API 656 Natural Hazard Triggered Technological Storage Tank Events

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Forward:

This publication contains considerations for addressing storage tank facilities which may be impacted by Natech events. Natech is a term originating from the European Joint Research Centre (JRC) and is in general use today both in academia and industry. It is an abbreviation for *Natural Hazard Triggering Technological Disasters*. Natechs are initiated by natural events such as hurricanes, floods, and earthquakes in addition to other natural events, but which also involve the release of hazardous substances which can impact facility operations, post-event recovery and infrastructure as well as to create environmental and health hazards.

Another important term related to Natech is the term resilience first used by Holling[1] to describe ‘’measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.’’

Numerous studies[2] and recent decades have shown an increasing number and severity of technological disasters associated with extreme natural events such as earthquakes, hurricanes, tsunamis and floods. These same studies show that petroleum and chemical storage facilities represent the largest contribution to hazardous materials releases.

The February 2021 extreme cold weather in Texas is a reminder of the interaction of technology with weather and why considering Natech is both something that can partially be addressed and mitigated by preparation and planning. Other notable examples are the release of organic peroxides on 31 August 2017 near Crosby Texas at the Arkema facility. Another and the most serious Natech of all time was the Fukushima Daiichi nuclear disaster triggered on 11 March 2011 by an earthquake and tsunami. Hurricanes often trigger multiple Natech events. Natech events are typically characterized by the potential humanitarian crises, disruption or damage to infrastructure, releases of large amounts of hazardous materials, impeded emergency response, and long recovery periods. Because the majority of Natech events involve storage tanks and the largest releases of hazardous materials, API 656 is aimed to address the current best practices associated with tank facilities under these conditions as well as to provide technical and engineering methodologies to assist reducing tank facility vulnerabilities, improve resilience, and worst case type scenarios. API 656 can also assist analysts prepare and advocate changes that can help to reduce damage to tank facilities and can improve tank facility resiliency. Finally, we hope that API 656 will spur interest in the sharing of and development of public databases and best practices under the common thread of Natech preparedness so that owners and operators have the tools needed for the assessment, planning and prevention of tank facility Natech disaster scenarios.

API 656 provides preparedness, assessment and resiliency concepts associated with Natech through a foundation of understanding underpinned by these principles:

- Common cause failure of local infrastructure and emergency response including domino effects.
- The relationship of industrial standards, aging equipment, grandfathering, and associated equipment vulnerabilities to Natech demands.
- Best engineering methods and practices for storage tank facilities.
- Best practices for secondary containment.
- Application and use of resilience principles.

[1] A place-based model for understanding community resilience to natural disasters, Susan L.Cutter, Lindsey Barnes, Melissa Berry, Christopher Burton, Elijah Evans, EricTate, JenniferWebb, Department of Geography and Hazards & Vulnerability Research Institute, University of South Carolina, Columbia, SC29223, USA

[2] Kameshwar, Padgett, Storm surge fratility assessment of aboveground storage tanks,
Krausmann, Cruz, Salzano Natech risk assessment and amanagement
Necci, Girgin, Krausmann Understanding Natech Risk Due to Storms
NEDIES workshop proceedings, Ispra, Italy 20-21 October 2003, Analysis of Natech

- Annotated bibliography of resource documents for Natech and resiliency appropriate for tank facility owners and operators.
- Appendices with tools to help address Natech proofing storage facilities

Due to the variability of Natech intensity and initiators, types of storage tank facilities, proximity to various types of facilities, infrastructure or hazardous substances, the corporate risk tolerance criteria and many other variables, no universal guideline or process is applicable to any given company, facility, or organization. Instead, the principles outlined in this publication can be applied as needed and as appropriate. Whether or not corporate senior management or policy makers should be motivated to counteract Natech is an important topic and partially addressed with guidance in this document and its appendices. The appendices provide insight about why more than "business as usual" is worth undertaking and that Natech is not unlike the typical insurance problem.

Another motivation for considering and planning for Natech is based on Presidential Policy Directive (PPD)-8 [2011] which defines resilience as —*the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies. PPD-21 [2013] expanded the definition to —the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.*

An important idea underlying the resilience concept is postulating scenarios that exceed design criteria as a result of Natech events and to consider the potential outcomes and likely results for these cases. While there may not be any feasible answers for these virtual scenarios, the value is in the exercise of postulating these severe consequences accompanied by hobbled infrastructure and emergency response and the resultant planning and communicating to stakeholders about what might be done to prevent, mitigate, and recover from them. The most notable case of where this type of thinking could have reduced the severity of a Natech incident by orders of magnitude is the disaster at Fukushima. Additionally, these tabletop exercises can provide insight or confirmation as to whether existing safeguards related to design, operation, recovery, and emergency response are reasonably adequate or need to be reconsidered for upgrading. If Natech events have exceedance levels greater than the design capacity or multiple simultaneous damage mechanisms occur or infrastructure experiences widespread incapacitation, then resiliency is a crucial concept that will help to minimize Natech aftermaths.

Finally, while many organizations have undertaken risk assessments and made changes to address the risks which may be for various purposes (i.e. regulatory, internal, insurance, etc.) these analyses often do not provide a sufficiency of scope or analytic methodologies to address the types of risks that arise from Natech (see Appendix 2).

Definitions

Tank Natech

Tank Natech events are disasters that initiate from natural hazards combined with technological infrastructure and hazards. These disasters often arise from the storage of petroleum and chemical liquids which have the potential to result in large scale consequences from hazard interaction, domino effects, and large scale impacts to infrastructure.

Resilience

Tank Facility Resilience is the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions caused by Natech.

Acronyms Used

References (Informative)

(See Appendix 10)

Scope

This document covers considerations for the occurrence of the Natech events that specifically impact petroleum and chemical storage facilities where these lead to releases of hazardous materials. Some Natech initiating events are shown in Table 1.

For some types and combinations of natural hazards this publication includes more or less guidance and information for the following reasons:

- The population of storage tank facilities is subjected to vastly different Natech likelihoods. For example, Lahars or tsunamis causing major tank facility damage are relatively uncommon and limited geographically, whereas hurricanes tend to affect broad swaths of the storage tank populations and at a high relative rate of recurrence.
- Much more is known about how to deal with certain types of Natechs than others.
- In some Natech initiators such as seismic the industry codes and standards are highly developed compared to other initiators such as volcanic.
- In some cases, there is little that can be done to mitigate design for the Natech events (i.e. tornados and wind driven projectiles). However, there are always preparedness, operational, and post event planning and actions that can mitigate the consequences of the event to speed recovery through resilience planning.

While many facilities may not need to prepare for Natech events, the basis for implementing preventive and mitigative strategies should be considered and understood by senior management and corporate leadership. It is the purpose of this publication to show some feasible approaches for considering and planning for Natech.

Since Natech is a vast topic with innumerable considerations this document is not meant to be comprehensive or complete, but merely as a starting point and guide for individual corporate endeavors to begin the journey associated with development of appropriate Natech related plans, to build new facilities and upgrades that are robust against Natech, and to understand vulnerabilities associated with older facilities.

Introduction

Most industrial standards and practices are based on addressing the potential for failure arising from multiple specific loads and combinations of loads to generate reasonably robust design bases. For example, building codes and industry standards provide precise and specific design criteria for natural events such as wind, seismic, or flooding. These criteria, however, have changed substantially over time in many cases and they continue to evolve. They do not typically consider Natech scenarios that exceed the design criteria or result in domino effect escalation of events. For example, in Hurricane Harvey (2017) flooding was a major Natech event affecting southern Texas where many highway routes were closed preventing emergency response and needed supplies resulting in delay or unavailability of emergency community resources.

Most tank facility owners and operators as well as designers just follow compliance with the basic codes and standards. But the intent of these is to provide reasonable criteria that are also cost effective and set minimum criteria for typical and anticipated conditions. Also, codes and standards represent standard practice, but they cannot take into account the many varied exceptional conditions that may be specific to certain facilities or types of events such as Natechs. These same codes and standards usually state that unique conditions may require additional measures but make them optional. For example, ASCE7-16 does not directly refer to Natech but one could interpret a Natech to be an extraordinary event where it is stated in Para 2.5.1 "Where required by the owner or applicable code, strength and stability shall be checked to ensure that structures are capable of withstanding the effects of extraordinary (low-probability, high consequence events)". ASCE7 leaves the decision to go beyond the code minimum requirements to the owner or operator, as it should be, since there are too many considerations and variables that cannot and should not be regulated or standardized in a code or an industry standard. But how does one set a design criterion more stringent than specified by a code, regulation or standard? One solution is to use recurrence intervals. More details are provided in Appendix 3 regarding engineering approaches to change these criteria.

Another obvious problem with existing storage facilities is that codes and standards have in some cases changed dramatically with time as engineering knowledge has developed. Consider that as recently as the 1990s there were three separate and private US building codes BOCA, ICBO, and SBCCI all with different approaches and requirements that were finally replaced by the International Building Code. ASCE7 was accredited under the ANSI process for standards development in 1985[3]. Many facilities pre-date these significant changes in standards. Without going into details of changes to the seismic, wind, flooding and other disaster initiating events substantial changes to the codes and standards requirements have occurred regularly in the last 50 years. As a result, most existing tank facilities are a mix of different design criteria and represent weak links in the event of a Natech or common cause failures and initiating events.

While it could be credibly argued that the industry codes and standards sufficiently address risks based on reasonably expected events, overly prescriptive rules tend to de-optimize efficient construction and building practices. But more can always be done to ensure that recovery, operability, and protection of critical infrastructure is possible even when design criteria are exceeded, or unanticipated dependencies create worse-than-anticipated disasters. This is the underlying concept of resilience in design and planning.

A good example of resilience planning is provided by the intentional release of 200000 kg anhydrous ammonia at a fertilizer plant during the Kocaeili Earthquake of 1999 due to loss of refrigeration. While a superficial understanding of ammonia, due to is much lighter density than air might lead one to believe

[3] https://www.structuremag.org/?p=387

that a careful release of ammonia is reasonably safe since it will rise and disperse, this is interestingly not always true. Kaiser and Griffiths[4] have shown that releases of ammonia vapor clouds can be more or less dense than air depending on the mass fraction of ammonia released which results in the mixture density being controlled by the presence of liquid droplets. Depending on this fraction the gas can be a vapor cloud that is always buoyant, always denser than air or fluctuating at the density of air. The Pensacola, Florida accidental ammonia release in 1977 remained a huge ground level vapor cloud for many hours representing a serious threat to life safety. Resilience planning means that these types of events should be considered and pre-planned to the extent possible. Additionally, it means that the owner and operators should review the past incidents associated with handling of similar chemicals with similar processes and be knowledgeable about what can and has happened in the past so that the lessons learned may be applied to the future. It means that all of the possible release mechanisms must be assessed and the impacts considered including any mitigations and emergency response functions while other problems with infrastructure exist such as evacuation orders, insufficient or inadequate emergency response personnel and so on.

While the focus of this publication is on Natechs and liquid storage in the petroleum and chemical industry it is important for those assessing Natech impacts to be aware of the storage location of large quantities of pressurized or refrigerated and liquefied hazardous compressed gases such as ammonia or chlorine as well as the potential path of possible vapor clouds formed by large releases. Hydrocarbon vapor clouds would typically not be formed during Natech events. Releases of these gases can cause evacuation orders which would cause facilities in the danger zone to be unable to sustain efforts to mitigate and contain their own potential releases.

Codes Criteria for Natural Hazard Severity

Most building codes as well as ASCE-16 rely heavily on exceedance of specified or design loading based on recurrence intervals. Consider Table 1 which shows various Natech initiators along with recurrence intervals associated with various design and building codes at various time. Note the disparity in recurrence intervals which range from 10 to 2500 years.

Much of the reason for this disparity is the historical development of codes and standards. For example, before the 1968 National Flood Insurance Act which created the National Flood Insurance Program (NFIP), the flood recurrence intervals were either unavailable or ranged widely based on location and jurisdiction. In 1968 the National Flood Insurance Act established the 1% base flood standard (100 year flood or recurrence interval) based on consensus. It was selected because it was already being used in some locations and there was pressure to ensure that regulations did not impede development of properties located in prime development areas near water using longer MRIs. Even at this time there was concern that the recurrence interval was too short and in spite of rising costs of flood disasters and damage levels reaching $6 billion annually[5] at the end of the century and many experts argue that it is too short. The *base flood,* also known as the 100-year flood, is the national standard used by the NFIP and all Federal agencies for the purposes of requiring the purchase of flood insurance and regulating new development and as a result is incorporated into building codes and standards.

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[4] https://d3pcsg2wjq9izr.cloudfront.net/files/3783/articles/5167/haz_tci_1997_1.pdf Source Characterization of Ammonia Accidental Releases for Various Storage and Process Conditions

[5] 2004 Assembly of the Gilbert F. White National Flood Policy Forum, "

Table 1Example Historical Code Based Recurrence Intervals

Natech hazard	Associated MRI (years)	Climate adjusted
Earthquakes	450, 2500	no
Hurricane winds	10,20,50,100,200,500,1000	yes
Riverine flooding	100	no
Tsunamis	less than 500	no
Tornadoes		no
Landslides		no
Coast flooding	2,5,10,20,50,100	yes
Extreme temperature		yes
Drought	75^{th},95^{th} percentile KBDI	yes
Wildfires		yes
Ice storms	50	no

Notes:
In Appendix 3 we provide recommendations for minimal MRIs.
The information in this table was compiled from the Rand Study[6]. The associated mean recurrence interval (MRI) is based on citation by various codes and standards. Values not shown are either unknown or inapplicable. *Climate adjusted* means that predictions to the end of the century (2100) have been made that allow for modeling Natech based on future projections. API 656 does not take these projections into account, but for facilities located in coastal regions or in drought prone regions it may be worthwhile to review the projections.

More details about recurrence intervals and flooding are given in Appendix 3. The terms "once in a hundred year flood" or even "100 year flood" are misleading as they are based on annual exceedance probabilities and do not provide the likelihood of a flood over a period of years. For example, according to Table 2 in an area with a 100 year flood plain, the probability of having that magnitude of flooding or greater over an exposure time of 50 years is actually 39%. This high probability of flooding means that flooding at a 100 year level or greater is not improbable and defenses to prevent releases caused by flooding must be in place for important infrastructure and any major storage facility with significant amounts of hazards petroleum liquids or chemicals. Moreover, this raises questions about what policy should be for reconstruction of new facilities and infrastructure after a Natech.

Owners and operators are not at the mercy of building codes and regulations especially when it comes to designing to prevent or minimize Natech triggered damage. Natech intensity or exceedance levels in terms of MRIs can be changed to suit the individual facility in a specific location to a more realistic level that provides acceptable risk according to the methods of Appendix 3. There are also useful equations to manipulate MRIs and Exceedance probabilities also given in the Appendix.

[6] 2016 Characterizing National Exposures to Infrastructure from Natural Disasters Narayanan, Willis, Fischbach, et al

Table 2 Flood probability over various exposure times[7]

WHAT ARE THE ODDS OF BEING FLOODED?

The term "100-year flood" has caused much confusion for people not familiar with statistics. Another way to look at flood risk is to think of the odds that a 100-year flood will happen sometime during the life of a 30-year mortgage—a 26% chance for a structure located in the SFHA.

Chance of Flooding over a Period of Years

Time Period	Flood Size 10-year	25-year	50-year	100-year
1 year	10%	4%	2%	1%
10 years	65%	34%	18%	10%
20 years	88%	56%	33%	18%
30 years	96%	71%	45%	26%
50 years	99%	87%	64%	39%

Even these numbers do not convey the true flood risk because they focus on the larger, less frequent, floods. If a house is low enough, it may be subject to the 10- or 25-year flood. During a 30-year mortgage, it may have a 26% chance of being hit by the 100-year flood, but the odds are 96% (nearly guaranteed) that it will be hit by a 10-year flood. Compare those odds to the only 1-2% chance that the house will catch fire during the same 30-year mortgage.

Retrospective Code Based Criteria

Codes are inherently behind the state of the art as one would expect. Only after the cycle of incidents, new research and publications, lessons learned and vetting by the industry standards consensus process do new rules or criteria end up in the codes or regulations. In most cases it takes years to implement changes and in some cases decades.

Climate change is receiving more study and the probable change in sea level rise (SLR) for coastal facilities is important to consider for both new and existing facilities. Coastal flooding resulting from high tides, coastal storm surge and tropical storms threaten the US gulf coast and Eastern Seaboard. Since 1900 global SLR has increased approximately 8 inches[8]. NOAA has developed 4 global mean SLR scenarios by 2100 shown in Figure 1 that depend on assumptions related to emissions, ice sheet loss and worst case glacial and ice sheet loss. The lowest projection of 0.2m (8 inches) at 2100 is based on linear extrapolation of historical SLR from tidal records. Although 8 inches does not seem significant, SLR influences the severity of any form of flooding near coast regions, can cause infiltration of sea water into freshwater aquifers, impact wetlands and wildlife habitat, and of course developed coastal lands. In addition, the mean SLR is an average and specific locations may have actual SLRs up to 30% more or less than mean seal level which is dependent on the location as well as ocean currents interactions at that location.

[7] https://www.fema.gov/pdf/floodplain/nfip_sg_unit_3.pdf
[8] Rand study

This is another reason that Owners and Operators should consider adjusting MRIs beyond code compliance minima where critical high-value infrastructure may be at stake.

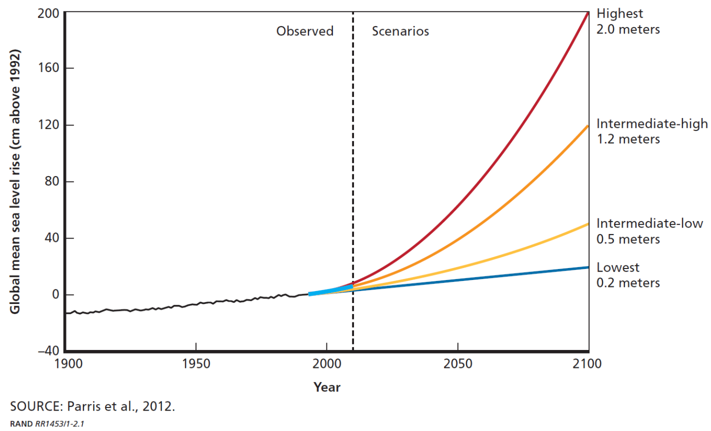


Figure 1 NOAA Scenarios for mean SLR to 2100

Grandfathering

The building code and standards criteria may not be sufficient for specific Natech events. There have also been significant changes to the codes and standards over recent decades meaning that if Natech stressors act on a tank facility then the older parts of the facility are more likely to fail due to what would be considered inadequate design today, but which is typically grandfathered. Failure of older facility components could trigger domino events during a Natech.

Another important feature of Natech planning is the concept associated with the term "*common cause*". A recent Natech common cause failure was the great freeze in Texas in 2021 which arose from a long durations ambient temperature under freezing temperatures which ultimately resulted in loss of energy supplies to the infrastructure (i.e. fuel and power). The largest loss of energy resulted in "freeze offs" which cut the supply of natural gas from hydrates formation in fuel supply lines for power generating facilities that resulted in another common cause failure which was loss of electric power. This type of event is called a "domino incident" where dependencies among systems can create entire related dependent systems to fail. As another example, in a large vapor release of volatile organic compounds, roads may be closed and normal emergency response method cannot be applied. The release of toxic vapors over a large area are a cause of degradation of many emergency response functions such as passage through access routes, ability of emergency response personnel to access affected sites, and general impairment of all functions associated with response and recovery. The idea of "double jeopardy" and "domino effects" is generally considered unrealistic or unjustified in typical risk assessments because likelihoods of such events are considered extremely rare or are not typically required or considered in the building codes or regulations. However, in certain locations and with certain initiators they do occur[9] especially when widely spread geographical areas and Natech are involved.

For those tank facility owners or operators wishing to examine the risks associated with Natech events, this publication provides possible approaches to understanding what strategies may have merit and what can be done to improve resiliency. Natech events have shown that cascading escalation of damage as well as difficulty in mitigating escalation is likely. For example, when there is a hurricane, the likelihood of heavy rain, storm surge, flooding, high winds increase damage mechanisms jointly making every aspect of preventing further mitigation of the problem more difficult as well as impeding emergency response efforts.

A good example is the Arkema incident in 2017[10] where in spite of well thought out emergency response plans, the flooding exceeded planning criteria and resulted in massive off-site toxic releases. The Arkema incident is another case example supporting the need to understand exceedance levels and recurrence intervals and adjusting them beyond code requirements depending on the severity of potential incidents.

Equipment designers are typically well aware of how to implement basic code requirements for wind, lightning, seismic, flooding, and other natural event. However, they are typically not asked to nor do they normally consider the emergency response aspects of these events nor of simultaneous occurrence of these events in combination with a widespread natural disaster. This is where resiliency planning considerations can have a significant payoff.

"Another[11] complicating factor is that civil-protection measures, commonly used to protect the population around a hazardous installation from dangerous-substance releases, may not be available or appropriate in the wake of a natural disaster. For instance, in case of toxic releases during conventional technological accidents, residents in close proximity to a damaged chemical plant would likely be asked to shelter in place or close their windows. This measure would not be applicable after an earthquake as the integrity of the residential structures might be compromised. Similarly, evacuation might prove difficult in case roads have been washed away by a flood or are obstructed by a landslide."

[9] 1999 Kocaeli Earthquake
2011 Tohoku Earthquake Nuclear (Fukushima Daiichi) meltdown tsunami
2012 Hurricane Sandy hydrocarbon/sewage spills
2005 Hurricane Rita hydrocarbon spills
2012 Hurricane Sandy hydrocarbon/sewage spills
2005 Hurricane Rita hydrocarbon spills
2011 Marmara Yalova AN release from seismic
2011 Sendai refinery simultaneous earthquake and tsunami, hydrocarbon releases and fire
1994 San Jacinto River flood, major tank and pipeline hydrocarbon releases
1994 Milfordhaven Thunderstorm, fires

[10] Put in reference here to CSB report

[11] Krausmann, Cruz, Salzano Natech Risk Assessment and Management

Motivation for Considering Natech

Undertaking a Natech assessment requires the support and urging of senior management since this work does not directly contribute to the short-term bottom line and it has a cost in terms of labor and resources. It requires leadership messaging and accountability just as any other important corporate endeavor. In order to support such a task there must be a compelling reason to support it. There must be belief by management that such an activity will yield a benefit that outweighs the costs. Such reasons are similar to those that support the costs of insurance whether it is a purchased commodity or an operational cost. Rather than dismissing the need to do anything regarding Natech, the question of determination of the need to consider Natech in some depth can be illuminated by some exploratory efforts or internal workshops as discussed in Appendix 1.

Undertaking more work and initiates when the workday is filled with urgent tasks that relate directly to the business of doing business, may seem to dilute the importance of work directly related to strategic long-term objectives which always requires longterm sustained effort. A business may operate for decades and then be wiped out or severely crippled by any number of causes. But in fact, most facilities will not be impacted by Natech in the foreseeable future. It is for this reason that most corporate executives typically take what we will call *the insurance problem* seriously. That is, they recognize that although the loss is unlikely to occur, an actual severe loss would degrade corporate value and they are therefore willing to consider the payment of premiums to mitigate damages should the worst outcomes materialize. In a similar context, considering the vulnerability of tank facilities to Natech and implementing appropriate countermeasures is not unlike the insurance problem. Undertaking a project such as a Natech assessment for a tank facility is not a trivial exercise and could even consume significant amounts of time and resources. However, there are many benefits which should be realized. First, by doing a systematic review of the facility design criteria, safeguards, emergency response plans, process safety information, potential impacts to neighboring infrastructure and facilities and other data buys knowledge about the potential outcomes of a disaster, how these outcomes can be mitigated and how recovery can be expedited. It may illustrate that several different types of responses and procedures are needed in the event of a natural disaster as compared with a typical release scenario that is not triggered by a natural disaster. The Natech assessment process is also a stepping stone to future risk assessments for any purpose - be they for tank overfill protection, regulatory purposes, management of change or other potential reasons. Natech preparedness establishes long term objective criteria for ensuring the long-term strategies and objectives of the business are appropriately managed.

An additional benefit of preparing for and understanding Natech events is the collection of data relevant for releases underlies many different types of risk assessments for both corporate risk studies as well as government mandated risk studies such as RMP and OSHA. Individual firms/designers should reach out to community leaders to address how the facility response to Natech will be addressed in community resilience plans. Many communities post their resilience plans on their government websites.

Like the wheels on a Las Vegas slot machine all of the items on the wheels must line up in order to produce a tank facility Natech. Unlike the slot machines there is evidence that the rate of Natechs is increasing, in part due to climate changes and in part due to more dense populations and infrastructure. Not only are lives lost and injuries incurred the damage function associated with Natechs which represents a concerning rise of Natech costs.

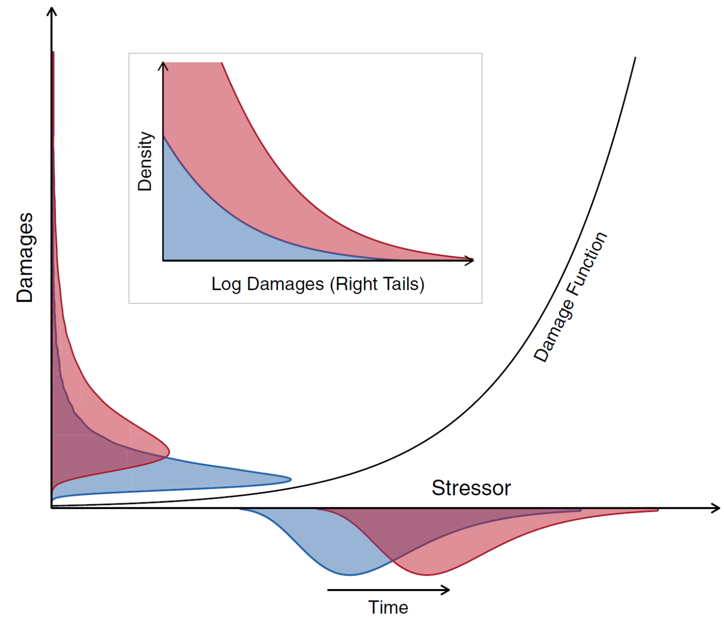


Figure 2 Coronese, Lamperti, Keller, Chiaromonte, Roventini Evidence for sharp increase in the economic damages of extreme natural disasters

Natech Consideration and Planning Process

Not only is it uncertain as to whether a facility specific Natech plan should be implemented, there is no one right way to plan for or implement a Natech preparedness plan. There are, however, a few general principles that apply to undertaking a plan for Natech should it be appropriate.

In fact, many of the processes that are already in general industry use such as hazard identification and risk assessment are applicable. The Natech planning process can incorporate various studies, plans and emergency response actions that have already been developed. These processes can be generalized to include Natech initiating events that consider degraded infrastructure and emergency response. Useful actions for a Natech plans include:

- Incorporate a collaborative planning team which includes all relevant stakeholders.
- The scope and goals of the Natech planning process should be clearly written statements with agreement of the stakeholders.
- The process should include the impact of the scenarios on society (populations, households, businesses, government, etc).
- The ability of the systems to recover intended functions within specified times under potentially degraded conditions.
- Assessment of existing systems and conditions including the fact that the design and safeguard criteria most likely have changed significantly with time and under different management regimes.
- Hazard and vulnerabilities due to the impacts of the disasters on infrastructure and emergency response.

- Impact of age of tank facilities since older, grandfathered equipment is more prone to failure than newer equipment built to modern codes and standards.

Some specific approaches might be:

- Answer the question as to whether any Natech initiator has a high enough recurrence to warrant further study.
- If so, setup internal team to address Natech planning goals with senior level management endorsement and support.
- Set up a team to work with neighbors, regulators and other possible external stakeholders.

How to start Natech assessment

Because there are so many initiating events, factors to consider, and complex analyses involved - the easiest approach may be to just ignore Natech until forced to do so - which could happen as a results of a Natech facility damages causing change within the owner/operator management philosophy or, because regulations move in a direction that begins to require these kinds of analyses. This publication offers some suggestions to initiate a self-motivated process and to find out if any real effort at all is warranted for Natech preparedness.

The combination of Natech initiating event, facility location, facility type, importance of the facility to the local infrastructure, and other variables means that no specific guidance for Natech assessment can be given in a publication such as this. However, we offer a possible systematic approach in Appendix 1. In general, the approach to addressing Natech preparedness might follow these lines:

Step 1 Triage (screening)

A first step is to consider Natech initiating events specific to a given facility location which includes consideration for the size, importance and nature of the adjacent infrastructure. This step should be conducted by close participation with senior level executives as they will decide what further actions are justified. The size and importance of the facility to both the owner as well as to the community are factors that suggest whether it is important to further investigate whether a formal Natech assessment should be conducted. For large companies that own many facilities, iterating through all of the storage facilities and locations is what we refer to as the “triage step”. The output of this step is the answer to the question “should we look at the potential outcomes of Natech in more depth”.

Step 2 (Informal Assessment and Evaluation)

The triage step allows for screening facilities that have exceeded a hurdle level and warrants a more in depth but informal review by an assessment team. After establishing a review team of SMEs and other stakeholders in this step, the review team characterizes the facility in terms of corporate and societal value. It determines what it considers acceptable exceedance levels are in terms of the initiator being considered as well as the possible scenario outcomes. The team should informally posit worst case scenarios and impacts. This should be done informally without large amounts of technical efforts since that should be reserved for the next stage of the process if the process is to be continued beyond this step.

Step 3 Formal Assessment

If Steps 1 and 2 have any residual facilities that are deemed to have sufficient impacts from Natech then the formal assessment can begin. At this step formal risk assessment and management methods are required. Typical risk assessment methods used for project risk and for compliance with PSM would typically not be adequate as they do not take into account the multi-attribute nature of the risks and tradeoffs as well as the concept of utility as described in Appendix 2. Since Step 3 will require significant time and effort by various stakeholders and SMEs this step does not occur unless the informal assessment of Step 2 suggests that there is a real threat from Natech.

Resiliency of Design and Operations

Resilient design is a phrase that became prevalent after Hurricane Sandy. It has appeared in the context of building and infrastuctural impacts resulting from the devastating natural disaster. But the idea is universal. It has been defined to mean “the intentional design of buildings, landscapes, communities, and regions in response to vulnerabilities to disaster and disruption of normal life”[12].

An example of the possible load cases (even if not probable) in the design phase can improve facility resilience. This can be illustrated by the incident involving an LPG sphere in a refinery near Tokyo Bay during the Tohoku earthquake of 2011. Tank 364 was about to be inspected and was out of service and filled with water to remove the hydrocarbon vapors. The earthquake struck with a peak ground acceleration of 0.114g causing the diagonal braces to crack. One half hour later a 0.99g aftershock buckled the legs and collapsed the sphere, severing the interconnected piping and releasing LPG leading to a serious refinery fire. Although the codes of design and construction were met, the weight of water is 180% of the design density of the LPG and the earthquake exceeded design conditions resulting in the failure.

[12] Resilient Design Institute

Although it seems very unlikely that a severe earthquake would strike exactly at the time of the hydrostatic vessel loading, this event shows that it can and does happen. Although it is good practice to keep water in tanks for as short a time as possible (usually a few days), the risk taken by this approach had significant consequences. A resilient approach would have considered this case in addition to asking what the consequences for this case might be.

While it is not the intent of this publication to advocate what should have been done in this case, the point is to illustrate that by considering what will happen when an unlikely event like this occurs and to consider the incremental benefit-cost of designing the vessel for water loading instead of the lighter product loading.

In flat bottom storage tanks, there are many instances of such examples:

- When a tank is jacked up to be moved, it may be lifted 5 – 10 feet off the ground. It is not uncommon for inspectors to inspect the bottom by being under the tank which can weight hundreds of tons. Consideration should be given to the occurrence of seismic events or sudden high wind during this period when the tank is elevated and potentially unstable based upon when the hazard and the people are present as well as the design details for the temporary support structures.
- As in the case of the LPG incident designing for a specific gravity for water instead of lighter liquids costs more, but it has the potential to prevent an incident such as that described and to have more resistance to failure should the event have an exceedance significantly beyond design. Effective risk analysis assesses these tradeoffs in objective and rational ways. It also raises the question - could some other method have been used to ventilate the tank instead of

filling it with water, could an analysis be done to show that the tank would survive and earthquake while filled with water? Would it have been worthwhile to design the tank seismically to handle being filled with water?

- Many large tanks in flood prone areas are unanchored. If one postulates a flood sufficiently high to float the tank are the costs of anchorage worthwhile? Can analyses show that the piping will safely keep the tank from breaking away and releasing contents? Would it be worthwhile to keep more product on hand during seasons prone to flooding to ballast tanks in the event of anticipated flooding?
- In many cases, although the seismic codes have become more stringent, many tanks are never re-evaluated for seismic risk and this may be one of the most significant Natech risks associated with tanks in seismic areas.

These types of questions are dependent on many site and condition specific factors which are not within the scope of this document. However, resilience provides a process that ensures that the issues are raised and discussed with the stakeholders, during design, and as part of the decision making process.

Tank Farm Secondary Containment

The use of secondary containment for petroleum and chemical storage facilities has withstood the test of time and is implemented in all fire codes as well as other oil and chemical regulations. Secondary containment is the last defense for releases. There have been many historical cases of large volume, catastrophic releases in the industry. Where the secondary containment failed releasing the hazardous liquid to the public and the environment, the enormous consequences to both the company and society clearly illustrate the high value of reliable functioning secondary containment.

Secondary containment could be called a redundant safety system in the event that the primary liquid containing envelope of the tank and piping systems fail. Secondary containment acts as a container of last resort until the liquid can be removed and the residual cleaned up. However, because secondary containment is so rarely used and is passive in nature, it tends to be assumed to be in good working condition. There are also numerous cases where secondary containment failed for various reasons.

In this document we consider some best practices for sizing, inspecting and reviewing secondary containment. In addition, we provide considerations for new secondary containment.

Appendices

1. How to start Natech assessment
2. Decision and Risk Concepts
3. Exceedance and MRI
4. Hurricane flood and wind
5. Excess floating roof rain
6. Resiliency
7. Secondary containment

8. Initiator Datasheets[13] (TG review)
    a. Lightning
    b. Seismic
    c. Tsunami
    d. Hurricane
    e. Flooding (Riverine and coastal)
    f. Tornado
    g. Landslide
    h. Extreme hi temp
    i. Extreme lo temp
    j. Ice storms
    k. Droughts
    l. Wildfire
    m. Volcano
9. Risk Factors for Natech
10. Annotated bibliography

Concluding Remarks

From the above material it should be clear that each facility must be individually addressed as no two have the same storage configuration, the same hazards associated with it, the same type and density of infrastructure, people, environment and assets. This means that a Natech assessment must be done individually for each site considering not only the facility itself but the physical surrounding potential hazards that arise from neighboring facilities with hazards. There are many good references that can facilitate understanding the different approaches that have been used. For example, the Design Guide for Improving Critical Facility Safety from Flooding and High Winds by FEMA 543 is directed to specific Natech initiators associated with buildings. But principles such as performance-based engineering are covered and may be applied to considerations for tank facilities. Whether or not research should be implemented by an owner or operator is warranted is the subject of Appendix 1. There is a significant body of literature that covers Natech and each organization will have to apply those methods, approaches and concepts that make sense to the organization and that fits with the organizational structure and capabilities.

[13] Each Initiating Event Appendix is formatted to be as similar as possible providing the initiating event, more appropriate references for the specific event, sample map of contiguous states showing contours of intensity and frequency of the initiating event, web resources that provide the most recent updated information related to the specified event, best practices, and if available, case examples.

1. Appendix 1 How to start a Natech assessment

This appendix is aimed at getting started with Natech assessment. It should be reviewed carefully with Appendix 6 on resilience since the criteria for a successful assessment incorporates resilience. In attempting to clarify concepts most efficiently, this "getting started" appendix focuses primarily on risk. However, risk is a general concept applicable to a wide variety of industries and is a complex concept in and of itself. Another useful appendix to review for the getting started phase of Natech risk assessment is to review Appendix 2 which shows that typical industrial risk assessment exercises often used for new designs or upgrading may be inadequate; and that more broad and general risk assessment and management methods more appropriate.

There are many possible approaches to assessing Natech risks and what should be done about them. The variety of oil storage facilities, locations, conditions, local infrastructure all figure in the potential risk exposure that is possible to not only a company but to local businesses, people and the environment that can range from little risk to extraordinary risk. Because Natech risks are not common does not mean that they should be ignored, hoping that nothing will ever happen. Assessing the Natech risks is challenging and there are many possible approaches. This appendix provides just one way of attacking the problem and may be developed as needed for the specific facility(s) being considered.

1.1 Phase 1 Preliminary Assessment

No facility or industry specific guidance on Natech assessment techniques can be given since each company has unique differences that will govern how the optimal approach to solving the problem of Natech assessment. The approach given in the appendix breaks the problem down into 3 phases.
Phase 1 is a screening exercises to determine if any work on Natech is warranted and if so, roughly what next steps are appropriate.
Phase 2 is further development of risk assessment and management related to significant risk that outputs from Phase 1.
Phase 3 is a thorough risk assessment and management of significant Natech risks.

Phase 1

This appendix provides suggestions and considerations for the phased approach to the development of a serious corporate effort for conducting a Natech assessment. This is parrticularly important for companies with many tank facilities since significant resources and knowledge are required for an effective assessment with multiple locations and facilities. Rather than assigning Natech assessment to individual operating units or companys, maximal efficiency may be achieved by making the assessment a "headquarters" activity.

An initial Natech risk focused assessment team is critical to the mission success for determining what, if anything, should be done about potential future Natech initiating events. The result of Phase 1 should be whether or not Phase 2 should be implemented.

A suggestion for the initial Phase 1 team composition is given in Table 1.

Table 1 Possible phase 1 Natech Assessment Team composition

Stakeholder	Why
Senior level manager	Establishes schedules and allocations of resources and personnel. Direct operating units to acquire information as needed. Provides company messaging and leadership regarding the Natech assessment.
Risk manager	Assess major threat levels to company arising from Natech. Assess risks caused by damage to local infrastructure caused by company facility.
SME tanks, equipment, and facilities	Knows potential failure modes and effects of equipment and Natech interactions and key role will be to assist Risk Manger to assess theat levels from equipment damage.
SME infrastructure	Knows potential failure modes and effects of both on and off-site infrastructure and key role will be to assist Risk Manger to assess threat levels from infrastructure damage.

The output of Phase 1 determines if any further work on Natech is required (Phase 2). The Phase 1 results should be documented with sound reasoning so that that other individuals either inside the company our outside the company who may need to trace the reasoning for what corporate actions were taken and why. This would be a likely request in the event the future brings a Natech event to the company facilities.

For many facilities the Natech assessment will end with little effort. This would be the likely outcome if there are few facilities, none of which are impacted by a Natech event, so that the books on this activity may be documented and closed. However, for facilities which have significant exposure the next Phase 2 of the assessment work should begin.

Phase 2

Phase 2 begins if any of the screening exercises in Phase 1 show that Natech poses a significant threat to the company or local infrastructure. Since Natech is heavily location dependent a first step is to jointly map high likelihood Natech initiating event areas and company facilities. Some possible suggested approaches are given in Table 2. A review of Appendix 2 should help to formulate and fill in the details for this effort.

Table 2 Facilities and tanks subject to Natech

Natech initiating event	Potentially impacted facilities/tanks	Possible dependencies among Natech initiators	Considerations
Lighting	List affected facilities	volcanic	largest tank fire source,

Seismic	tsunami (likely to occur in certain seismically active regions)	seismic event must be large and severe to broadly affect infrastructure. Inflexible attachments to tank increase release likelihood
Tsunami	seismic	damage to piping, tanks and equipment
Coastal flooding	wind, storms, hurricane, storm surge	moving water sheets, storm surge and breaking waves (similar to riverine flooding)
Riverine flooding	hurricanes, rain storms	secondary containment, tank buoyancy and sliding failure
Wind	most severe when a tornado or part of hurricane	wind buckling, amplification of other Natech risks. Small diameter tanks subject to overturning
wildfire	wind	ignition source
extreme high ambiet temp	wildfire	easier ignition of spills
extreme low temp	ice storm	inoperable valves, cracks in valves and piping, floating roof freezing to shell
ice storm	low temperatures	excessive weight on tank roofs and structure including piping
drought	extreme high temp wild fire	disposal of process water
volcanic	lightning	ash can sink floating roofs and lahars can push tanks causing catastrophic failure

Approach

The Natech assessment results becomes more important as the number and sizes of facilities for a company increases. We suggest that the phased approach allows for screening and prioritizing so that any risk reduction needed can be systematically applied over time.

Table 3 illustrates how prioritization might be brainstormed by a Natech team considering the wide range of businesses, assets, infrastructure and locations in the organizational structure using a scenario based generator.

Table 3 Natech scenario generation table

Natech Initiator	Impact	Receptor(s)
Geological	*Loss of containment*	*Adjacent properties*
Earthquake	*Tanks*	*Adjacent environment*
Flooding	Piping	Human/density
Landslide	Shipping	Urban

Hydrometeorological	*Material*	*Rural*
Storm	Natural gas	Tribal
Tropical cyclone	Crude oil	Other/regional
Tornado	Poisonous gase (chlorine, ammonia, etc)	Environment
Wind	Fire	River/creek/reservoir
Flooding	Explosion	Wetland
Lightning	Escalation	Refuge/T&E species/animals
Extreme hot ambient temp		Farmland
Extreme low ambient temp		Marine/waterways/distrbn
Multi-hazard		*Infrastructure*
Domino effects		Water resources/distrbn
Adjacent industrial triggers		Power gen/grid
Emergency response systems		Medical/hospitals
		Transportation networks

If the Natech team believes there is a reasonable expectation of exposure to a Natech event, then formulating and characterizing this possibility can show that more detailed risk assessments can be applied to protect corporate assets, and to provide stability for the business model should the business and infrastructure be damaged by Natech.

Many initiators can be dismissed and in some cases all of them. In others there may only be one initiator which is of concern but there can be many (as is usually the case for Hurricanes). It is important to consider dependencies among initiators. For example, in a seismic event where the facility has exposure to tsunamis then both initiating events should be considered. In another example, when hurricanes occur the likelihood of high rain fall, storm surge, and high winds can occur together.

In Phase 2 the team is not conducting rigorous formal studies but doing an informal analysis and developing considerations to determine if there is potentially a Natech outcome that should be studied in more depth and more formally. This work may involve determining whether the equipment and tanks designs are up-to-date, adequate, and appropriate. The Phase 2 team will review the current emergency response plans to determine how well they can address the outcomes of the Natech threats that cause major releases.

More details about hazard intensities, the consequences and impacts are an important goal of this phase and these may be difficult to correctly assess since they are site specific to the hazard, and surroundings and local infrastructure. Nonetheless, an experienced team that knows the local community, types of infrastructure and facilities in the neighborhood and the local culture can quickly identify Natech scenarios that could have significant impacts to their facility, and the surrounding infrastructure and communities as well.

1.2 Phase 3 Formal assessment

If the results of the Phases 1 and 2 show that further analysis is justified, then formal methods should be applied to the problem of dealing with a possible Natech and its risk mitigation. A careful review of the literature and resources (see bibliography) is suggested. Establishing the types and magnitudes of loads and combinations of loads as well as estimates where failures that can result in releases is suggested. This allows for setting of reasonable recurrence intervals that balances the size of potential losses with the capacity of the of the facility to withstand the demands without major releases.

High value and important infrastructure such as refineries are examples of where recurrence intervals should be considered for increasing to appropriate values. As demonstrated by Appendix 3 a 100 year recurrence for Natech initiator demand with the potential to cause significant releases may be inadequate since the event will occur with a 39% chance in 50 years and a 63% chance in 100 years. In general, the more societal and infrastructural value a facility has the greater the integrity level needed. Such integrity levels may depend on design for longer MRIs, more detailed considerations for combining multiple loadings, modifications to equipment and emergency response plans. These risk management decisions are best addressed with use of modern tools and technology such as the application of multi-attribute decision and risk (see Appendix 2).

Another important aspect is the application of risk assessment and management. Many typical methods used to for routine risk assessment may not be adequate if they do not account for tradeoffs and for high value losses meaning that they are not considerate of multi-attribute utility theoretic methods.

Phase 3 work will typically be time consuming and labor intense occurring over a long period of time. This is a key reason why senior level management must be involved and be bought into the purpose and value of the assessment and strategy to deal with Natech.

Appendix 2
Understanding Natech Risk and Decision Concepts

Introduction

Natech events are, by definition, complex: they are “disasters” caused by any of a wide range of natural hazards. The potential causes are numerous, varied, and can lead to infrastructure damage in many different ways.

Appendix 1 of this document notes that given the breadth of potential natural hazards that constitute the basis for Natech events, the first step in thinking about such events is to employ a triage-like process that identifies which causes are relevant for consideration in what areas and to what degree. Different geographic areas are subject to Natech threats of different types but rarely involve all types and rarely concurrent peak intensities. For these reasons, Appendix 1 suggests starting with a triage of relevant threats and the threatened assets in different locations in an organization as a way of compartmentalizing Natech risk assessment and focusing on those particular combinations of location and assets that pose a genuine Natech-type risk.

Once a triage or screening process has identified areas of operations that are vulnerable to a Natech event, the next step (Phase 2 and/or 3 in Appendix 1) is to employ risk assessment and risk management analyses to identify potential and preferred courses of action to protect against the adverse impacts of the event.

The purpose of this appendix is two-fold.

1. The first objective of this appendix is to provide reminders of the structure and focus of defining, identifying, quantifying, and managing the risks associated with events of this magnitude. It should be realized that many risk assessment systems in corporate use for everyday operations may be inadequate to address these problems and will lead to distortions resulting in sub optimal decision making to mitigate the risks. This appendix is focused particularly on a formal and methodological link between the information collected in risk assessment activities and the resulting risk management decisions that are made. This linkage is often ad hoc and informal. Unfortunately, that is not adequate for significant Natech risks.
2. The second (and secondary) objective is more conceptual: conducting a rigorous risk assessment for something as potentially complex as a Natech event is time consuming and expensive. Will the information gathered by the risk assessment be valuable enough to decision makers to warrant the risk reduction investment? The second general topic of this appendix is a brief overview of how the value of information can be estimated before it is collected. That is, before it is known what the information obtained by the risk assessment is, can the value of that information to the decision makers be estimated? If

so, this would be an important consideration before investing large amounts of key resources in a risk assessment activity.

Using these two purposes as guidelines for the content of this appendix, the first part is devoted to a summary of the structure and detail that is necessary for responsible risk management decision making in the public interest based on the evaluation of threats of “disasters due to natural hazards” impacting petroleum and chemical storage facilities and infrastructure. The second, shorter, portion, describes the basic approach to estimating the value of risk assessment information before it is collected.

Risk-based decision making

A Natech event is defined by David Yu, a Natech researcher at Purdue University, as “any disaster arising from damage caused by a natural hazard to infrastructure that relies on technology.”

A key word in this definition is “disaster,” the implication being that these are large-scale events which are relatively rare. The purpose of studying these types of events in terms of their causes, their impacts, and their frequency, is to aid decision makers in deciding how best to reduce their frequency, their impact, or both.

Making decisions about how best to mitigate the threat of high-impact events that have a small probability of occurring is one of the most challenging responsibilities of risk management. It is difficult to use traditional empirical methods to get accurate estimates of the chances of occurrence and it is equally difficult to come up with appropriate valuation of the impact of such large-scale events.

The following discussion addresses the challenge of risk-based decision making (RBDM). This broad category includes decisions under uncertainty as well as the collection of special applications such as risk-based inspection, risk-based prioritization, risk-based budgeting and other so-called “risk based” processes for making choices. A review of the literature reveals that proposed RBDM approaches range from simplistic to involved, but few start from a methodological base or include detail on the definitions of either *risk* or *decision* and how they are related.

Instead, many approaches in practice (as well as in the literature on risk and decision) provide an ad hoc set of steps that start with data collection and to make the process operational, often provide packaged software that is typically a ‘black box’ (in the sense that inputs and outputs are specified but few specifics are provided on what goes on inside) or, worse, proprietary, where the analytical logic engine is not revealed at all.

The purpose of this appendix is to:

1. provide working definitions of "risk" and "decision,"
2. describe the methodological basis for converting these definitions into analytical practice,
3. show how analysis is typically converted into an aid to decision makers, and
4. show how the value of risk assessment information can be estimated before it is collected.

1. Defining "risk" and "decision"

A. Risk is about value

In the late 1700s a question arose in Amsterdam regarding the behavior of shippers transporting goods from the port in Amsterdam to St. Petersburg, Russia.

The chances of shipwreck or loss of cargo on the voyage were well known, having been empirically established over the previous years of shipping. These chances could be adjusted for time of year, type of ship, experience of the crew, and weather. The market value of the cargoes for these ships was known, as well – in many cases, contracts had already been signed for their sale in St. Petersburg, and since the cost of the cargo was known, it was straightforward to calculate the shippers' profit. It was clear as well, what the monetary impact was if the ship was lost altogether. The chances of ship or cargo loss as well as the monetary impact of a loss were well known. From these two inputs, it was easy to calculate the 'expected loss' associated with a voyage. Insurance was available at reasonable prices that would cover the expected loss; according to the calculations, it improved the overall expected loss for shippers (the expected benefit of the insurance was greater than the cost).

The perplexing question was this: why were the shippers not buying the insurance? There were several possible explanations. It could be that they didn't understand it was to their benefit, but that was unlikely. These were experienced shippers who well understood the economics of shipping. The discovery of the answer to this question shippers' management of risk changed value assessment from then on. The reason the shippers did not value the insurance the way the insurance providers did become clear: the insurance providers were calculating the expected loss to a shipper using the *monetary* measure of the cargo. The shippers were calculating the expected loss using the *value to them* of the monetary measure of the loss.

This insight is profound: the value of a loss is determined by the person to whom the loss occurs and this value may not be the monetary value of the loss.

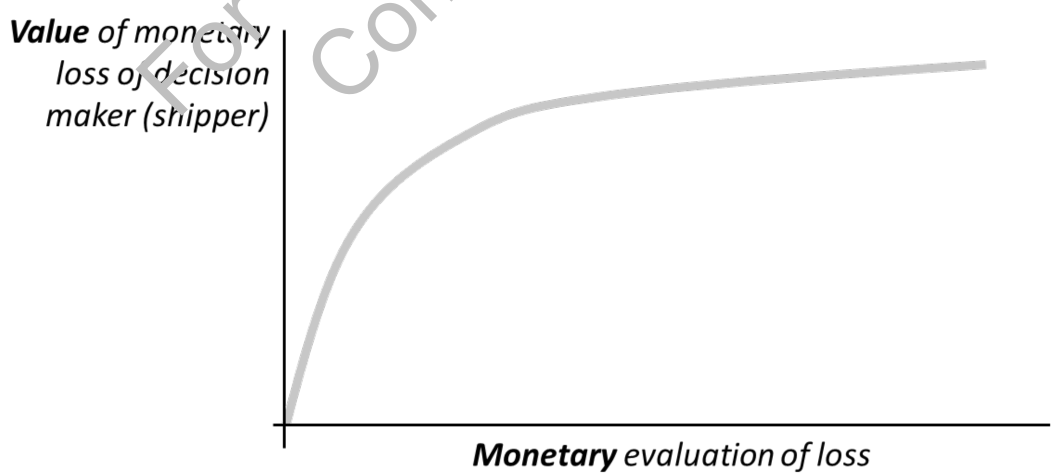
The insurers estimated the value of the cargo in strictly monetary terms – that is, the value could be determined from the ship manifest without any reference to or input from the individual shipper. But the shippers are the ones who estimate the *real value* of the cargo: it is the value of that monetary amount to *that particular shipper.*

The value or impact of a loss is determined not by the accountants who tally up the monetary value but by the person (in this case, the shipper) who suffers that material loss, and that could be radically different from a straight accounting sum. The value was a *personal* assessment of what that much money in sales was worth to that shipper at that time in the shipper's business and life. Clearly, a shipment of exactly the same goods sold for the same prices could have differing values to the shipper depending on lots of other things – how needy the shipper was at the time, what plans the shipper had for the future, how greedy the shipper was, and a host of other influences.

One key contributor to a shipper's valuation of potential loss (or gain) turned out to be the shipper's risk tolerance; some decision makers are highly risk averse, some are risk neutral, and some are risk takers. Leaving this decision maker characteristic out of the valuation process results in a misunderstanding of what choices are most attractive to that decision maker.

The next portion of this section describes how valuation of consequences progressed from using a monetary sum to using a value function, later referred to as "utility" measures of value.

This early research with shippers showed that there was a difference between the monetary outcome of an event and the value of that outcome to the shipper, as shown in the graph below.



The graph above was derived from assessing how shippers valued monetary losses and gains. Their value, in general, didn't change linearly with the monetary value of the loss or gain. As a simple example, a loss of one dollar out of ten was as painful as a loss of ten out of one hundred or one hundred out of a thousand. This constant ratio led to the natural log function (shown in the graph above) as the best estimate of how a shipper valued losses. The "value" of a monetary outcome to a shipper was not linear in the amount of the monetary outcome.

Takeaway: The valuation of an outcome occurs "in the head of the decision maker", not in a spreadsheet constructed by an accountant.

When *shippers' valuation* of monetary consequences was taken into account, their lack of interest in the insurance made complete sense.

This discovery wasn't just a theoretical insight, it was a behavioral insight: this is how people make decisions about potential impacts to assets they value in their business life and in their personal life.

When potential impacts are small relative to a person's or organization's total assets, monetary valuation works well. But when those impacts potentially a large portion of a person's or organizations total asset position, the non-linearity in monetary value starts to play a significant role in decision making. For shippers in the 1700s, the loss of an entire shipment to Russia was very large relative to their overall business, so straight monetary valuation does not accurately reflect their personal perspective on a loss of that size.

This valuation insight from the 1700s was made more rigorous in the 1940s and more formally included in decision modeling in the 1960s with the emergence of utility theory. It is one reason why risk assessment for Natech events (and the resulting risk management decision making) is challenging: evaluating the impact of large-scale events requires more sophisticated assessment than straight accounting tallies.

A full description of utility theory is beyond the scope of this appendix. The foundational development done by Von Neumann and Morgenstern in their book "Theory of Games and Economic Behavior" established five axioms (assumptions) about how people address value assessments. One of the axioms, for example, is that if A is more valuable than B, and B is more valuable than C, then A is more valuable than C (the transitive assumption). Given that these five axioms accurately describe how a person deals with value assessments, then the set of derived theorems describing combinations and multiples of comparisons of values also accurately describe human value assessments.

Subsequent empirical investigations of people making valuations showed that humans don't always behave according to the derived theorems. This led to, among other things, behavioral economics as practiced today, influenced by the empirical work of researchers such as Amos Tversky, Daniel Kahneman, and others.

In later parts of this appendix, expected monetary value is used as a decision criterion for ease of presentation. The monetary value being used can be thought of as the monetary equivalent of value-adjusted accounting sum. How to determine that amount is beyond the scope and purpose of this appendix but resides in the domain of utility theory.

Risk isn't (just) about gains and losses

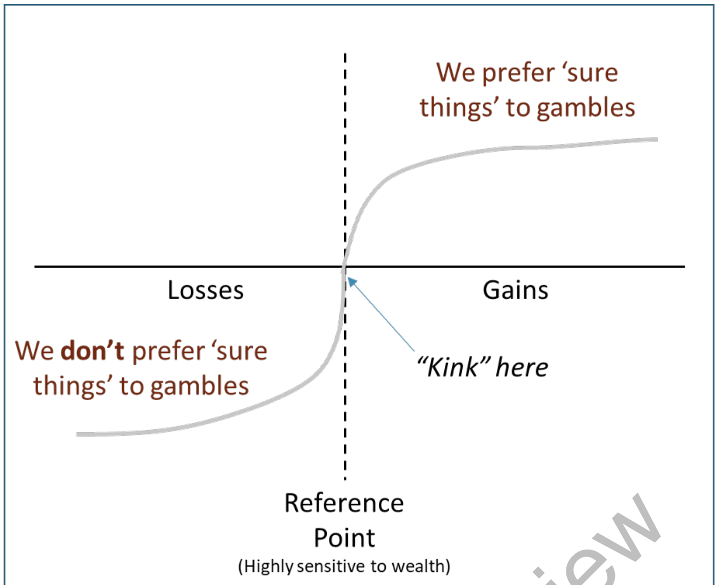
The way in which a person values a gain (the ship makes it to St. Petersburg) or a loss (ship and goods lost at sea) is highly sensitive to a person's wealth level. The takeaway from the subsequent research showing the importance of the "reference point" in assessing a person's valuation of losses and gains meant that consideration of current total wealth should be established before estimating the value of losses and gains – these should be evaluated relative the current wealth level. This is, on reflection, an obviously important consideration: a $100 loss to a person with a total wealth of $200 is more painful than a $100 loss to a person with a total wealth of $200,000, all else equal.

The routine and wide use of expected monetary value as a proxy for a decision maker's actual valuation includes the (hidden) assumption that the gains and losses are very small relative to the decision maker's total wealth and can be treated as being valued linearly in the amount of the gain or loss; that means there is no risk tolerance adjustment or total wealth adjustment to these gain-or-loss amounts.

As an aside, how a person values overall wealth cannot be assessed by measuring how the person responds to gains and losses. This insight, though seemingly straightforward, was not fully acknowledged until the 1980s in response to the work of Kahneman and Tversky, for which Kahneman later received the Nobel prize in economics (2002).

When the amounts of gain or loss are large relative to total wealth, research has shown that people respond to uncertainty about gains and losses very differently. In general, people are reluctant to accept gambles on gains and prefer a sure thing but show the opposite preference for losses: sure-thing losses are less preferred than gambles.

The most common value functions for gains and losses observed in empirical research are shown in the graph below.



The graph above illustrates the results of empirical research which found that people in general are risk averse with respect to potential gains (they prefer sure-thing gains to gambles) but are risk taking with respect to losses (they prefer uncertainties on losses to sure-thing losses).

The attitudes toward gains and losses need not be as symmetric as the illustrative graphic above indicates. The "reference point" is related to total wealth – the research indicates that a person's attitude toward risk is most usefully assessed relative to their wealth, not relative to just suffering a loss compared to not suffering that loss. The shapes of these gains and losses curves and the associated preferences are very sensitive to the "wealth" reference point.

This is obvious but rarely taken into account in risk assessment. The "pain" of losing an asset – a tank, a tank farm, a manifold, a section of pipeline – depends a lot on what the loss or gain is compared to. A loss of the same type may be very painful for a small regional oil company, for example, but negligible for a large multinational.

Losing a tank compared to not losing the tank is a big deal. Losing a tank compared to the totality of tanks and the business model supported by the tanks may not be very painful at all: 150 tanks compared to 149 tanks (loss of one tank) may give a very different sense of the impact.

Takeaway: the reference point for assessing the value impact of a loss is critical to getting an accurate valuation for risk.

This points out a second challenging aspect of Natech risk assessment: establishing the appropriate reference point is an important component of estimating the value of a loss for an organization. This is rarely done explicitly. For example, if a Natech event could wipe out a number of storage tanks in a specific area, the valuation of that risk assessment is typically a comparison of the valuation of the loss (assets, clean-up, business interruption, etc) versus *not* suffering that loss – that is, zero loss is the reference point.

This insight encourages the risk assessors to select a corporate or business-model reference point: the impact of the loss in this case would be the overall value of the business model with the effected storage tanks in operation versus the value of the business model with those storage tanks destroyed.

To summarize the discussion to this point, the valuation approach taken when dealing with Natech events is very important because the effects of Natech events can be beyond the scope of typical day to day operational losses. Two important aspects of valuation that are typically ignored in routine organizational risk assessments are potentially critical to Natech risk assessment.

- The first is that for large losses, as Natech events may cause, the loss is not linear in monetary value, so the straight use of expected monetary value as the proxy for risk may not be an accurate reflection of the corporate significance of that loss.
- The second is that the reference point – the size or business model or the organization – may be an important consideration in evaluating the effects of a potential Natech event.

The *overall point* of the discussion of this section is that the *approach* taken to monetized risk assessment when applied to Natech events is an important consideration of the overall risk management decision making.

What if there are multiple dimensions of risk?

Some events can have adverse impacts on a number of different assets. For example, large-scale, catastrophic loss of containment can adversely impact finances, human safety and long-term health, corporate reputation, scarce environmental resources, key customers, and more.

How is the value of adverse impact on each of these assets estimated? Can a dollar amount be assigned to the loss of a customer? The loss of a life? The loss of a bird sanctuary? The loss of reputation?

We've already shown that dollars are not even a good measure of the value of dollars, so it's not surprising that something more than an accountant is needed to be able to usefully quantify the adverse impacts on these assets in the same units.

There are ways to usefully monetize losses of both tangibles and intangibles, but this is done through the use of value functions or utility theory, not by counting up costs, which misses the valuation mark.

An important question for assessing the risk of large-scale events ("disasters") such as Natech events is this: When is straight monetary valuation adequate for decision making and when should nonlinearities due to size and risk attitudes be employed?

The most common rule of thumb (based on fairly extensive empirical research with organizations facing potential large-scale losses) is that straight monetary valuation seems adequate when potential losses are less than or equal to an organization's net annual profit. When potential exposure exceeds this amount, nonlinearities should be a formal part of the risk assessment. These non-linearities are often estimated based on the risk tolerance of the decision makers relative to the reference point in the risk assessment. In practical terms, a lot of empirical research has shown that the most useful reference point for an organization is their net annual income. Gain and losses that are of a size approaching the size of the net annual income warrant investigation of the organization's risk tolerance and the impacts of the gains and losses to the organization's annual net income going forward.

Just as important, how can the adverse impacts on these different assets be combined to give an overall estimated valuation of the impact of the event? Are all the assets of equal importance to the decision makers? How are impacts at different levels to different assets of different levels of importance combined in a way that captures the overall value of the adverse impact?

Methodological structure is particularly important to avoid biases and double counting the dependence effects when evaluating events that impact multiple assets.

Summary: Risk is about value

The term 'risk' comes from the early Italian word '*risicare*, which meant "to dare." Risk isn't a burden, it's a choice. One historian said the three greatest discoveries of humanity were fire, the wheel, and risk management. The reason risk management is given such a high status is that it provides a basis for making decisions that is neither fatalist (what will be will be) nor fantasist (I control the future). Risk is a choice, not a fate; it is influenced by the actions we dare to take.

To use risk as a basis for the decisions we make requires several pieces of information to make the risk understandable.

1. *What is asset* we value that we believe might be adversely effected by our decision? Our choices or actions may adversely impact lots of things, but risk has to do with those things of value. Clarity about risk requires clarity about what the asset of value is that might be diminished.

2. *How is the asset measured?* What is the metric that specifies changes in the asset? Some assets have "natural measures" like dollars for money or bushels per acre for crop yield. But there are other assets for which a measure has to be constructed; for example, my reputation might be the asset of value to me (this is a common asset for many companies) or my overall health, so measures have to be developed for these types of assets, too.

3. *The direction of increasing value* has to be specified. Is more money preferred or less money? A better reputation preferred to a poorer one? Is more horsepower in an engine preferred to less? If so, without bound? The direction of preferred change for many assets is obvious but there can be cases where this has to be given some thought.

4. *How is value measured for this asset?* If money is the asset, then dollars might be how the asset is measured. How is the *value* of dollars measured? Is $10 twice as valuable as $5? Is $10,000 twice as valuable is $5,000? How is the value influenced by uncertainty? Is a 50-50 chance of nothing or $10,000 the same value as $5,000 for sure?

5. *How does the value change as impacts change the status of the asset* of value? This is an important point: measuring changes in value associated with changes in the asset means that there has to be a reference point. For example, if the asset to be acquired is the winnings from a lottery and the outcome could be an additional $20 (for a win) or a loss of $5 (the ticket cost and no win), is the value of $20 compared to the value of a negative $5? Or, should the comparison be the value of total net worth plus $20 for a win versus the value of total net worth less $5 for a loss?

6. *What if there are multiple possible states* of an asset? Then the valuation of those possible futures has to take into account both the values of the future states of the asset and how they should be combined – average them? Some other method? There are various ways to do this; specifying how this is to be done is part of being clear about risk.

It's important to begin any risk-based decision process by specifying the assets of value, how they are measured, how value for the assets is measured, and how changes to the assets are translated into changes in the overall value to the decision maker.

B. Risk is also about uncertainty

Risk is fundamentally about impacts to some asset that is valued and usually about adverse impacts to that asset. The asset maybe something tangible like an oil tank but it might be something intangible, as well, such as reputation or customer goodwill.

A working definition of *risk* can be characterized this way:

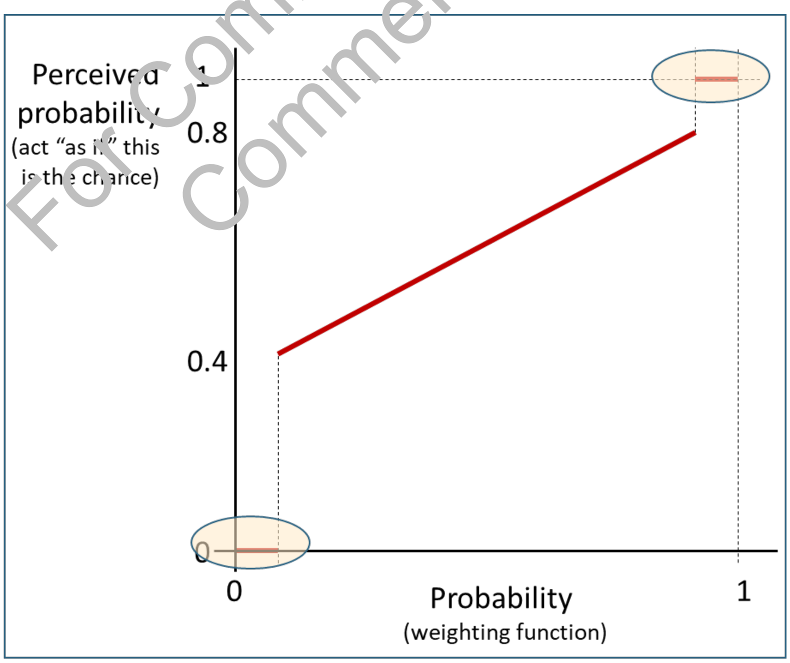
The possibility that something bad could happen.

There are three common components of risk:

- The possibility: a <u>scenario</u> that is plausible
- Something bad: a <u>value</u> statement; good and bad are valuations
- Could happen: the <u>uncertainty</u> of the scenario resulting in the impact

Uncertainty acts like a "weighting function" on the estimated impact to the asset. Typically, this is estimated by multiplying the adverse impact on value by the probability that impact will occur. Probability is the weighting function on estimated value loss.

Empirical research has found that, in general, people have little intuitive feel for small or large probabilities. People's reaction to probability statements are, on average, shown in the graph below.



The horizontal axis represents the *stated probably* of an event. The vertical axis shows how people, in general, *interpret* – and act on – this stated probability. In particular, probabilities below about 15% are treated as though the event will not happen. Probabilities above about 90% are treated as though they are 1; the event is certain to occur.

This research indicates people generally have three categories for uncertainty: impossible, certain, and "maybe," with some shades of variation in "maybe", as shown in the graphic.

Takeaway: Intuition is a poor guide for appreciating the risk associated with low probability events.

The empirical research in how uncertainty is interpreted highlights a third challenge to Natech risk assessment: there is little to no intuitive feel for very small probabilities. Rare events, as a result, may pose a real threat and that is acknowledged theoretically, but there is typically no sense of urgency to include them in routine risk management practices.

The result is that total risk of an operation is systematically underestimated because rare but high-impact events are not formally included in the overall estimates of the cost of doing business. In the same way that ignoring depreciation costs or machine aging leads to inaccurate estimates of true operational costs, ignoring low probability high consequence events has the same result. Finding the balance of what to include in overall risk management decision making requires at least preliminary consideration of the cumulative estimated risk of rare events. If the expected impact over the typical planning horizon of the organization – usually three to five years – is material relative to the net annual income, then these events should be included in estimating the overall expected cost of doing business.

C. Decisions are bets

Clarity about risk is clarity in thinking about the future. Decisions are irrevocable allocations of resources – time, money, personnel, thought – in an effort to influence the future to be more to our liking.

More things *can* happen in the future than actually *will* happen. Some future states are more attractive to us than others and that attractiveness can be quantified as a value. Some future states are more likely than others and the likelihood each occurs can be quantified as a probability.

Decisions function like bets: resources are allocated in such a way that the chances and the value of more attractive future states are increased.

Serious research into decision making started in earnest in the 1960s. One of the first steps was to define “decision.”

Definition: a decision is an irrevocable allocation of resources.

The key word is “irrevocable” because up until the time the resources are actually allocated (time, money, personnel, thought, effort, etc.), it isn’t a decision, it is a “plan.”

It’s easy to confuse decisions with plans. Plans may provide a map of how resources will be allocated but, according to the definition, those resources are allocated only when the decision has been made.

Takeaway: Decisions are irrevocable allocations of resources; they function like bets since they are designed to make future outcomes more to our liking.

The distinction between plans and decisions is fundamentally important because plans have no influence on the future; only decisions – allocation of resources – have the potential to influence how the future will play out. Risk assessment doesn’t alter the future and risk mitigation plans don’t, either.

This is an important influence in the Natech risk management domain: because the events are rare, risk assessment and risk management plans may be seen as adequate for addressing the threat, whereas these activities have no impact on Natech risk. Actually allocating scarce resources (beyond the investment in assessment and planning) is not urgent.

2. Risk-based decision making

Risk is fundamentally about value: how can assets that I value be adversely impacted and how likely is that to happen?

Decisions are allocations of resources in such a way that assets I value are more likely to be beneficially impacted – so that the future is better than the present. In this way, decisions are bets.

A risk-based decision is an allocation of resource made to reduce either the chances or the amount by which assets I value are adversely impacted in the future.

Risk assessment – that is, estimates of the adverse impacts to valuable assets – has to include explicit consideration of the decision that is being evaluated to know what aspects of the asset to measure.

This is obvious but often overlooked. If I am evaluating potential adverse impacts to a car, it's important to know that the decision under investigation is how to protect the car from rain. There are many things I can measure on a car – I need to focus on those aspects that could be adversely impacted by exposure to rain (window leaks? Paint damage? Etc).

Risk-based decision making is decision making process that *explicitly* takes risk into account when evaluating decision alternatives to reduce that risk. From the discussion to this point, this means decisions would explicitly consider each of the following:

- What is the decision?
- What is the asset(s)?
- How are changes to this asset measured?
- How does value change as changes to the asset occur?
- What alternative actions are available?
- How are these alternatives forecasted to change the asset value?
- How do the forecasted changes in the asset impact the future? (This is the reference point issue.)
- What is the reference base for comparing possible futures?

Each of these steps is done explicitly in risk-based decision making.

Takeaway: Risk assessment has to take into account the decision being evaluated so that the necessary aspects of the asset are included in the assessment.

A. Evaluating decisions

To estimate the impact of a decision, it's obvious three things are needed:

1. a forecast of the future without the decision being made,
2. a forecast of the future with the decision being made, and
3. a forecast of the overall cost of making the decision (the resources that will be allocated).

Since the future can't be known with certainty, all three of these forecasts are accompanied by estimates of their uncertainty.

Takeaway: To evaluate a decision, it is necessary to make explicit forecasts of the future with and without the forecasted effects of the decision.

B. Choosing a decision process

The preceding discussion defines risk, decision, what is entailed in making risk-based decisions, and finally what is necessary for evaluating a decision before it is made.

Because Natech events have, as discussed, the challenges of being rare, being large-scale, and potentially have large organizational impacts, determining *how* to make decisions is important

This section discusses how to choose a process for making and evaluating decisions. That is often the first decision that has to be made.

There are a many different procedures and approaches for making decisions and managing risks that have the same label: risk-based decision making. These come from a wide range of sources, too (consultants, company planners, researchers, academics, regulatory agencies, and more). Some of these are proprietary ("black boxes"), some are ad hoc sets of rules or procedures, and some are based on methodologies that have axiomatic bases and can be tested for compliance with assumptions about the inputs.

Choosing the appropriate level of detail and auditability is an important component of making and defending decisions. Because Natech events have the potential of adversely impacting the public in multiple ways (health, safety, environment, stress, and more), the decision process should be "auditable" in the sense that it can be explained to lay audiences and will hold up to technical, legal, and public reviews.

Simple ad hoc decision processes can be completely adequate for some risk-based decisions: which restaurant to eat at, whether to work this weekend to catch up with workload, which candidate to hire, or similar choice settings. There may be some decisions where a coin flip is an adequate decision process if the primary concern is fairness (for example, starting an NFL game).

But there are decisions of such magnitude and consequence that it is important to make certain there are no systemic biases, that there is no double counting, that forecasts are made in a rational and consistent way, that the whole process can hold up to public and legal and technical review.

For decisions of this sort, such as decisions impacting risks to the public or shareholder returns, or where auditability and defensibility are essential, it is important to have a methodological basis for the decision. This means that there are structural properties the inputs must have, there are ways to test if these properties are present or not, and there are guarantees that if these properties are present and the methodology is followed, the results of the forecasts can be trusted to be fully consistent with the inputs.

Methodologies with these properties are available and can be implemented. Methodologically based approaches to decision making and analysis provide the decision makers (as well as those impacted by the decisions) with all the desirable properties of efficient, even optimal, allocation of resources given the desired futures, and defensibility of the decisions to a wide range of audiences.

Since risk is about value, *utility theory* provides an explicit (axiomatic) methodology for quantifying value. *Probability theory* provides a methodologically based approach to quantifying uncertainty. *Statistical decision theory* provides an axiomatic basis for using utility theory and probability theory to produce quantitative *forecasts* of expected value (expected utility) that are fully consistent with the inputs to the risk-based decision process.

Takeaway: Deciding how to estimate risk and make decisions is fundamental to the quality of the decision-making and should be given serious thought.

3. Concluding comments on risk-based decision making

There is a very wide range of risk-based decision-making processes proposed from a lot of different sources with varying degrees of complexity and quality.

The first risk-based decision a decision maker must make is which of these decision processes to use: what is the appropriate level of detail and auditability for the decisions at hand?

As a simple rule of thumb, a decision process that starts with collecting data without mentioning the decisions being evaluated, the specific assets of value, how they are measured, and how the value of those measurements is quantified for the decision maker, is a risk-based decision-making process that is not starting at the right point and is not proceeding in a way that is designed to support decision making and risk management.

II. Estimating the value of risk assessment before it is conducted

1. Introduction

Risk assessment is gathering information, both of things as they are and for forecasts for how they are to be under different circumstances.

This information gathering can be quite time consuming and expensive in other ways. Is it possible to estimate the value of that information before collecting it? That is, is it possible to know how useful information will be before seeing what that information is?

The answer is "yes," it is possible to estimate the usefulness of information before it is gathered. The rest of this section explains the basic logic behind this estimation process and why it is particularly valuable for Natech events.

2. The value of information (risk assessment) for Natech-type events

Estimating the impact of, and loss of value due to, a Natech event requires assessment of what could happen and the severity of damage and disruption that causes to, for example, a tank facility. There are many available decision theory methods that may be useful in determining how much effort should be directed at acquiring the information needed to determine whether a tank Natech program should be established.

Because each facility is different, no universal method or guidance can be given to say what should be done about investing in tank Natech preparation and investing in prevention beyond the current programs for emergency response.

The following basic and artificial example illustrates ideas that can be used to help determine the worth of considering and investing in Natech-proofing tank facilities.

In the context of this example, the decision maker is required to choose one best decision from a set of alternatives, one of which is to do nothing different (i.e , "business as usual"). The "do nothing differently" alternative ignores the threat of Natech and continues risk management practices as they currently exist.

In decision theoretic jargon we must postulate potential future outcomes which are called *states of nature*. States of nature are mutually exclusive and collectively exhaustive. In addition to thinking about and defining states of nature, framing a set of appropriate decision alternatives is necessary. As a result, the consequences for each decision alternative employed in each of the states of nature are estimated. These estimated outcomes are associated with the specified decision alternative and state-of-nature and compiled in a Payoff Table (below). Payoffs may be positive or negative. In the example payoff table below, there are three decisions and three states of nature. This yields nine possible (estimated) consequences represented by values or payoffs or costs or benefits arising from the individual decisions and the states of nature that occur.

	States of Nature		
	State 1	*State 2*	*State 3*
Alternative 1	P(1,1)	P(2,1)	P(3,1)
Alternative 2	P(2,1)	P(2,2)	P(2,3)
Alternative 3	P(3,1)	P(3,2)	P(3,3)
Probability	Pr(State 1)	Pr(State 2)	Pr(State 3)

Although a payoff table such as this may be treated deterministically with methods such as minimax, maximax, minimum regret, or other common rules of thumb, none of these incorporate uncertainty into the evaluation. Since uncertainty is a key component of risk assessment in this case, a more apt approach in the case of a tank Natech event is to estimate the probability of each future state occurring and employ the decision rule based on the expected monetary value of each decision alternative.

In the following simplified example, it is assumed that a significant amount of work has gone into framing the decisions as well as establishing the potential Natech hazardous states of nature that can be broadly classified into independent and mutually exclusive states of nature. There is no requirement that there be three states of nature or that there be three decision alternatives: any number of alternatives and future states can be considered.

A. What does information look like?

When gathering information about the future for this problem, what does that information look like and how will it be used?

Within the context of how the decision problem is formulated, the information gathered is about the probability that each future state of nature occurs.

Correctly formulating the decision problem initially is clearly very important and influential on all the succeeding assessments. In this case, three possible future states have been identified; only those future states can occur and every other possible future state is assigned probability zero – that is, all other future states are viewed as impossible.

For real decisions, the initial formulation is given much more detail, but this illustrative example shows how important characterizing states of the future is. Here a discrete distribution is used (three possible states, each with its own probability, and probabilities sum to one). A continuous distribution can also be used for some analyses, but the basic logic is still the same.

The assessment provides more information about the probabilities of the future states occurring.

There are two general types of information: perfect information, which tells the decision maker exactly which state will occur with complete certainty; and imperfect information, which gives a guess at which state will occur and this guess can be used to update the probability estimates depending on the quality of the guess.

The example analysis that follows assumes the information is perfect to illustrate how information is used.

B. How does information help the decision maker (when does it have value?)

The only information that has value is information that changes the mind of the decision maker and results in the decision maker choosing a different alternative.

This has significant implications for how information is evaluated. Consider these two situations:

1. The decision maker has settled on Alternative 1 and "under no circumstances" will any other alternative be selected. This means there is no value in collecting information – it can't change the decision maker's mind, so skip gathering information and go straight to implementing Alternative 1.

2. The decision maker has no idea which alternative to choose. This means the information will have no value because it can't "change the mind of the decision maker" – the decision maker's mind is not made up.

This is an important aspect of risk assessment and information gathering.

Takeaway: information only has value if it has the potential to change the decision maker's mind about what alternative is best.

This has an implication that is important:

Takeaway: information only has value if the decision maker has specified what alternative will be chosen before the information is gathered.

3. Example analysis

In this example, senior management is interested in whether it is worthwhile to assess and possibly implement plans to prevent Natech and to ensure maximized resilience. They set up a team to examine the problem.

After some review of the facility location, the potential Natech future states, they conclude that they have three alternatives:

1. do nothing (business as usual)
2. chose to address the most likely Natech event A (e.g. seismic event) and implement upgrades and preventive measures to reduce risks
3. because the facility is in a geographic location where the risks of two types of Natech events, A and B, are possible, they chose to address the second most likely Natech B and provide upgrades and prevention measures to reduce those risks as well.

In the decision making process they determine that either there will be no Natech event in the planning horizon, or A will occur, or B will occur, but decide the joint occurrence A and B will not be addressed.

A study has been carried out to determine the measures to prevent/mitigate the two types of Natech events as well as the safeguards and upgrading and the associated costs. They have also reviewed the exceedance probabilities for the two events, A and B, and established the mean recurrence intervals and a projected lifespan for the facility.

The formulation of the decision alternatives, states of nature, and associated probabilities and consequences are compiled in a payoff table. Positive values are costs, which include not only financial loss but other aggregated loss of value to the company.

Payoff Table (positive values are costs)			
Decision alternative	No event	Natech A	Natech B
1. Do nothing	0	250	500
2. Natech proof event A	10	100	400
3. Natech proof event B	30	200	150
Probability	*90%*	*8%*	*2%*

For alternative 1, if nothing is done to prevent the damage caused by Natech A or B events, then the facility damages are shown for each state of nature. If, over the period of interest, no event occurs, then the state of nature shows that there will be no costs where the 0 is shown. However, if events A or B occur, the costs are 250 and 500 units, respectively, if alternative 1 (do nothing) has been selected. If alternative 2 is selected, which will cost 10 units and is aimed to address Natech event type A, we see that the costs decrease from 250 to 100 if event A occurs. But if event B occurs, there will be some benefit from Natech proofing against event A and this is seen by the cost reduction under state of nature Natech B by a reduction of costs from 500 to 400.

Alternatives 2 and 3 include the cost of 10 units to Natech proof for event A and 30 units to Natech proof for event B as shown, but each has some benefit in assisting to reduce damage for both events.

If alternative 3 is implemented, which is to Natech proof against event B, then the cost of event A occurs is estimated to be 50 units, and for event B the cost is estimated to be 350 units.

A. How to choose an alternative: a "decision rule"

Now the payoffs for each alternative and state-of-nature combination have been established. The next step is to identify the best alternative using the expected monetary value, which is the probability weighted sum of each decision alternative scenario outcome. Note that in some cases the expected utility instead expected monetary value is the correct metric to use, however to keep this example straight forward we use expected monetary value.

The expected cost for each of the alternatives is shown here:

$$Expected\ cost(Do\ nothing) = 0 \cdot 0.9 + 250 \cdot 0.08 + 500 \cdot 0.02 = 30$$
$$Expected\ cost(Natech\ A\ proof) = 10 \cdot 0.9 + 100 \cdot 0.08 + 400 \cdot 0.02 = 25$$
$$Expected\ cost(Natech\ B\ proof) = 30 \cdot 0.9 + 200 \cdot 0.08 + 150 \cdot 0.02 = 46$$

These expected costs are shown in the right-hand column of the payoff table below.

Payoff Table (positive values are costs)

State of the world:	No event	Natech A	Natech B	**Expected cost**	
1. Do nothing	0	250	500	30	
2. Natech proof event A	**10**	**100**	**400**	**25**	**Optimal decision**
3. Natech proof event B	30	200	150	46	
Probability	90%	8%	2%		

The preferred alternative is the one with the lowest expected cost. In this case, alternative 2, Natech A proofing, has an expected cost of 25 units, lower than the other two alternatives.

B. Perfect Information

The decision makers have characterized what the possible Natech events are for their tanks, what alternative investments in preparedness they are considering, what the estimated cost impacts of the potential Natech events would be, and how likely the events are to occur over the planning horizon under consideration.

This may have been done in a kind of pre-screening exercise or a triage exercise that identifies what part of the organizations are potentially exposed to a Natech event and the cost estimates may be rough categories of cost to help get started. See Appendix 1 for more information.

Now the issue is whether to invest more money in further risk assessment. Will the information gathered have any value to the decision maker, and, if so, what is its estimated value?

Remember, the value of the information must be estimated before the information is gathered.

There are two rules, stated earlier, that indicate if this valuation step can be taken:

1. Has an alternative choice been made in the absence of the new information?

2. Could the information potentially change the mind of the decision makers"

The answer to the first is "yes:" Alternative 2 is the current choice.

The answer to the second is also "yes." This can be seen by looking at the payoff table below. Since the information will be "perfect," that means the decision maker will find out which future state will occur, for certain, the other two will not occur, and this information will be accurate.

If the information is that no event will occur, the best choice is alternative 1 (do nothing). If the information is that Natech B will occur, the best choice is alternative 3 (B proofing).

Payoff Table (positive values are costs)

State of the world:	No event	Natech A	Natech B	**Expected cost**	
1. Do nothing	0	250	500	30	
2. Natech proof event A	**10**	**100**	**400**	**25**	**Optimal decision**
3. Natech proof event B	30	200	150	46	
Probability	90%	8%	2%		

Only if the information is that Natech A will occur does the alternative choice stay the same. So the information has the potential to chance the decision maker's choice. That means it has value for the decision maker.

C. How much that information is worth.

The payoff table below shows the value of the information in each possible case. The value of the information that no event will occur is the difference between what the current cost would be under alternative 2 (10 units) and what the cost would be with the new alternative selected, which is 0 units. So, if the information is that no event will occur, the value of that information is 10 (current cost) and 0 (the new cost after switching alternatives), or 10 units. That value is shown in the bottom line of the diagram below.

In like manner, the value if the information is Natech A is zero because the decision maker will just do what was planned in the first place, so there is no benefit. If the information is Natech B, the value is the difference between the current 400 units and the new 150 units, or 250 units.

So the value for each possible information content is known, but it isn't known what the information will be – it hasn't been gathered or received yet.

So each of these values is weighted or multiplied by the chances that is the actual information that is acquired. The chances of no event information is the same as the chances of no event in reality, so that is 90%. Likewise, for the other two possibilities for the information.

The value for each of the possible states of the information is multiplied by the probability that is actually the information that is acquired. The result is the expected value of this perfect information.

In this case, the value of information is estimated to be 14 units as shown below.

Payoff Table (positive values are costs)

State of the world:	No event	Natech A	Natech B	Expected cost	
1. Do nothing	0	250	500	30	
2. Natech proof event A	**10**	**100**	**400**	**25**	**Optimal decision**
3. Natech proof event B	30	200	150	46	
Probability	90%	8%	2%		
				EVPI	
Value of perfect info	*10*	*0*	*250*	***14***	

3. Interpreting the value of information

What does this mean? Obviously, perfect information about the future is not available. The expected value of perfect information provides the decision maker with an *upper bound* on the value of information about the future.

The only available forecasts, that is, risk assessments, of what may occur in the future are imperfect, so that information will be worth less, sometimes significantly less, than the 14 unit value of perfect information. So the 14 units serve as a reference point: the decision maker should only be willing to pay less than 14 units for internal (or external consultant) risk assessments forecasting future exposures due to Natech events.

On a conceptual level, thinking about the value of risk assessment forecasts about what could occur in the future allows the organization's decision makers to ask themselves questions before engaging in large-scale risk assessments.

In general, these questions should help frame the step of conducting a risk assessment:

1. Is the current choice of what to do already established? If not, it is not possible to evaluate additional information because it is only valuable if it can change the current decision choice and if that is unknown, there is nothing to change.

2. Can the information that is gathered possible change how the decision maker evaluates the overall situation and what to do? If not, stop. Risk assessment will have no value. Just act.

3. If the information gathered can change the what the decision maker evaluates the overall situation, is it possible the risk assessment information could change the decision of what to do? If not (if the decision has been made and won't change), then stop; the information has no value.

4. I the risk assessment information could potentially change the decision maker's mind about what is best to do, then it is time to estimate what it is worth so that the organization doesn't overpay for information that costs more than it can possibly save the organization.

4. Conclusion

Natech events not only result in potential direct physical damages but also in destruction of other dimensions of value such as loss of reputation, market share, health and safety of the public or workers, environmental impacts, loss of shareholder trust or loss of key customers, as well as other aspects of corporate value.

Although Natech events can be considered "rare," they are definitely possible. The most recent extreme low temperature events in Texas and the triggered occurrence of various disasters associated with the infrastructure highlight the need for consideration and preparedness against Natechs. While the ultimate answer may be that the best option is business as usual for a given site, the answer cannot be known without some initial investigation.

Overall takeaways

- Risk is about an organization's valued assets.
- Identifying those assets, how they are measured, and how their value is measured, is the foundation for conducting risk assessment.
- Decisions are irrevocable allocations of resources. A plan is not a decision and plans are not decisions.
- The value of a risk assessment can only be estimated if the current decision choice has been identified in the absence of a risk assessment.
- Risk assessment information only has value if it has the potential to change the mind of the decision makers about how best to protect valued assets. If decisions have already by set and are not going to be changed, then risk assessment information has no value.
- It is possible to estimate the value of risk assessment information.
- The first step in structured thinking about an organization's Natech risk may be a triage step to see what aspects of the business model and what geographic regions of operations are potentially exposed to Natechs, what their nature might be, and what aspects of the business they might impact, how intense and how valuable the local infrastructure is, and the environment surrounding the facility. See Appendix 1.

C. Summary comments

The introduction to this appendix described its two purposes: the first was to provide a hopefully helpful reminder of the structure and focus of rigorous risk definition, identification, quantification, and management for events of the potential size and impact of Natech-type risks. The second was to suggest that, given the level of rigor warranted for managing risk in the public interest, a first-stage triage may provide a useful starting point for many larger organizations. In this way, the organization can identify those particular regions, areas, and asset combinations that would be susceptible to a Natech event, what type that might be, and what assets would be put at risk. In that way, the next stage of actual risk assessment can be designed to fit the particulars of these areas, resulting in better decision making and safer operations.

Appendix 3

Structural Assessment Criteria for Natural Hazards

1 Introduction

The table below reproduced from the Rand study, "Characterizing National Exposures to Infrastructure from Natural Disasters" shows that the return periods for various natural disaster initiating events vary widely. These return periods are typically reflected in the various industry and building codes and based in historical development. They do not necessarily represent the most appropriate return periods for a specific site and company since they are based on generic building codes and standards and do not consider the unique risks associated with petroleum and chemical storage facilities. In preparing for Natech risk each facility should consider what the appropriate interval is based on their own assessments. It is possible and even likely that different return periods for different types of Natech and equipment are appropriate.

Table 1.2
Return Periods Associated with Each Hazard

Hazard	Return Periods
Coastal flooding	2/5/10/20/50/100 years
Extreme temperature	2/5/10/20/50/100 years
Drought	75th/95th percentile KBDI
Wildfires	N/A
Earthquakes	500 and 2,500 years
Hurricane winds	10/20/50/100/200/500/1,000 years
Ice storms	50 years
Riverine flooding	100 years
Tsunamis	≤500 years
Tornadoes	100,000 years
Landslides	N/A

NOTE: KBDI = Keetch-Byram Drought Index. N/A = not available.

2 Exceedance levels for facilities

Terms and Symbols.

- *Exceedance*: high level of a natural hazard, e.g. 10' over flood stage.
- *MRI*: Mean Return Interval(years) of a given exceedance.
- *p*: Annual probability = 1/MRI

The criteria which govern the design of a structure are *serviceability* (whether the structure can adequately fulfill its function) and *strength* (whether a structure can safely support and resist its *design loads*). A structural engineer designs a structure to have enough strength and stiffness to meet these criteria.

Structural loads are forces, deformations, or accelerations borne by structure components. Loads may cause stresses, deformations, displacements, and failures of structures.

In structural engineering, the *design load* is the maximum load which a structure is expected to support.

The design load includes predictable static and dynamic loads resulting from the planned use of a structure and must also consider unpredictable loads due to natural hazards such as extreme weather or seismic activity.

The bulk of ASCE7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* is devoted to developing equations, tables, and graphs that relate the level or magnitude of an environmental hazard (snow depth, wind speed, rain accumulation, flood depth, etc.) to the loads it produces on structural elements.

p_N is the probability of one or more exceedances in *N* consecutive years and *p* is the annual probability of exceedance. The relationship is:

$$p_N = 1-(1-p)^N$$

Most natural hazards are random[1] (e.g. floods, earthquakes, etc.) and are therefore only statistically predictable over the long term; for example a 100-year flood[2] stage has 1% probability of occurring next year but has a 26% chance of occurring at least once in the next 50 years[3] and a 5% chance of occurring two or more times. ASCE7-16 generally suggests a design risk of 2% in 50 years ($p_{50} = 0.02$) for structures required to respond to disasters well as long-lived structures. The corresponding 1-year risk (annual probability of exceedance) is $p = 1-(1-0.02)^{1/50} \approx 0.000404$ and $MRI = 1/p = 2475$ years.

This appendix is about extrapolating published exceedances, such as 25, 50, 100 and 500-year levels, to more conservative levels as appropriate. We have written an R[4] program, PEMEPT.R, to extend published exceedance values to smaller risk levels. This program is made available free on github[5]. Figure 1 was produced by PEMPT.R; it is an *exceedance graph*[6] of 0.2 sec transverse seismic ground motion (Ss) at the Naval Aviation Air Station at San Diego[7]. The vertical axis (exceedance) is ground acceleration expressed as g-force, and the horizontal axis is the mean recurrence interval (MRI) of that

[1] I.e., deterministically chaotic. V. Krishnamurthy, *Predictability of Weather and Climate*.
[2] USGS "Floods and Recurrence Intervals"
[3] Symbol "p" is the annual probability; the n-year probability is 1-(1-p)^n
[4] Getting Started with R and RStudio
[5] https://github.com/rbitip/API656/tree/main/Appendix-3
[6] The graph is produced by the PEMY Exceedance Projection Tool, PEMEPT.R listed in (5).
[7] Source: ATC Hazards by Location Reference Document ASCE41-17

g-force level. Black dots are published values and the red dot (5.35 g's) is our projection to 2% probability in 50 years (MRI = 2475). A structure designed to that risk level must be able to resist that g-force. ASCE7-16 chapters 11 through 22 explain how to convert seismic g-force into forces acting on structural elements.

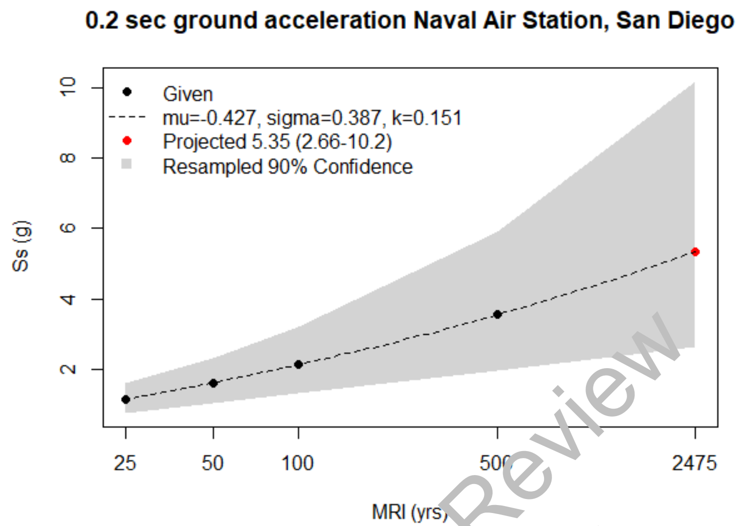


Figure 1. Exceedance Graph of 0.2 sec Ground Acceleration at San Diego Naval Air Station

3 Extreme Value Analysis: The Statistics of Natural Hazards

Natural Hazards considered in ASCE7-16 are Flood, Tsunami, Snow, Rain, Ice, and Seismic Activity. The common thread is the excess load (force or pressure) that a hazard (or combination of hazards) exerts on the structure. The statistical problem is to estimate the probability of experiencing a load that exceeds the design limit. The statistical tool, Extreme Value Theory[8], is used for most hazards. The output of an Extreme Value Analysis is a table or graph of *exceedances*, their annual probabilities (PE's), and their mean return intervals (MRI's).

The simplest method of extreme value analysis (EVA) of ongoing processes such as river stage, wind speed, snowfall, etc[9], involves fitting a cumulative probability distribution to a series of annual maxima (Figure 2) and fit a GEV[10] distribution to a graph of the upper quantiles (results in Figure 3).

[8] https://en.wikipedia.org/wiki/Extreme_value_theory
[9] As opposed to catastrophic events such as earthquake and tsunami.
[10] Defined in section 3.1

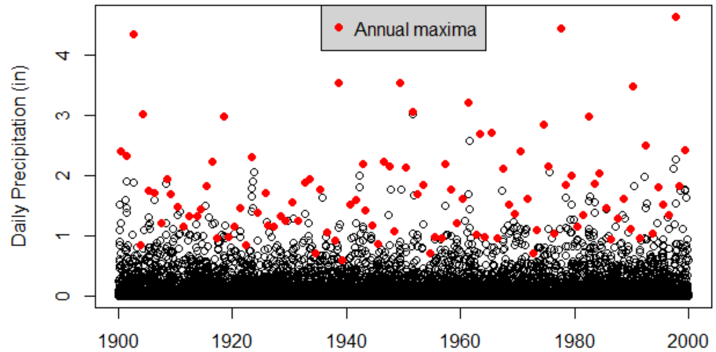


Figure 2 Daily Rainfall and Annual Maxima at Ft Collins, CO

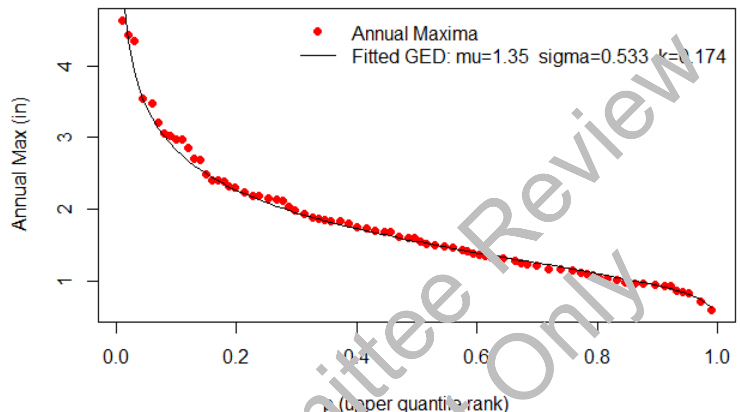


Figure 3. GEV fit to Ft Collins Rainfall.

Low probability, extreme exceedances are then computed from the quantile function of the fitted GED (see Equation 1).

A designer will likely never need to actually run a statistical Extreme Value Analysis on raw data but sometimes needs to know how to interpolate or extrapolate published exceedances, such as 100 and 500 year flood stages, to an exceedance value required by a code, standard, or for self-insurance e.g., the 1000-year flood.

3.1 Generalized Extreme Value Distribution (GEV) Models

3.1.1 GEV Quantile Function

Symbol E_p is the level (e.g., flood stage, snow depth, etc.) of an exceedance that has probability p of happening in any given year; for example, the 500-year flood stage has probability $p = 1/500 = 0.002$. The GEV quantile[11] function expresses E_p as a function of annual probability, p.

$$E_p = \mu + \sigma \cdot Q_p \text{, where}$$
$$Q_p = \begin{cases} \left(\left(-\ln(1-p) \right)^{-k} - 1 \right) \Big/ k & \text{if } k \neq 0 \\ -\ln\left(-\ln(1-p) \right) & \text{if } k = 0 \end{cases}$$

Equation 1. Exceedance quantile as a function of annual probability.

Terms and symbols for the GED model

E_p is an exceedance, a hazard level that is equaled or exceeded with probability **p** per year.

Q_p is the standardized (unitless) upper quantile of the GEV distribution with shape **k**.

k is the shape parameter. It controls the curvature. k = 0 is the Gumbel distribution, k < 0 is a Fréchet distribution, and k > 0 is a Reverse Weibull distribution.

μ (Greek letter mu) is the location parameter; changing it shifts the curve left or right without changing its shape.

σ (Greek letter sigma) is the scale parameter; changing it makes the curve steeper or shallower without changing the shape.

Starting from a data set of raw, annual maxima like Figure 2, the parameters **μ, σ,** and ***k*** are usually estimated by fitting a Generalized Extreme Value Distribution (GEV) to the annual maxima. However, a designer will have to work with a handful of published exceedances (the black dots in Figure 1). Assuming that the published values were computed with Equation 1, we have developed a way to use reverse engineering to recover the parameters **μ, σ,** and ***k*** via nonlinear regression[12]. Then we plug those values into Equation 1 to extrapolate the published values to a rarer exceedance (the red dot in Figure 1 is the extrapolated 2475-year exceedance). We explain how to do that in the github repository[13].

It turns out that the reverse-engineered parameter values for the data in Figure 1 are μ = -0.427, σ = 0.387, and *k* = 0.151. So now we can extrapolate to other annual probabilities.

[11] A quantile is a percentile with percent expressed as a decimal fraction. For example, the 75th percentile is the 0.75th quantile. An upper quantile is the is determined by the probability of observing a value greater than the quantile, so the 0.75th lower quantile is the 0.25th upper quantile. For example, a 100-year flood elevation is the 1% upper percentile of annual flood maxima, which is the 0.01th upper quantile.

[12] We use R function nls, which implements Nonlinear Least Squares.

[13] https://github.com/rbitip/API656/tree/main/Appendix-3

For example, let's calculate the exceedance that has only 2% probability of happening in a 50-year period. The equivalent annual probability is $p = 1-\left(1-p_{50}\right)^{1/50} = 1-\left(1-0.2\right)^{1/50} \approx 0.000404$ The exceedance level is 5.35 g. calculated in Equation 2 by plugging μ, σ , *k*, and *p* into Equation 1.

$$\begin{aligned} Q_p &= \left(\left(-\ln\left(1-.000404\right)\right)^{-0.151}-1\right)/0.151 &= 14.92 \\ E_p &= -0.427+0.387\cdot 24.44 &= 5.35 \end{aligned}$$

Equation 2. 2% in 50 years exceedance

3.2 Case Study: Predicting Exceedances for fluvial flooding.

The concepts above can be put into practice for any natural hazard that can produce a Natech disaster. We have chosen fluvial, or riverine flooding, which occurs when excessive rainfall in a watershed over an extended time period causes the stream that drains that watershed to exceed its capacity.

3.2.1 The Site

The watershed for this cases study is the Iowa River Basin[14] and the site of interest is Hancher Auditorium, a performance venue of the University of Iowa in Iowa City.

The original facility was built pre-FEMA on the west bank of the Iowa River in 1972 but experienced extensive flood damage in 1993 and 2008 (Figure 5) and was replaced in 2019 by the new auditorium designed by architect Cezar Pelli. The new structure is about 240 meters NNE and 3 meters higher than the old. Figure 6 combines 2010 imagery of the mothballed old structure and 2020 imagery of the new structure in their correct geographic positions (note the continuity of the riverside walkway). The old structure has been demolished.

Figure 4. Hancher Auditorium & Voxman Music Building: Iowa River Flood of 2008

Figure 5. Composite 2010 and 2020 images of Hancher Auditorium sites.

3.2.2 Risk of Flooding

Flooding occurs at this site when runoff from snowmelt and rainfall in the Iowa River Basin is greater than the capacity. Inundation depth at the site is determined by the *discharge rate* of the river (cubic feet per minute), the roughness of the terrain surrounding the site, and the surface elevation profile along the line through the site perpendicular to the river channel (a cross section). The questions we need to answer are, "What is the elevation at the site? What discharge rate will produce a flood that reaches that elevation? and "What is the probability of exceeding that discharge rate?"

FEMA Flood Insurance Rate Maps (FIRM's) answer the questions for 1% and 0.2% flood risks (100 and 500 year flood). Figure 6 is a FIRMette, a one-page portion of a regional FIRM. Instructions for locating and downloading a FIRMette are here[15]. FIRMs can also be viewed in Google Earth™ ; instructions are here[16].

[14] Wikipedia: The Iowa River
[15] https://www.fema.gov/media-library-data/1519223606571-24c4843da253d19
[16] https://www.fema.gov/media-library-data/1510779572238-0eef55ac3e03da4f6f47f75926e7da2a/Accessing_the_NFHL_through_GoogleEarth_Flyer.pdf

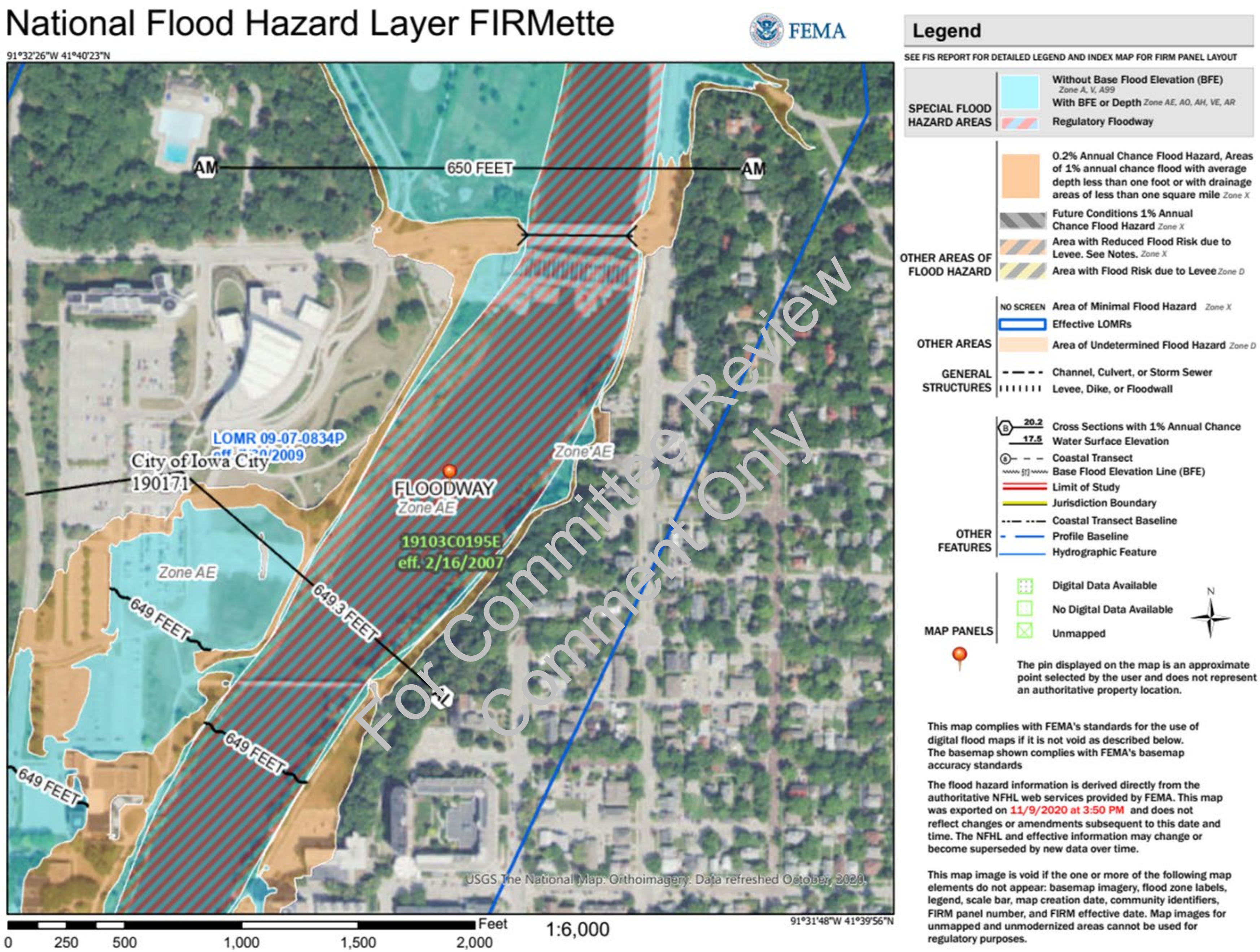


Figure 6. FIRMette that Includes Hancher Auditorium Site.

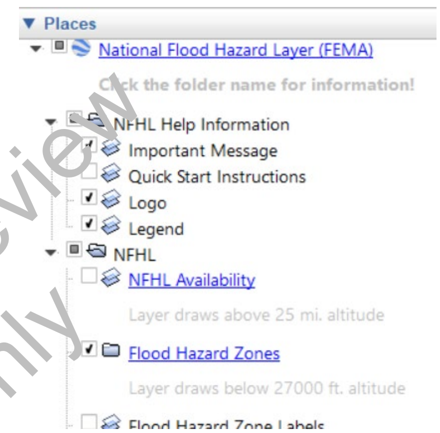
Terminology

Regulatory Floodway is a legal term. It is the channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the water surface elevation more than a designated height.

Base flood means the flood having a one percent chance of being equaled or exceeded in any given year.

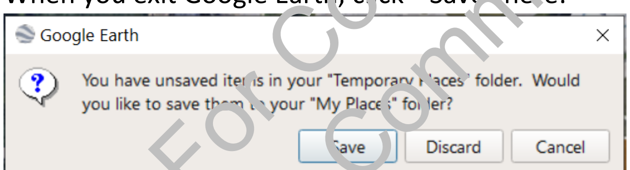
Base flood elevation means the water surface elevation of the base flood. It shall be referenced to the North American Vertical Datum[17] of 1988 (NAVD).

3.2.3 Installing The National Flood Hazard Layer (NFHL) in Google Earth™



Sidebar with NFHL pulled down

- Download and install Google Earth Pro freeware.
- Download the FEMA_NFHL_v3.2.kmz as instructed in Footnote 16.
- Double click on FEMA_NFHL_v3.2.kmz, to install NFHL in Google Earth.
- In the sidebar, under Places, uncheck everything except:
  - ✓ Legend
  - ✓ Flood Hazard Zones
  - ✓ Base Flood Elevations
  - ✓ Cross Sections and Coastal Transects
  - ✓ Profile Baselines
- Navigate to your site to see something like Figure 8.
- When you exit Google Earth, click "Save" here:



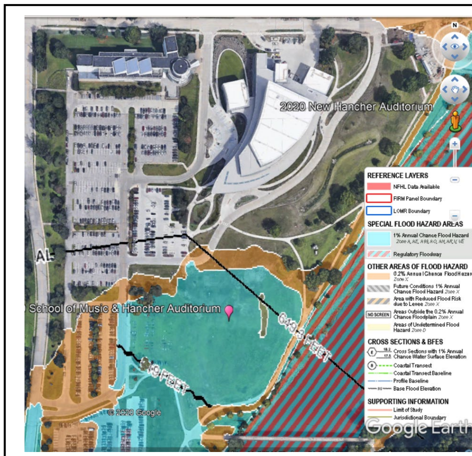


Figure 7. Study Site with NFHL Overlay

That's it, everything that FEMA has to say about flood risk is now on display. In particular, although we see the elevation of the 100-year flood (649.3ft) the elevation of the 500-year flood (0.2% per year) is not reported Unfortunately, we can't use Google Earth elevations because they are relative to a different datum: EGM84; therefore, we'll read latitude and longitude of points with Google Earth and look up their NAVD88 elevations in a different app.

[17] The datum is a refinement of "sea level." The datum is intended to be a shell of constant gravitational force pinned to mean sea level. The North American Vertical Datum, NAVD88 datum, currently used in FIRMS, was constructed via a national leveling network, not direct gravimetric data; it will be replaced in 2022 by a gravimetric datum. The gravimetric datum used by GPS systems and Google Earth™ is the Earth Gravitational Model (EGM84, EGM96, or EGM2008).

3.2.4 Extrapolating NFHL Exceedances

Our published exceedances are the NAVD84 elevations at the coordinates where the 649.3 foot cross section crosses the 1% and 0.2% flood boundaries Use the pin tool to create placemarks at the two crossings. Right click the pin and select "properties" to see the latitude and longitude (Figure 8).

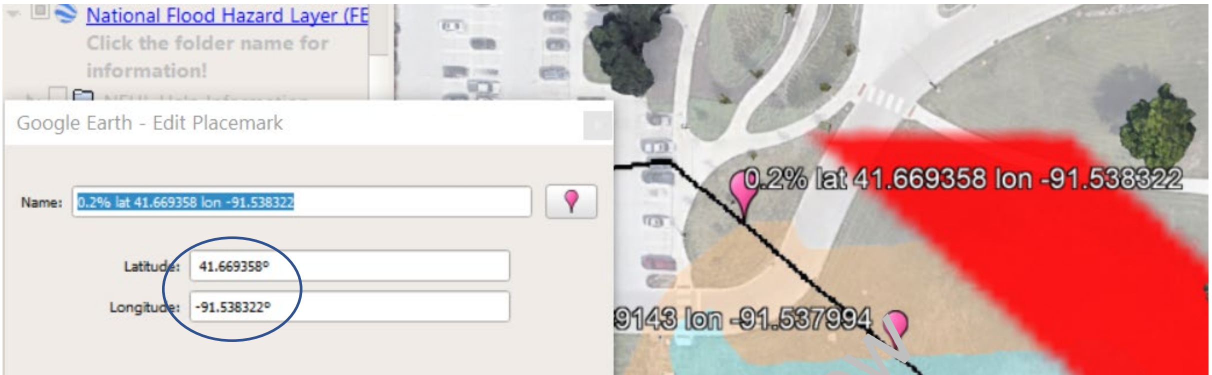


Figure 8. Google Earth™: coordinates of 1% and 0.2% exceedances .

Open the National Map[18] (TNM) and look up the NAVD84 elevations (Figure 10 and Table 1)

MRI	Lat	Long	Elevation
100	41.669137	-91.537998	649.47'
500	41.669346	-91.538318	653.50'

Table 1. Elevations at uphill edges of 100 & 500 year floods.

Enter the elevations in the projection tool (Figure 10). Since there are only two published exceedances, we are forced to use the two-parameter Gumbel distribution (shape parameter k=0). The projected 0.0404% exceedance is 655.233 feet.

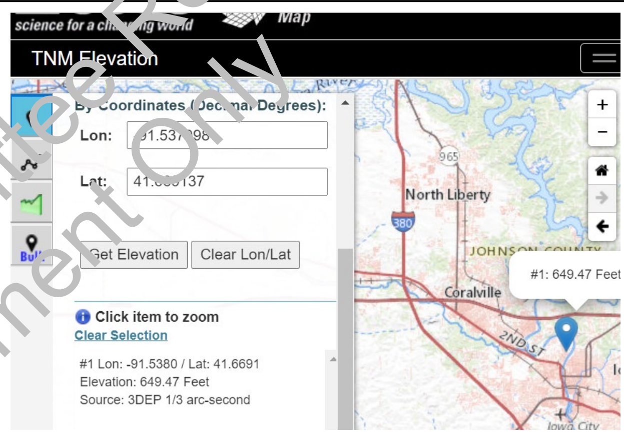


Figure 9. TNM Elevation Tool

18 Find elevation by latitude and longitude

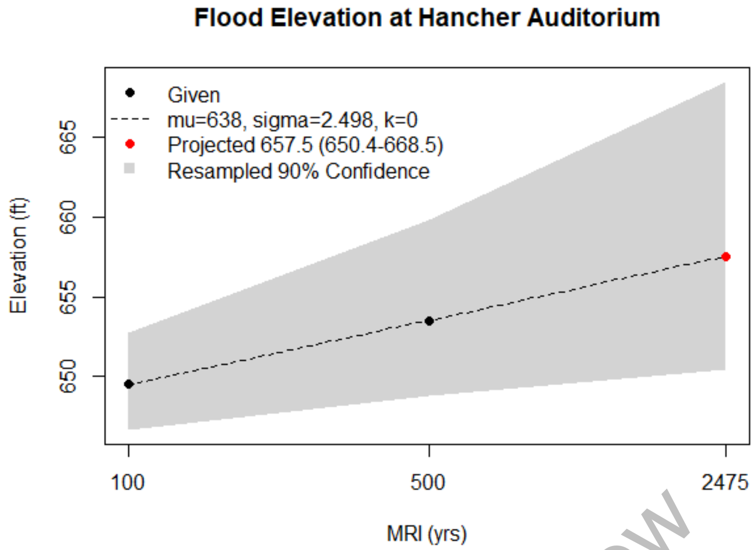


Figure 10. Gumbel projection of 100 & 500-year inundations

MRI	P5	P25	P50	P75	P95
100	646.6	648.0	649.2	650.5	652.8
500	648.8	651.0	653.1	655.4	659.9
2475	650.4	653.7	656.9	660.7	668.5

Table 2. Resampled Percentiles of Flood Exceedances

3.3 Problems with Two-Point Extrapolation and Indirect Measurement

Since the GEV model (Equation 1) has three parameters, we can be sure it was used to compute published exceedance quantiles only if a GEV model is a near-perfect fit to four or more exceedance quantiles, as it is in Figure 1.

Fluvial flooding is particularly problematic since at most sites there are only two published exceedance quantiles, 1% and 0.2%. Secondly the underlying hazard is water discharge rate (cu ft/min) and water surface height or stage is computed indirectly from two *Rating Curves*[19], the measured stream gage rating curve and computed rating curves along cross-sections such as the 649.3 foot transect in Figure 6.

Smemoe[20] , has shown how to compute annual exceedance probability flood maps using professional software tools[21] HEC-1 to simulate storm events, and HEC-RAS to construct maps.

Additional work (presumably by FEMA and USGS) is needed to facilitate use of recurrence intervals other than 100 and 500 years.

[19] USGS "Creating the Rating Curve"
[20] Floodplain Risk Analysis Using Flood Probability
[21] https://www.aquaveo.com/software/wms-hec-ras

4 Interpolation Example from Real World Problem

4.1 Overview

Tank T-XX is located at a terminal in Vancouver. It is a 120 ft diameter tank with a 67 ft shell height. It is a double wall tank where the primary inner tank is secondarily contained by another tank large tank which is 130 ft in diameter by 62'-6 7/8". The tank was constructed and placed into service and buckled during the painting of the roof because the painters blocked off the rooftop vents causing an internal vacuum when the ambient temperature dropped. Note that this is a very common failure mode for newly constructed tanks. The buckling occurred only in the upper courses of the primary or inner tank but the outer secondary contain was not damaged. The owner wishes to operate the tank through the winter on a reduced capacity basis with the existing shell buckling until the tank can be repaired in the spring.

Since the tank will be operated with a reduced liquid level the question about the integrity of the primary tank which can be subjected to snow loads arises. The question is specifically can the tank safely carry the potential snow loads. It is known that the tank cannot sustain the prescribed Canadian Building Code snow loads so the question becomes how much snow load can be expected and will the structure be suitable for that particular load.

The purpose of this example is to show how extreme value statistical analysis can provide a reduced snow load by starting with the prescribed Canadian Building Code loads requirements and reducing it using a rational approach. If this can be done, then a decision to either accept or reject the risk of operating through the winter can be made.

4.2 Approach

The Canadian Building Code (CBC) uses a 50 year mean recurrence intervals for ground snow loading, Ss, and rain loading, Sr, to compute the specified roof load, S. The formula, equation (0.1), involves adjustment factors to convert ground loads to roof levels,

$$S = 0.8 \cdot S_S + S_R \qquad (0.1)$$

Values for 50-year ground loads at Burnaby (Simon Fraser University) are SS = 2.9 kPa = 60.6 psf and SR = 0.7 kPa = 14.6 psf. The design load (specified roof load) is S = 3.02 kPa = 63 psf. To put this in perspective, it is the pressure exerted by about 3 feet of wet snow.[22]

Since T-XX will be operated in its present condition for at most one winter season, our approach is to rescale the given 60.6 psf 50-year ground snowload to a five-year mean recurrence interval (MRI), which has 20% chance of happening in one year. Since the specific rain load, SR = 0.7 kPa, is relatively small, we use the 50-year MRI without adjustment, which makes our method conservative.

To estimate 5 year snowload MRIs at Vancouver, we first scraped[23] annual maxima of daily snow accumulation (in inches) from the website: Vancouver - Extreme Daily Snowfall for Each Year. Then we fitted the data to a Frechet distribution and computed the daily snow accumulation MRIs shown in Table 3 using a Generalized Extreme Value (GEV) distribution.

---

[22] Snow Weight Table

[23] Data Scraping in R Programming: Part 3 (Importing Tables from HTML, Cleaning, and more) | Analytics Steps

Recurrance Interval (years)	Gauge Snowfall (inches/day)	Recurrance Interval (years)	Gauge Snowfall (inches/day)
2	5.2	15	11.1
3	6.5	20	11.9
4	7.4	25	12.5
5	8.1	30	13.0
6	8.6	35	13.5
7	9.0	40	13.8
8	9.4	45	14.2
9	9.7	50	14.5
10	10.0		

Table 3. Annual Maximum Daily Snow Fall (inches)

We now have 50-year recurrence levels for maximum daily gauge snowfall (14.5 in) and for maximum ground snow load (60.6 psf). Assuming, that annual maximum ground snow load is proportional to annual daily maximum snowfall, the conversion factor is[24],

$$conversion = 60.6 / 14.5 = 4.2\ psf\ \ /\ \ in \qquad (0.2)$$

While the linearity assumption could be questionable it is the best we can do, since we have found no raw data for annual maximum ground snow loads nor have we found ground snow load recurrence values for other recurrence intervals. Our estimates can be made more conservative by using the estimated 5-year recurrence value level although there will be only one year of exposure for T6.

Interpolated ground snow load recurrence values are in Table 4.

Recurrence Interval (years)	Snowfall (inches/day)	Groundload Ss (psf)	Recurrence Interval (years)	Snowfall (inches/day)	Groundload Ss (psf)
2	5.2	21.8	15	11.1	46.6
3	6.5	27.3	20	11.9	50.0
4	7.4	31.1	25	12.5	52.5
5	8.1	34.2	30	13.0	54.6
6	8.6	36.1	35	13.5	56.7
7	9.0	37.8	40	13.8	58.0
8	9.4	39.5	45	14.2	59.6
9	9.7	40.7	50	14.5	60.9
10	10.0	42.0			

Table 4. Interpolated Ground load (psf) Recurrence Levels

[24] Conversion factor units are psf/inch; its numerical value, 4.2 psf/in, would represent about 1 day's accumulation of damp new snow (0.78 psf/inch) falling at 5 inch/day. The 50-year maximum, 60.7 psf, could be the result about **4** day's accumulation of damp new snow falling at 14.5 inch/day.

Finally, we computed recurrence levels for specific roof loads, S, using equation (0.1)

Recurrence Interval (years)	Specific Roof Load (psf)	Recurrence Interval (years)	Specific Roof Load (psf)
2	32.0	15	51.9
3	36.5	20	54.5
4	39.4	25	56.6
5	41.6	30	58.3
6	43.4	35	59.7
7	44.8	40	60.9
8	46.1	45	62.0
9	47.2	50	63.0
10	48.2		

Table 5. Interpolated Specific Roof Load psf Recurrence Level

Since tank T-XX will be exposed to only one year of snow load, we use a conservative 5-year recurrence level, 41.6 psf, as the design value. The probability that the 5-year level will be exceeded in the first year is about 20%.

4.3 The Data

A scatter plot of interpolated snow load data is shown with the building code 50-year limit indicated by the dotted red line, as expected, the 50 year limit was exceeded twice in 116 years. A smoother for the median is plotted in blue and the 95 percent confidence band shaded in grey. In the year that the tank will be repaired, the most likely value of the maximum snow load is about 30 psf. Note that non-homogeneous stochastic extreme value analysis could be conducted that would account for the global warming effect seen in the trend line but this is an additional level of complexity that may be considered optional and which is not implemented here.

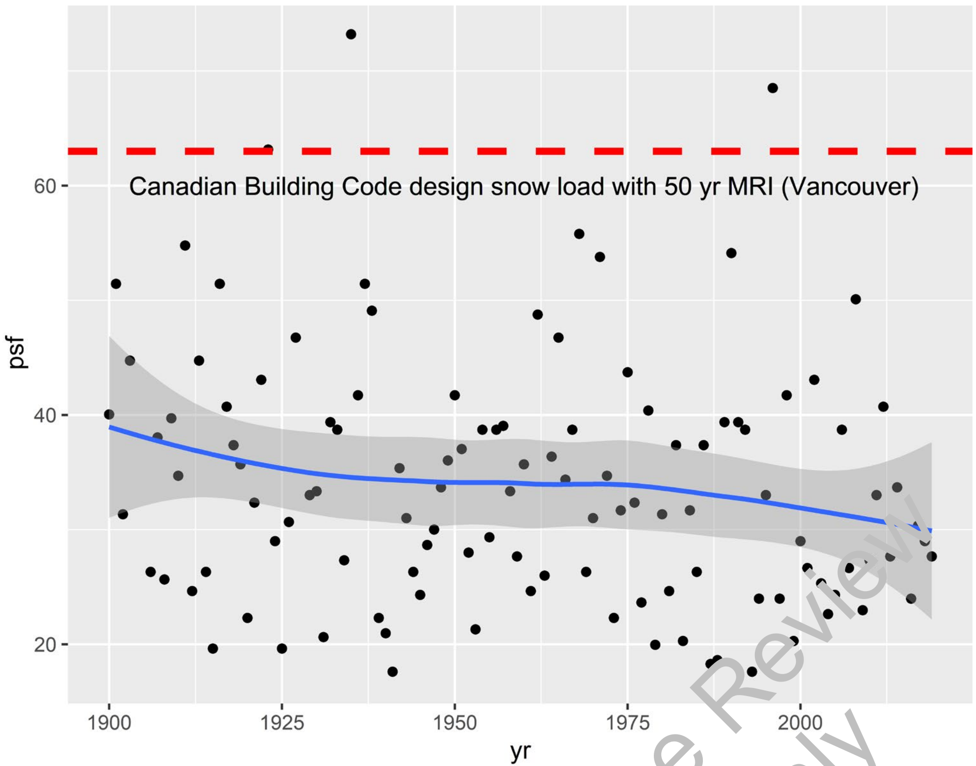


Figure 11 Interpolated Maximum annual roof loading in Vancouver BC since 1900

Figure 12 shows the distribution of the 116 years of interpolated roof-load values as a histogram and an empirical density, with the best fitting GEV density shown as a dashed line. As expected, this is an extreme value distribution[25] and is skewed right.

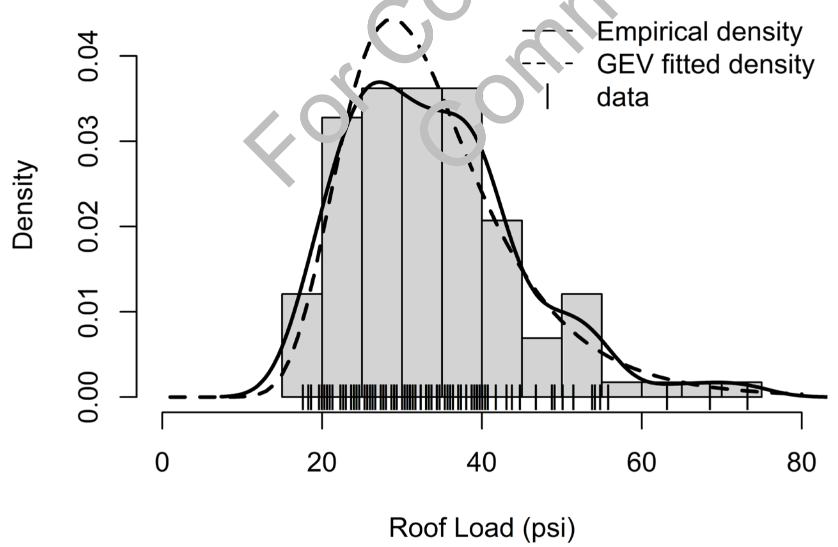


Figure 12. Distribution of Interpolated Roof Load Values

[25] GEV parameters are location: 28.9, scale: 8.30, shape: 0.0258

Figure 13 shows that the GEV distribution is an excellent fit to the data.

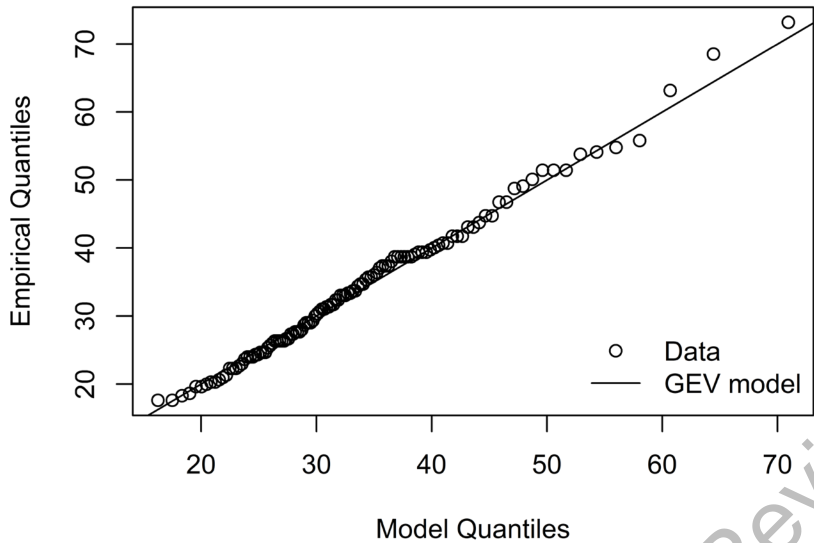


Figure 13. Q-Q plot: data vs GEV model quantiles.

4.4 Conclusion

Using extreme value analysis of the data we have shown that a reasonable design criterion for operating the tank in the current buckled and damaged state is to assume a roof snow load of 42 psf which is about two-thirds of the CBC criteria for new construction. There is only a 20% chance that this load would be exceeded if the repairs are completed in the current year.

Consultants may now work with a 42 psf snow load with owner acceptance of a probability of exceedance for snow loading based on a 5 year MRI. This becomes a risk-based problem that the owner may now consider regarding options to operate over the winter.

5 A More Useful Table

The information presented in Section 1 is repeated here for convenience but with the addition of two tables that make it easier to work with exceedance probabilities and MRIs.

Given these symbols and definitions:

MRI	mean recurrence interval
p	annual probability of exceedance = 1/MRI
pN	probability of one or more exceedances in N consecutive years of exposure

As well as these equations:

p_N is the probability of one or more exceedances in N consecutive years. The relationship is:

$$p_N = 1-(1-p)^N$$
$$p = 1-(1-p_N)^{1/N}$$

The following tables can be useful as will be shown by several examples.

Table 6 Exceedance probability over an N consecutive-year exposure period

		N =						
MRI	p	25	50	100	475	1000	2475	5000
10	10.00%	93%	99%	100%	100%	100%	100%	100%
25	4.00%	64%	87%	98%	100%	100%	100%	100%
50	2.00%	40%	64%	87%	100%	100%	100%	100%
100	1.00%	22%	39%	63%	99%	100%	100%	100%
475	0.21%	5%	10%	19%	63%	88%	99%	100%
1000	0.10%	2%	5%	10%	38%	63%	92%	99%
2475	0.04%	1%	2%	4%	17%	33%	63%	87%
5000	0.02%	0%	1%	2%	9%	18%	39%	63%

Notes:
Given exposure period N and an MRI or annual probability of exceedance the exposure probability is given.
The pink region shows exposure probabilities over period N that exceed 50%.
The values of 475 and 2475 have been included since these represent the commonly used building codes requirement of a 10% chance of exceedance in 50 years and a 2% chance of exceedance in 50 years.

Table 7 MRI for Exposure Probabity

		N =						
		25	50	100	475	1000	2475	5000
pN		0.0400	0.0200	0.0100	0.0021	0.0010	0.0004	0.0002
0.020	2.00%	1238	2475	4950	23512	49499	122509	247492
0.050	5.00%	488	975	1950	9261	19496	48252	97479
0.100	10.00%	238	475	950	4509	9492	23491	47457
0.250	25.00%	87	174	348	1652	3477	8604	17381
0.500	50.00%	37	73	145	686	1443	3571	7214
0.750	75.00%	19	37	73	343	722	1786	3607
0.900	90.00%	11	22	44	207	435	1075	2172

Notes:
Given exposure probability pN and exposure period N, the table gives the corresponding MRI.
The pink region shows MRIs that are greater than 500 years.

Armed with these tables the tank facility owner or operator can answer questions such as these:

Example question 1: If a structure was built to withstand a seismic event with a collapse level where the exceedance probability is not more than 10% in 50 years of exposure what is the MRI? Table 4 shows that the intersection of the row with pN=10% and the column with 50 years gives the MRI=475 years.

Example question 2: Given the conditions of Example Question 1, what is the annual probability of exceedance for the structure at collapse? The annual probability of exceedance is the reciprocal of the MRI=1/475=0.21%. This value can be seen in Table 1 under the column for p.

Example Question3: Your facility was constructed for specified flood levels with an MRI of 100 years and you want to know what the exposure probability is over the periods 50, 100, and 475 years. At row with MRI=100 in Table 3 and siting the columns for 50, 100, and 475 we obtain the exposure probabilities of 39%, 63%, and 99% respectively. There is a better than even chance that the flood exceedance level will be realized in 100 years (63%) and will occur with near certainty within 100 years (99%).

Example Question4: We know that the 2% chance of exceedance in a 50 year exposure period for a tsunami event is 2475 from Table 4. But your management would like to estimate the MRI for a 1% chance in 50 years. In this case we look to the equations given and compute

$$pN = 0.01$$

$$N = 50$$

$$p = 1 - (1 - pN)^{1/N} = 1 - (1 - .01)^{1/50} = 4975 \text{ years}$$

Appendix 4 Hurricane Tank Failure Envelope

Introduction

The most likely Natech events associated with petroleum storage facilities in the U.S. are hurricanes and tropical storms. Hurricanes may result in devastating tank Natechs as seen in the aftermath of disasters such as Hurricane Harvey. These tropical storms bring torrential rains, surging floodwaters, and forceful winds that can cause catastrophic petroleum releases from storage tanks. Hydrogeological storms are characterized by the multiple occurrences of high winds, flooding, moving surface waters and breaking waves in coastal regions. Simulations of the storm forces across a wide range of conditions provides an understanding of the failure envelope and mode of failure.

The most important petroleum tank storage failure modes resulting from storms include sliding, flotation, tipping, and overturning. The API taskgroup used a computational program[1] based on ASCE7-16 to find how different vertical flat bottom storage tank configurations and hurricane loading conditions caused tank failures during a hurricane Natech. This analysis yielded an envelope of tank failure conditions that can be used by owners and operators to develop Natech mitigation strategies and guidelines.

The program was used to simulate tanks of varying diameter undergoing flood loadings of varying elevations and wind loadings of varying wind speeds. Cone, dome, and open (external floating roof) tanks are considered separately since they behave differently under identical conditions. The simulation determines failure and failure modes with three force/moment equations: the horizontal force, vertical force, and moment. If the hurricane loading forces are greater than the restorative forces that prevent failure, then the tank is considered to have failed. For horizontal forces, this failure mode is sliding; for vertical, flotation caused by negative buoyancy and for moment, overturning. The program sorts through which tanks would fail due to a force imbalance and which would not – the line between the two establishes an envelope of tank failure conditions. The calculated tank failure envelope data provided in this appendix provides guidance for tank owners and operators in risk screening their tanks.

Assumptions

The recommendations made in this appendix were based on ASCE7-16 flooding and wind loading calculations applied to representative API 650 tanks. Thus, best judgment is required in applying these approximate calculations to tanks where the below assumptions do not hold.

The tanks and loading conditions considered are combinations made by varying the following parameters:

- The tank diameter ranging from 10 to 300-ft.
- The tank's roof can be either a cone, dome, or open (external floating roof) roof.
- The differences in flood and product level, or RFL, range from -5 to 3 ft[2].

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[1] PEMY Consulting, LLC. "Hurricaner" Program. Code to show plots and plots placed on a github.com repository - https://github.com/rbitip/API656/tree/main/Appendix-4

[2] The parameter RFL = flood level less product level normalized to the density of water and is called the *relative flood level* illustrated later in the appendix.

- The wind speeds considered are 90, 120, 170, and 220-mph.

A notable assumption is that the dead loads, flooding loads, and wind loads all contribute 100% of their forces, unlike the load combinations outlined in ASCE7-16. The simulation results detailed here present an overall conservative perspective on hurricane Natechs because the loads are combined with no reduction factors for simultaneous occurrence.

Here are other notable assumptions made in the simulation:

- The tank is assumed to be a rigid body.
- The tank is assumed to be unanchored.
- The tank is built to API 650.
- The tank is assumed to be ASCE7-16 risk category III.
- The tank product is assumed to be water (specific gravity of 1.0).
- The load combination factors are 100% for each loading type.
- Buckling failure modes are not considered (since this rarely results in loss of containment).
- The shell height is set to 48-ft.
- The shell course thicknesses are determined by the one-foot method.
- The bottom thickness is 1/4-in. There is no annular plate.
- The shell course and bottom thicknesses do not include corrosion allowances.
- The roof/wind girder weight is determined by a polynomial fit of roofs designed in the ITS tank design software.
- The maximum coefficient of static friction is 0.4.
- Cone roofs:
  - Cone roofs slopes are set to 1:16 (0.0625).
  - Cone roofs are assumed to have no horizontal wind loadings on them because of their shallow slope.
- Dome roofs:
  - Dome roofs "slopes" (f/D) are set to 0.0878 (the most common value)
  - Dome roofs are assumed to have negligible weight besides that of a wind girder.
- Open roofs:
  - Open roofs are assumed to have no vertical uplift due to wind.
  - Open roof tanks have a wind girder.
- Note: regardless of roof type, the tank shell has horizontal wind loadings, independent of the roof.
- For the calculation of the buoyancy force, the volume of the tank bottom and shell material is neglected.
- Wind is assumed to be a constant force (loadings calculated per ASCE7-16)
- Breaking waves in coastal flood zones are not considered.

Hurricane Loadings

The hurricane loadings considered by the ASCE7-16 simulation consist of flooding and wind forces. Only hydrostatic forces are considered for flooding – that is, buoyancy forces. Forces from water currents and breaking waves are not considered. Wind forces include the effect of wind speed pressure on the shell and uplift on the roof. In general, these forces operate in the upward and leeward direction. In the simulation, these forces are given positive values.

The tank's design and product fill weight impart restorative forces that oppose the hurricane loadings. The weight of the tank, which is a function of its diameter and design, and the weight of the internal fill product provide a counterweight against upward vertical forces. The net downward forces also directly increase the friction force that prevents the tank's sliding. These restorative forces operate in the downward and windward direction. In the simulations, the downward forces are given negative values.

In general, for the simulation, positive forces and moments are due to the hurricane loading while negative forces and moments are due to restorative forces that resist the hurricane forces. When the applicable force balances are positive, the tank is failing; when they are negative, the tank is not failing.

Net Horizontal = Wind – Friction
Net Horizontal = Wind – 0.4 (Tank Weight + Product Weight – Buoyancy – Wind)

Net Vertical = Buoyancy + Wind – Tank Weight – Product Weight

Net Moment = contribution from all forces besides friction

	Horizontal	Vertical	Moment
Flooding (+)	Reduced friction due to buoyancy	Buoyancy forces	Vertical component and reduction to friction
Wind (+)	Wind pressure on shell and roof	Wind pressure on roof	Both horizontal and vertical components
Tank weight (-)	Increased friction due to weight	Weight	Vertical component
Product weight (-)	Increased friction due to weight	Weight	Vertical component
Friction (-)	Dependent on vertical forces	None	None

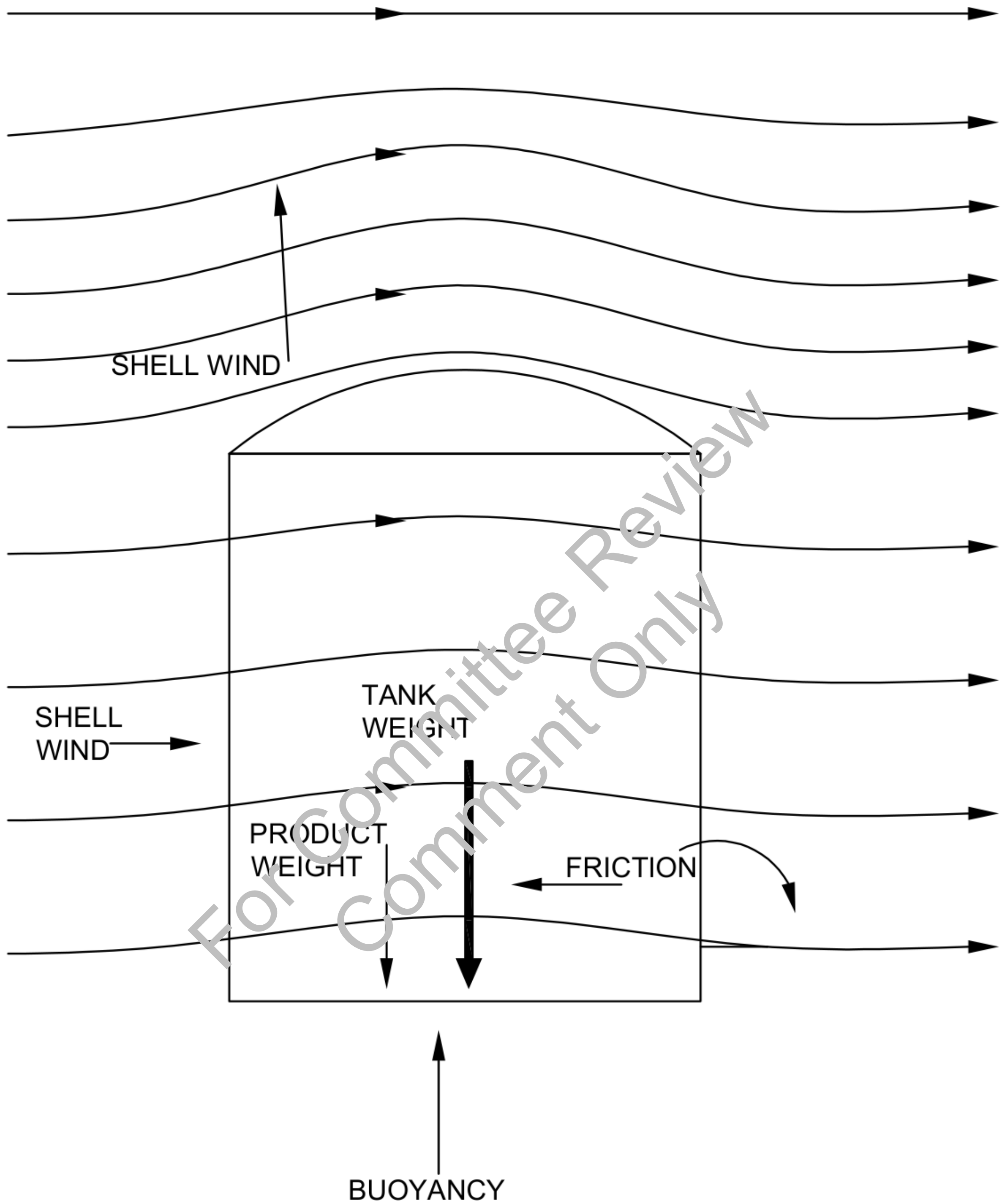


Figure 1. Pseudo-free body diagram showing the different forces at play during a hurricane NATECH.

Relative Flood Level (RFL)

In the simulation, the floodwater outside the tank is assumed to consist of water (G = 1.0), and so is the product inside the tank[3]. Normally, the buoyancy forces/weight of displaced flood water and the weight of internal product is calculated separately. It is possible to combine these two simulation variables into one and simplify the simulation input and output. Since they have the same density, the combined effects of buoyancy and internal product weight due to flood height/product height can be summed by one net height value – “relative flood level” or RFL.

The relative flood level is defined as the flood level outside the tank less the product level inside the tank, assuming the tank is stationary and not buoyant. FRL can be positive or negative. If it is positive, the flood water is higher than the internal product fill, and if negative the water in the tank is higher than the flood waters outside the tank. The net sum of buoyancy forces and internal product fill weight is equal in magnitude to the weight of water in the tank if it were filled or removed to the RFL – if RFL is positive, the force is positive and upwards; if RFL is negative, the force is negative and downwards.

$$B - W_p = \rho(\pi D^2/4)(\mathrm{h_f} - \mathrm{h_p}) = \rho(\pi D^2/4)(RFL)$$

$$h_f - h_p = (RFL)$$

Where B is the buoyancy force; W_p is the weight of product; ρ is the density of water; D is the tank diameter; h_f is the flood height outside the tank; h_p is the internal product fill height; and RFL is the relative flood level. It is useful to think of RFL as the net up or downward hydrostatic pressure on the tank in terms of feet of water column. Note: this calculation neglects the negligible buoyant volume of the shell and bottom plate material.

[3] This assumption is unconservative for tanks with lower specific gravities. There is an RFL conversion equation given later in this appendix for tanks products of different specific gravities.

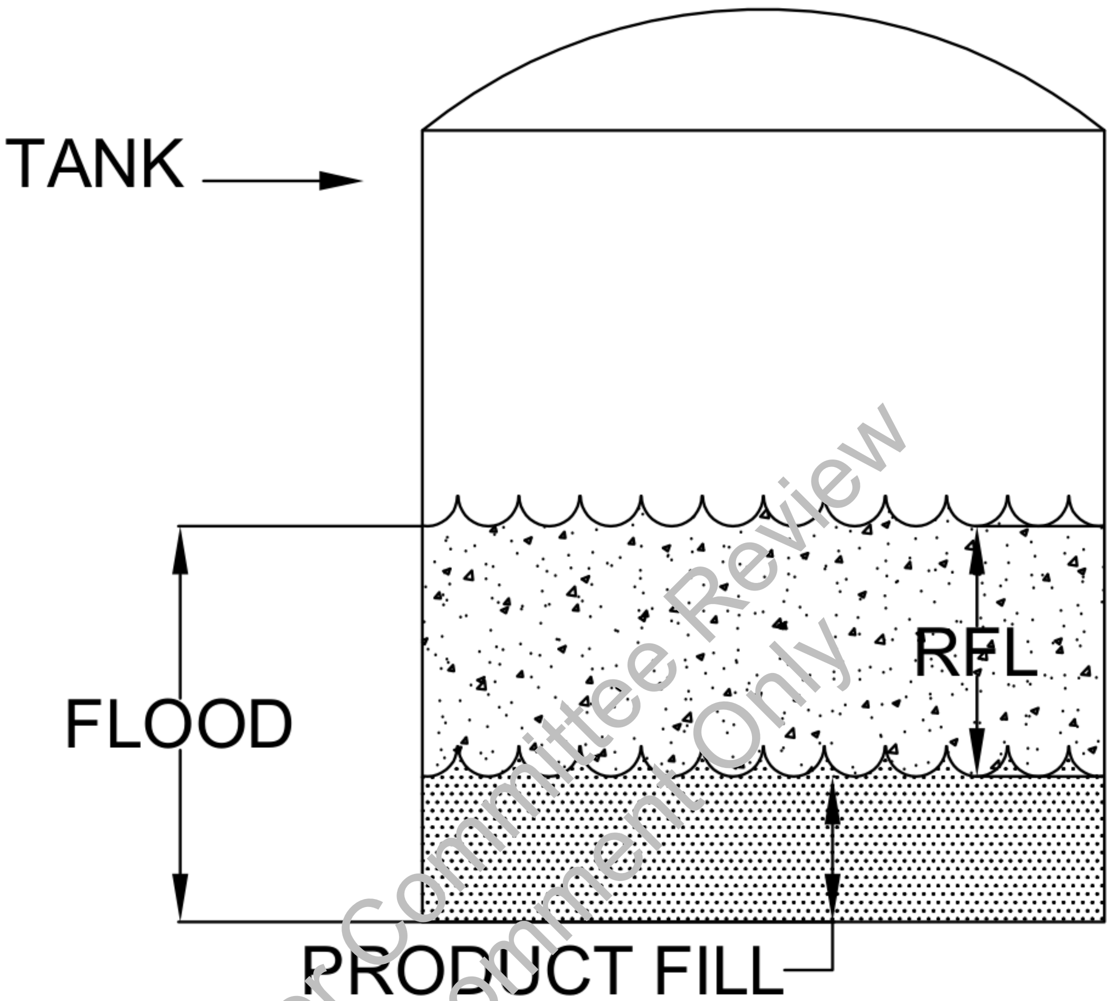


Figure 2. Relative Flood Level (RFL) is a measure of the net buoyancy force acting on the tank.

RFL is a useful measure and is a good replacement parameter for the buoyancy force and product weight parameters. This is for multiple reasons.

- Flood elevations and product fill height can be directly compared to charts in this document and do not have to be converted to forces/weights.
- Product fill height is a direct “tuning nob” to prevent sliding, flotation, and overturning failure modes. Reading RFL values on charts in this document can be directly converted to recommended product fill heights for tank owners and operators.

The rest of this appendix uses RFL when giving recommendations for tank fill heights in the event of an impending hurricane. These values, called RFL^*, are the maximum RFL before failure due to flotation, sliding, or overturning. For a given flood level, it is recommended that the product fill level is increased such that the tank's RFL is reduced below RFL^*. A higher RFL^* is desirable – a greater allowance of RFL means the tank can withstand higher flood levels without requiring as much internal product fill to offset hurricane loadings. Consider a tank undergoing hurricane loadings, including flood elevations of 5-ft.

- A tank with an RFL^* of +1.0-ft means that the tank's RFL should be less than 1-ft. With a flood elevation of 5-ft, the recommended internal product fill height should be at least 4-ft.
- A tank with an RFL^* of -1.0-ft means that the tank's RFL should be less than -1-ft. With a flood elevation of 5-ft, the recommended internal product fill height should be 6-ft or more (i.e. the 5 ft flood elevation minus the -1 ft RFL^*).

RFL For Other Specific Gravities

If the internal product has a specific gravity that is not 1.0, then some conversion is required to convert relative flood level (RFL) to the same balance of external flood level and internal product fill level. For a given RFL, the flood elevation must be specified to find this internal product fill height.

$$h_p = \left(h_f - (RFL)\right)/G$$

Where G is the specific gravity of the internal product. If $G = 1$, then this is the same as the definition of RFL.

For example, if a chart in a following section states that the sliding failure envelope for a given tank and loading scenario is at RFL^*= 1.5-ft, what if the tank is filled with product of $G = 0.7$?

- If the flood level is 1.5-ft, then the internal height of product should be at least 0 to have the same RFL and avoid sliding.
- If the flood level is 2-ft, then the internal height of product should be at least (2-1.5)/0.7 = 0.714-ft.
- If the flood level is 2.5-ft, then the internal height of product should be at least (2.5-1.5)/0.7 = 1.42-ft.

Tank Weight

If we neglect the wind component of hurricane loadings, only the vertical forces are of concern. Using relative flood level (RFL), the only considerations are the tank weight and the water buoyancy/weight from the RFL. For a given tank weight, it is easy to find the maximum RFL before flotation failure – the RFL for which the tank will begin to undergo flotation/buoyancy failure.

$$0 = B - W_p - W_t$$

$$W_t = B - W_p$$

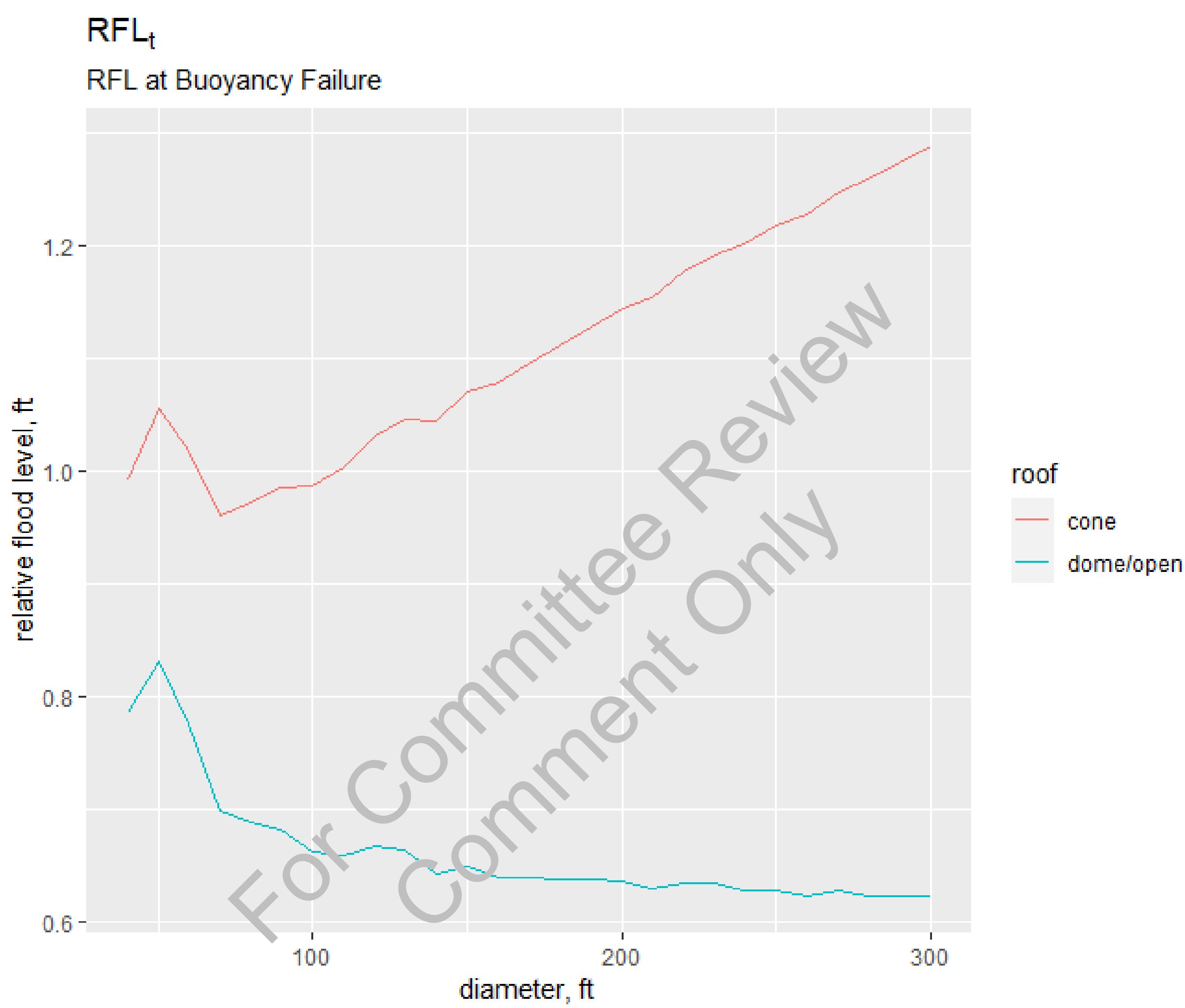
From the RFL section, $B - W_p$ can be substituted:

$$W_t = \rho(\pi D^2/4)(RFL)$$

$$W_t/(\rho\pi D^2/4) = (RFL)$$

The RFL that a cylindrical tank's weight can overcome by itself (with no wind loadings), or RFL_t, is proportional to its weight divided by the area of its base.

The below chart illustrates this for tanks of different diameters.



The RFL_t for cone roof tanks is greater than the RFL_t for dome and open roof tanks. This means cone roof tanks can innately resist buoyancy more than dome and open roof tanks because of their greater weight.

For example, compare two 100-ft diameter tanks, one with a cone roof and one with a dome roof.

- The cone roof tank has an RFL_t of approximately 1-ft – the tank would have a flotation failure at 1-ft greater water level outside the tank than inside the tank. For example, if there were 4-ft of flood waters outside the tank, the tank would have a flotation failure if it were filled with 3-ft or less of product.
- The dome roof tank has an RFL_t of only 0.3-ft – the tank would have a flotation failure at 0.3-ft greater water level outside the tank than inside the tank. If there were 4-ft of flood waters

outside the tank, the tank would have a flotation failure if it were filled with 3.7-ft of product or less. The dome roof tank requires 0.7-ft more product fill to avoid failure than the cone roof tank.

The cone roofs have greater weight because of the inclusion of rafters and support structures for the roof – in contrast, the dome and open roof tanks only major contributor to roof weight is a wind girder. The simulation's shell and bottom weights are dependent only on the diameter and do not change based on the roof type.

Observations:

- Cone roof tanks weigh more than dome and open roof tanks. They have more resistance to flotation failure than the other roof type tanks. This difference increases as tanks grow in diameter.
- Cone roof tanks resist flotation better and better with greater diameter – dome and open roof tanks resist flotation worse at larger diameters, trending toward RFL_t of near zero.
- All roof type tanks have similar weights at small diameters. The contribution to total tank weight from the roof is less for smaller tanks than larger tanks.

Failure Envelope for Hurricane Conditions

The ASCE7-16 simulation tested cone, dome, and open roof tanks of diameters from 10 to 300-ft in varying wind and flooding conditions. The sub-plots that make up charts A, B, and C (see the following pages) show three curves each. Each curve represents the failure envelope for each failure mode considered in the simulation – sliding (horizontal forces), flotation (vertical forces), and overturning (moment). The value of the curve is the RFL^*, the greatest relative flood level (RFL) before that failure mode occurs i.e. the net force is equal to or greater than zero. The lowest of these RFL^* values for a given diameter indicates the RFL at failure for which the primary/dominant failure mode will occur.

For example, consider the top left sub-plot on chart A: cone roof tanks undergoing 90-mph wind speeds. For tanks of 100-ft diameter, the lowest RFL^* value is for the blue curve, which corresponds to the sliding failure mode. RFL^* is approximately 0.4. This means that a 100-ft cone roof tank undergoing 90-mph winds would fail in the sliding mode for $RFL \geq +0.4$-ft.

Chart Types:

- Chart A provides an overview of the failure envelope for different failure modes of tanks from 10 to 300-ft diameters. Each subplot shows these failure envelope curves for a specific roof type and wind speed combination. Roof types consist of cone, dome, and open roofs – wind speeds range from 90 to 220-mph.
- Chart B only displays tanks of diameter 40 to 300-ft to show the failure envelope curves which may be harder to see in Chart A. This chart has fixed y-axes. This allows for easy direct visual comparisons between the failure envelope curves of different sub-plots.

Observations:

- In general, the dominant failure mode is sliding.

- The only exception to this is for very small tanks of all types for lesser wind speeds (diameters less than 15-ft, 90-mph wind speeds) or for small dome roof tanks (diameters less than 40 to 50-ft). In these cases, the dominant failure mode is overturning.

- Small tanks are much more susceptible to the sliding and overturning failure modes, especially at higher wind speeds.
  - Consider cone roof tanks in 220-mph wind speeds. 40-ft diameter tanks fail to the sliding mode at an RFL of about -4-ft ; 100-ft tanks at about -2-ft; 200-ft tanks at about -1-ft; and 300-ft tanks at about -0.5-ft. That means 40-ft diameter tanks undergoing 220 mph winds would require at least 4-ft more product fill height than flood height to avoid sliding, whereas a 300-ft tank would only require 0.5-ft more.
- At 90-mph wind speeds, tanks do not require any greater fill than the flood elevation ($RFL^* \geq +0$-ft)

Tabular Results

Below is a tabular representation of the data presented in chart A. To find RFL^* values for diameters not listed in the table, interpolate between data points in the table. The same can be done to find RFL^* values for wind speeds not listed.

Note: the RFL^* values were calculated at a resolution of ±0.02-ft.

Key:

- rows: wind speeds, in mph.
- columns: tank diameters, in feet.
- values: RFL^*, or RFL at failure, in feet.

Cone Roof Tanks:

	20-ft	40	60	80	100	150	200	250	300
90-mph	-0.12	0.06	0.30	0.38	0.46	0.64	0.78	0.88	0.96
120	-1.34	-0.60	-0.24	-0.08	0.06	0.32	0.50	0.60	0.70
170	-4.16	-2.32	-1.5	-1.14	-0.88	-0.40	-0.16	0.00	0.14
220	-7.96	-4.56	-3.18	-2.54	-2.12	-1.40	-1.02	-0.80	-0.64

Dome Roof Tanks:

	20-ft	40	60	80	100	150	200	250	300
90-mph	-0.50	0.04	0.24	0.24	0.28	0.36	0.40	0.40	0.40
120	-1.94	-0.52	-0.16	-0.10	-0.02	0.16	0.24	0.22	0.22
170	-5.22	-1.84	-1.10	-0.88	-0.72	-0.32	-0.16	-0.18	-0.18
220	-9.66	-3.60	-2.34	-1.94	-1.64	-0.98	-0.70	-0.70	-0.72

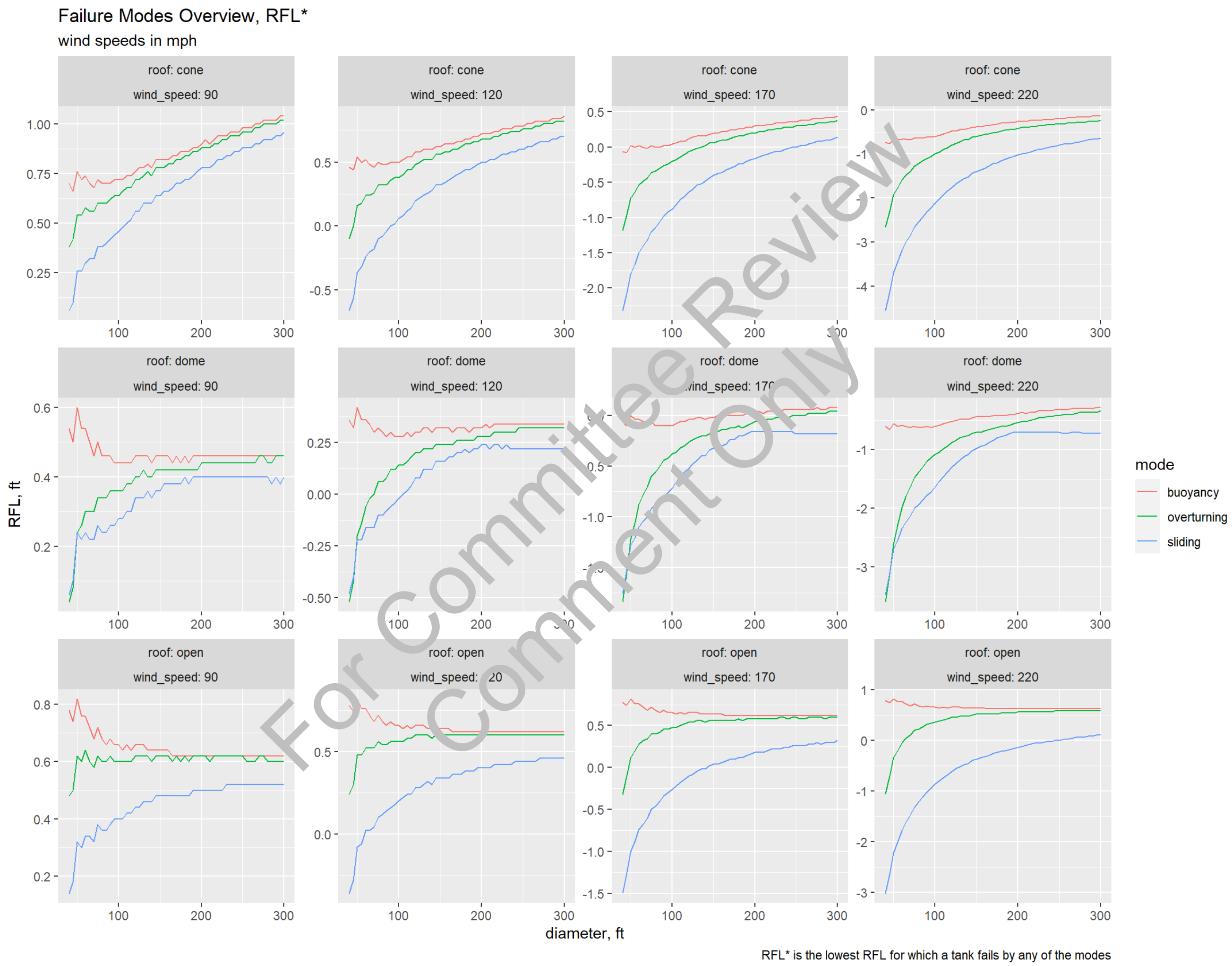
Open Roof Tanks:

	20-ft	40	60	80	100	150	200	250	300
90-mph	0.06	0.14	0.34	0.36	0.40	0.48	0.50	0.52	0.52

120	-0.94	-0.36	0.02	0.12	0.20	0.34	0.40	0.44	0.46
170	-3.22	-1.50	-0.74	-0.46	-0.26	0.04	0.18	0.26	0.32
220	-6.28	-3.02	-1.78	-1.22	-0.86	-0.38	-0.14	0.00	0.10

Chart A

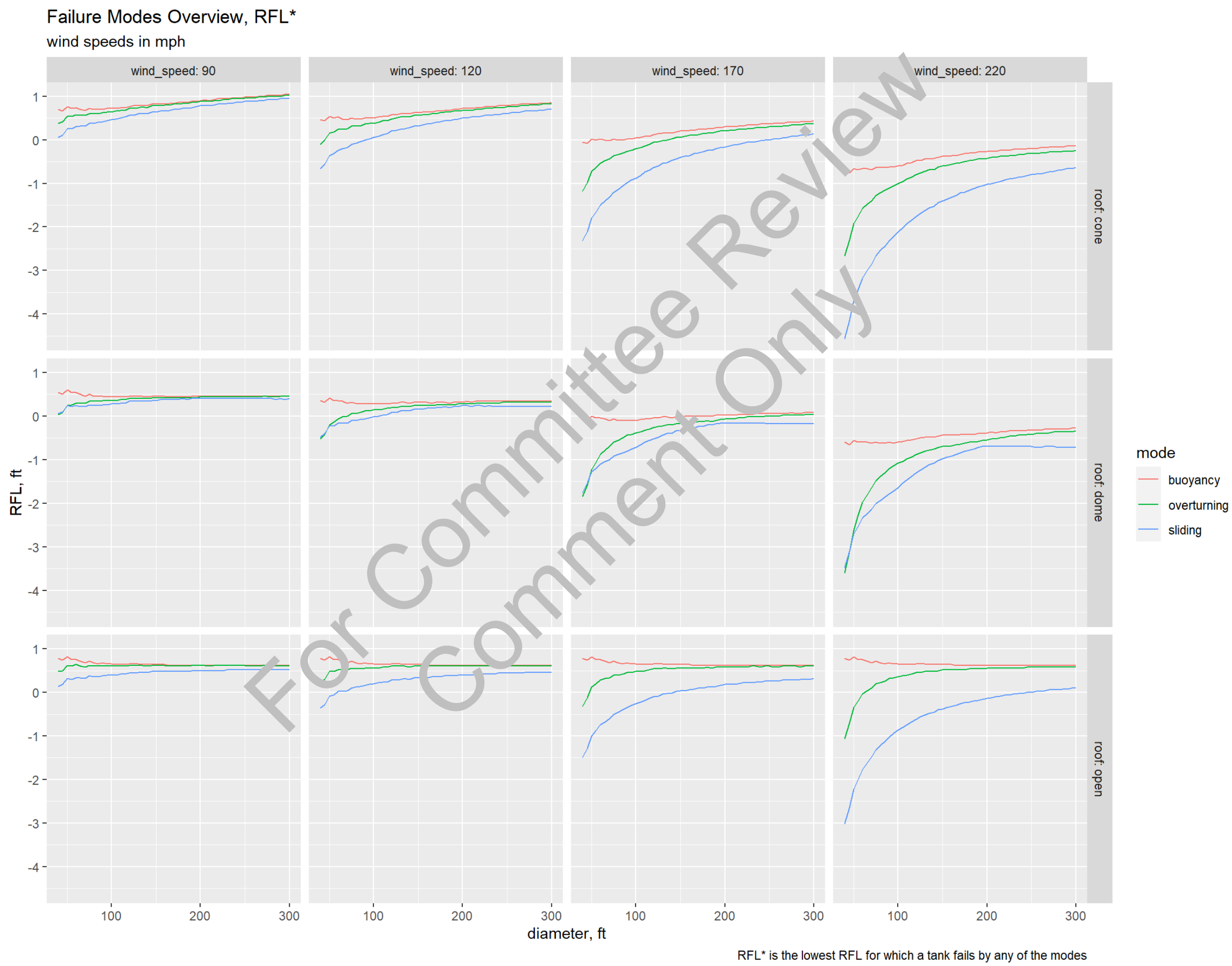
Failure Modes for all diameters[4]



[4] Higher resolution versions of these figures can be found at https://github.com/rbitip/API656/tree/main/Appendix-4.

Chart B

Fixed axis comparisons of failure modes for 40' and greater diameters: these sub-plots have the same y-axis for all plots. It's easy to see that tanks undergoing greater wind speeds have more stringent RFL requirements (especially for smaller diameter tanks) than tanks undergoing lesser wind speeds.



Using This Appendix

The information in this appendix is based on tanks designed to API 650. These tanks were designed using thicknesses based on the 1-foot method with no corrosion allowances. Roof weights were based on tank weight versus diameter relationships found in a tank design program[5]. Therefore, the tank weights could be significantly underestimated for tanks with corrosion allowance or unique design criteria. Nonetheless, the use of this appendix provides a quick and easy way to risk rank all tanks at a specific location or facility if the tanks are constructed to API 650. The only needed input tank data is the diameter of the tank and the type of tank roof. This appendix should not be used for tanks constructed to API 620 or tanks that are not vertical, cylindrical flat bottom tanks.

The wind and static floodwater loadings detailed in this appendix covers a majority of hurricane loading scenarios. However, tank owners and operators should make sure to perform their own analyses for storm surges, moving surface water, and breaking waves. There can be complications with secondary containment that necessitate these considerations.

The default approach for use of this appendix is straightforward – tank owners can prepare recommended fill heights for tanks based on the RFL^* values in the failure envelope charts and tables. There are two other recommended uses for this appendix:

1. to consider the sensitivity of tanks to ranges of hurricane conditions.
2. to consider the relative risk between tanks in a population of them.

Determining Hurricane Loading Conditions

The first step to using this appendix for a given tank population is to find what the expected flood levels and wind speeds are for their location. Start with data from ASCE7-16.

Flood hazard maps can be obtained from authorities in the jurisdictions where the tank is located. In the USA, FEMA provides flood map services. Flood rate insurance rate maps, or FIRMs, can also denote special zones called special flood hazard areas. These are areas in floodplains that are subject to a 1% or greater chance of flooding in any given year. These areas can be delineated on a FIRM as A-zones or V-zones, with designations including but not limited to A, AO, V, or VE. The base flood elevation, or BFE, is the elevation of flooding with a 1% chance of being equaled or exceeded in any given year[6]. The BFE is indicated for A- and V-zones in FIRMs, and for tanks in these special flood hazard areas, it is a good starting point to determine floodwater levels for tanks. This BFE is used in tandem with the calculated RFL^* values in this appendix to find the minimum product fill level before tank failure.

Wind hazard maps can be obtained from authorities in the jurisdictions where the tank is located. ASCE7-16 provides wind hazard maps for the continental USA, Alaska, Hawaii, Puerto Rico, Guam, the US Virgin Islands, and American Samoa[7]. The AT Council website[8] also provides basic wind speed values if provided addresses or coordinates. These wind hazard maps provide basic wind speed values based on risk category and location (this appendix assumes storage tanks are ASCE7-16 risk category III). Basic

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[5] ITS program v20.2.1.3

[6] Information on flood loadings and floodwater elevations is provided in ASCE7-16, Chapter 5.

[7] Information on wind loadings is provided in ASCE7-16, Chapter 26. The wind hazard maps are located in ASCE7-16 section 26.5.

[8] hazards.atcouncil.org

wind speed corresponds to an approximate 7% chance of being equaled or exceeded at least once in 50 years (an annual exceedance probability of 0.143%, or a mean recurrence interval of 700 years). These wind speed values are used to calculate RFL^{*}, the RFL values at which failure occurs. This RFL^{*} value, along with the flood elevation, can be used to determine the minimum required fill level before tank failure.

The base flood elevation and basic wind speed values are the recommended starting points to determine a tank's hurricane loading conditions. Flood elevations and wind speeds should be probabilistically combined to determine realistic loading conditions for tanks undergoing hurricane loadings. Using the base flood elevation and basic wind speed values together represent the worst-case wind and hydrostatic conditions. Tank owners and operators should use engineering judgment to determine what range of values for flood elevation and wind speed to consider in the assessment of risk and safety for their storge tanks.

Determining Recommended Fill Levels for Hurricane Loadings

Once the appropriate flood elevation and wind speeds are determined, it is straightforward to find the minimum fill level for a tank undergoing those hurricane conditions.

1. Consult the RFL^{*} chart or table (see the "Failure Envelope for Hurricane Conditions" section) for the appropriate tank roof type – cone, dome, or open.
2. For the given wind speed and tank diameter, find the appropriate RFL^{*} for the tank.
    a. If the tank diameter is not included in the chart, interpolate between the RFL^{*} values for the diameters provided.
    b. If the wind speed is not included in the chart, interpolate between the RFL^{*} values for the wind speeds provided.
3. For the given flood elevation, use the RFL^{*} to find the product fill height at failure (see the "Relative Flood Level (RFL)" section).
    a. It is important to consider if the tank is elevated higher or lower than the surrounding area for which the flood elevation is measured. Subtract or add to the flood elevation if appropriate.

This procedure yields the estimated product fill height at failure for the given hurricane conditions. Fill heights greater than this estimation are recommended to avoid failure under hurricane conditions.

In ASCE7-16, the design flood elevation, or DFE, is 1-foot greater than the base flood elevation. Adding 1-foot to the flood elevation in step 3 of the above procedure would yield a recommended minimum product fill height estimate for the tank for the given hurricane conditions. This 1-foot safety factor should be appropriate for all but the most severe hurricane loading conditions.

Example:

A tank in the Galveston, TX area: • Diameter: 100-ft • Roof Type: Cone • Product Specific Gravity: 1.0 • Base Flood Elevation: 18-ft • Basic Wind Speed, Risk Category III: 160-mph

For 100-ft cone roof tanks, there are no RFL^* presented for 160-mph tanks, only for 120-mph and 170-mph tanks.
100-ft diameter, cone roof, 120-mph: $RFL^* =$ +0.06-ft
100-ft diameter, cone roof, 170-mph: $RFL^* =$ -0.88-ft

100-ft diameter, cone roof, 160-mph: RFL^* is found by interpolation.

0.06-ft + (160-mph – 120-mph) x (-0.88-ft – 0.06-ft) / (170-mph – 120-mph)
= 0.06-ft + (40-mph) x (-0.94-ft) / (50-mph)
= -0.692-ft

100-ft diameter, cone roof, 160-mph: $RFL^* =$ -0.69-ft

At a flood elevation of 18-ft, the tank's product fill height at failure is 18.69-ft of water. The recommended minimum fill height is 19.69-ft of water (for a design flood elevation of 18+1=19-ft).

Assessing Sensitivity to Hurricane Loadings

It is unlikely that predicted flood elevation and wind speed values will match the exact conditions encountered during the next hurricane Natech. It is likely that the conditions during the Natech will be more or less severe than the predicted conditions. Thus, it is prudent for tank owners and operators to consider how sensitive a tank's stability is to variations in flood elevation and wind speed during a hurricane Natech.

Determining a tank's sensitivity to flood elevation changes is straightforward using RFL. For a tank filled with product of specific gravity 1.0, the RFL requirements are the same regardless of flood elevation. There is a 1:1 correspondence between flood elevation and internal product fill height. If the RFL^* is -2-ft, it is recommended the internal fill height be 2-ft greater than the flood elevation.

- If the flood elevation is 10-ft, the internal fill height should be at least 12-ft.
- If the flood elevation is 5-ft, the internal fill height should be at least 7-ft.

Tanks storing product with lower specific gravity are more sensitive to flood elevation changes, however. For example, a tank filled with product of specific gravity 0.7 requires 1/0.7 or 1.42 times the fill height of a water tank to have the same product weight. That's almost 50% more required fill height. Consider our above example, where RFL^* is -2-ft.

- If the flood elevation is 10-ft, the internal fill height should be at least 12 x 1.42-ft, or 17-ft.
- If the flood elevation is 5-ft, the internal fill height should be at least 7 x 1.42-ft, or 10-ft.

A tank's sensitivity to wind speed changes is nonlinear, unlike the case for flood elevation changes. The velocity pressure applied to the shell and roof of a tank increases with the square of the wind speed – however, the pressure profile on the roof changes with roof geometry and wind speed. Interpolating between wind-speed values on the appropriate charts in the "Failure Envelope for Hurricane Conditions" section yields some insight to the tank's sensitivity to wind speed.

Consider the Galveston tank example in the previous section – a 100-ft diameter cone roof tank. The RFL^* was calculated for 160-mph using the 120-mph and 170-mph values. Adding the computed RFL^* for 200-mph using the 170-mph and 220-mph values is a useful addition. The 120-mph and 200-mph values show how RFL^* changes within a ±40-mph bracket of wind speeds around the benchmark wind speed of 160-mph:

- 120-mph: $RFL^* =$ +0.06-ft
- 160-mph: $RFL^* =$ -0.69-ft
- 200-mph: $RFL^* =$ -1.62-ft
    - 170-mph: $RFL^* =$ -0.88-ft
    - 220-mph: $RFL^* =$ -2.12-ft
    - -0.88 + (200-170) (-2.12 + 0.88) / (220-170) = -1.624

Wind speed	RFL^*	Change in RFL^* from 160-mph
120-mph	+0.06-ft	+0.75-ft
160-mph	-0.69-ft	0-ft
200-mph	-1.62-ft	-0.93-ft

Starting from 160-mph: a 40-mph wind speed reduction requires 0.75-ft less product fill, whereas a 40-mph wind speed increase requires 0.93-ft more product fill. If a tank owner were concerned about potential 40-mph variations in wind speed from the design 160-mph wind speed, 1-ft extra product fill would be recommended at the least. Calculating RFL^* changes at more wind speeds would allow a tank owner to make a more informed decision.

Sample Hurricane Loading Calculation

This section details an example hurricane loading calculation based on the flooding and wind provisions of ASCE7-16. Given the tank design and hurricane loading parameters, what is the minimum required product fill height required to prevent sliding, flotation, or overturning failure?

The program used to create the charts and tables in this appendix uses the same kind of calculation detailed here for a wide range of tank diameters, roof types, wind speed, and flood elevations.

Note:

- Sample tank properties:
    - Designed to API 650
    - Diameter, D: 100-ft
    - Height, H: 48-ft
    - Roof type: cone roof
    - Product specific gravity, G: 1.0
    - Flood elevation, h_f: 10-ft
    - Wind speed, V: 120-mph
- Assumed properties:
    - Maximum coefficient of static friction, μ: 0.4
    - Rain elevation, water speed: 0
    - terminal elevation, berm height, tank elevation: 0

- ASCE7-16 Risk category: III
- Wind exposure category: C

Tank Geometry and Weight

The tank is designed to API 650. The shell course thicknesses are determined by the one-foot method. The weight of the tank shell is equal to the volume of steel comprising the shell times the density of the steel. The shell and bottom of the tank are assumed to be comprised of A36 steel, with a density of ρ = 0.284 lbf/in3.

- The one-foot method for shell course thicknesses (API 650) yields:
  - 0.5625, 0.4375, 0.3750, 0.3125, 0.2500, 0.2500-in
- Shell course heights are each 8-ft.

The weight of the shell is:

$$(\pi D)(\sum ht)(\rho) = 224{,}837.5\text{-lbf}$$

The thickness of the tank bottom (t_b) is assumed to be 1/4-in. The weight of the bottom is:

$$(\pi D^2/4)(t_b)(\rho) = 80{,}299.11\text{-lbf}$$

The weight of the cone roof was determined by formula. This cone roof weight formula is based on a polynomial regression of API 650 cone roof tanks designed in ITS. The weight of the roof is:

$$1.014D^{2.6229} = 178{,}582.1\text{-lbf}$$

The total weight of the tank without product is:

$$W_t = 483{,}718.7\text{-lbf.}$$

The moment from the weight of the tank without product is:

$$M_t = W_t D/2 = 24{,}185{,}936\text{-lbf-ft}$$

Flood Loadings

The buoyancy force due to flooding is equal to the weight of floodwater displaced by the tank. The flood elevation h_f is used directly because the terminal and tank elevation are both 0-ft. The flooding buoyancy force is:

$$B = \pi D^2/4(h_f)(62.4) = 4{,}900{,}885\text{-lbf}$$

The moment from the buoyancy force is:

$$M_B = BD/2 = 245{,}044{,}227\text{-lbf-ft}$$

Wind Loadings

Basic Wind Parameters

These wind parameters are used in the velocity pressure calculation (ASCE 7-16 chapter 26):

$$K_d, K_{zt}, K_e = 1$$

α = 9.5 and z_g = 900 are parameters used in calculating the velocity pressure exposure coefficients K_z and K_h for exposure category C.

$$K_z = 2.01\left(H/2/z_g\right)^{(2/\alpha)} = 0.9371758$$

$$K_h = 2.01\left(\left(H + f/2\right)/z_g\right)^{2/\alpha} = 1.091754$$

The velocity pressures q_z and q_h are used in the calculation of wind pressures and forces on the shell and roof, respectively.

$$q_z = 0.00256 K_z K_{zt} K_d K_e V^2 = 34.54805\text{-psf}$$
$$q_h = 0.00256 K_h K_{zt} K_d K_e V^2 = 40.2464\text{-psf}$$

Shell Wind Loadings

The gust-effect factor G = 0.85 and the force coefficient C_f = 0.63 are used in the calculation of the shell wind force (ASCE7-16 chapter 29). The horizontal wind force on the shell is:

$$F_s = G q_z C_f D H = 88{,}802.3\text{-lbf}$$

The moment on the tank from that shell force is:

$$M_s = F_x H/2 = 2{,}131{,}255\text{-lbf-ft}$$

Roof Wind Loadings

The gust-effect factor G = 0.85 and the internal pressure coefficient (GC_{pi}) = 0.18 are used in the calculation of the roof wind force (ASCE7-16 chapter 29). The design pressures on cone roofs is calculated for two zones – one windward (zone 1) and one leeward (zone 2). The location of the dividing line between these two zones is dependent on the H/D ratio, by interpolation (ASCE7-16 figure 29.4-5):

$$b = 47.6\text{-ft}$$

$$b\% = (b - D/2)/(D/2) = -4.8\%\ (4.8\%\ \text{windward})$$

The forces on the cone roof are calculated per zone. The external pressure coefficient C_p is defined for each zone. The zone force F is the product of the average zone pressure P and zone area A for each zone. The zone force contribution to moment M is the product of the zone force F and the zone centroid location x.

For zone 1:

- $C_{p1} = -0.8$
- $P_1 = q_h\left(GC_{p1} - (GC_{pi})\right)$ = -34.61191-psf
- $A_1 = (D/2)^2 \sin^{-1}\left((D/2-b)/D/2\right) - (D/2-b)\sqrt{Db-b^2}$ = 3,687.083-ft2

$$F_1 = -P_1A_1 \text{ = 127,617-lbf}$$

- $x_1 = D/2 - (0.53(b\%) - 0.425)D/2$ = 72.522 ft

$$M_1 = F_1x_1 \text{ = 9,255,038-lbf-ft}$$

For zone 2:

- $C_{p2} = -0.5$
- $P_2 = q_h\left(GC_{p2} - (GC_{pi})\right)$ = -24.34907-psf
- $A_2 = \pi D^2/4 - A_1$ = 4,166.899-ft2

$$F_2 = -P_2A_2 \text{ = 101,460.1-lbf}$$

- $x_2 = D/2 - (0.53(b\%) + 0.425)D/2$ = 30.022-ft

$$M_2 = F_2x_2 \text{ = 3,046,036-lbf-ft}$$

One of the assumptions in the appendix is that the horizontal force acting on cone roofs is zero due to the shallow slope. The net vertical wind force on the roof is:

$$F_r = F_1 + F_2 \text{ = 229,077.1-lbf}$$

The moment on the tank from that roof force is:

$$M_r = M_1 + M_2 \text{ = 12,301,074-lbf-ft}$$

Net Wind Loadings

- The only horizontal wind force is the wind shell force F_s = 88,802.3-lbf
- The only vertical wind force is the wind roof force F_r = 229,077.1-lbf
- The net wind moment $M_w = M_s + M_r$ = 14,432,329-lbf-ft

Product Weight

The weight of the product inside the tank is dependent on the product fill height, h_p. The product weight is:

$$W_p = h_p(\pi D^2/4)(62.4G) = h_p\text{(490,088.5-lbf/ft)}$$

The moment from the product weight is:

$$M_p = h_p(490{,}088.5)D/2 = h_p\text{(24,504,425-lbf)}$$

Friction Force

The maximum static friction force, which acts in the horizontal direction, is dependent on the net vertical force, including the product weight. It is:

$$f = \mu \sum F_y = 0.4 \sum F_y$$

The net vertical force is $\sum F_y = B + F_r - W_b - W_p$. B, F_r, and W_b are known. Replacing those terms with their known values and replacing W_p with its formula yields:

$$f = 0.4(W_b - B - F_r) + 0.4W_p = h_p(196{,}035.4\text{-lbf/ft}) - 1858497\text{-lbf-ft}$$

Force/Moment Equilibrium Equations:

First, an overview of the forces and moments:

- Tank weight force and moment
  - W_t = 483,718.7-lbf.
  - M_t = 24,185,936-lbf-ft
- Buoyancy force and moment
  - B = 4,900,885-lbf
  - M_B = 245,044,227-lbf-ft
- Wind forces (shell and roof) and moment
  - $F_s = Gq_zC_fDH$ = 88,802.3-lbf
  - $F_r = F_1 + F_2$ = 229,077.1-lbf
  - $M_w = M_s + M_r$ = 14,432,329-lbf-ft
- Product weight force and moment
  - $W_p = h_p$(490,088.5-lbf/ft)
  - $M_p = h_p$(24,504,423-lbf)
- Friction force
  - $f = h_p$(196,035.4-lbf/ft) - 1,858,497-lbf-ft

Failure occurs when any of the net horizontal force, net vertical force, and net moment are positive. When they are positive, the hurricane loadings (wind or buoyancy forces or moments) are greater than restorative forces (tank or product weight, friction).

$$\sum F_x = F_s - f < 0$$

$$\sum F_y = B + F_r - W_b - W_p < 0$$

$$\sum M = M_b + M_r + M_t + M_p < 0$$

Simplify:

$$\sum F_x = 1{,}947{,}299\text{-lbf-ft} - h_p(196{,}035.4\text{-lbf/ft}) < 0$$

$$\sum F_y = 4{,}646{,}243\text{-lbf-ft} - h_p(490{,}088.5\text{-lbf/ft}) < 0$$

$$\sum M = 235{,}290{,}620\text{-lbf-ft} - h_p(24{,}504{,}423\text{-lbf}) < 0$$

Isolate h_p:

To avoid sliding ($\sum F_x < 0$): $h_p > 9.933405$-ft

To avoid flotation ($\sum F_y < 0$): $h_p > 9.480416$-ft

To avoid overturning ($\sum M < 0$): $h_p > 9.601965$-ft

The maximum of these three values is the minimum required product fill height to avoid failure, 9.93-ft.

Following the recommendations of this appendix, the recommended minimum fill height would be 1 or 2-ft greater, at 10.93-ft to 11.93-ft.

References

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Appendix 5 Floating Roof Tanks Rainfall Risk

API 656 NATECH Committee

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We present a way to approximate roof flooding risk from widely available hydrological intensity-duration-frequency (IDF) tables and demonstrate the accuracy of our approximation using data from the Harris County, TX, Flood Warning System (HCFWS) rain-gauge network.

Introduction

Standing-water Events

The space above an annular pontoon floating roof is a broad, shallow, open-topped cylinder with a drain at bottom-center. Standing water will build up if rainfall intensity (inches per hour, iph) exceeds roof-drain drawdown rate (ddr) expressed in inches per hour.

Roof-drain flow rate is generally expressed as volume per time unit; for example, gravity flow through 4" pipe is about 15,000 gallons per hour. Our forecasting system requires re-expressing drain rate (volume per hour) as drawdown rate (DDR) expressed as inches of water depth per hour. Thus, for example, a 124-foot diameter tank contains 7528 gallons per vertical inch ($7.48 \cdot \pi \cdot 62^2/12$) so the drawdown rate would be about 2 inches per hour (iph) (15,000 /7528).

Floating roofs are required by API Standard 650 to withstand 10 inches of rainfall over 24 hours *with primary drains inoperative*. The standard is hard to interpret; 10 inches of water accumulated due to *partly inoperative* drains exposes a roof to the same stress, as does 10 inches accumulated over a longer or shorter time interval. For that reason, we have developed statistical tables to predict the depth and frequency of standing water events for fully operational as well as impaired roof drains.

For our hypothetical 124-foot tank with 2 iph nominal drawdown, rain would have to fall at an average rate of 12 inches per hour (iph) for at least one hour to exceed the 10-inch limit. As of August 28, 2017, the [US one-hour rainfall record] was 13.5 inches per hour (Burnsville, WV, 1943-08-04), so 10 inches of standing water is possible but very unlikely for properly sized, fully operative roof drains. See also International Plumbing Code[i].

In fact, Hurricane Harvey's 60-minute maximum near the Exxon storage terminal at Baytown, TX was about 4.12 inches per hour, Figure *1*.

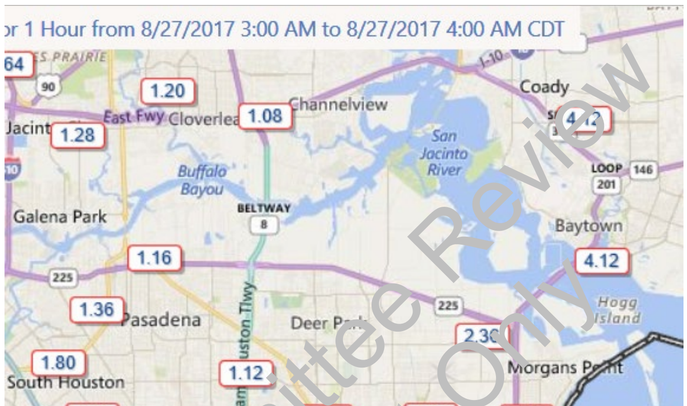

Figure 1. One hour of rainfall data during Hurricane Harvey, Harris Co. TX.

At that rate, our hypothetical tank would have accumulated a little over 4 inches of standing water, as shown in Figure *2*.

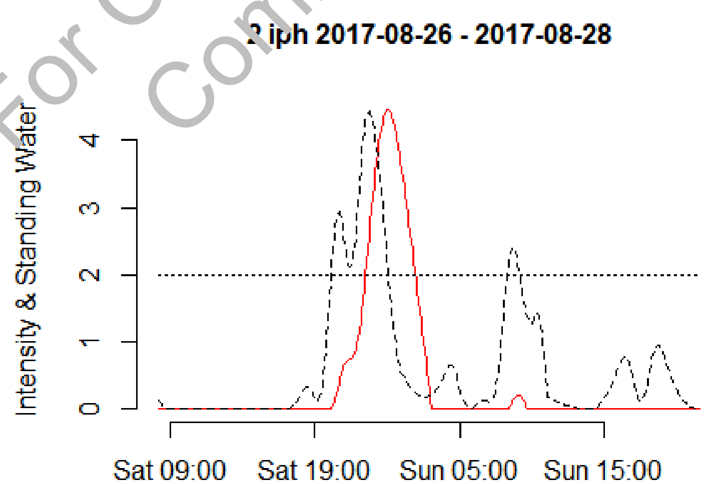

Figure 2. Gage 1540 Harvey Rain Event.
dotted: drawdown rate (in/hr), dashed: rain intensity (in/hr), solid: standing water level (in).

Why Do Floating Roofs Sink?

It appears that a well-maintained floating roof with drain operating at full capacity is very unlikely to experience 10 inches of standing water. So why did fifteen floating roofs fail in Harris County, TX during Harvey? Based on the few published analyses of roof failures we have found, we think the answer is, either the drain was partially clogged, improperly sized, or one or more pontoons were sufficiently corroded to take on water. Other failure modes are referenced in an endnote[ii].

In this paper we quantify how a compromised roof drain raises the probability of high levels of standing water. Since standing water adds extra stresses to a roof it will raise the probability of failure; however, engineering analysis is needed to quantify how standing-water-induced stress influences the probability of roof failure by each of the possible failure modes.

Rain Gauge Data

The rain gauge in Figure *2* is part of a grid of 133 rain gauges maintained by the Harris County, TX, Flood Warning System (HCFWS). Continuous 5-minute data for years 1986 to the present are available for 61 of the gauges.

Identifying Standing Water Events

Standing water accumulates when rainfall intensity (in/hr) exceeds the (possibly compromised) drawdown rate (in/hr). We define a Standing Water Event as a continuous period of positive standing water beginning and ending with a dry roof (zero inches of standing water).

Figure *3* shows the history of a standing water event in a hypothetical tank located near HCFWS gauge 1540. The event began at 22:00 on Wednesday, Jan 21, 1998 and ended just after 03:00 on Jan 22. We assumed that the roof drain was compromised to the extent that the drawdown rate was only 1 in/hr. The dashed line is a hyetograph: a graph of rainfall intensity in inches per hour (iph). Note that standing water increases only when intensity exceeds draw down rate.

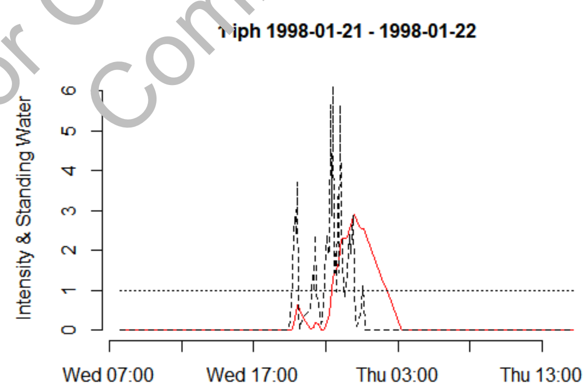

Figure 3. Rainfall Hyetograph and resulting standing water assuming 1 iph drawdown.

Depth-Drawdown-Frequency (DDF) Table.

We summarize the statistical risk of various depths of standing water in a Depth-Drawdown-Frequency (DDF) table, analogous to Intensity-Duration-Frequency (IDF) tables used in infrastructure planning[iii].

Table *1* shows estimated maximum standing water at various drawdown rates and return periods based on pre-Harvey data. For example, a partly clogged drain with 2 in/hr drawdown rate (DDR) would experience 1.21 or more inches of standing water once in 10 years. Tabled values are percentiles of Generalized Extreme Value distributions fitted to annual standing water maxima at each draw down rate.

DDR (in)	0.25	0.5	1	2	3
RP (yrs)	Maximum Standing Water (in)				
2	2.34	1.71	1.14	0.62	0.32
5	3.12	2.35	1.63	0.91	0.51
10	3.89	2.99	2.14	1.21	0.73
25	5.20	4.10	3.07	1.77	1.16
50	6.48	5.21	4.03	2.36	1.65
100	8.08	6.62	5.29	3.14	2.35
1000	16.78	14.69	13.05	8.11	7.56

Table 1. Gauge 1540 max. standing water by return period (RP) and drawdown rate (DDR).

Figure 4 is a plot of the fitted standing water values in Table *1*.

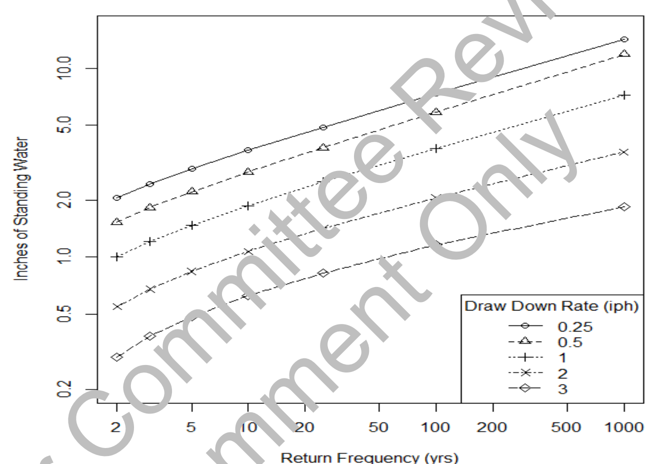

Figure 4. DDF: Max Standing Water **D**epth by **D**raw down Rate and Return **F**requency.

IDF Approximation of DDF

It is difficult to find the three decades of high quality 15-minute rainfall data needed to compute a DDF table for a given location. For that reason, we investigated using rainfall Intensity-Duration-Frequency (IDF) tables from NOAA's Precipitation Frequency Data Server[iv] to approximate standing water DDF tables.

NOAA Precipitation Frequency Server

NOAA has IDF tables for 43 of the lower 48 states[iv] computed from rainfall data through April 2017 over a grid of rain gauges in each state. Table *2* is an excerpt of the IDF table for NOAA's Goose Creek gauging station near Baytown terminal in Houston, TX. Rain gauge data underlying this table included Hurricane Harvey.

	Return period (years)						
	2	5	10	25	50	100	1000
Duration	Inches of Rain						
5-m	0.61	0.76	0.89	1.08	1.22	1.37	1.96
10-m	0.96	1.21	1.42	1.72	1.95	2.19	3.05
15-m	1.22	1.53	1.79	2.15	2.43	2.73	3.88
30-m	1.75	2.18	2.54	3.05	3.43	3.83	5.56
1-h	2.33	2.93	3.44	4.14	4.68	5.27	7.90
2-h	2.92	3.77	4.53	5.66	6.58	7.61	12.0
3-h	3.27	4.30	5.26	6.71	7.95	9.35	15.2
6-h	3.90	5.24	6.55	8.56	10.3	12.4	20.9
12-h	4.59	6.23	7.85	10.3	12.6	15.1	26.7
24-h	5.32	7.29	9.24	12.3	14.9	18.1	32.5

Table 2. IDF Table for Goose Creek Station, TX

Given the wide availability of up-to-date IDF tables, it would be useful to be able to approximate tank roof flooding risk from IDF data.

How the Approximation Works

To illustrate how our approximation works, consider a tank that can drain 1.5 inches of water per hour (ddr = 1.5). We can approximate the 25-year standing water event for that tank from the 25-year rainfall maxima in Table *2*. For example, the 3-hour 25-year maximum is 6.71 inches of rain. In 3 hours, 4.5 inches of that accumulation would drain off leaving 2.21 inches of standing water.

That is fine if the 25-year standing water event happened to last 3 hours from dry to maximum. In general, we need to do the same calculations for other durations and take the maximum of those. Figure 5 repeats this calculation at each duration. Maximum standing water is 2.66 inches at two hours. So, we know that about once in 25 years there will be a two-hour interval in which 2.66 inches of standing water are added to any existing standing water, consequently the 25-year standing water maximum must be at least 2.66 inches.

Duration	Hours	25 year Rainfall	Drawdown ddr x hours	Net standing water
5-m	0.08	1.08	-0.13	0.96
10-m	0.17	1.72	-0.25	1.47
15-m	0.25	2.15	-0.38	1.78
30-m	0.50	3.05	-0.75	2.30
1-h	1.00	4.14	-1.50	2.64
2-h	2.00	5.66	-3.00	**2.66**
3-h	3.00	6.71	-4.50	2.21
6-h	6.00	8.56	-9.00	0.00
12-h	12.00	10.3	-18.00	0.00
24-h	14.00	12.3	-21.00	0.00

Figure 5. Approximate 25 year standing water is 2.66 inches when ddr=1.5 iph.

Figure 6 is the approximate DDF table computed by this method; the nominal drawdown rate is 1.5 inches per hour. The table shows standing water risk at full capacity as well as 75, 50, 25, and 10% capacity. If the drain is operating at 0.15 inches per hour (10% capacity), ten inches of standing water is a 25-to-50-year event.

Draw down rate	Return period (years)						
	2	5	10	25	50	100	1000
	Inches of Standing Water						
1.500	1.00	1.43	1.94	**2.66**	3.58	4.85	11.9
1.125	1.21	1.81	2.32	3.41	4.58	5.98	14.2
0.750	1.58	2.27	3.03	4.46	5.80	7.90	17.7
0.375	2.17	3.18	4.30	6.31	8.10	10.6	23.5
0.150	3.00	4.43	6.05	8.70	11.3	14.5	30.7

Figure 6. Approximate maximum standing water by drawdown rate and return period, Goose Creek.

Potential Accuracy of the Approximation

Figure *7* shows a standing water event at HCFWS gauge 1540 assuming drawdown rate (DDR) 1.0 inches per hour. Maximum standing water was 2.92 inches at 00:05 on 1/22/1998 starting from no standing water at 21:55 on the previous day, an interval of 2 hours.

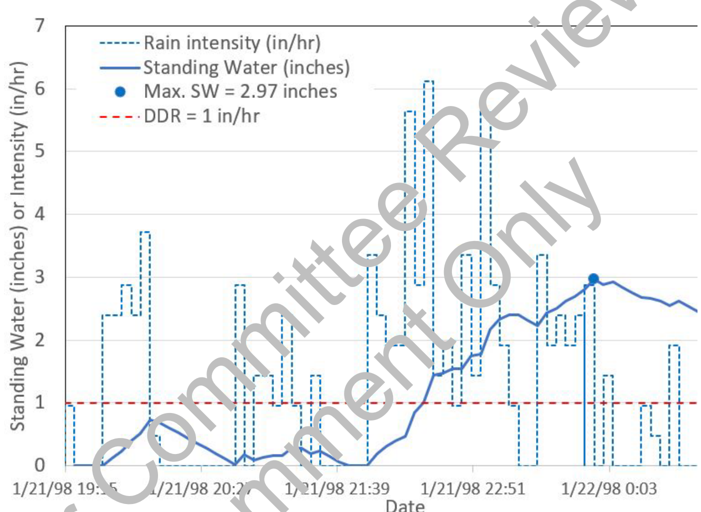

Figure 7. Rain event of 21-Jan-1998.

The dashed line in Figure *8* is the 3-hour interval with maximum average rainfall intensity (ARI), 1.9 inches per hour. The diagonal line shows theoretical standing water assuming constant intensity 1.9 iph. Total accumulation is:

$$(ARI - DDR) \times duration \ = \left(1.9\frac{in}{hr} - 1\frac{in}{hr}\right) \times 3\ hr \ = \ 2.7\ in$$

Actual maximum standing water is 2.97 inches, so the approximation is about 9% low.

There are two reasons for the error. First, during the circled interval on the time axis there was no standing water and therefore no drawdown; however, the approximation assumes constant rainfall intensity and therefore continuous drawdown. Second, there happened to be positive standing water at the beginning of the 3-hour window which is not included in the estimate.

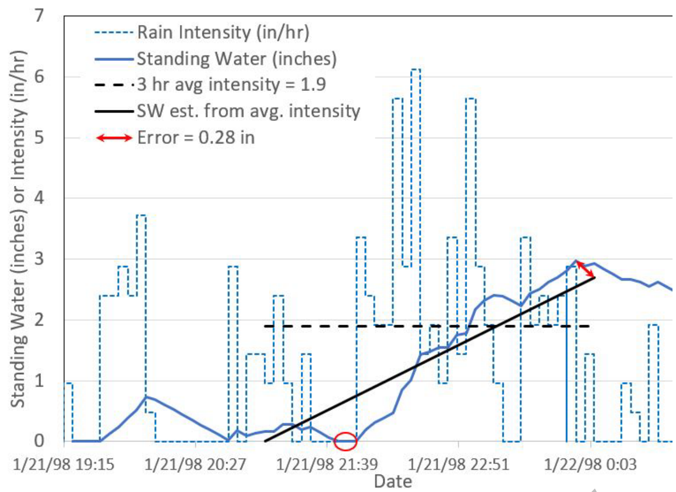

Figure 8. Max standing water approximated by 3-hour average intensity.

Figure 9 shows that it is possible for the estimate to be perfect when the interval of maximum constant intensity starts with zero standing water and includes no intermediate stretches of zero standing water. Unfortunately, without access to raw data there is no way to know if or when this is true.

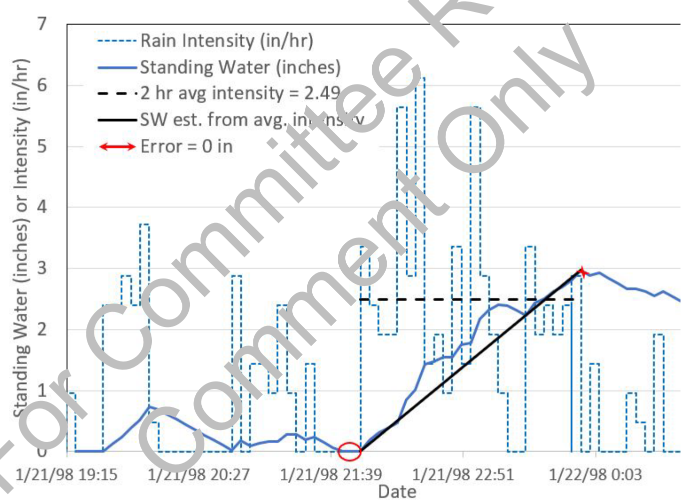

Figure 9. Max standing water approximated by 2-hour average intensity.

Error Analysis of the IDF Approximation

While it is true that for any standing water maximum there is a corresponding maximum average rain intensity interval that produces a perfect approximation, another source of error emerges when estimating standing water percentiles from rain intensity percentiles.

This component of error can be computed at a given site from raw 5-minute data or it could be estimated using simulated 5-minute data, generated with a Poisson cluster stochastic rainfall generator[v]. We illustrate the raw-data method with 5-minute data from the average of Harris County, TX.

Our error analysis used the average 5-minute rain accumulation of HCFWS gauges 1540 and 1520, north and south of Baytown in Figure *1*.

We computed annual maximum rain accumulation for years 1986 – 2013 at durations 5 minutes through 4 days and fit Gumbel distributions to each duration to produce the IDF table graphed in Figure *10*.

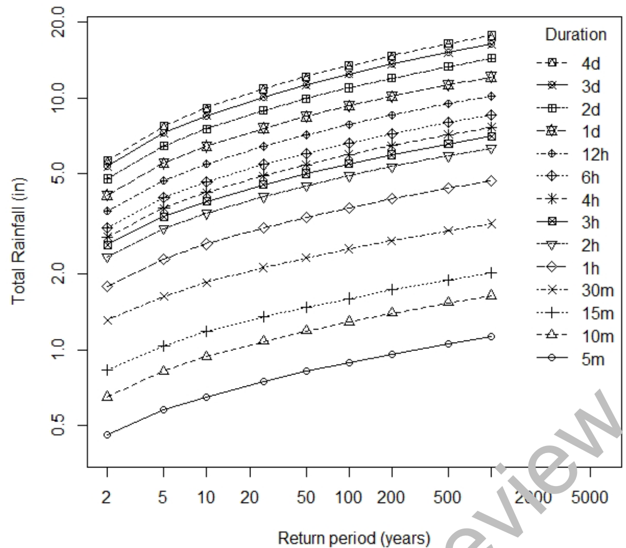

Figure 10. Baytown IDF, Gumbel-smoothed

Next, we computed, directly from raw rainfall data, annual maximum standing water at drawdown rates from .1 to 4 inches per hour and fit Gumbel distributions to each drawdown to produce the true DDF table. Approximate (symbol) and exact (curve) DDF values are in Figure *11*

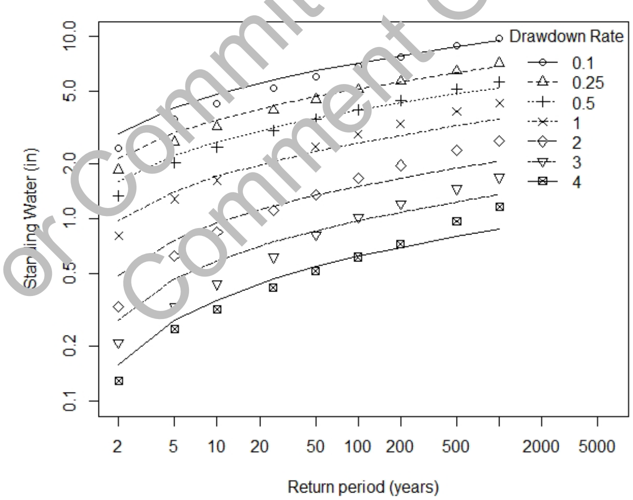

Figure 11. Approximate and Gumbel-smoothed Exact DDF at Baytown.

Approximation errors for Figure *11* are listed in Table 3. Errors for extreme standing water events (5 or more inches of standing water) are highlighted; for extreme events, absolute errors are less than ± 0.55 inches and percent errors are less than ± 7%.

Draw-down (in/hr)		Return Period (years)								
		2	5	10	25	50	100	200	500	1000
0.1	%	.19	.16	.13	.11	.7	.4	.2	1	2
	in	.47	.56	.55	**.55**	.44	.28	.13	.07	.22
.25	%	.16	.12	.9	.6	.3	.1	1	2	5
	in	.29	.31	.28	.23	.15	.06	.04	.15	.33
.5	%	.19	.10	.7	.4	.2	1	3	6	**7**
	in	.26	.20	.17	.12	.06	.02	.12	.29	.42
1	%	.21	.10	.5	0	6	11	14	17	19
	in	.17	.13	.08	.01	.14	.31	.46	.66	.82
2	%	.48	.21	.12	.4	1	10	15	20	23
	in	.16	.13	.10	.05	.01	.16	.29	.47	.62
3	in	.33	.42	.34	.21	.5	4	10	16	20
	in	.07	.14	.15	.13	.04	.04	.12	.23	.33
4	%	.23	.12	.13	.12	.6	.2	4	18	25
	in	.03	.03	.04	.05	.03	.01	.03	.17	.29

Table 3. DDR approximation errors. Highlighted: standing water events of 5 or more inches.

Conclusion

Approximate standing water depths can be computed from NOAA IDF tables. These estimates, accurate to about a half inch, are used in sizing floating roof tank drains, but drainage calculations are based on ideal conditions that are not representative of major weather events.

The failure of floating roofs during major weather events is a fairly common failure mechanism for floating roof tanks. The ability to drain water from the roof is dependent on the hydraulic potential of the water on the roof.

The hydraulic potential is dependent upon the drain hose size, floating roof height, height of water in the berm area, valve position, and obstructions present in the floating roof drain hose.

These factor in the ability to flow water off the roof point to the need to clear drain intakes regularly to maintain adequate drawdown rates. Dust and debris, birds' nests, and more can get inside of floating roof hoses and prevent or reduce the flow of water from floating roofs. It is a good practice to oversize floating roof drain hoses during the design stage. Floating roof drain hoses that are already in use can be tested to determine the current flow rate, and cleaning can improve those drain hoses that are underperforming.

Endnotes

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[i] International Plumbing Code, Roof Drains

[ii] Maintenance & Reliability of Floating Roofs https://onestopndt.com/blog/storage-tanks-maintenance-reliability-of-floating-roofs/

[iii] API 650 C.3.4.1 "Floating roofs shall have sufficient buoyancy to remain afloat on liquid with a specific gravity of the lower of the product specific gravity or 0.7 and with primary drains inoperative for the following conditions: 250 mm (10 in.) of rainfall in a 24-hour period over the full horizontal tank area with the roofs intact. "

[iv] NOAA Atlas 14, point precipitation server. https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html

[v] A Poisson Cluster Stochastic Rainfall Generator That Accounts for the Interannual Variability of Rainfall Statistics: Validation at Various Geographic Locations across the United States, https://www.hindawi.com/journals/jam/2014/560390/

Appendix 6 – Resilience Concepts and Principles

Overview

Steps to incorporate resilience into project design:

1. Meet all applicable codes, standards, and industry practices for structural safety.
2. Identify stakeholders – end users (customers, communities), owners and operators, authorities and regulators, insurance, general public.
3. Include 'time to recovery from failure' as part of the design and evaluation process.
4. Review and finalize performance goals with key stakeholders - identify system resilience goals (e.g., time to resume operations after damage). Are sustainability or climate adaptation requirements to be included?
5. Quantify resilience goals – establish project design and acceptance criteria that include functional recovery.
6. Develop design options for Design Hazard Events, and check performance for Routine and Extreme Events.
7. Expand risk assessment to include likelihood of functional recovery in a specified time, potential consequences for stakeholders (e.g., end users, environment), and interdependencies (e.g., need for power, transportation; impacts on fuel supply, economy).
8. Prioritize alternative design solutions with:
    a. Resilience tradeoffs between optimization, robustness, redundancy, uncertainty (degradation, future hazards/loads).
    b. Benefits vs costs assessments of design alternatives.

Introduction

Resilience is broadly defined as the ability to prepare for disruptive events, adapt to changing conditions, and to withstand and recover rapidly from disruptive events. A disruptive event is a discrete (acute) event that causes damage to a system such that it is unable to perform its intended function or service the damage may also result in other consequences, such as contamination or physical damage to other property or systems. A key component of resilience is recovery of function (e.g., intended use or services) within a specified timeframe. Recovery often occur in stages, depending on the level of damage and role of the facility or system in the recovery of other systems. Resilience is an encompassing, umbrella concept that gives context to and identifies correlations between pre-event and post-event activities and outcomes as indicated in Figure 1.

Facility design characteristics, such as redundancy and robustness, can greatly reduce damage levels. Tank facilities must also address degradation over time due to corrosion, cyclic loading, and (potentially) inadequate maintenance. Facility performance may also be impacted by stressors---slowly-changing conditions over time---that modify design assumptions. Examples include sea level rise and increased flood elevations near ports and increased land and atmospheric temperatures.

The pre-event condition of a facility, and its ability to absorb or distribute loads, provides the initial conditions for resisting a hazard event. Facility condition at the time of a disruptive event and the intensity or severity of the event determines the likely level of damage and consequences.

During recovery stages, the minimum operational level supports recovery and reduces losses after the disruptive event. Recovery depends on personnel, supply chain, temporary measures, and the plan for recovery. Resumption of a basic level of system services may require temporary solutions (e.g., generator for electric power) as repairs or construction are completed. Full recovery takes place when all repairs and construction are completed, including any improvements. At this stage, the facility or system is best able to resist damage by future events.

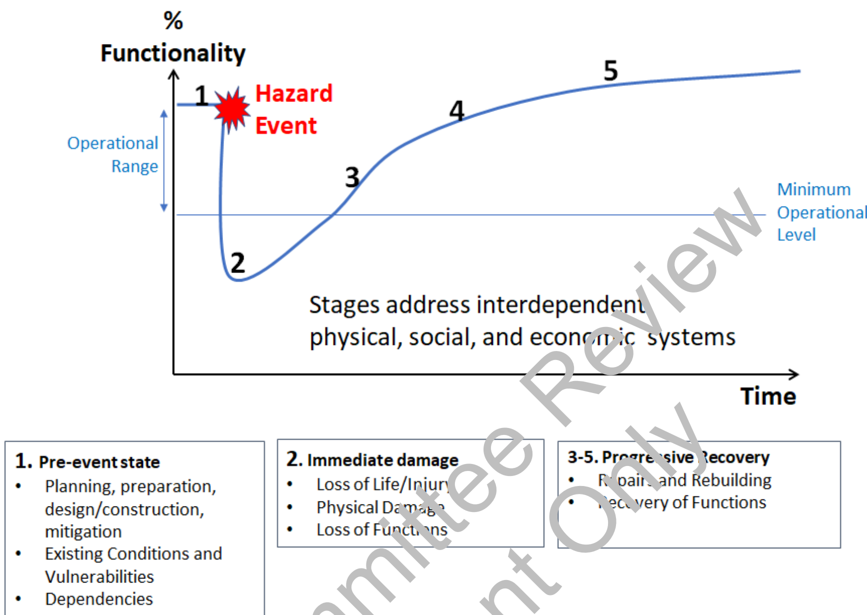


Figure 1: The stages of resilience for pre- and post-event activities.

To improve resilience in facilities, some additional information and steps can be added to the pre-event design process.

Improve data collection and problem definition

- Identify customers and end user current and future needs for services, including the impact of service disruptions.
- Identify dependencies on other systems for operational needs (e.g., staff, contractors, transportation, power), and supplies needed for temporary measures (e.g., steady fuel supply for generators).
- Document failure impacts and consequences that include direct and indirect effects. Examples include gas price increases, evacuation, business closures, loss of revenue to owners and others, health impacts, and damage to the environment. Some of these consequences can be readily addressed while others will have long-lasting effects.
- Identify performance goals for the design of new facilities and mitigation of existing facilities. Performance goals, particularly those based on time to recovery of basic and full functionality, will bring resilience into the design process and can help prioritize repair and reconstruction efforts after a disruptive event.

This information can inform the development and prioritization of design options and improve coordination with other designers and communication clients.

Improve the design process with sensitivity analyses

Facility performance and recovery after disruptive events depends on: Hazard event magnitude, facility capacity, existing condition at time of event, type of damage (ductile vs brittle, local vs global), and dependencies on other systems. Design questions for resilient performance include:

- How long will it take to recover functions for a hazard event given the estimated damage and loss? Include direct and indirect damage and losses.
- Resilient facility design requires tradeoffs on optimization vs uncertainty, robustness, redundancy.

The three levels of hazard events can be described as follows:

- *Routine events* are more frequent but should cause minimal damage and no loss of community functions.
- *Design events* are used to design the built environment; design loads are specified in codes and standards.
- *Extreme events* may also be defined in building codes for some hazards; they are likely to cause some damage.

Design of facilities is anchored by specified design loads in codes and standards. Facility robustness and redundancy can be better assessed by evaluating the expected performance for a more severe or 'extreme' event. Such events are likely to cause damage but hopefully will not result in collapse. This philosophy is similar to that used for evaluating the performance of structures for earthquake events, and can be extended to other hazards. Figure 2 shows the frequency of NaTech accidents for a range of hazard types. Additionally, evaluation of potential damage to the facility and supporting infrastructure should be considered for less severe or 'routine' events. These assessments will allow insights into the need for redundant site access or power lines or for temporary measures required to maintain functionality, in addition to improvements to increase facility resilience.

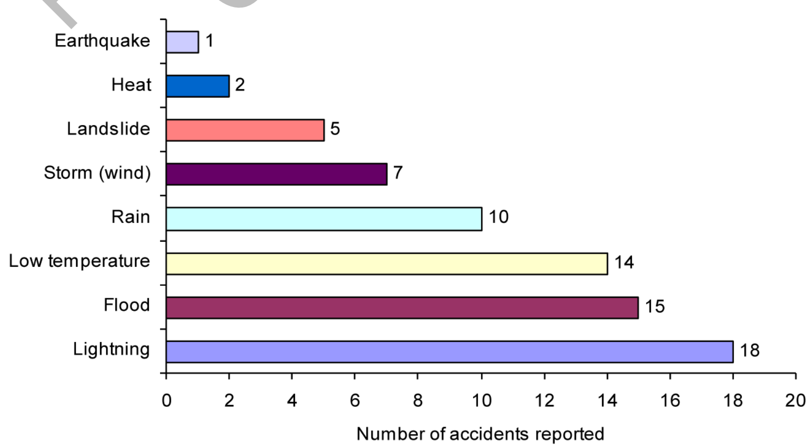


Figure 2. NaTech Reports from 5 countries, 1990-2009
(Source: MAHBulletin, Number 6, Dec 2014, JRC93386)

Expand evaluation criteria for design options

Alternative design solutions are often evaluated based on optimizing construction cost and meeting code requirements. However, this may not be sufficient to address resilience goals. Additional evaluation criteria can be used to address reducing damage and shortening recovery of function as well as minimizing impacts on customers, the environment, and local communities.

Figure 3 shows an example of how facility performance goals for functional recovery times can be used to consider alternative hazard scenarios and alternative design options. A table that shows relative performance, such as that in Figure 3, can also be used to communicate results to owners and other stakeholders.

Building Clusters	Support Needed	Design Hazard Performance								
		Phase 1: Short-Term			Phase 2: Intermediate			Phase 3: Long-Term		
		Days			Weeks			Months		
		0	1	1-3	1-4	4-8	8-12	4	4-24	24+
Source										
Raw or source water and terminal reservoirs		90%								
Raw water conveyance (pump stations and piping to WTP)		90%								
Water Production		90%								
Well and/or Treatment operations		60%		90%						
Transmission (including Booster Stations)										
Backbone transmission facilities (pipelines, pump stations, and tanks)		90%					90%			
Water for fire suppression at key supply points (to promote redundancy)		90%				90%				
Control Systems										
SCADA or other control systems		90%								
Distribution										
Critical Facilities										
Critical Medical		90%								
Critical Government		60%		90%						
Housing/Neighborhoods										
K-12 Schools				30%	60%		90%			
Child Care Centers				30%	60%	90%				

Performance Goal | Performance Gap | Anticipated Performance

Figure 3. Summarize analysis results against performance goals **(need to tailor for tank facilities).**

Benefit-cost analyses can also help prioritize design alternatives. Significant benefits can be obtained for modest cost increases, which may be offset in insurance premiums. Tradeoffs between alternative solutions can be quantified for many factors, but some factors may be more qualitative in nature. A resilience focus should address optimized performance and facility capacity to absorb and withstand events through increased robustness and redundancy with consideration of uncertainty due to degradation and future conditions. Other evaluation criteria can also be developed, such as impacts related to cascading consequences of design options. Enumeration and assessment of costs and benefits for each design option might include:

- ***Direct losses*** primarily address losses due to damage to physical infrastructure or losses due to interrupted functionality.
- ***Indirect losses*** may include business interruption, unemployment, inability to conduct business due to power outages, etc.
- ***Direct benefits*** may include reductions in damage and losses.
- ***Indirect benefits*** may include reductions in business losses, environmental impact, etc.

- ***Externalities*** are costs or benefits that impact a third party from implementing a strategy, such as public health or widespread water pollution.

Supplemental Materials

ABS Group, How the Petrochemical Industry Can Enhance Extreme Weather Resilience

https://www.abs-group.com/Knowledge-Center/Insights/How-the-Petrochemical-Industry-Can-Enhance-Extreme-Weather-Resilience-/

MAHBulletin, Number 6, Dec 2014, JRC93386

https://ec.europa.eu/jrc/sites/jrcsh/files/natech-lessons-learned-bulletin-no6.pdf

NIST Community Resilience Resources

Planning and Design Guidance

https://www.nist.gov/community-resilience/planning-guide

- C.R.P. NIST (2020). Community Resilience Planning Guide for Buildings and Infrastructure Systems: A Playbook, NIST SP1190GB-16, Gaithersburg, MD. https://doi.org/10.6028/NIST.SP.1190GB-16
- C.R.P. NIST, "Community Resilience Planning Guide for Buildings and Infrastructure Systems, Volume II" Special Publication (NIST SP) 1190v1, Gaithersburg, MD. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1190v1.pdf
- C.R.P. NIST, "Community Resilience Planning Guide for Buildings and Infrastructure Systems, Volume I" Special Publication (NIST SP) 1190v2, Gaithersburg, MD. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1190v2.pdf

Economic benefit cost guidance and tools

- https://www.nist.gov/community-resilience/edge-and-economic-decision-guide
- https://www.nist.gov/services-resources/software/edge-economic-decision-guide-software-online-tool

Motivation

Secondary containment[1] can be thought of as a reservoir, large pan or even a tank to contain spills from tank and equipment ruptures or when liquids are transferred between tanks and pipelines and other equipment typically found in petroleum storage facilities. In fact, some small tanks address secondary containment by constructing the tank within another tank to provide this function. In this appendix we are primarily referring to conventional secondary containment for tank farms as being constructed with dikes or berms constructed of earth or concrete with groups of large tanks located within these barriers or berms (Figure 1 and Figure 2).

Recognize that there are numerous definitions for and variations of secondary containment and a good place to review these details in provided by the EPA Oil Spills Prevention and Preparedness Regulations[2]. To reiterate, here we refer to secondary containment as meaning tank farms or tanks contained inside berms or dikes where spills are contained in the same area as the tanks. Secondary containment can be effective in draining the spilled liquid away from equipment so that if a fire initiates, the resulting consequences are less severe since it is not adjacent to the tanks or overheating electrical and instrumentation control lines. It also protects the environment by blocking the spillage from entering other areas which may be sensitive environments or allowing it to disburse widely due to flowing water such as streams and rivers. Note that secondary containment walls are sometimes referred to as *bunds* especially in the UK. The term *dikes* is often reserved for vertical concrete containment walls but there is no universal or formal definitions of these terms.

Although most of this appendix is specifically aimed at tank farms with large flat bottom tanks there are many secondary containment tank types. Table 1 is an example of the type of assessment that can be made in anticipation of various Natech hazards.

[1] Unfortunately, there are different meanings to the phrase "secondary containment". There are regulatory and industry definitions and they often conflict and contradict definitions written by other standards development organizations or regulatory bodies.

[2] https://www.epa.gov/oil-spills-prevention-and-preparedness-regulations/overview-spill-prevention-control-and

Appendix 7- Appendix API 656 Best Practices for Secondary Containment

Figure 1 Secondary Containment Berm

Figure 2 Secondary Containment Berms

Functionally, the secondary containment should be reasonably “liquid tight” meaning that it can contain all of the spilled liquid until it can be collected and/or cleaned up. Obviously, secondary containment would not be effective if the bottom of the containment were constructed over a highly permeable gravel layer, for example. On the other hand, it would be completely effective if it were built over an impermeable site such as one where the site soils are naturally impervious as is the case for most clay soils. Many terminals were simply constructed on native soil prior to regulatory concerns over containment and make the assumption that ordinary soil is sufficiently impermeable for containment purposes – and this turns out to be true in many cases - but certainly not all. It’s important to realize that the time to cleanup the spill and the site impermeability are related and both factors matter in the amount of contamination that can escape the facility. As leakage through the facility penetrates through the liner the quicker it can be cleaned up the less the depth of penetration.

It is useful to think about secondary containment in two functional modes – (1) containment of small spills and (2) containment of large volume catastrophic spills. Statistically, most spills are small. Considering small spills first, and we are talking about spills above the secondary containment floor onto the ground inside the berms – not pressurized buried piping leaks which is not addressed by tank secondary containment. For more information on this topic see API 2611. In addition, many tanks are built directly on the soil so long-term pressurized leaks, like the piping leaks are not addressed by secondary containment and single bottom tanks (more on this later). It should be noted that when bottoms are replaced or a new tank is built a *release prevention barrier* or *RPB* should generally be used. More details can be found in API 650 Appendix I.

Now if a surface spill occurs within the secondary containment, then the driving force for penetration of liquid into the ground (injecting it) depends on the pressure head driving (i.e. the depth of liquid on the surface), the type of liquid spilled, and the hydraulic conductivity of the soil to flow or soil permeability. For small spills which means pressure head is small, perhaps a few millimeters to a few inches, the rate of transport through the soils is small. In this case there is almost always adequate time except in highly permeable sand or gravel to clean up the spill which means removing the contaminated soil and oil. In very large spills where the depth of liquid may be several feet then the driving force for fluid transport is significant and unless the soil is relatively impermeable then there may be only several hours to a day or so to remove the contaminated soil before it escapes to the groundwater and environment.

Another problem with the idea of requiring completely impermeable liners is that in spite of a perfect liner (which does not exist) the penetrations of piping, electrical or other lines are very difficult to permanently seal especially given time and ground movement and moisture cycles. These leak paths are often far easier pathways for spills to penetrate the liner and escape to the environment than by permeation of the soil or liner. A useful analogy is to think of a steel or plastic bucket full of water. The bucket can be considered impermeable. However, if there is a leak in a seam or a hole in the bottom, the overall permeability is somewhat meaningless. There is fluid quickly draining from the bucket and the hole or seam is the problem, not the bucket permeability.

Secondary Containment

Even though secondary containment emerged as an industry best practice independently of regulations, today's regulations require the containment of spills. Secondary containment can take various forms. The most common form for clusters of larges tanks is earthen berms that surrounds the facility. The idea is to contain the capacity of the largest tank so that in the event of a catastrophic release, the secondary containment will prevent spread of the hazardous substance. In addition, some extra capacity for rainfall or contingency is required in most cases.

The three most important drivers for secondary containment are:

1. The SPCC regulation arose from the Exxon Valdez spill of March 24, 1989 which was the worst oil spill disaster in US history until the Deepwater Horizon incident in 2010. Eleven million gallons of crude oil spilled into Prince William Sound destroying the local environment and depositing oil slicks over 1300 miles of coastline as well as killing wildlife. The spill was caused by the tanker's impact

with Bligh Reef tearing a hole in the hull releasing the oil. This incident was the initiating event for creation of the Oil Pollution Act of 1990 and ultimately resulted in the first version of the Spill Prevention Control Countermeasures regulation in 1973 which became effective in January 1974. In addition to many other rules the SPCC requires application of secondary containment to facilities that handle oil which has the potential to spill into navigable waters of the US (which is nearly all petroleum and chemical facilities).

2. NFPA 30

NFPA 30, Flammable and Combustible Liquids Code, published by the National Fire Protection Association is an industry standard that addresses the potential hazards associated with the storage, handling and use of flammable and combustible liquids.

3. Transportation related facilities under 49CFR Part 195.

States may layer additional requirements for containment above those specified by the SPCC rule.

NFPA 30 is enforceable under building and fire prevention codes in well over half of the states. It is also enforceable in several local jurisdictions and may include enforcement under Occupational Safety and Health Administration (OSHA) regulations.

NFPA 30 refers to the general topic of controlling the location of a major unexpected spills from a tank *spill control* or *impoundment*. NFPA 30 requires spill control primarily for fire protection purposes but has been revised to mention the additional purpose of preventing the spills from entering waterways, public sewers and adjoining properties. The NFPA 30 spill control requirements apply to all flammable and combustible liquids except to Class IIIB liquids.

NFPA 30 recognizes at least two types of secondary containment where large volumes of liquid are stored:

1. Remote impounding: Where control of spills is provided by drainage to a remote impounding area which is isolated from the storage tanks so that spilled liquid does not collect around the base of the storage tanks.
2. Diking or local containment or impoundment: Where the spill is stored inside the tank area by dike walls or earthen berms.

In either case, the idea is to contain the volume of the largest tank within the impounding area. Remote impounding allows credit to be taken in using portions of (1) and (2) to achieve the volume requirement.

NFPA 30 considers remote impoundment to be an inherently safer alternative since it has less stringent requirements for remote impounding versus local impounding. Intuitively, remote impounding should be safer than standard local secondary containment because large volumes of liquid cannot accumulate in the tank farm near the tanks which could be ignited but are drained to a remote area impoundment pond. This can be observed, for example, in NFPA 30 Table 22.4.2.1 where the shell-to-shell spacing for tanks is less stringent if there is remote impounding. For example, for floating roof tanks, the remote impoundment spacing between any two tanks can be as little as 1/6 the sum of the diameters whereas with bermed or diked secondary containment the spacing is ¼ of the same sum. Unfortunately, remote impoundment is relatively rare because of the space and proper site drainage profiles needed.

It may be tempting to reduce the area of land required by building higher secondary containment walls or berms but convention allows up to a height of 6 feet above the base as firefighting and access become more difficult and the high walls can be considered to create a confined space for trapping toxic or flammable vapors. When high walls are applied then refer to NFPA 30 Chapter 22 for details.

We do not delve into other kinds of secondary containment such as tank within tanks, or tanks with compartmented or integral walls since these are relegated to smaller tank systems. Also, not addressed is best practices for remote impoundment. The basic rules for these systems can be found in NFPA 30.

Another precaution to be aware of is that there is confusion on terminology. Secondary containment may mean the space between the two bottoms of a double bottom tank, but here we refer to it as the impoundment for the largest tank volume. Care should be exercised when communicating these terms.

Past Work on Liners

Contamination of pristine aquifers and the concern over oil spills caused more interest in the integrity of secondary containment. One of the central debates about secondary containment involved the leak tightness of the containment where tightness refers to 2 mechanisms of release:

1. Permeability of liner (which means the soil, installed liners or clay covers)
2. Integrity of penetrations such as piping, drains, or other equipment that must pass through the liner of the containment.

Prior to 1998 the Health and Environmental Affairs Department of API conducted a study that resulted in API Publication 341. A publication is informational and not to be taken as a guideline, recommended practice or standard. This work arose out of the pressure from the EPA to require that secondary containment liner systems be "impermeable". There is actually no system that is completely impermeable. Even a welded steel secondary containment has the potential for weld and seam defects that would render it permeable.

An additional important consideration is that a catastrophic release if cleaned up quickly enough does not have time to permeate deeply into the soils and liners minimizing the environmental damage. This means that the goal of a perfectly impermeable liner is not really a critical goal. Rather the goal is to (a) prevent the spill or leak from occurring, (b) quickly clean up the spill, and (c) ensure that the containment is sufficiently impermeable to maintain function over the duration needed. The ability to quickly react to spills and clean them up is a function of the emergency response divisions of companies and how they practice and are funded. One of the exacerbating factors of the Exxon Valdez incident was the poor response and unpreparedness of the emergency response activities.

In spite of the relatively simple idea of lining a tank farm with a plastic liner, there are many problems that arise from this attempt to protect the environment. Consider a sheet of cling plastic wrap for food. It will contain liquid and seems like a perfect barrier. But it does not scale up well to the size of a tank farm. A sheet of plastic several hundred yards in the length and width dimensions changes the ball game. Since sheet is manufactured with fixed widths, seems must be incorporated into lining tank farm secondary containment which introduces a whole suite of potential failure modes and problems. For example, improper mixes of plasticizers in an HDPE liner, incorrect fusion temperatures, contamination and so on mean that the seams can have defects and are not really “impermeable”. These can be latent failure modes for liners if appropriate inspection practices and testing techniques are not applied to the liner. Wind can lift and tear surface liners but those that are buried cannot be fully inspected and are subject to damage by equipment and traffic operating in the secondary containment. Perhaps the biggest problem with elastomeric liners is that of ensuring a long-term sealing of penetrations through the liner such as conduit, piping, and instrumentation loops.

Clay liners are highly impermeable but are subject to chemical degradation in certain cases, can dry, crack and lose their liquid tightness as well.

While installed liner systems have been installed in many locations that require them, it is unknown how effective they really are. There is no easy or certain way to test these facilities or to get feedback on their effectiveness. API 341 was published at a time when the regulatory solution was thought to be best accomplished by wholesale application of installed liners. But it was realized that there are many problems with them. For example, surface liners are degraded by sunlight UV exposure and the wind can rip up the liners. Penetrations are difficult to maintain integrity because of ground movement which can tear and rip the penetration seals. Complex piping systems make it prohibitively costly to attempt to do a really good job on sealing the pipes and penetrations. The UV exposure and wind problems are eliminated by burying the liner, but other problems arise as a result. The most significant problem with buried liners is that the pressure created by vehicles in the secondary containment area often tear the liner seams making them unfit for service; moreover, the failure remains undetected. Buried liners also makes inspecting the seams at a future time impractical to impossible.

Liners have indeed evolved and improved but limited resources should be focused on maximizing the desired results and this is usually done by prevention so that the problem is eliminated before it happens. But because sufficiently many spills from secondary containment have occurred there is no arguing the case that status quo is sufficient. Whether or not a liner should be installed is an engineering optimization problem that requires careful analysis; installation of liners should not be a mandated solutions, but a choice among alternatives, the best of which should be selected based on optimization of all relevant factors. As a rule, the more sensitive the site and the more permeable the natural soils are the more likely a liner will provide benefit should spills occur if properly engineered and designed.

Unfortunately, no industry organization has created any new construction or inspection criteria specifically for secondary containment. One could apply standards for diked secondary containment by adopting concrete water storage reservoirs standards because such standards are meant to be liquid tight. For example, ACI 350 Code Requirements for Environmental Engineering Concrete Structures is a useful standard that makes provisions for sufficient rebar to minimize through wall cracks, thermal expansion, water stops and liquid tight joints. However, few regulations require the use of this standard for secondary containment. In addition, the costs for a containment built to such standards would be at least an order of magnitude more than conventional and current practices.

Certainly, for soil-based berms and containment there are no good and appropriate standards for their construction. Although ACE 350 is available for concrete liquid containing structures, one must sift through reservoir construction best practices to determine what kind of requirements would be appropriate to ensure the long-term integrity of the earthen containment. The lack of standardization for constructing earthen berms is an area where industry development could improve the construction and integrity of new facilities. There is also a lack of best practices or standardization for the inspection of secondary containment. In the meantime, companies should engage competent civil engineers experienced in these areas to optimize the secondary containment design and integrity for new facilities and to develop practical techniques for inspecting and assessing the integrity of secondary containment.

The Tank Bottom Problem

It is a fact that every refinery and most terminals are undergoing remediation from past leaks, spills and ground contamination. Perhaps much of the cause goes back to times when few cared about the protection of the environment. In retrospect, it would have been much less costly for society to have undertaken both the preventive measures and ensure the integrity of the liner system in legacy facilities at the time of construction.

There is one point that makes installing even the perfect liner system ineffective. Liner systems that are retrofitted into secondary containment areas of tank farms only line the areas outside tanks – not the area under the tank footprint. Both tanks and buried pressurized piping are a significant cause of past contamination. However, there is still a large fraction of tanks that have single bottoms and these are not protecting the environment in the event of a bottom corrosion hole or crack. The protection of the tank footprint is called a Release Prevention Barrier (RPB) and is extensively covered in API 2610[3] and design details are given in API 650 Annex I. API encourages the installation of RPBs when tanks are taken out of service, or the bottom is replaced as well as for new tanks. This means that this high-risk situation will eventually reduce when enough existing tanks are retrofitted with RPBs and tank operators ensure that they are installed when the bottom is replaced.

Tanks owners and operators can reduce the potential for pressurized bottom leaks by installing RPBs at the earliest practical time and keep a scorecard related to track how many tanks have unprotected bottoms and their contents history.

Testing and Inspection

It is not industry practice to hydrostatically test secondary containment to ensure its integrity. Doing such a test would be unwise for many reasons such as:

- Undermining the foundation support throughout the containment due to changing the mechanical properties of the soil – even if only temporarily.
- Trapped moisture under tanks and in conduits and piping trenches would cause accelerated corrosion.
- Flooding secondary containment may redistribute dissolved salts especially in marine locations that would spread an active corrodent throughout the facility shortening its life.

[3] API Standard 2610, Design, Construction, Operation, Maintenance, and Inspection of Terminal and Tank Facilities

- It is difficult to impossible to define or accurately measure leakage that counts as escapement from containment as opposed to soaking up of water volume.

For this reason as well as others it is hard to judge in advance the liquid containing integrity of earthen berms or any secondary containment in advance especially given that practices for buried piping, sealing of penetrations in the containment and a host of other factors that affect the integrity of the liquid containing structure.

Fortunately, rarely is the secondary containment filled with liquid. But unfortunately, it is not only possible but likely that many existing secondary containments would not be able to stand up to being filled with liquid due to inadequate design and construction. Experts in geotechnical and civil engineering should be consulted on assessing the adequacy of the secondary containment from a hydraulic integrity perspective for questionable facilities.

Secondary containment Penetrations

Ideally, the secondary containment will have no penetrations for piping, electrical, or other conduits. While it would be possible to pump out secondary containment the most practical option for removal of water or oil is through drain sumps and systems which will penetrate the secondary containment. The motivation for minimizing penetrations is because they all represent a common failure point. If necessary they should be carefully engineered to minimize the potential for washout of soil or backfill adjacent to the pentetration.

Examples of Secondary Containment Failures

Buncefield

On 11 December 2005 the Buncefield oil terminal in Hertfordshire, UK a gasoline storage tank overfill resulted in a severe tank farm fire and explosion. The incident involved 22 tanks and 7 secondary containment systems. Significant environmental damage was also caused by leakage of petroleum products and contaminated firewater through failed secondary containment. About 786 000 liters of foam concentrate were used to control the fire.

The secondary containment consisted of earthen floors with vertical concrete walls (dikes) built in the 1960s. The notable failures of the secondary containment can be summarized by:

- Burnout of expansion joint caulking and no embedded water stops resulting in drainage of contaminated firewater foam solution between sections of wall outside of the containment.
- Poor sealing of pipe and conduit penetration resulting in leak paths through the secondary containment walls.
- Leakage through tie-bolt holes that were superficially plugged with morter that failed with radiant heat from the fire and the hydrostatic loading from the product spilling from the tanks.

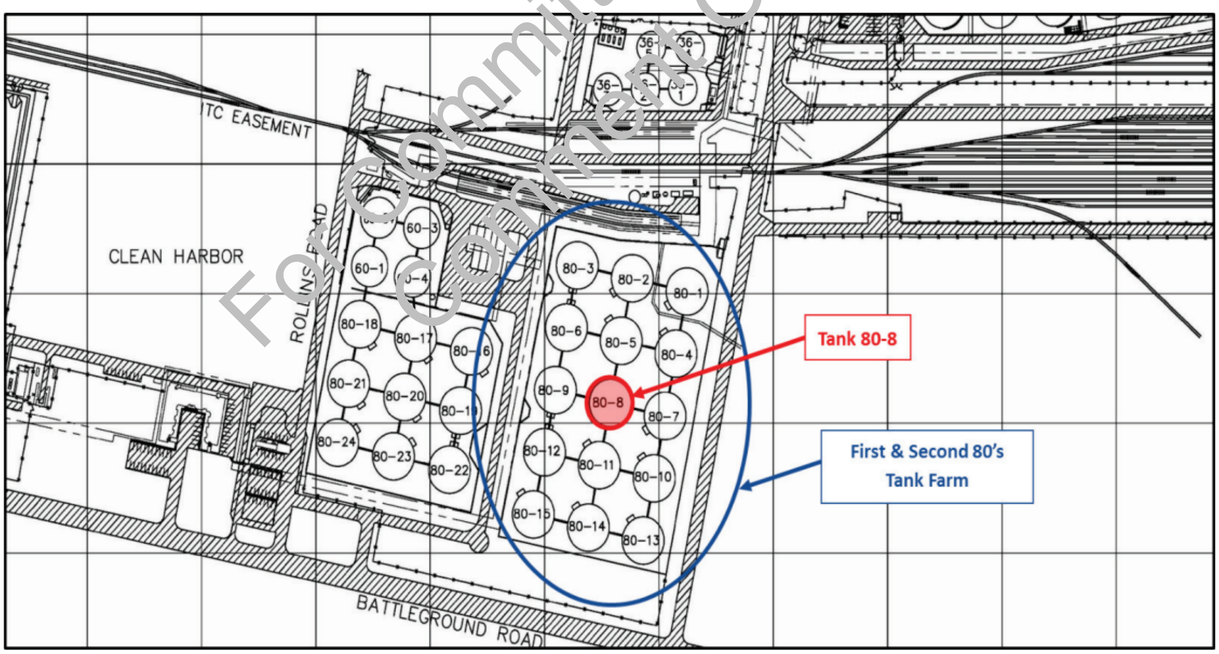
The Buncefield Standards Task Group recommended the following key points[4]:

[4] https://mosen.global/wp-content/uploads/2011/01/Lessons_from_Buncefield.pdf

- Design bund walls and floors as a water-retaining structure to BS EN 1992-3 (BSI, 2006a) or equivalent, using best practice from the water industry (e.g. UKWIR, 2011).
- Ensure all bund walls and floors have properly designed and carefully built joints, with central water stops that should be stainless steel sheet in the highest risk category sites.
- Avoid through-wall tie-bolt methods for fixing formwork and use cast-in types or suitable framing.
- Do not route pipework through the concrete floor slabs.
- If it is not possible to avoid pipework passing through bund walls, then provide proper puddle flange connections to form a watertight seal.
- Set up a regular inspection maintenance regime as befits any safety-critical element of the facility.
- For existing facilities, carry out a baseline survey to find out how bunds have been built and whether there has been a change in use/risk; if deficient, address any shortfall by extending or upgrading the secondary and/or tertiary containment.

Intercontinental Terminal Company (ITC) Tank Fire

This incident occurred at Deer Park, TX on 17 March 2019. The end result was a massive fully involved fire of 15 tanks as shown in the Figure.



As a result of fire fighting large quantities of fire water/foam solution accumulated in the secondary containment as shown in the plot plan. While the secondary containment walls were steel-reinforced concrete there were no dowels between the sections of the dikes. The dike wall were separated only by plastic water stops. As a result, when the hydraulic head was high enough the water stops ripped and the sections of dikes toppled and dumped the entire contents of the secondary containment containing, oil, foam solution and water into the Deer Park storm water channels which connect to the Houston Ship Channel creating massive pollution.

Chemical Tank Failures

Fertilizer Tanks

Fertilizer is classified as a chemical but shares many common features of secondary containment for oil storage tanks. There have been many large volume fertilizer releases[5]. In these cases, earthen berms were used for secondary containment. In most cases they worked as intended but some escape of product to the environment occurred. Some facilities had elastomeric liners in addition to the native soil and others did not. Many of these incidents were due to poor tank welding and construction practices leading to catastrophic and sudden failure. When this happens there is the potential for the moving liquid to wash over berms and a fraction of the liquid escaping to the environment. In one case, temporary earthen berms were constructed in addition to the existing berms which provided reduced spillage into the environment.

Freedom Chemical Incident

The incident took place on Jan 9, 2014 in Charleston, West Virginia. The chemical storage facility had a release of methylcychohexanemethanol (MCHM) which contaminated the potable water supplies of 300,000 residents when approximately 11,000 gallons of escaped from a hole in the bottom of T396. Of interest is the fact that the secondary containment had obvious and numerous deficiencies such as gaps under the concrete block wall secondary containment. As a result the chemical flowed into the Elk River where it it was sucked into the intake of the West Virginia American Water treatment facility and then distributed as potable water. The US CSB report[6] documents the incident investigation. The risk should have been fairly obvious due to obvious deficiencies: "The secondary containment or dike wall, originally designed to control leaks, had cracks and holes from disrepair that allowed the mixture, containing Crude MCHM and PPH, stripped, to escape the containment. The leak also found a pathway to the river through a subsurface culvert 7 located under adjacent ASTs". This incident caused bankruptcy of Freedom Chemical as well as criminal prosecution of and fines for the owners of this company.

Tertiary Containment

PHMSA has applied a definition to tertiary containment[7].
"The definition of the word "tertiary" is in the place or position counted as number three. The main purpose of a tertiary containment system is to prevent the release of oils from breakout tanks to the environment in the event of a failure of both the primary and secondary containment systems. Thus, it is the number three or third line of protection. Additionally, it would be employed to contain leakage, a product release, and drainage. In this case, it is intended to assure that the operator does not lose control of the petroleum product and drainage because of such an event. It also allows time for additional measures to be deployed if an incident escalates.

[5] https://www.epa.gov/sites/production/files/2013-11/documents/tanks7.pdf
[6] https://www.csb.gov/assets/1/20/final_freedom_industries_investigation_report_(5-11-2017).pdf?15829
[7] https://www.phmsa.dot.gov/regulations/title49/interp/PI-14-0010

Appendix 7- Appendix API 656 Best Practices for Secondary Containment

"The tank, in these circumstances, would be the primary containment system, while a diked or remote impoundment would be the secondary. A remote or diked impoundment comprised of various combinations such as site drainage, sumps, diversion tanks, pits, ponding areas, lagoons, and/or impervious liners would be considered the tertiary containment".

Preplanning and Preparation

New site secondary containment can be sized and designed with state-of-the-art methods and considerations. However, existing secondary containment constitutes almost all existing secondary containment and is therefore the focus here. Secondary containment cannot easily be modified or changed. Therefore, it is important to understand the risks as well as ways to minimize and mitigate risks should a scenario occur that results in partially or completely filling the containment with oil or contaminated fire water foam solutions.

Here is a list of what may be the most critical secondary containment considerations:

- Possible spill volume and containment volume
- Volume of diked subdivisions of secondary containment (see NFPA 30-21 Chapter 22)
- Site characteristics and drainage
- Anticipated volume of fire water usage during design and worst case scenarios
- Hydraulic integrity of secondary containment assuming full (at least 48 hrs)
- Leak tightness of secondary containment including liner permeability, penetration tightness, integrity of drainage closure valves and other components
- Ability to isolate tanks and equipment inside secondary containment when there is a spill from a safe location either manually or automatically
- Design of critical equipment, controls and pipeways susceptible to destruction by fire and prevention through drainage and pooling of liquids
- Fire protection of pumps inside secondary containment (rotating equipment is an ignition source)
- Properties (flammability, toxicity, persistence, clean up potential, biohazard, etc.) of stored liquid
- Likely types of fire fighting foam to be used and pre-fire planning
- Decisions in advance about collection and containment of contaminated fire water/foam solutions should anticipated quantities be exceeded.
- Isolation of drains with water seals or traps to prevent fires in secondary containment from propagating to other areas through undergound lines and connections

The foam and fire water drainage and sizing problem

Historically, the extinguishment of a fire was so much more important than worrying about containment of spent firefighting foam water the industry standards and best practices did not address its containment and handling. While this is for the most part still true, it is widely recognized that spent foam water solutions are not innocuous and serious considerations must be given to its containment, testing, storage, treatment and release. One key problem is the recognition of the hazards of the foam concentrate chemicals which is discussed later. A review of relevant documents (see reference section) is important for planning and the management of change to use of new foam types and application rates.

Sizing secondary containment for containing foam water solution

NFPA 11 and API 2021 provide the minimum flow and time requirements for foam application rates which provide a basis for how much contaminated spent foam water will be used. But this does not provide answers to how much spent solution will actually be used or accumulate. There are many difficulties with attempting to establish how much water and foam will be used or stored during a fire event for these reasons:

- Criteria for types of fires to be fought. For example, are resources set up to fight the single largest credible tank fire that will occur, or multiple tank fires which is usually considered too extreme for normal design bases.
- Availability of water supplies and duration
- The real world required foam application rates which can vary depending on terrain, wind, and other unique facility conditions as well as the knowledge and training of the fire brigade
- The amount of foam solution needed depends on many criteria resulting in a wide variability between anticipated pre fire planning usage and actual requirements needed for extinguishment.
- Accumulation of firewater in some facilities is not an issue but in others may hamper fire fighting and must be constantly drained.
- Sizing fire water volume is done differently by different companies. For example, some assume that only 75% of the fire water rate is applied (and the rest lost or evaporated) whereas others assume different percentages.
- Type of chemicals, petroleum and fires involved (pool fires, 3D pressurized, etc.)

Larger facilities typically have the following types of separate drainage systems:

- Stormwater and surface drainage
- Oily water
- Sanatary sewer
- Chemical

Larger facilities may have all while terminals may have only a stormwater system and a sanitary system (these are always separate systems). In the event of a hydrocarbon spill the surface and stormwater systems typically will apply. These systems should have a specification for the design basis flow rates and this should be documented.

The storm or surface drainage flow rate is typically governed by the maximum of the rainfall rate or the design the maximum fire water rate, not the sum.

Fire Fighting Foams

For typical chemical and petroleum fires the use of “Class B” foams is understood to be the application of aqueous film-forming foam (AFFF), alcohol resistant aqueous film-forming foam (AR-AFFF), film-forming fluoroprotein foam (FFFP), alcohol resistant film-forming fluoroprotein foam (AR-FFFP), and fluoroprotein foam (FP, FPAR).

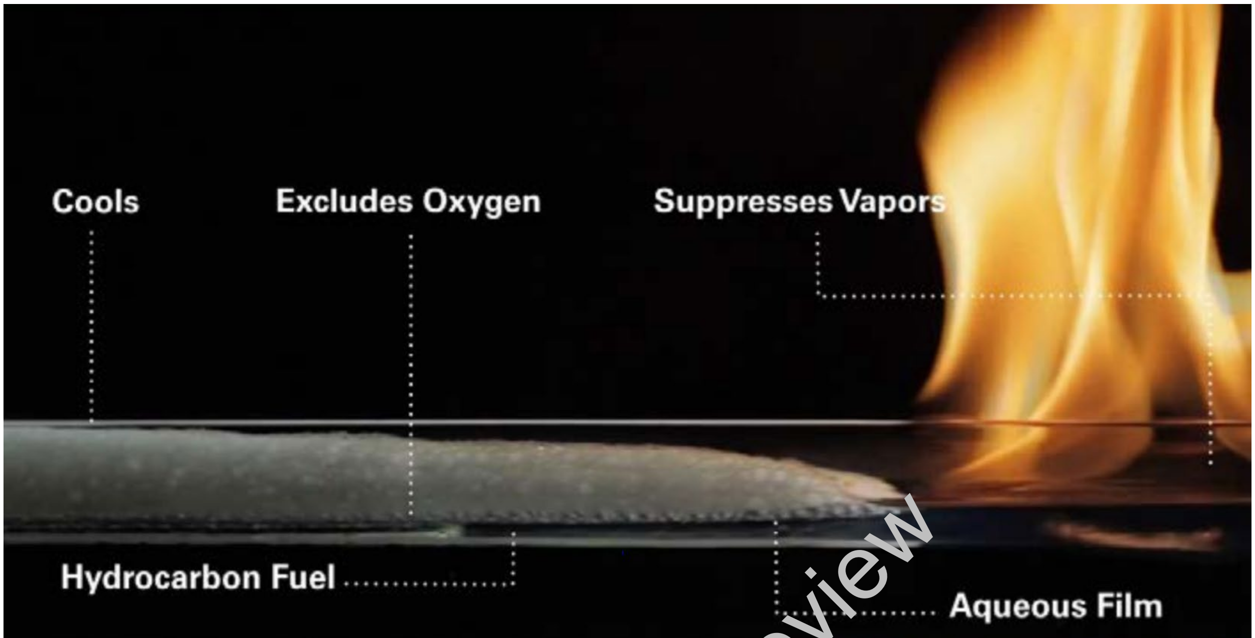


Figure 3 How fire fighting foam works

Dispensed foam flows over a stable hydrocarbon pool or liquid surface, blocking access to oxygen and preventing evaporation of the hydrocarbons by forming a blanket or layer over the burning pool. A simplified version of how these useful surfactants work is given in (figure).

Minimize Fire Risk

The best way to reduce risks of emissions from spent fire fighting foam is to reduce the likelihood of tank fires. Perhaps the most significant factor in reducing tank fires is ensuring tanks have fixed covers. Tank rim seal fires have a frequency of 0.0016 per year for external floating roof tanks, whereas the frequency for fixed roof tanks is at least 1 order of magnitude less, according to OGP[8]. Thus, internal floating roof tanks have about an order of magnitude lower likelihood of becoming involved in a fire. This is particularly true for Class 1 flammable, volatile liquids, since the vapor from these liquids pose a constant risk of rim fires from lightning strikes or other external ignition sources.

A decision/risk assessment can show whether or not the lower costs of installing external floating roof tanks outweigh the benefits of reduced fire potential from lightning-initiated tank fires. Typically, the total costs of a fire related tank incident will be many times the cost increment for fixed roof tanks. Following safety protocols for tank entry and cleaning, such as given in API 2015 and API 2016, minimizes the potential for maintenance-related incidents.

[8] OGP Risk Assessment Data Directory Report No. 434-3 March 2010

Effective, tank-specific pre-fire planning coupled with quickly enacted and well-coordinated incident command systems go a long way to reducing the amount of foam water solution required.

Planning and training exercises that involved collecting the fire foam solution for the most likely tank fire scenarios will assist in reducing the potential for contaminating the environment. A review of API 2021, API 2001, and API 2610 would be appropriate for ensuring that the pre-fire planning has captured all the necessary elements of a good plan.

Operationally, preventing overfills is vital to preventing serious fire incidents. The best way to accomplish this is by compliance with the 4 or 5 edition of API 2350. Best practices for storage tank operations are given in API 2610. For example, pumps inside secondary containment represent a significant hazard, as all rotating equipment is subject to bearing failures and should always be considered a potential ignition source. For pumps that are inside secondary containment, the best practice is to 1) install heat sensors to provide early fire warning, and 2) install dedicated pump containment and sprinkler systems based on a hazard assessment and use of sound risk management. The ability to isolate tanks, pumps and equipment that can fuel the tank fire is critical.

API Foam Guidance[9]

API has developed *Firefighting Foam Transition Guidance* (2020). The document shows how to assess the use of existing foam use and supplies, review the potential scenarios, select replacement foam, and ensure that the replacement foams will work as needed. An entire management of change (MOC) process is needed to assess the impact on existing systems and ensure that the new systems will work as intended. The MOC would also include impacts on emergency response, training, and testing processes. There are useful appendices that include checklist to ensure that the transition away from fluorinated compounds is appropriate and smooth.

Resilience

The importance of secondary containment resilience cannot be over emphasized. An approach is needed to assess, with resilience in mind, the weaknesses, faults, problems, and deficiencies with design and construction of legacy secondary containment., For example, designing secondary containment for volume of firewater, plus required freeboard, may provide an absolute minimum design, but there is no way a priori to reliably estimate the upper bound on the volume of spent foam-water, as such depends on the demands of an as yet unknown firefighting situation.. Resilience asks to assume the worst case of a containment overflow, and have a plan in the event this happens. There are always options to consider in these situations, including a change in business practices and the storage of certain chemicals or products. Other areas where resiliency thinking can help can be ascertained by reviewing some of the issues outlined in this Appendix as well as input and support by internal and external SMEs.

[9] https://www.api.org/-/media/Files/Oil-and-Natural-Gas/Refining/Firefighting-Foam-Transition-Guidance-October-2020.pdf

Appendix 7- Appendix API 656 Best Practices for Secondary Containment

Other Sources of Information

API 2001 Fire Protection in Refineries
API RP 2021 Management of Atmospheric Storage Tank Fires
API 341 Dike Field Liner Survey
AI 2610
API 2350
Api 351 Overview of soil permeability test methods

https://www.dec.ny.gov/docs/remediation_hudson_pdf/der17.pdf
DER-17: Guidelines for Inspecting and Certifying Secondary Containment Systems of Aboveground Petroleum Storage Tanks at Major Oil Storage Facilities
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.521.7556&rep=rep1&type=pdf
fraction of liquid spilled from secondary containment from catastrophic tank spills
HSE Secondary Containment https://www.hse.gov.uk/comah/sragtech/techmeascontain.htm

Appendix 7 Table 1

Secondary Containment

Secondary containment NATECH matrix addresses failure of secondary containment mechanism

Type of Containment	Earthquake	Tsunami	Flood (exposure to running water)	Flood coastal	Wind	rain	flood	lightening	See Note 2
Basin Tank	P	L	P						
Double wall tank	P	L	P						
Concrete Encased AST	P	L	P						
Protected tank (UL2085)	P	L	P						
Flame Resistant (UL 2080)	P	L	P						
Tank in Steel Dike (unit)	P	L	P						
Tank with steel dike and weather shield	P	L	P						
Tank with steel dike sealed	P	L	P						
Tank in basin (sides taller than tank, open top)	P	L	P						
Earthen dike (native)	F	F	F						
Earthen dike (imported clay material)	F	F	F						
Earthen dike with synthetic liner	P	F	F						
Concrete dike	F	L	P						
Fabricated steel dike	P	L	P						
Remote impoundment pond(native material)	F	C	F						
Remote impoundment pond(clay lined)	F	C	F						
Remote impoundment pond(synthetic lined)	F	C	F						
Remote impoundment pond(native material) large tanks (>75K gal)									
Remote impoundment pond(clay lined) large tanks (>75K gal)									
Remote impoundment pond(synthetic lined) large tanks (>75K gal)									

Note 1: Example of one way to show vulnerabilities of various secondary containment. Each facility should adjust the table as appropriate and fit for purpose.
Note 2:: Additional columns could be Drought, fire, Elevated temp (120F), Cold temp (-40F), Snow over 18”, Ice Storm, Landslide

P Will remain functional as containment assuming proper design.
F Failure of unit, repair required
C Capacity of containment is occupied by water until water removed
L Will function until the water exceeds the height of the containment/ tank top then failure possible if water enters tank/containment via tank openings

Appendix 8 – Natech Initiating Events

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Sample map(s): 10

Appendix NH1: Lightning

Lightning poses a regular risk to petroleum tanks and facilities. Lightning can ignite petroleum vapors in and around tanks and facilities, and lightening is attracted to tall metallic structures (common at petroleum facilities).

Technical References:

API 2003 – Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents
API RP 545 – Recommended Practice for Lightning Protection of Aboveground Storage Tanks for Flammable or Combustible Liquids

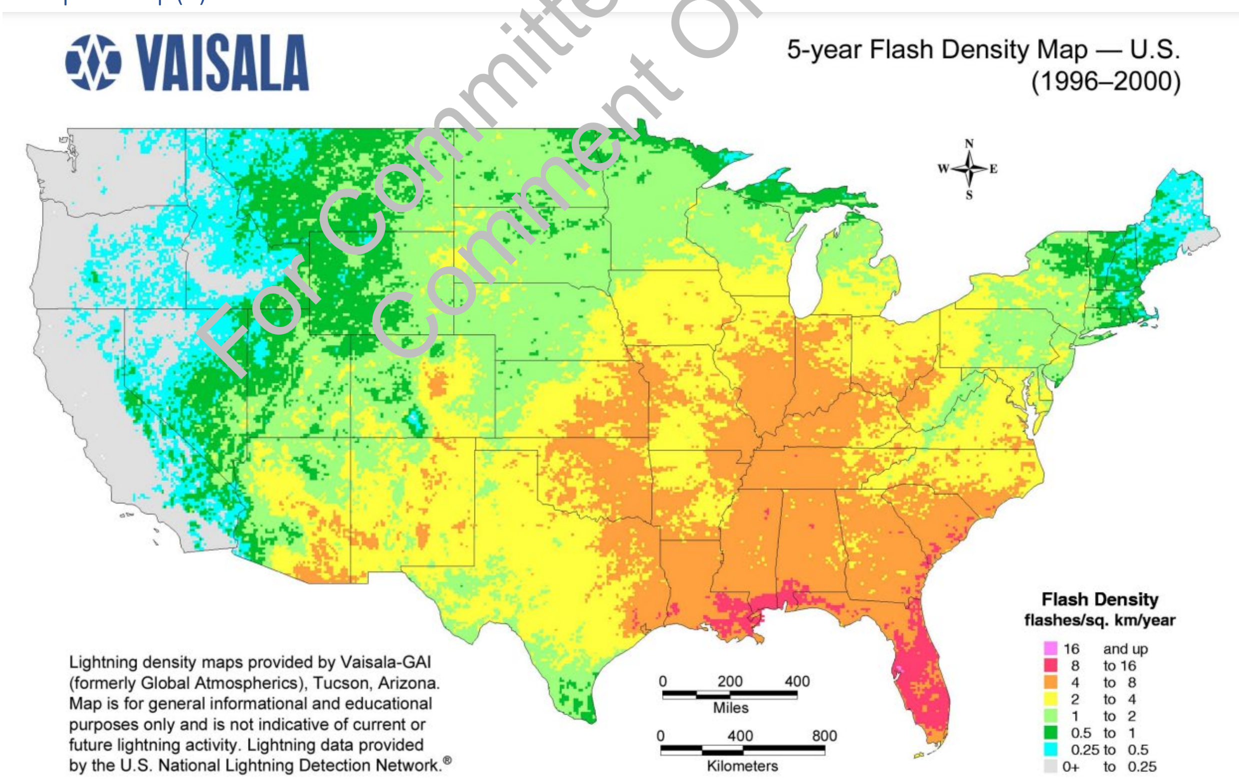
Web map references:

http://lightningsafety.com/nlsi_info/lightningmaps/US_FD_Lightning.pdf

Best practices:

1. Use the National Weather Service website to determine the risk for lightning in your area.
2. Do not fill tanks when a potential lightning storm is passing overhead.

Sample map(s):



Appendix NH2: Hurricane and Wind

Technical References:

ASCE 7-16 – Minimum Design Loads and Associated Criteria for Buildings and Other Structures
API 650 12th Edition – Welded Tanks for Oil Storage

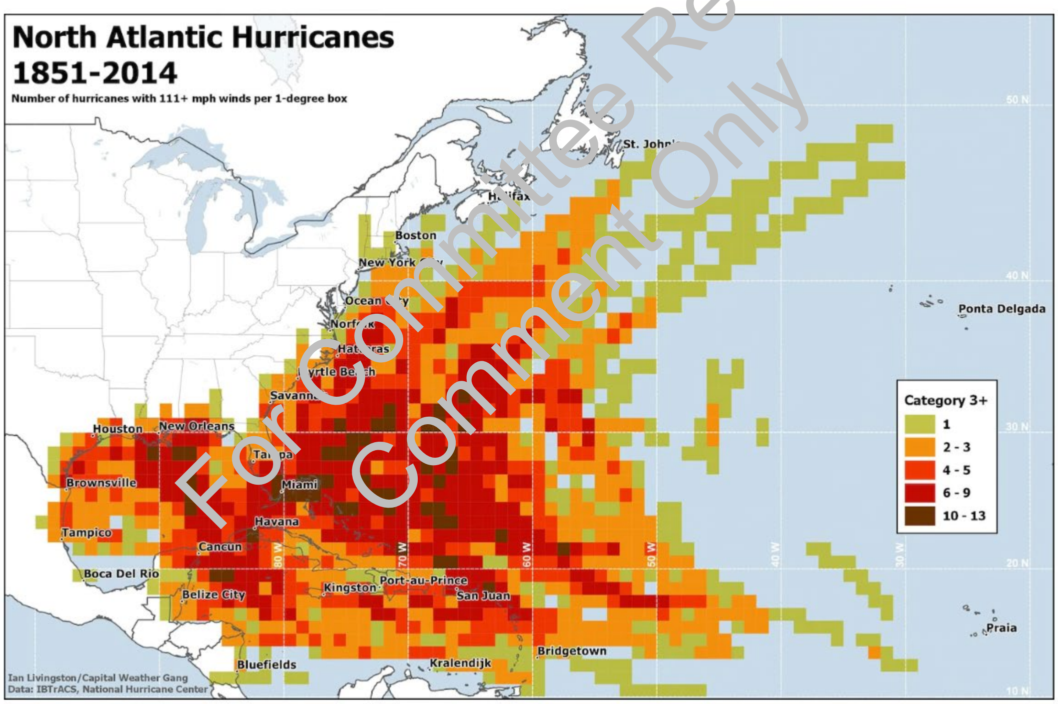
Web map references:

https://webapps.usgs.gov/infrm/estbfe/ - USGS tool for determining the Base Flood Elevation (BFE)

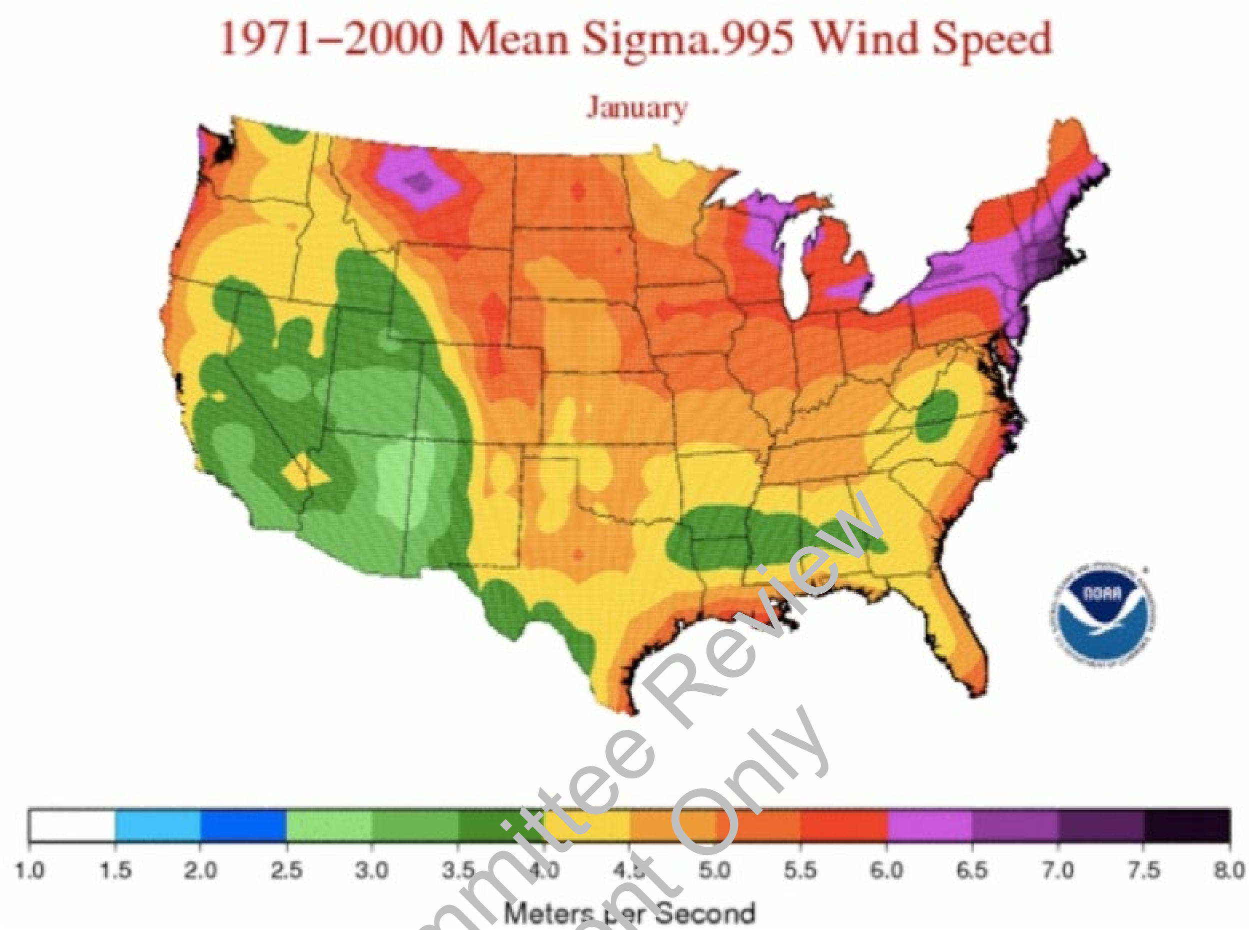
Best practices:

Rank tanks for sliding and overturning (see Appendix 4).
Establish product and/or water ballast levels and protocol for emergency acquisition of product to ballast tanks for incoming hurricane (see Appendix 4).
Establish pre-hurricane procedures for filling tanks in preparation for hurricane.

Sample map(s):



Category 3 — major status — or greater hurricane occurrences across the North Atlantic. (Ian Livingston)


1971–2000 Mean Sigma.995 Wind Speed
January
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
Meters per Second

Appendix NH3: Tsunami

Technical References:

Web map references:

https://nws.weather.gov/nthmp/documents/Tsunami_Assessment_Final.pdf

Best practices:

Sample map(s):

Table A. Qualitative tsunami hazard assessment based on NGDC and USGS databases.

Region	***Hazard based on runups***	***Hazard based on frequency***	***Hazard based on local earthquakes***	***Number of reported deaths***
U.S. Atlantic coast	Very low to low	Very low	Very low to low	None
U.S. Gulf coast	Very low	Very low	Very low	None
Puerto Rico and the Virgin Islands	**High**	**High**	**High**	**172**
U.S. west coast	**High**	**High**	**High**	**25**
Alaska	**Very high**	**Very high**	**High**	**222**
Hawaii	**Very high**	**Very high**	**High**	**326**
U.S. Pacific island territories	**Moderate**	**High**	**High**	**1**


Tsunami events in the United States and Puerto Rico
**1964 Prince William Sound
1960 Chile
Alaska
Puerto Rico / Mona Rift
1867 Virgin Islands
1700 Cascadia
900 Puget Sound

Appendix NH4: Seismic

Technical References:

ASCE 7-16 – Minimum Design Loads and Associated Criteria for Buildings and Other Structures
API 650 12th Edition – Welded Tanks for Oil Storage

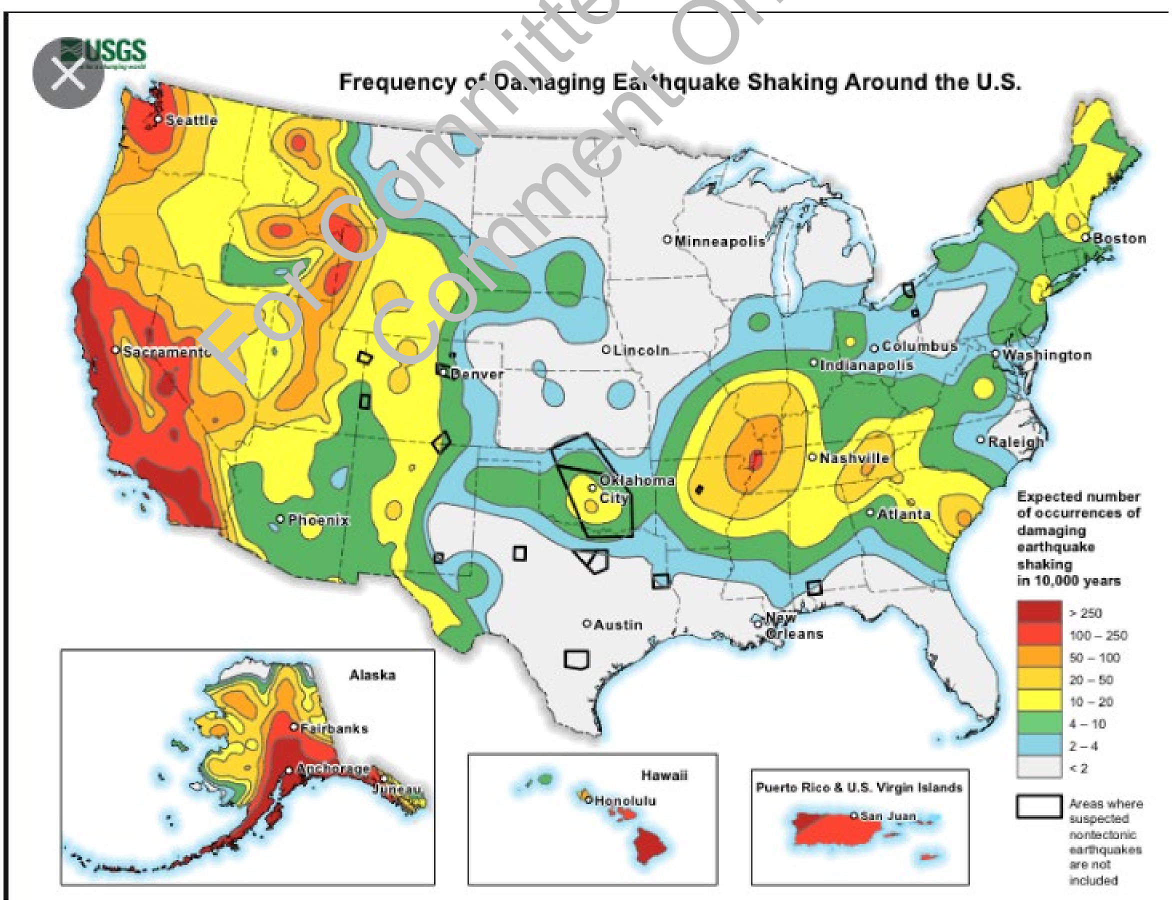
Web map references:

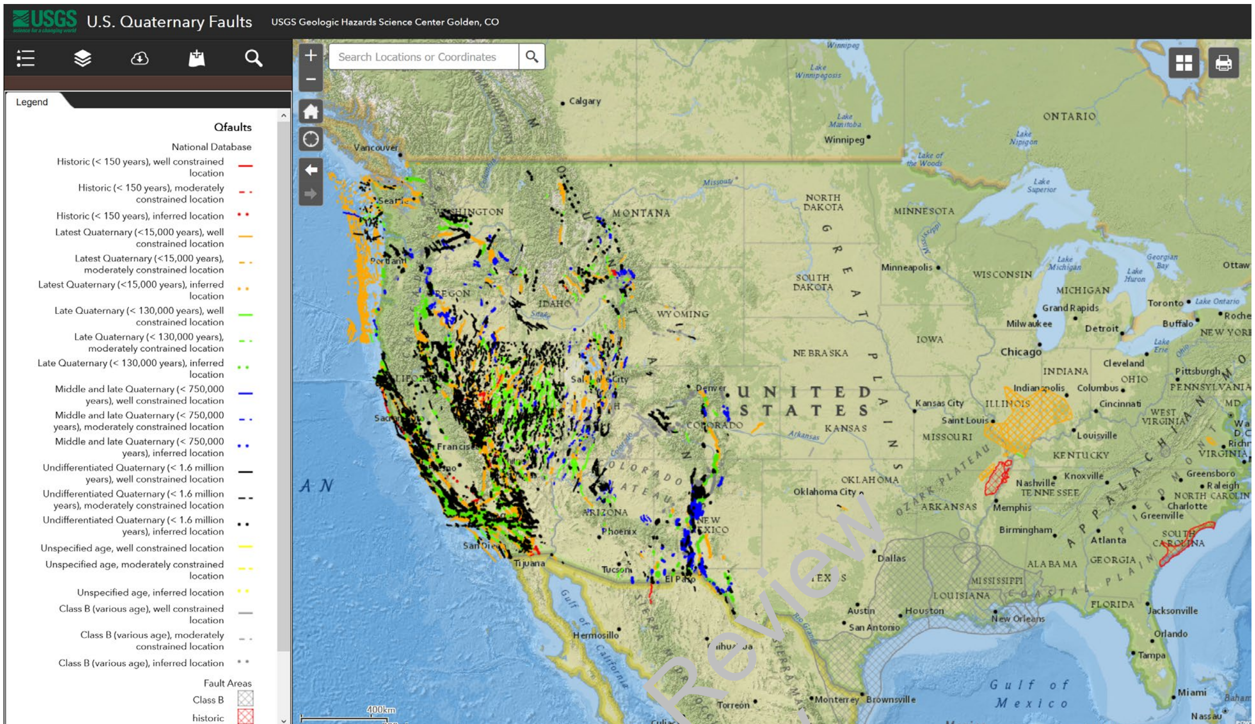
https://www.usgs.gov/natural-hazards/earthquake-hazards/faults?qt-science_support_page_related_con=4#qt-science_support_page_related_con
https://www.usgs.gov/natural-hazards/earthquake-hazards/seismic-hazard-maps-and-site-specific-data

Best practices:

1. Determine if your facility is in a location with a high risk for seismic activity.
2. Use the USGS Unified Hazard tool to get the Hazard Curves and Uniform Hazard Response Spectrum for your location. - https://earthquake.usgs.gov/hazards/interactive/
3. Analyze tanks for sloshing and keep liquid inventory below the limit for loss of containment.
4. Review the tank anchorage as well as foundation design and ability.
5. Review secondary containment.
6. Review older tanks using API 650 seismic guidelines.

Sample map(s):





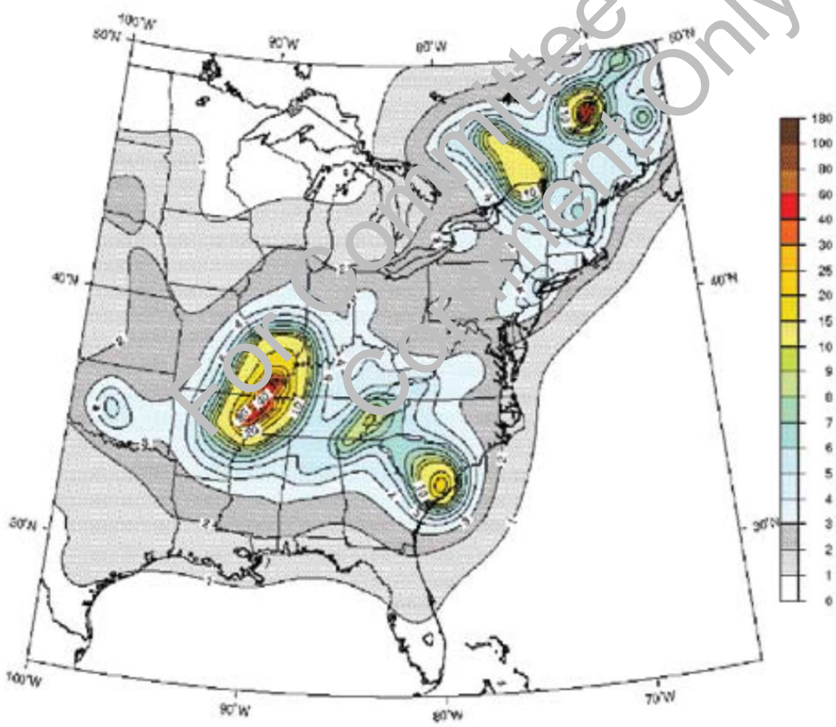


Figure 3-1. Probabilistic earthquake hazard map for the eastern United States within 100 km offshore. The map shows the peak ground acceleration with a 10 percent probability of being exceeded in 50 years. The Charleston, South Carolina, area stands out as the only section of coast where significant ground shaking of 10 percent of the acceleration of gravity or more is expected (Frankel et al., 2002).

Appendix NH5: Volcano

Technical Reference(s):

Web map reference(s):

http://xxxxxxxxxxxxxxxxxxx

Best practice(s):

Sample map(s):

Appendix NH6: Landslides

Technical reference(s):

Web map reference(s):

https://maps1.arcgisonline.com/ArcGIS/rest/services/USGS_Landslides/MapServer

Best practice(s):

Sample map(s):

Risk Factors for Natech

Consequence factors:

Adjacent properties

- Is residential property next to the site. If Natech caused releases how would they be affected considering the pathways, the terrain, the weather, the site specific conditions.
- Is industrial property next to the stie. Do neighboring facilities have significant amounts of hazardous substances that could be released during Natech increasing severity of our Natech releases. Are these hazardous substances highly flammable or toxic and could large quantities be released?

Access

- Is access to emergency responders restricted in some way by the existing roads and access? How much worse would access be made by a release of the volume of one of the tanks? By all tanks?
- Are there any scenarios in which pressurized hazardous substances such as ammonia, chlorine or other quantities of pressurized and hazards gases where they might have to be released to prevent greater threats to the local infrastructure.
- If a Natech triggered multiple nearby site fires in the area of your facility including yours, what priority would be placed on setting up and conducting emergency response?
- If power, water, or other utilities lost from a Natech event, how would your emergency response be affected for spills and releases? fires?
- Is theref there is inadequate containment volume for worst case releases, fire fighting or other reasons caused by Natech events.
- Considering multiple tank fire scenarios, are there sufficient valves to isolate the liquids in tanks or other vessels?
- communications with other stakeholders during emergencies
- If evacuation orders are issued due to widespread Natech hazardous vapor or gas release will you have adequate time and personal to secure the facility during the crisis?
- how quickly can you mobilize product and/or water to ballast tanks if flooding occurs? Do you know the minimum levels that need to be in the tanks to stabilize them?
- Event A is airplane flying. Event B is radar registers airplane. P(A)=.05. P(B|A)=0.99 and P(B|notA)=0.1. Draw tree diagram for this scenario showing all possible outcomes. Illustrate the false positives and alarms. Compute P(AB), P(B) and P(A|B)

Natech initiator		escalation	Natech considerations
Lightning	ignite external floating roof tanks or tanks being filled	multiple tank fires threats to pressurized lpg, ammonia or other gas storage, initiator for bleves or boilovers	reduced emergency response services and personnel occurrence with flooding and wind aggrevates emergency response

Put this somewhere:

Storage of liquid hydrocarbons with vapor pressures well below atmospheric pressure have a significant safety advantage over volatile hazardous chemicals such as ammonia or chlorine. If there is a container or piping failure then the release can be contained in secondary containment. For relatively non toxic volatile hydrocarbons such as LNG there is still value to secondary containment. The initial liquid release will vaporize quickly until the ground under the spill and other heat sinks cool off to cryogenic temperatures will result in a vapor cloud which cannot be contained by secondary containment. But fortunatetly most of the liquid will remain in containment and vaporize only as fast as it can receive heat from the air which is relatively slow. This means that for LNG and other volatile hydrocarbon liquids there is still value to secondary containment. But for chemicals such as ammonia or chlorine the toxicity levels are so low that even a small vapor cloud can be extremely hazardous.

A more refined version of this concept is shown in the table[1] below.

Table 6.3 Technology Hazard Matrix With 1 = Low Hazard and 5 = High Hazard

Equipment	Liquefied Gas	Compressed Gas	Cryogenic Liquid	Liquid	Fine Dusts
Pressurized (above-ground)	5	4	4	2	1
Pressurized (underground)	2	3	2	2	1
Atmospheric	—	—	5	3	3
Pipeline (above-ground)	4	3	4	2	1
Pipeline (underground)	3	2	3	1	—

Underground equipment is considered buried or mounded.

Also put this in the appendix 8 under seismic:

We recommend that if a facility is subject to a Natech that all tanks be seismically assessed using the criteria of ASCE7-16. Note that seismic assessment is typically not a standard practice for storage tanks since they have usually undergone an assessment at the time of construction so that the assessments are based on older or out of date codes and standards.

[1] Krausmann, Cruz and Salzano – Natech Risk Assessment and Management

Original PHA Team Leader/Secretary:
Original PHA Team Members:

SUBSYSTEM LIST

1. Transfer Area Setting, Environmental Factors, and Emergency Response
2. Human Factors Affecting Entire System
3. Piping, Valves, Fittings, Gauges, and General Vessel Issues
4. Product Transfer from Rail car to Transport Truck

RISK (R) RANKING MATRIX

Severity (S) / Likelihood (L)	1- Little or No Effect	2- Minor Release at Point of Failure	3- Area Evacuation or Offsite Release	4- Employee Injury, Significant Property Damage (>$100K) or Small off Site Evacuation	5- Multiple Injuries or Fatalities, Major Property Damage, or Major Offsite Evacuation
1- Credible but Unlikely	0	1	3	6	7
2- Once in Facilty Life	0	2	5	7	8
3- Once every 5-20 years	0	3	6	8	9
4- Once every 1-5 years	0	4	8	9	10
5- More the Once per Year	0	6	3	10	10

PHA Team Leader/Secretary:
PHA Team Members:
Subsystem: Storage Area Setting, Environmental Factors, and Emergency Response

SCENARIO NUMBER	WHAT-IF	CAUSES	CONSEQUENCES	S	L	R	EXISTING SAFEGUARDS (Engineered or Administrative)	RECOMMENDATIONS
1.1	The discharge of a pressure relief device (PRD) is placed in an area where employees can be exposed or access to equipment compromised?	• Poor siting of equipment	• Potential employee exposure				•	•
1.2	The location of a PRD does not take into account air flow around the storage tanks, prevailing winds, and surrounding structures?	• Poor equipment placement	• Potential employee exposure • Increased possibility that valves may not be accessible				•	
1.3	Flammable vapor is released and not vented from the area where the release occurs?	• Inadequate ventilation	• Concentration may buildup, potentially resulting in fire hazard or explosive atmosphere				•	
1.4	Equipment or valves are not accessible to personnel wearing SCBA during emergency or for normal operations?	• Tight spaces around vessels, equipment, ladders, etc.	• Prevents quick access during emergency, resulting in prolonged release and increased exposures • Delays, fall hazards				•	•
1.5	Valves are not situated to isolate major components of the system?	• Poor design • Changes made to piping without considering access	• May hinder control and management during an emergency, resulting in prolonged release or increased exposures				•	•
1.6	Ignition sources (open flames, surfaces at greater than 550°F, electrical, etc.) are present in an area with an explosive mixture of flammable liquid/vapor?	• Leak into area with non-explosion proof equipment • Railroad • Automobile/ ATV/transport truck/Transloader engine • Hot rail car (wheel/break areas) • Rail engine	• Potential for explosion				•	•
1.7	Nearby occupied space has non-existent, insufficient, or inoperable venting?	• Existing closed space is not vented properly	• Potential for explosion				•	•
1.8	Transfer/ storage area is located near alarge employee population?	• Transfer Area layout	• Increased exposure in the event of a release or explosion				•	•

SCENARIO NUMBER	WHAT-IF	CAUSES	CONSEQUENCES	S	L	R	EXISTING SAFEGUARDS (Engineered or Administrative)	RECOMMENDATIONS
1.9	Controls are located in or near equipment making access difficult during release?	• Poor design	• Loss of access to controls in the event of an emergency				•	•
1.10	The discharge of a pressure relief device (PRD) or product release can affect nearby residential or commercial site ?	•	•					
1.11		•	•					
1.12	Critical safety systems (e.g., alarms, E stops, critical gauges, etc.) are poorly located, identified, or maintained?	• Poor design or installation • Poor maintenance	• Impedes emergency response				•	•
1.13	There is insufficient or no site security?	• Lack of awareness or budget • Neglect	• Potential vandalism theft				•	•
1.14	Site's electrical area classification does not segregate flammables from ignition sources?	• Electrical equipment not designed for propane transfer area	• Fire or explosion					•
1.15	Emergency plan, evacuation routes, and assembly points are not sited with consideration of possible incident locations?	• Poor emergency response plan	• Evacuating employees enter a hazardous area				•	•
1.16	There is a loss of electrical power/ electrical control during operation?	• Fuse • Wireless transmitter failure	• Safety equipment potentially does not operate • Loss of operation of valves and/or equipment				•	•
1.17	Loss of site air pressure causes loss of system control	•	•					
1.18	There is a drop in Site waterpressure?	• Water supply problem	• Safety shower / eye wash non operational				•	
1.19	There are severe winds, floods, extreme weather, etc., or airplane crashes into Transfer Area?	• Weather, mechanical failure, human error, etc.	• Potential damage to pipes, PRVs on tanks, and vessels				•	•

SCENARIO NUMBER	WHAT-IF	CAUSES	CONSEQUENCES	S	L	R	EXISTING SAFEGUARDS (Engineered or Administrative)	RECOMMENDATIONS
1.20	There is a fire in the transfer area?	• Fire in materials stored near area • Equipment starts on fire • Fire involving released propane • Railroad traffic could cause fire (switches occur at night) • Nearby building fire • Area wildfire	• PRVs may open, releasing flammable liquid/vapor outside • Explosion					•
1.21	There is a fire in other areas of the property near the Transfer Area?	• On site building • Neighboring building • Wildfire in area	• PRVs may open, releasing flammable liquid/vapor outside • Explosion					•
1.22	Tank contents reacts with other chemicals (i.e. oxidizers) in storage area?	• Leak in common areas	• Chemical reaction					•
1.23	Prescence of hot surfaces in area that could ignite release	•	•					•
1.24	Containment area for liquid storage is overwhelmed by liquid release?	• Combination of large release and fire water overwhelm containment •	• release escapes containment • Vapor builds up in underground areas					•
1.25	Is there rail operations nearby that could affect the site in the event of a derailment?	• Train operates at excessive speeds • Inclement weather • Train operator error •	• Train impacts storage equipment • release					•
1.26	Can water from outside of containment area encroach dike area and compromise the containment and storage tanks within (moving water near site)	•	•					
	Can tidal action compromise containment dike and/or tank foundations	•	•					
	Could site access roads be rendered impassable due to snow/flooding/tree fall due to wind/wildfire/landslide	•	•					

API 656 Appendix 10 Annotated Bibliography

(E. Krausmann et al., 2020)
Natech book
This reference is probably the most comprehensive and is a book with 15 chapters. The aim of the book is given in the introduction; "*This book aims to address the entire spectrum of issues pertinent to Natech risk assessment and management in an effort to support the reduction of Natech risks*". Chapter 2-4 are introductory with historical examples and lessons learned. Chapter 5-6 use an engineering perspective to address prediction and measurement of Natech. Chapter 7-12 are dedicated to Natech risk assessment. Chapters 13-14 provide organization prevention and mitigation measures. Chapter 15 summarizes the concepts of effective Natech risk reduction.

Chapter 2 provides details for the following Natech events:

- Kocaeli Earthquake 1999, Turkey Natech.
- Acrylic fiber plant in Yalova on the Marmara Sea and release of acrylonitrile
- Tohoku Earthquake and Tsunamic and Fukushima Daiichi Nuclear Plant Natech, March 11, 2011
- LPG tank farm Tokyo Bay, March 2015
- Sendai Refinery earthquake and seismic Natech, March 2011
- San Jacinto River Flood, 1994, United States
- Hurricane Katrina and Rita, 2005, United States
- Milford Haven refinery, 1994, United Kingdom

Chapter 3 gives lessons learned. It shows that most Natechs involve release of oils, fuels, and hydrocarbons. The remaining release involve fertilizers, and chemicals. Chapter 4 covers the barely existent regulatory framework for Natech (such as the EU Seveso Directive and the PSM regulation in the US but points out the shortcomings associated with Natech. The Japan High Pressure Gas Safety Law is also mentioned as well as what the state of Natech prevention is in some other countries. There is a brief discussion of the OECD guiding principles for chemical accident prevention. An OECD Natech Addendum was published in 2015 and supplements the guiding principles.

Chapter 5 attempts to provide the theoretical basis for prediction of natural disasters and seem mostly like a detailed listing of methodologies that have been attempted for estimating the severity of natural events. Chapter 6 characterizes the release based on the chemical properties. It also covers the equipment involved such as tanks, pressure vessels and pipelines. Chapter 7 covers Natech risk assessment. This chapter is a compilation of various methodologies that companies tend to use.

Chapter 8 gives a summary of the development of some risk assessment software designed specifically for Natech (RAPID-N, PANR, TRAS 310, TRAS 320). Chapter 9 goes into quantitative methods and software (ARIPAR-GIS, RISKCURVES). Chapter 10 is a case study in the use of RAPID-N) while chapter 11 is a case study for ARIPAR-GIS and Chapter 12 a case study for RISKCURVES.

Chapter 13 covers prevention measures and there is significant focus on storage tanks and pipelines.

Chapter 14 addresses organization measures for Natech which are administrative programs and controls used for risk reduction. Emergency response, resilience and early warning are touched on.

Chapter 15 summarizes the previous chapters in terms of recommendations.

OECD (Risk, 2020)
Natech risk survey results
A survey was conducted in 2017 on Natech risk management. Fourteen countries and three institutions representing science and industry responded to the questionnaire. There is increasing societal recognition of increasing risk from the involvement of Natech in the release of hazardous chemicals. The document references the Japan 2011 tsunamis and earthquake as well as Hurricane Harvey. It points to the growing body of literature and, in particular, literature from the Joint Research Center of the European Commission. The gaps identified by the document indicates those in the regulatory domain through the survey. The stated purpose of the survey is to identify and assess gaps as well as good practices for Natech risk management. The report gives a consensus-based list of recommendations based on the project. These are:

- Raise awareness of unique risk features of Natechs.
- Governments should develop methods to support implementation in the OECD Guiding Principles on Chemical Accident Prevention, Preparedness and Response.
- Improve the quality of Natech Risk Management.
- Use good practices such as databases to capture Natech information useable for risk management.
- Improved natural hazard mapping.
- Include climate change effects in Natech risk management and assessment.
- Improvements in communication, training, education.
- Improvements in Natech governance, regulations, enforcement.
- Interestingly, little was said about community resiliency.

Since the respondents to the questionnaire were limited in number and were representatives of governments, countries, and industries the results may have biases that make could possibly affect the recommendations and observations.

(Kaiser & Griffiths, 1982)
Release of Ammonia
Unlike another highly toxic cloud formed by a release of chlorine, ammonia is “lighter than air” and has a molecular weight of 17 which is about half the density of air so it should form a buoyant cloud that dissipates. But experience shows that ammonia releases can result in persistent ground vapor clouds that are, of course, a serious danger to animals and people. Several incidents are cited that make this case:
Houston, TX 1976, a release from a tanker truck resulting with evidence of burnt grass over a significant area indicating the vapor cloud.
Pensacola, Fl 1977, where a derailed punctured tank car where an ammonia vapor cloud a mile in diameter and 125 feet high persisted on the ground for a period of time.

The article shows that releases from pressure vessels seem to generate ground hugging clouds in Table 1 because the critical variable F, the mass fraction of released ammonia in the vapor phase is over 20%.

("Disaster Resilience: A National Imperative," 2012)
Disaster resilience
This is an important reference because it seems to be the counterpart of all the work done by the EU and knowledge shown in the Krausman book (E. Krausmann et al., 2020).The topic of resilience is complex due to the participation of all levels of government and the many elements required to make a system of resilience effective. This work has numerous recommendations throughout. It covers topics such as disaster risk assessment and management. Some useful tools are discussed are the FEMA catastrophe modeling tool HAZUS and the SHELDUS (Spatial Hazard Event and Loss Database for the US).

(Cruz & Suarez-Paba, 2019)
Advances in Natech Research
This paper attempts to summarize the state of the art for Natech research by a review of 230 peer reviewed papers and reports on the subject. The paper shows what we already know (a) the frequency and severity of Natechs is increasing (b) Natech research and interest was originally focused on seismic but has shifted to hydrometeorological scenarios. At the center of this refocus is of course climate change. The study concludes that improved Natech assessment and management have resulted from these studies and advocates better education about Natech issues.

(Zuluaga Mayorga et al., 2019)
Parametric fragility curves for storage tanks
The paper develops fragility models for API 650 and API 620 tanks. However, they don't take into account that API 620 tanks can be non cylindrical and therefore their models do not apply to these tanks. As first steps, they develop limit state models for flooding and then seismic and extreme wind. A reliability function is then used to simulate the probability of failure. Although the approach seems reasonable, it is technically difficult to implement and the details for the simulation are not provided. This method should be tested for accuracy against real tank failure that have occurred and which have been documented before a large amount of effort and confidence should be placed in the methodology.

(Coronese et al., 2019)
Increase in economic damage of extreme natural disasters
The plot in Figure one shows how a slight shift in a distribution can amplify the damages if the damage function is convex. The study uses simulations to shown how the tail of the distribution skews more right and flattens the tail. The study shows that the right skewing and flattening of the tail distribution for catastrophic events and those focused in temperate regions suggesting that natural disasters have migrated beyond the tropical regions.

(Kameshwar & Padgett, 2018a)
Storm surge fragility
The paper does not provide the data allowing for determining how good the model fits to real cases of failure. It would be useful to check real failure cases using the fragility model to give the modeling a reality check.

(Sanders, 2019)
CCPS Monograph
On 29 August 2017 Hurricane Harvey caused an organic peroxide fire and explosion at the Arkema Chemical Plant in Crosby, Texas. As a result, the incident was investigated by the U.S. Chemical Safety Board, which issued a recommendation to the Center for Chemical Process Safety on 24 May 2018 requesting the development of guidance to help companies assess their U.S. facilities risk from potential extreme weather events. The focus of this document is the preparedness of chemical facilities for meteorological and geological natural disasters. It "addresses the assessment and planning for natural disasters" through guidance but does not attempt to set a standard or expectation for actions that can be taken to mitigate the risk. The document covers essential risk assessment methods such as hazard identification, data collection, critical equipment, evaluation, recovery, and recommissioning. It has useful tables and examples in the appendices.

(Fema, n.d.)
Highlights ASCE 24-14
This article provides a summary of the latest requirements listed in ASCE24-14 for flood resistant design and construction. Although most of the provisions address building structures it also covers non-building structures such as tanks. The article defines flood design class which supersedes the risk/occupancy classification of older editions of ASCE7. The flood design class governs the design criteria for buildings and structures. There is a new requirement that the design flood elevation be based upon the 500 year flood elevation.

(*Introduction to RAPID-N for Natech Risk Analysis and Mapping A Beginner's Guide*, n.d.)
Rapid-N
This document provides information about what the Rapid-N software (developed by the European Commission Joint Research Center) does, how to implement it as well as providing some tutorials on its use. Rapid-N was developed with seismic in mind but has been expanded for flood hazards as well as hazardous pipelines. The purpose of Rapid-N is to perform risk analysis with minimal data requirements for a single plant or multiple plants. It is an online tool but data can be controlled so that it accessible only to the owner inputter or be made public. The modeling methodology is open to the user and can be modified as needed. In order to understand whether this tool would be useful to an owner, our conclusion is that it would have to be tested on a case basis and a decision made as to whether it provides the information needed for decision making more efficiently than other methods.

Here are one user's thoughts after using the RAPID-N program for a short period of time:
"I tested the program on several tanks of different dimensions and roof types storing different kinds of product. I mainly used the program to analyze the seismic risk of tanks given applied spectral accelerations, trying to make some comparison to seismic design codes like ASCE7-16 or API 650 Annex E. RAPID-N has an impressive feature where it will estimate or assume the remaining dimensions of a plant unit (e.g., a storage tank) given the bare minimum description (diameter, height, etc.). This allows users to perform analyses without having to fill in every possible input parameter for the tank. RAPID-N has a built-in library of fragility curves. The program will automatically choose a fragility curve it determines is appropriate for the given scenario (e.g., earthquake severity, tank contents, tank type,

etc.). It is possible to pick a fragility curve, but RAPID-N does not have an easy way to select one appropriate for your use case unless you thoroughly investigate each fragility curve and its accompanying documentation. It is also possible to add your own fragility curves. When performing my own sample analyses using RAPID-N, I encountered several issues that indicated RAPID-N was not the right program for my use case. A minor issue: the fragility curves RAPID-N assumes for anchored and unanchored storage tanks only uses PGA, and does not allow any extra granularity with an input response spectrum/ some important accelerations (e.g., does not use the 0.2-s and 1-s period accelerations). This is disappointing as the extra granularity in input and results would be appreciated. Most importantly, the fragility curve results seemed to be the same between tanks of different dimensions with different product at the same plant. Since we know that just tank diameter, height, and product specific gravity can greatly affect the performance of a tank during seismic accelerations, this means that the results of the RAPID-N analysis would be unhelpful for my use case.
There may be a more appropriate fragility curve in RAPID-N's library - however, poring over the documentation for each would take too much time to be worthwhile for my use case."

(Kameshwar & Padgett, 2018b)
Fragility Indicators
The ideas of fragility for storage tanks that originated with seismic work is proposed to be applied to damage functions and losses incurred by hurricane related hazards. The focus of the study is based on 4500 tanks in the Houston Ship Channel for simulated storms. The damage mechanism are floatation and buckling but exclude debris impact from storms. There is a complicated explanation for a protocol of analysis that begins with the results of a finite element analysis model picking certain combinations of failure and using a Latin hypercube sampling process generates failure envelopes. The process continues on to explain what was done but it is difficult to follow. The methodology is based on a "DL-MFA methodology" that the authors developed. A logistic regression model takes this output and then uses it to determine fragility. This model gives a binary output for failure or non-failure. The end result is a probabilistic assessment of the potential damage and resiliency of the tanks in the Houston Ship Channel. The conclusions are that (a) wind buckling has a relatively low probability of occurrence even in hurricane level winds, (b) storm surge is likely to result in failure and (c) anchorage of tanks could significantly reduce the damage while improving resiliency.

(Vet et al., n.d.)
Natech Disaster Management Workshop, 200 pages, 2003, Italy
Thirteen countries from the EU and Japan and the U.S participated the NEDIES (Natural and Environmental Disaster Information Exchange System) workshop proceedings where papers on Natech are presented and documented. The proceedings start with 4 keynote talks: (1) the power blackout on 28 September 2003 that occurred in Italy, (2) the Kocaeli earthquake, (3) the Tokachi-oki earthquake in Japan on 26 September 2003, and a paper by Laura J. Steinberg titled "Natechs in the US: Experience, Safeguards, and Gaps". In addition, there are various country papers as well. The papers represent the issues of Natech at the time of the conference and have the common themes that are now fully recognized such as the need for central databases so that more can be learned about Natechs, training and awareness, policy changes that address emergency response and planning and so on.

As with most of the literature the paper states that there is insufficient recognition of natural disasters and technology as well as the dearth of data supporting the lessons learned. This paper identifies floating roof tanks to be especially vulnerable to natural hazards. It mentions that while dikes normally contain spills during a storm the flood waters act to move the hazards materials sometime up to hundreds of kilometers through the river network. The paper mentions RAPID-N for semi-quantitative analysis, but also PANR for quantitative risk assessment and PANR for qualitative risk assessment. It also mentions eNatech which is a database for the collection and analysis of worldwide Natech data.

(*Understanding Natech Risk Due to Storms*, n.d.)
Understanding Natech risks due to storms, 2018
Paper gives the descriptions of storm types, their causes, and some descriptions of the storm effects. It describes the effects of buoyancy of tanks due to flooding and effects of storm surge. A few important references are covered such as the European industrial incident databases ARIA, MHIDAS, TAD, eMARS and FACTS. Table 1 lists the number of Natech events in each database ranging from 33 to962. There are pie charts showing the proportion of incidents by various initiators such as seismic, landslide, etc. The pie charts show the role of storage as a contributor to Natech and it is probably the most significant of all building elements. The conclusions state that storage equipment is the most vulnerable to storm damage and that fires and explosions are the most common scenarios. As expected, lightning has the highest number of records. Rain and flooding rate high on the proportion of causes. Wind is the least probably triggering event for Natech.

Analysis of hazardous material releases due to natural hazards in the United States
The paper summarizes data from the National Response Center spills between 1990 and 2008. Rain-caused releases were the most common cause of Natech followed by hurricanes and then wind and other weather related causes.