Managing the risk associated with severe wind and flood events in the chemical processing industries

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Natural hazards can present severe exposures to industrial facilities. This is particularly true in the Chemical Processing Industries, where facilities are often sited in coastal areas prone to hurricanes or rivers susceptible to flood. The exposures these hazards present are often under recognized and underappreciated. During our loss investigations, there is a common perception that these events are considered "Acts of God" in which limited to no control can be offered and adequate insurance coverage is often considered to be the primary protection strategy. In addition, due to the wide spread and life changing nature of these events, lessons learned are not always well captured or mitigated in future events.

This work explores the history of these events with illustrative case studies in the chemical manufacturing industry and considers the ability to reduce the risk by adopting key Process Safety elements into the management of these hazards. This includes observations from the 2017 hurricane seasons, including hurricanes Harvey and Maria.

Introduction

Natural Hazards

Natural hazards are a group of perils, which occur naturally, as a result of geophysical, meteorological, hydrological or climatological upsets. Natural hazard events include:

Earthquake	Surface water	Drought
Landslide	Snow	Wildfire
Tsunami	Avalanche	Wind
Volcanic activity	Hail	Hurricane/Cyclone
Extreme Rain	Ice Storms	Tornado
Flood	Freeze	

These exposures present are largely defined by the physical location of a facility. The location establishes which of the above perils are credibly present and the frequency and severity in which they may occur. These events can negatively impact plant buildings, equipment, and continuity of operations. If not properly managed, this may result in significant financial impact to the company owning these assets. Historically, natural hazards account for more than 15% of all commercial and industrial property insurance losses globally in any given year. In some years with extreme activity, natural hazard losses have approached 50% of all losses. In 2017, over a span of 26 days, FM Global clients experienced 2,600 natural hazard losses.

As a result of factors such as globalization, urbanization, climate change, the number and severity of natural hazard events and their impact on major industrial facilities has been increasing steadily for the last 30+ years as illustrated in Figure No. 1.

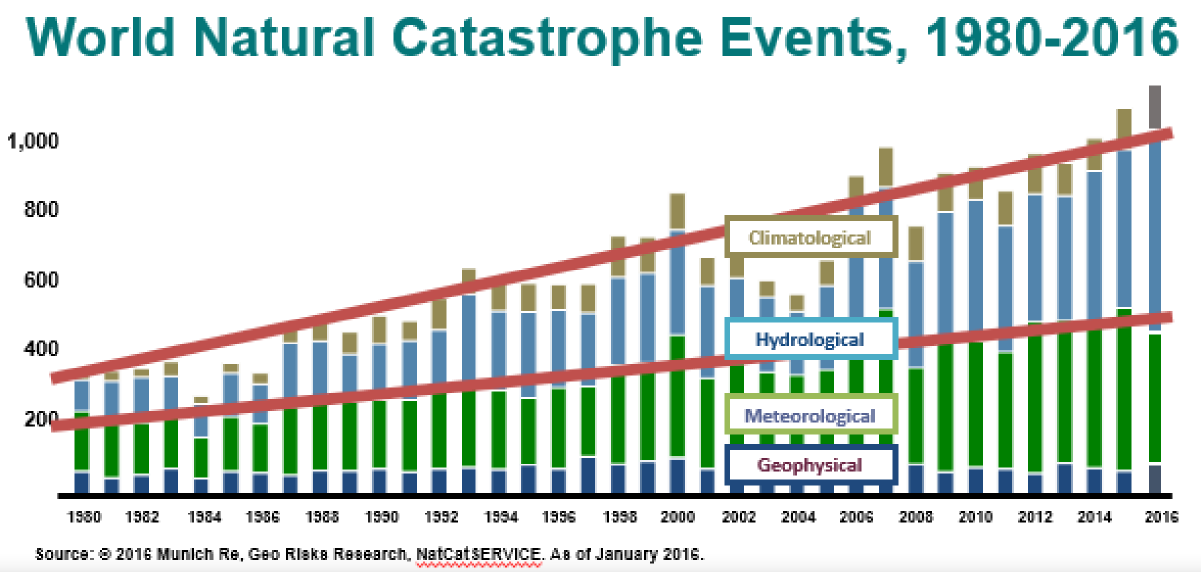

Figure 1: World Natural Catastrophe Events, 1980-2016

Impact on the Chemical Industry

It has been said to fully appreciate Process Safety, managers should live at chemical sites. While impractical as this may sound a more realistic correlation can be made to natural hazards. To gain a full appreciation of natural hazards and its potential for damaging effects, site managers should fully participate in the sites storm ride out crew. This appreciation is genuinely understood when you start to feel the reduced pressure associated with a hurricane as your ears pop and chest weighted down, howling winds and generation of loud sudden noises of flying debris impacting your building, loss of power and lighting limiting your vision, rising water to your feet wetting your clothes, and various other cascading effects over a prolonged period.

Like many other industries, the Chemical Industry can have significant natural hazard exposures. Their proximity to river or coastal geographic areas makes them prone to damage and chemical releases during such events. A common expectation is that through specific site selection and design, natural hazards will be mitigated. However, this is rarely the case as the true potential for loss, even under proper site selection and design, is often misunderstood. Past events have demonstrated the lack of comprehension and hazard conception associated with natural hazards. The enormous energy within hurricanes, floods, earthquakes, freeze, and other natural hazard events are often difficult to comprehend when experience is lacking. It is rarely recognized that a facility located in a 100-yr flood boundary or subjected to 100-yr wind speeds will experience significant property damage and business interruption.

Our loss history in chemical processing facilities continues to increase as events become more frequent. Our natural hazard risk analysis at chemical processing facilities continues to express a growing potential for loss events. The following graph depicts our current loss history of natural hazard events compare to other risk categories. Over the referenced 10-year period, natural hazards represented 17% of all the losses to FM Global's chemical clients.

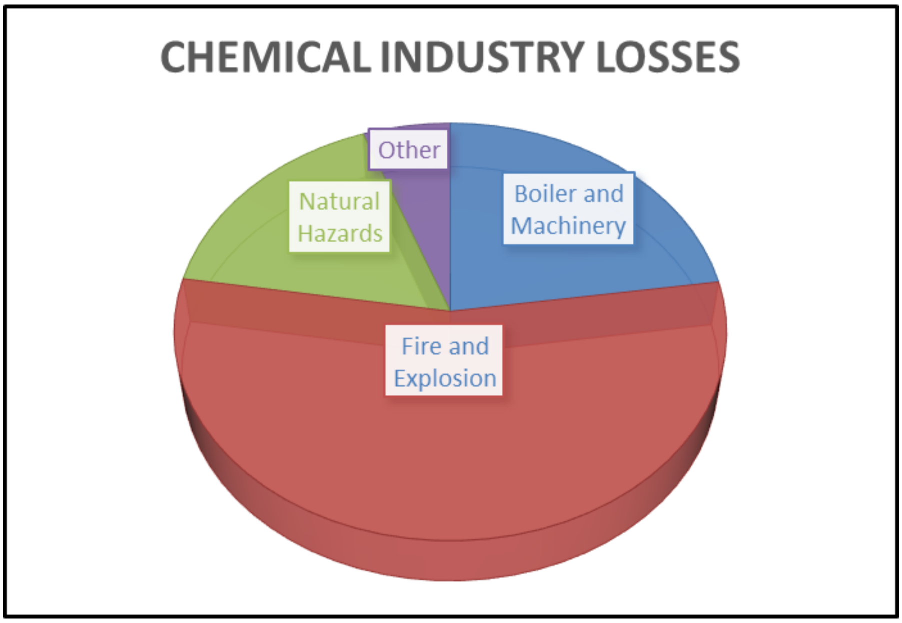

Figure 2: FM Global loss data for the chemical process industries, 2008 – 2017.

Natural hazard events, as rare and infrequent as perceived, are not part of a normal process operating condition and as such are not addressed in many Process Safety programs. The general assumption is these hazards were addressed during the design and construction phase. Compliance with these design specifications is expected to limit and prevent any episodic releases that may lead to health hazards to employees, contamination or significant property damage and resulting business interruption. These design standards are based upon strength of various structures and similar parameters, but rarely include process serviceability. They also are based upon a perceived likelihood of the hazard occurring without a full appreciation of the consequences of such events that are perceived as low probability. Process Safety professionals have a good appreciation for probabilities and the overall risk of such events and are uniquely qualified to assist in such risk discussions.

The following sections explore the frequency of the exposure, mitigation, and risk management techniques that can be integrated into the facilities Process Safety program to deal with natural hazard exposures and the need to consider natural hazards in these process safety elements. It is a complete understanding of all the perils related to site specific natural hazards and its process variables, process conditions, safety knowledge, and ultimately mitigation measures that will influence the natural hazard exposure and resulting risk. Process safety programs as establish will naturally assist in this understanding.

Understanding the Hazard

The first step in understanding and managing natural hazards risk is understanding the potential exposure. Are you in a flood zone? Is your site prone to severe wind events? A location in an elevated area may not have a credible flood exposure, just as location distant from coastal areas may not be credibly exposed to a hurricane. To understand the risk, the probability of an occurrence and relative magnitude of the event should be understood. From this, a basis of design can be established to mitigate the hazard and response plans can be developed for prompt recovery.

Resources and Tools

Determining if a location is exposed to a specific natural hazard, is usually determined geographically and displayed on mapping tools. This includes wind-speed maps, flood maps, etc. Such tools are often developed by government entities, code and standard writing entities, and insurance companies. This paper will focus mostly on the natural hazard risks of flood and wind/hurricane. The reference section provides a list of available resources to help identify the inherent exposure present at a specific location for these perils.

Probability of Occurrence

Natural hazards are commonly related to a return period or mean recurrence interval (MRI) which is an estimate of the likelihood of the event of a specific magnitude to occur. This is a statistical measurement based on historic data denoting the average recurrence interval over an extended period of time. The return period is commonly misinterpreted as a regular interval in which the event of a specified severity will occur at a location.

The mean return period of an event (e.g., flood, winds, damaging ground motion, rainfall, etc.) is the average number of years between successive events. A mean return period of 500 years does not imply that successive events will be exactly 500 years apart. Nor does it imply that there is 100% probability of its occurrence in a 500-year period. For example, compare rolling a 6-sided die. There is a one-in-six chance of rolling a "3" [i.e., a "return period" of 6]. However, in six rolls of the die, it is possible that a "3" will not be rolled and it is also possible that a "3" will be rolled more than once.

The following relationship gives the probability of an event occurring <u>at least once</u> in a given period:

$$P = 1\text{-}\exp(-t/T) \qquad (1)$$

where, P is the probability that an event of mean return period “T” will occur <u>at least once</u> in a time period “t”. For example, the probability of a 500-year event occurring at least once in 50 years is:

$$P = 1\text{-}\exp(-500/500) = 0.632\ (63.2\%). \qquad (2)$$

Put another way, there is about a 37% chance that a 500-year event will not occur in a given 500-year period. Assuming independence of events, the probability of a 500-year event occurring at least twice in 500 years is 26%. A good representation to assist in the comprehension of the natural hazard risk is provided in Table No. 1 below:

Return Period	**Facility Life (Years)**			
	10	25	50	100
	Natural Hazard Event Probability			
10 years *(10% annual probability)*	65%	93%	99%	100%*
25 years *(4% annual probability)*	34%	64%	87%	98%
50 years *(2% annual probability)*	18%	40%	64%	87%
100 Years *(1% annual probability)*	10%	22%	40%	63%
500 Years *(0.2% annual probability)*	2%	5%	10%	18%

Table 1: Probability of event at least once during the facilities lifetime.

Probability can also be considered in terms of the same Risk Matrix, used in Process Safety evaluations. Most natural hazard maps identify hazards with a MRI of 10 to 1,000 years. Where organizations have an established methodology of risk ranking, using a risk matrix, they are encouraged to risk rank natural hazards using these tools.

When risk ranking, it is important to understand that MRI is not a probability of occurrence, but a probability that the event will not be exceeded. A location in a 100-year flood zone has a probability of occurrence of <u>at least</u> 1% in a given year. The 1% probability is basically at the boundary line as drawn on the map. If the location is relatively close to the river and at a lower elevation, the actual probability of occurrence may be much higher than the stated 1%. Correspondingly, a location outside of a 100-year flood zone, but within a 500-year flood zone has a probability of an event happening between 1% and 0.2% in a year. As a result, for order of magnitude risk ranking, 100-year natural hazard exposures are typically characterized as 10^{-1} and 500-year exposures are categorized as 10^{-2} on a risk matrix. This may vary by the risk ranking definitions on various risk matrices.

Event Severity and Design Basis

Flood Design:

Flood hazard maps [1] are typically accompanied with flood profiles, which will provide specific flood depths for the various recurrence intervals. As a result, at a given point along a river, the 100-year elevation would be given as X and the 500-year elevation as Y. This allows ready comparison to the elevations of buildings and equipment. This creates a simple basis of design, with specifications to elevate buildings or equipment above a certain level. Safety factors are typically addressed by adding a specified amount (often one to two feet) for construction purposes.

Flood maps provide a static representation of a flood footprint to a body of water. However, the terminology used on flood maps varies by country. In Australia, high hazard flooding (i.e. 100-yr event) includes flood depth and velocity as these are considered two key factors in relationship to the amount of energy release over the footprint boundary.

In general, flood maps do not show the more likely events (10% annual exceedance [i.e. 10-year], 2% annual exceedance [i.e. 50-year]). Thus, the maps do not show how early flooding will start at a facility. A facility may start to flood much earlier than the 100-yr. annual level and result in significant flood depths. The chances of the facility flooding are based on where the floor level is as compared to the flood level associated with the return frequency. Other limitations include the following:

A. Frequently and as shown by our loss history, flood losses occur at locations that are not shown to be in a mapped flood zone. Examples not normally covered by a standard flood map include collapse of a road embankment across the floodplain during an event, blockage by debris of a structure diverting floodwaters off the watercourse, diversion of floodwaters via a navigation canal, and faulty operation or failure of a levee or a dam.

B. Connections from adjacent flood zones to below-grade areas (e.g. City of Houston downtown pedestrian tunnel system) are not always covered by flood maps.

C. The flood maps may not address smaller bodies of water (e.g., small streams, local drainage ditches, small culverts passing below buildings or contributory drainage areas less than one square mile).

D. Flood defence systems may be shown on flood maps and/or the current condition of the flood defence sometimes is not well represented by the maps, which may have been developed years earlier. The system may have reached the end of its designed lifespan, have been poorly maintained, or the flood map might not show the increased extent of flooding caused by upstream development or changes in the environment since the map was developed.

Flood maps across the world take various approaches to mapping the flood exposure protected by flood defence systems. Some maps may not consider flood defences and show an area as flooding, while some maps will show the same area as not even being flood exposed.

FM Global provides a Global FloodMap, with a worldwide view of moderate (i.e. 500-yr) and high-hazard (i.e. 100-yr) flood boundaries across the globe [4]. Unlike maps based solely on historical flood data, this map is built using hydrology and hydraulic science, and considers, among other factors, rainfall, evaporation, snowmelt and terrain. While these maps have some limitations as described above, it provides a starting point in a comprehension of the hazard.

Wind Design:

With wind, the recurrence interval is typically defined for the entire map. Wind maps are available in the United States from SEI/ASCE 7 (ASCE 7), "Minimum Design Loads for Buildings and Other Structures", Structural Engineering Institute/American Society of Civil Engineers [5]. The most current version of this standard (ASCE 7-16) provides wind maps based upon ultimate wind speeds on a 300-yr, 700-yr, or 1,700-year MRI. The selection of the map to be used in design is based upon the importance of the building. As these are considered ultimate wind speeds, with factored pressures. A safety factor of 1.6 is embedded into the design. Safety factor is typically addressed by applying a multiplier to the anticipated forces, which accounts for potential inaccuracies in the design wind-speed, variability in the strength of construction materials, workmanship and weakening due to aging, wear and tear, etc. Variability in the strength of construction materials and poor workmanship issues are prevalent in our loss history.

The design parameters for a facility against natural hazards should be captured as process safety knowledge supplementing the basis for understanding the natural hazards impact on the process. The information is documented and made part of the overall process safety management package, which can eventually be included as data from the process hazard analysis and process risk management steps. This can also be used for employee training, future process changes, etc. The process reaction under these loads should be well defined. The serviceability of process structures and equipment during these events, as well as their design limitations should be understood [7].

Mitigation

Insurance can be a critical component in managing natural hazard risk. It should not be the only method. A detailed hazard analysis should be conducted for each credible natural hazard. This should define the design basis for the event and the potential impacts to the facility. Once these hazards are understood, mitigation efforts can be applied to further reduce the risk.

Flood Mitigation:

Managing the flood risk starts with elevation. Elevating the site, process, buildings, utilities, equipment, and/or inventory should be considered. The ultimate strategy is to ensure that as much of the facility can continue operating without interruption due to flooding. When elevating, it is important to utilize a common elevation datum relative to the flood elevation datum. It is also important to understand the flood elevation basis and local conditions that may pose an increase in this elevation. There are many concepts that can be used to help reduce flood damage and downtime. The logical options in order of reliability are:

A. Designing the facility to be constructed outside of any flood hazard (new construction) or permanently relocating the existing facility or operations.

B. Raising the site above a practical flood elevation considering 500-year level as the benchmark. This can include relocation of equipment and production lines to areas higher than the flood.

C. Building permanent flood defenses around the site also considering 500-yr flood level.

D. Protecting a portion of the site's critical assets by raising above or protecting to 500-year standards (e.g., building low-level earthen embankments or flood walls, landscaping, and walls to redirect storm water and sheet flow away from important areas).

Figure 3: Example of a key monomer pump elevated above the 500-yr flood elevation.

E. Deploying emergency devices such as flood doors, flood gates, check valves on drainage systems etc. and emergency response plans until permanent solutions are made.

Often the most effective flood mitigation approach is a combination of approaches. Proper design of the processes and buildings that will potentially be flooded is required to keep damage to a minimum. Shallow flood waters that fill basements seldom damage the basic structure. Structural damage becomes a possibility when deep waters rise up to the first story walls or high velocity flows are experienced. Wall or vessel damage at grade and below level floor does not normally occur when water rises equally both inside and outside, as the forces are hydrostatically balanced. However, waters rising on the outside only can quickly over-stress a wall, vessel or tank and cause its collapse or uplift.

One of the most important steps ensuring flood damage is minimized after the flood has receded is to quickly clean up the damage the flood has created. To accomplish a fast clean-up, power, heating, and air conditioning must be restored quickly. Therefore, when designing the location or selecting equipment for power and HVAC systems, consider the following:

A. Electrical equipment, particularly dry-type transformers, high-voltage air circuit breakers, and modern control equipment that uses semi-conductor circuitry are highly susceptible to water damage. Coastal flood water can leave salt deposits creating paths for arcing.

B. Boilers, furnaces, and ovens will sustain extensive damage if flood waters rise while the unit is firing or still hot, the unit is susceptible to considerable permanent deflection. Fine silt will penetrate combustion, air, and gaseous fuel piping as well as burner assemblies.

C. Tanks can sustain major damage. Tanks will become buoyant as flood waters rise, damaging the tank, associated structures, and equipment. As tanks or equipment move, a loss of containment of the tanks contents is possible. If secondary containments, such as dikes or bunding are overwhelmed, their contamination over a large area may occur.

D. Equipment located outside, although adequately weather resistant, is susceptible to the same damage as equipment located indoors. Weather protection is usually not sufficiently tight enough to keep out flood water. Velocities of greater than 7 feet per second will knock over most outside equipment that hasn't been specifically designed to resist the force of the moving flood water.

Wind Mitigation:

During a windstorm, damage to the structural frame of a building or process structure seldom occurs. The total wind load acts on components and cladding, creating load paths through the various components and back to the supporting structural members (beams, joists, purlins, girts, studs, etc.). The ability of the vessel or building to resist this wind load is based on the "weakest link" in this load path, which is usually the supporting components and cladding.

Windstorms are typically concurrent with or followed by significant rainstorms. Cladding failures allow rainfall to accumulate within breached areas, wetting down contents, with extensive damage resulting. If it is not raining during the failure, the possibility of contents getting wet remains until the cladding is repaired and/or replaced. For this reason, keeping the building or equipment envelope sealed is one of the most effective ways of mitigating the windstorm risk. The goal is to prevent any breach of the envelope that could let rain, wind-driven rain, or debris enter. The envelope can be breached by any of the following:

1. Lightweight cladding or inadequately secured steel, aluminum, or plastic panels tearing away from the structure supports.
2. Hatches, windows, doors, and lightweight wall cladding being broken by windborne debris, such as gravel on control room roofs, weak supporting structures (e.g. trailers), scaffolding, or weak piping insulation.
3. Hatches, windows, or doors blown in or out by the pressures exerted on the equipment or building.
4. Roofing and roof deck materials being torn and/or peeled off structures including concrete roofs over control rooms.
5. Inadequately secured roof-mounted equipment being blown out of place, damaging the roof cover allowing wind driven rain into a control room.

Some cost-effective methods of limiting breaches in these areas include:

1. Replacement of lightweight cladding with heavyweight materials.
2. Increased banding on process piping and equipment insulation.
3. Bracing hatches, dock doors and windows from internal and external pressure forces.
4. Protecting doors and windows with impact resistant materials such as shutters, impact resistant glass, heavyweight steel cladding, etc.
5. Selecting an adequate roof assembly which includes an increased number of fasteners in the corners and perimeter, where the wind uplift is the greatest and elimination of aggregate gravel roofs.
6. Securing all roof mounted equipment, to prevent dislodgment.

The thought process, methodology and the team assembled for a Process Hazard Analysis can assist in formulation of other vulnerabilities to the facility. The mitigation factors to these vulnerabilities should also be included in the sites Management of Change process. Changes in building and or process components, such as equipment bracing, building cladding, new roof covers, power distribution, piping insulation, equipment elevations, material storage, etc. or any other component affecting the natural hazard exposure should be included. Any change from original design intent represents a deviation. If the impact of this deviation is not fully understood, the changes even if minor, such as roof flashing over control rooms, can defeat mitigation items. [7]

Catastrophe Preparedness / Response

A well-developed catastrophe preparedness/response plan will consider all hazards, risk factors, mitigation components and focus on event preparation, recovery and site stabilization including impacts to the neighboring community. The primary mechanism to manage the risk should be the mitigation efforts described in the section above. These well-conceived passive and active protection system should then be augmented by the preparedness/response plan.

In an effective catastrophe preparedness/response plan, consideration is given that most of the community is heavily impacted. Employees may be forced out of their homes residing with friends and/or relatives while reporting to work. The facilities and operational bases of most municipality emergency organizations are themselves heavily impacted. Many key organizational work places such as hospitals can be made inoperable. Even most high-rise buildings in the city, although structurally surviving, are not useable because of the flooding and/or the lack of electricity. Municipality infrastructures are so badly disrupted that there will be stoppages or extensive shortages of electricity, water, sewage services as well as other means of communication and transportation. One additional consequence for consideration is the regional character of a catastrophe promoting many leadership roles to be taken by outsiders to the community. This will lead to many nearby facilities themselves becoming competing sources for unequal inflow of goods, personnel, supplies and communication.

For all natural hazards the following preparedness response activities should be considered:

- Pre-event preparations: (where possible)
    - Understand the preparedness of key suppliers, product receivers, neighbors, employees and municipality that can inhibit production and recovery
    - Event monitoring and communication on expected arrival time and severity of the event.
    - Establishing clear criteria for when certain actions should be taken, such as shutting down site operations and initiating various portions of the preparedness plan.
    - Installing any non-fixed flood protection equipment, storm shutters, relocating mobile equipment, trailers, etc.
    - Removing any debris that can blow around or float including scaffolding.
    - Ensure backup power supplies (generators) are functional with filled fuel supplies,
    - Set up emergency communication equipment,
    - Monitor access to property and outside utilities during and after the event
    - Ensure response teams have all necessary supplies (food, water, medical supplies, flashlights, communication equipment, boats, etc.)
    - Purchase all response equipment needed prior to the event. Equipment such as generators, etc. will not be available immediately before and for an extended period after large events.
- During the event:
    - Keep various protection systems, including fire protection, operational for as long as possible.
    - Monitor access to property and outside utilities during and after the event
    - Removing debris or other accumulations if it is safe to do so.
- Post event
    - Return fire protection systems into service promptly.
    - Stabilization of the loss, including securing any compromised structures, mitigating any active or continuing leaks, covering damaged hatches, windows or roofs, water and humidity removal, etc.
    - Ensure the integrity of the electrical system and then restore the electrical services on an item-by-item basis.
    - Check all ignitable liquid storage and flammable gas piping and storage systems for leaks before returning to operation.
    - Remove debris or other waste accumulation that create a hazard promptly.
    - Establish a recovery plan for the rapid restoration of production operations to continue as many portions of the business which includes prioritizing clean-up actions, prioritizing the rebuilding or replacement of vital pieces of equipment that are most critical, etc.
    - Establishing communications with municipality leadership assisting in infrastructure stabilization activities where possible.

The amount of warning time is important in developing a meaningful response/preparedness plan. The majority of wind and flood events can be prepared far in advance, with ample time to initiate critical actions. Some events such as floods, tornados, etc. occur so quickly that there is no time to do any meaningful preparation immediately prior to the event. In such cases, the preparedness response plan should focus on the recovery phase.

Flood Preparedness / Response

It is important to consider the weather event that will trigger the flood, and where the flood waters will come from, likely warning time, depth of water expected, length of time water will remain in the facility, description of the critical areas likely to be flooded, and the business impact. In the United States, the USGS provides river gauge data FloodAlert which serves as a readily available, reliable, and practical method to obtain a flood warning. The flood emergency response should also consider a procedure that describes the steps to shut down/de-energize utilities in an orderly manner to reduce ignition sources and the amount of damage. Other flood considerations should include the following:

- Raise and relocate highly valuable and easily moved equipment. This may include items such as pumps or metering equipment.
- Close flood gates, erect stop logs, water barrier tubes, etc.
- Shut down ignitable liquid and flammable gas systems.
- Cover large stationary machines with water-displacing, rust-preventive compound.
- Fill empty storage tanks to a safe hydraulic level to prevent them from floating.
- Close isolation valves on storm water drainage systems.
- Inspect sump pumps to ensure they are in operation or ready for operation.
- Shut down operations that depend on outside power sources. Grid instability and power surges have shown to severely damage process equipment.
- Anchor or move outside storage, stock and moveable equipment, including trailers to secure areas.
- Fuel all mobile equipment that might be needed following the storm. Stock extra fuel if possible. (Fuel supplies may be limited following the storm due to availability of electrical power to operate pumps).
- Cover all vital equipment or records with water resistant material (e.g. plastic sheeting).
- Clean all roof drains and catch basins.
- Protect openings (windows, dock doors, hatches etc.)

Wind Preparedness / Response

Hurricanes can create havoc over very large geographic areas and impact thousands of or millions of people. All preparedness plans should contemplate the impact on the larger community and its impact on your ability to get goods and services. This include the impact on the sites workforce and their inability to be fully engaged during and shortly after the event. The following actions should be considered for hurricane response.

- Shut down operations that depend on outside power sources. Grid instability and power surges have shown to severely damage process equipment.
- Anchor or move outside storage, stock and moveable equipment, including trailers to secure areas.
- Fuel all mobile equipment that might be needed following the storm. Stock extra fuel if possible. (Fuel supplies may be limited following the storm due to availability of electrical power to operate pumps).
- Cover all vital equipment or records with water resistant material (e.g. plastic sheeting).
- Clean all roof drains and catch basins.
- Protect openings (windows, dock doors, hatches etc.)

Case Studies

Case Study 1: Hurricane Maria and Pharmaceutical Plant

Hurricane Maria impacted a pharmaceutical facility in Puerto Rico posing wind speeds of 150 mph gusts. The facility had undergone major reconstruction over the previous years to harden buildings, outdoor process vessels and infrastructure using 175 mph wind speed in its construction design. The 200,000-sq. ft. roof system over the clean room environment was enhanced, windows were shuttered, dock doors were braced and emergency power generation was provided on N + 1 which included fuel supplies for a 72-hour duration. Outdoor process vessels were provided with additional bracing and strapping of piping insulation was enhanced.

Several days before the storm and in anticipation of the hurricane, the site made final preparations to secure the facility which included filling up outdoor storage tanks, filling all fuel levels for emergency generation and placing operations into safe standby mode. This included filling one process vessel near the clean room with hydrogen peroxide from outdoor storage vessels.

As the hurricane made landfall approximately eight miles south of this facility, the hurricane quickly impaired power and water supplies. Emergency response teams isolated emergency generators as flying debris impacted outdoor power lines and ceramic insulators.

In the cleanroom building, approximately twelve exhaust ventilation stacks and HVAC hoods became dislodged. These stacks and hoods were secured using 3/8-in. tie down cables tied into the wood curbs. This equipment subsequently traveled over the roof cover puncturing approximately 70 holes. Water from the roof entered the building through these holes, wetting over 58,240 sq. ft., including several clean rooms. The water was several inches deep on the floor.

One stack dislodged over the cleanroom was the relief line for the process vessel with hydrogen peroxide. The damaged line allowed metals into the vessel, which included corroded portions of the stack along the roof line. In addition, the loss of power inhibited water delivery for cooling lines to this vessel. The loss of cooling and contamination from metals accelerated the decomposition of the peroxide, which subsequently deformed the vessel. Fortunately, the broken stack allowed gases and vapors to escape.

The facility resumed partial production operations three months following this event. Improved securement of roof mounted equipment would have greatly reduced the damage and reduced the downtime.

Case Study 2: Hurricane Harvey and Organic Peroxides Facility

Hurricane Harvey caused extensive flooding to an organic peroxides production facility in Crosby, Texas. As the event progressed, flooding predictions became progressively worse. This site implemented a response plan that had been successful in mitigating previous incidents. Much of the activity was oriented around ensuring there was sufficient refrigeration of the finished organic peroxides, to prevent explosive decomposition and an overall loss of containment.

Initial activity focused on switching to a fixed backup generator, to ensure proper refrigeration of the materials. As the event progressed, the backup generator was flooded. Site activity then switched to relocating the materials to portable refrigerated trailers. The ability to provide power to the trailers was subsequently compromised and the flooding was too deep for trucks to remove the trailers. Ultimately the site was evacuated and the material eventually exceeded the self-accelerating decomposition temperature (SADT), resulting in decomposition and eventually explosion/fire involving several trailers.

This event has been widely reported and there is significant commentary on the sites ineffective emergency response. While there may have been opportunities for improvement of the emergency response, there also appear to have been opportunities in understanding the flood exposure, the catastrophic consequences to the municipality infrastructure and the provision of improved mitigation measures. Below is a side by side picture showing site flooding and the 500-year flood zone, established by FEMA.

Figure 5: FM Global - RiskView image, showing FEMA flood zones. 100-yr. is purple and 500-yr. is yellow

Figure 6: Areal photo of site during peak flooding (Associated Press)

From the areal photo's, the level on flooding is consistent with flooding between a 100 and 500-year event. Comparison of the nearest river gauge station, with published flood profiles shows the event was very close to the 500-year event. All indications are that the event was within or very close to the published 500-year flood levels. As such, the event was predictable, with a reasonably well-defined probability of occurrence, that would likely have placed in the "Likely" or even "Very Likely" category on most corporation's risk matrices.

In reality, the site did a pretty admirable job of emergency response. However, the activity started too late and was insufficient to account for the lack of fixed mitigation efforts. These should include ensuring all buildings handling unstable materials are sufficiently elevated above the 500-year elevation and that all components of the emergency utility service are also elevated. A safety margin above the established flood level (such as 2-feet above the 500-year level), can account for additional uncertainties.

With the appropriate understanding of the hazard and fixed mitigation efforts, coupled with the strong emergency response actions, this site could have prevented the materials reaching and unstable state and the associated fire/explosions.

Conclusions

Natural hazards can present severe exposures to all industrial facilities, including within the chemical industry. Natural hazards account for 17% of losses to FM Global's chemical clients in the last 10-year. The 2017 US hurricane season again reinforced that these exposures exist. Neither of the events materially exceeded the predicted wind of flood levels for most facilities. The perception that such events are "Acts of God" and beyond foreseeable and incorrect. With the proper understanding of the hazard, mitigation, and emergency response procedures, these risks can be proactively managed. Foundationally, this is the same as Process Safety programs, where plant equipment is evaluated for potential hazards, the appropriate protective layers established, and a robust emergency response program in place.

References

Flood Maps

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[7] 2007 AIChE Spring Meeting & Global Congress on Process Safety paper 25a entitled "*Natural Hazards and Process Safety Management Elements - a Natural Mix*".

Global Flood Map:

FM Global offers Global Flood Map to all interested parties free of charge. This mapping tool allows a quick determination of whether is a potential flood exposure, even in areas of the world where there are no government flood maps available. This should be used in addition to official flood maps, which may have a higher degree of granularity and accuracy for a specific site/location.

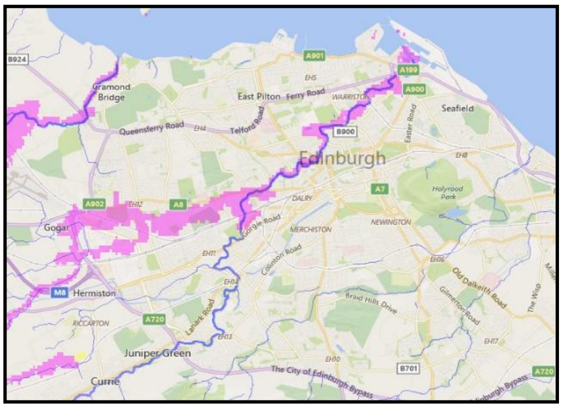

Figure 2 – FM Global – Global Flood Map of Edinburgh