurricanes and tropical storms*, University Press of Florida, Gainesville, Fla.