US DOT PHMSA Research Project #731: Consistency Review of Methodologies for Quantitative Risk Assessment

Final Virtually Held Information Dissemination Meeting

November 16, 2020

DOT PHMSA Contract #693JK31810006

Discussion Topics

- Project Sponsor and Project Team
- Project Challenge, Objective and Tasks
- Background Information
- Project Tasks
- Results and Conclusions
- Knowledge Transfer / Potential Next Steps
- Closing Discussions / Q&A
- Appendix

Project Sponsor: US DOT PHMSA

- PHMSA's Project Team:
  - Technical: Thach Nguyen
  - Contractual: Ben Patterson, with Bob Smith
  - Supported by others in the PHMSA LNG Team
- **Public Final Report** issued October 26, 2020
- **Project public webpage:** https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=731
- Project need/concept was developed at PHMSA's Pipeline Safety R&D Forum, Cleveland, OH, Nov. 16-17, 2016
- The project provided timely input to support PHMSA's response to the Executive Order issued on April 10, 2019 to the Secretary of Transportation, which included to initiate a rulemaking to update 49 CFR Part 193

Project Team:

Prime Contractor: Gas Technology Institute (GTI)
- Rich Kooy, PE, Senior Institute Engineer
- Ernest Lever, R&D Director, Energy Delivery

Subcontractor: BLUE Engineering and Consulting Company
- Filippo Gavelli, PhD, PE, Consultant
- Jake Piekarz, PE, Consultant
- Phil Suter, Consultant
- Bryant Hendrickson, PE, Consultant

Subcontractor: C-FER Technologies (1999) Inc.
- Smitha Koduru, PhD, PEng, Engineering Manager
- Tyler Paxman, MSc, EIT, Research Engineer
- Hafeez Nathoo, EIT, Junior Research Engineer
- Maher Nessim, PhD, PEng, FCAE, C-FER Fellow

Subcontractor: Idaho National Laboratory
- Bob Youngblood, III, PhD, NS&E Directorate Fellow, Probabilistic Methods and Tools Dept.

Lead Author Responsibility and Credit by Report Section

Content		Company
Executive Summary		Project Team
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Project Objective: Develop a Standard Methodology for Performing Quantitative Risk Assessments

Purpose and Challenge:

- PHMSA LNG regulations are generally prescriptive in nature.
- Both government and private sector expressed desire to move towards a risk-based approach for evaluating potential impacts to life and property.
- Quantitative risk assessment (QRA) can be deployed to:
  - clearly define the probability of success,
  - identify high risk areas for action,
  - mitigate identified risk(s),
  - show ongoing improvements to risk management though metrics, and
  - improve regulator confidence about an operator’s ability to manage risk.

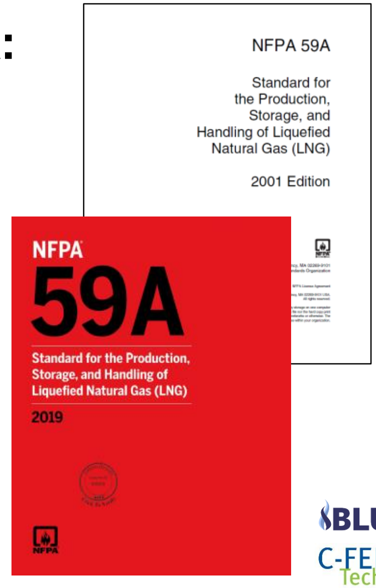
Context:

49 CFR Part 193 Federal Code:

- Currently incorporates by reference the 2001 (and 2006) editions of NFPA 59A
- Prescriptive methods are used to manage risk

QRA-related content in NFPA 59A:

- 2001 and 2006: None
- 2009: Appendix E created (i.e. supplementary information)
- 2013: Chapter 15 created
- 2016: Chapter 15 retained
- 2019: Chapter substantially expanded (now Chapter 19)



Project Tasks

- Task 1: Form TAP and Gather Initial Input
- Task 2: Perform Global Review of QRA Methodologies for LNG and Related Facilities
- Task 3: Develop Outline of Consistent Methodology
- Task 4: Perform QRAs on Representative Benchmark Facilities
- Task 5: Perform Sensitivity Analysis to Refine/Probe QRA Methodology
- Task 6: Compare Proposed QRA Methodology to NFPA 59A 2019
- Task 7: Develop Guidelines for QRA Methodology
- Task 8: Develop Final Report with Recommendations
- Task 9: Project Management

Total Project Funding (for all tasks) = $858,584 | 100% funded by US DOT PHMSA

Task 1: Form Project Technical Advisory Panel (TAP) and Gather Initial [and On-going] Input

*A Hearty **Thank You*** to TAP members from the Project Research Team for your Reviews, Input, Time

- **American Gas Association (AGA): Ted Williams**, Senior Director, Codes and Standards
- **Chart Industries: Tom Drube,** P.E., Vice President, Engineering
- **FERC: Joseph Gray III**, E.I.T., LNG Engineer, Office of Energy Projects - LNG Branch 1
- **National Grid: Chris Conlon**, Process Safety Director
- **ExxonMobil Production Co.: Caroline Deetjen**, Process Safety Engineer, in cooperation with **Daryl Kenefake**, P.E., CSP, Senior Technical Professional Consultant – Loss Prevention
- **PHMSA: Thach Nguyen**, General Engineer and Agreement Officer Representative
- **PHMSA: Sherry Borener**, Ph.D., Senior Research Advisor/Chief Data Officer
- **Shell International E&P**: **Shawn Murphy**, Team Lead, LNG Market Access

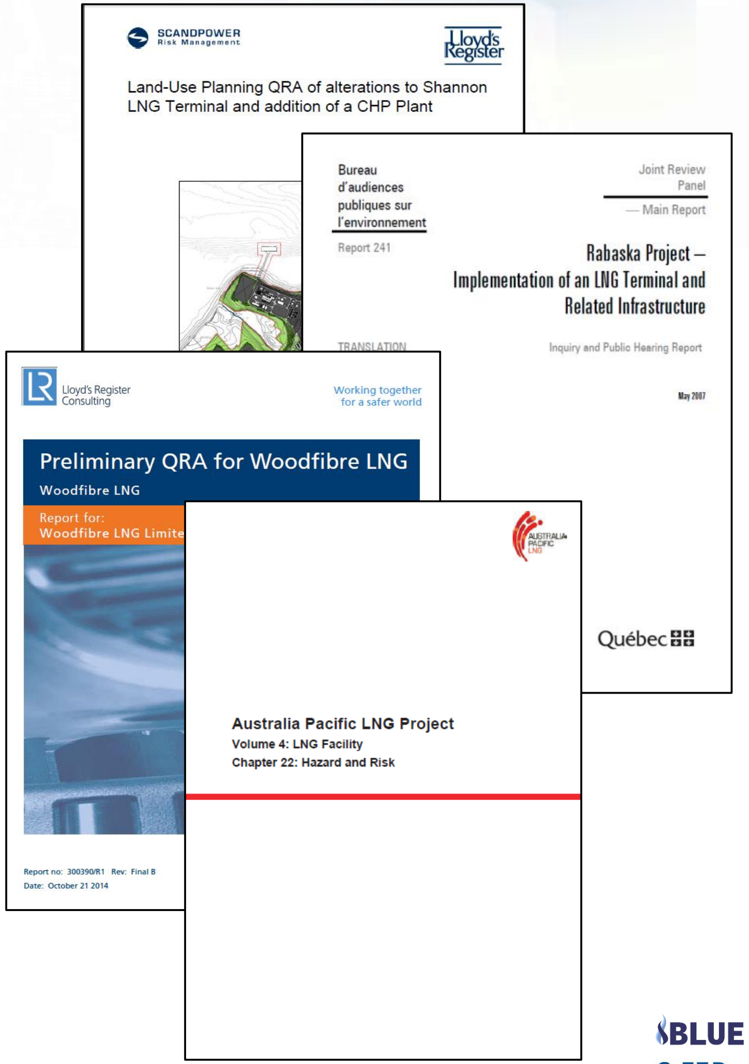
Task 2: Perform Global Review of QRA Methodologies for LNG and Related Facilities

Approach

- Literature review of public domain QRA reports of LNG facilities to assess global consistency
- Sources included:
  - public databases
  - search engines
  - websites of regulatory bodies
  - industry advisory panel
  - past experience of the project team

Overview

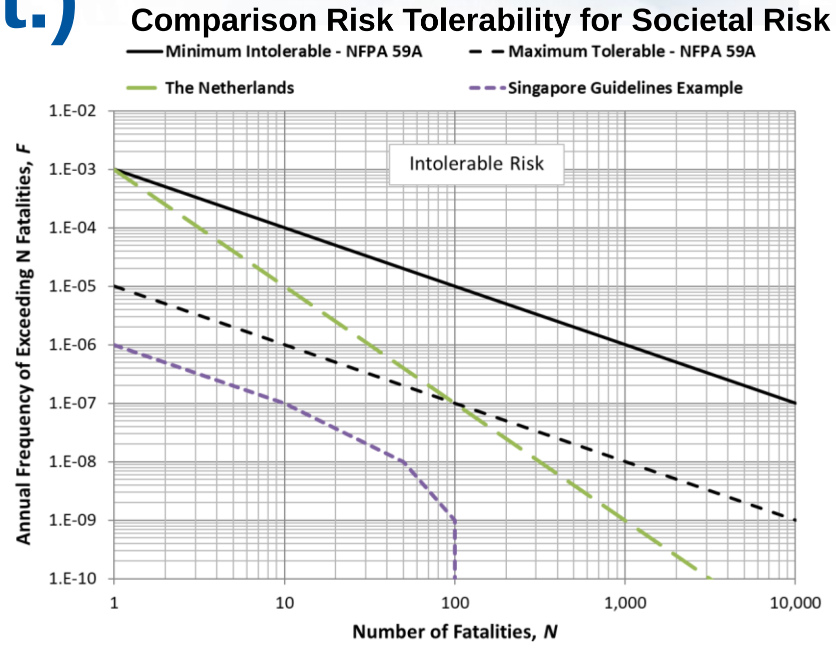
- Fewer than 20 public domain QRA reports collected, all for large-scale import and/or export facilities
- No QRA reports found for small- or mid-scale, peak-shaver, or fuel production facilities found
- Seven export facilities chosen for thorough review
- Appendix B of Public Final Report provides details



Task 2: Perform Global Review of QRA Methodologies for LNG and Related Facilities (cont.)

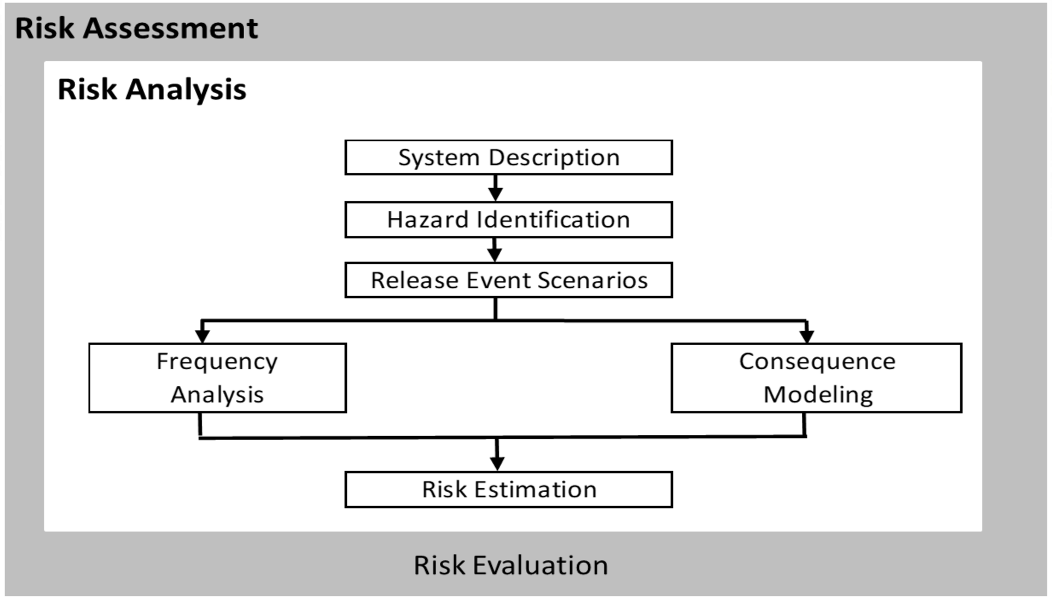
Overall Consistent Steps in Global Practices

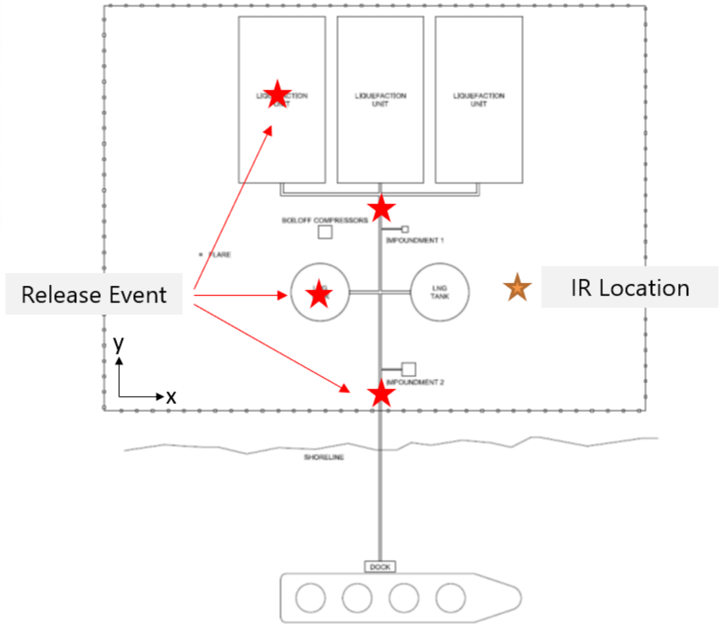
- **System Description**
- **Hazard Identification**
  - Generally performed using SME inputs and recommendations from standards
  - Preliminary HAZID typically identifies worst-case scenarios due to limited design
  - Little consensus between standards w.r.t. hazardous events
- **Frequency Assessment**
  - Estimated through historical failure rate data
  - Event trees can be used to specify failure rates for specific hazard scenarios (e.g. jet fires, pool fires)
- **Consequence Assessment**
  - PHAST and SAFETI frequently used
  - Consider ambient weather data of the region
  - Domino effects typically not quantified
  - Fatality evaluation based on heat flux, product concentration and overpressure thresholds or probit models



- **Risk Estimation and Evaluation**
  - *Individual risk*: Annual chance of fatality of an individual at a fixed location at all times
  - *Societal risk*: F-N curve representing risk to surrounding population
  - Typical acceptance criteria consist of three zones, each with a specific limit
- **Risk Mitigation**

Task 3: Develop Outline of Consistent Methodology





Societal Risk (SR)

- Will be quantified with an F-N curve (frequency vs. number of fatalities)
- The expected number of fatalities (N) will be calculated by considering the density of receptors and their presence within hazard zones resulting from release events

Location-Specific Individual Risk (IR)

- IR at a given location is the sum of the individual risk incurred by release events: $IR_{(x,y)} = \sum_{i=1}^{n} IR_i$
- Estimated as location-specific risk (i.e. exposure time of receptor is not considered as a variable)

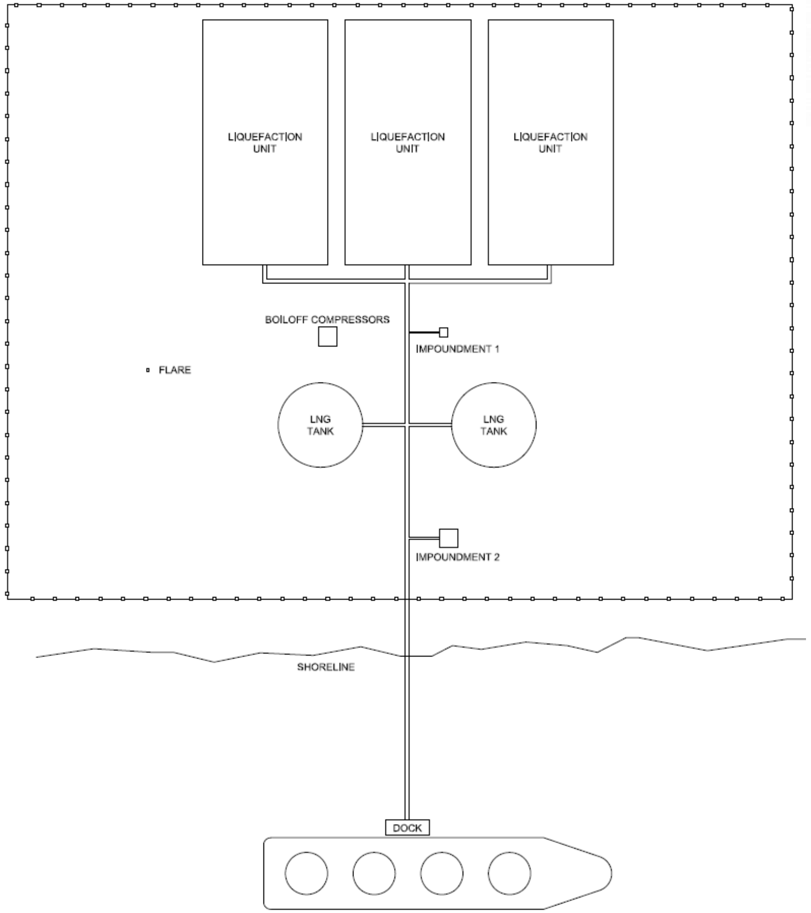
Task 4: Perform QRAs on Representative Benchmark Export and Peak Shaving Facilities

Sub Task	Title	Report Section	Overview
4.1	Facilities and Systems Definition	4.3, D.1	Prepared Preliminary Design Basis (Process Flow Diagram and Plot Plan) for two facilities in different locations.
4.2	Hazard Identification	4.4, D.2	Considered Jet Fire, Flash Fire and Toxic Vapor Dispersion as examples to apply QRA methodology.
4.3	Consideration of Uncertainty in Analysis Process	4.2, D.7	Assessed uncertainty in release event, frequency and consequence parameters. Considered unknowns (assumed values) and uncertainties (aleatory and epistemic).
4.4	Frequency Analysis	4.5, 4.6, D.3, D.6.2	Used NFPA 59A 2019 as primary source for failure frequencies; augmented by other recognized sources. Analyzed weather combinations for 12 cases. Used event tree to assess probability of both immediate and delayed ignition for gas and liquid releases.
4.5	Consequence Analysis	4.7, D.4, D.5, D.6.3	Performed using Phast software
4.6	Risk Estimation	4.8, D.6.4.2, D.6.4.3	Used NFPA 59A 2019 fatality thresholds for LSIR, and population densities of 25 and 3,000 people/km2 near export and peak shaver facility, respectively.

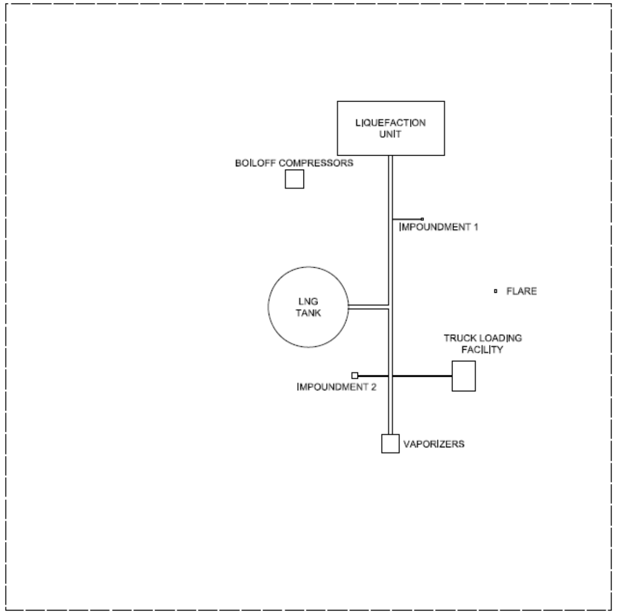
Task 4.1: Facilities and Systems Definitions

- Layout and conditions were based on previous DOT PHMSA research project #640
- Developed to Preliminary Design Basis
  - Plot plan of facility layout by sub-system areas, and overall boundaries
  - Process Flow Diagrams (PFDs)
  - Process design conditions

Export Facility Plot Plan
Gulf Coast Location



Peak Shaver Facility Plot Plan
Northeast US Location



Task 4.6: Individual Risk Estimation - Overview

Probability of Fatal Event — Probability of Hazard Intensity given an event — Probability of Hazard Events — Probability of Each Weather Combination — Frequency of Release Events

$$IR_{(x,y)} = \sum_{i=1}^{n} \left(\sum_{j=1}^{J} P[I_i|H_j] \cdot \left(\sum_{l=1}^{L} \sum_{k=1}^{K} P[H_j|HE_k, W_l, E_i] \cdot P[HE_k|W_l, E_i] \cdot P[W_l] \right) \cdot P[E_i] \right)$$

- Facilities and Systems Definition (Task 4.1) provides facility layout
- Frequency Analysis (Task 4.4) provides event frequencies
- Consequence Analysis (Task 4.5) provides hazard intensity contours
- Individual Risk calculated by combining these results
- Four major steps shown on the right

Fatality Distances
- Compare hazard intensity contours to fatality thresholds

Fatality Contours
- Combine wind direction and fatality distances

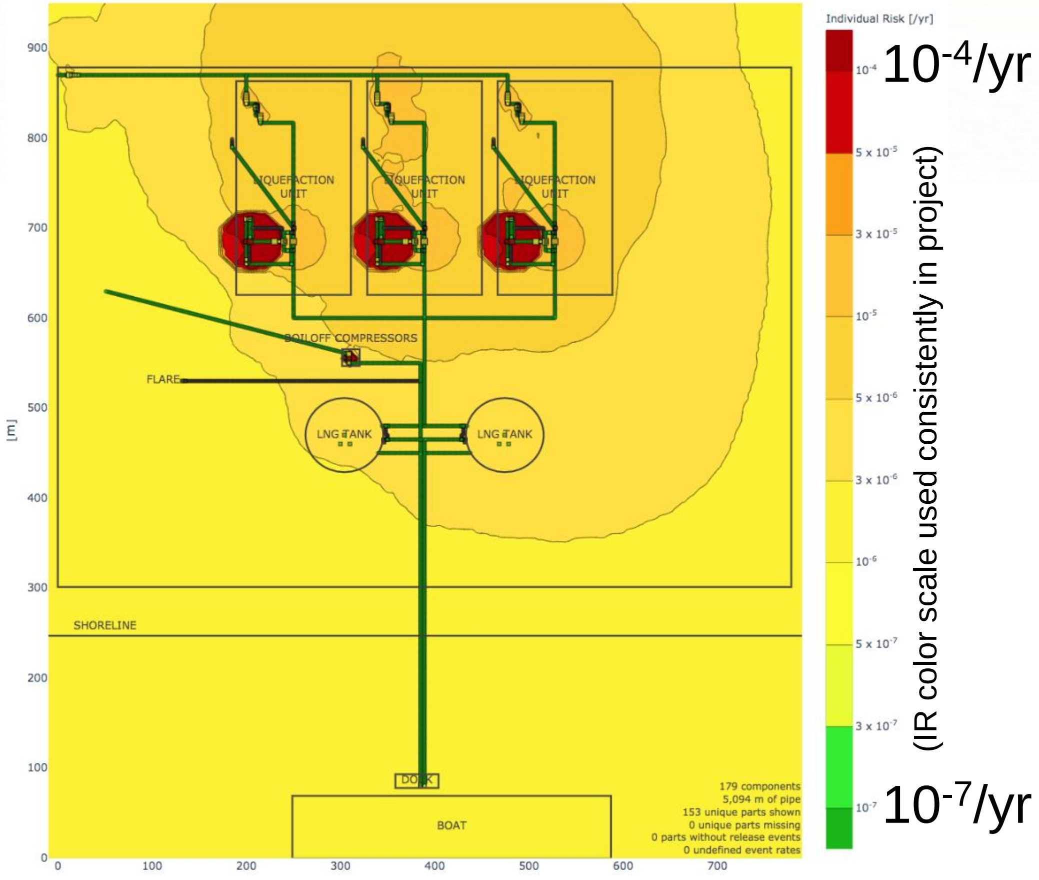
Equipment Locations
- Position equipment using Facilities and Systems Definiton (Task 4.1)

Individual Risk
- Combine equipment locations, fatality contours, and event frequencies

Task 4 Results: Baseline Individual Risk

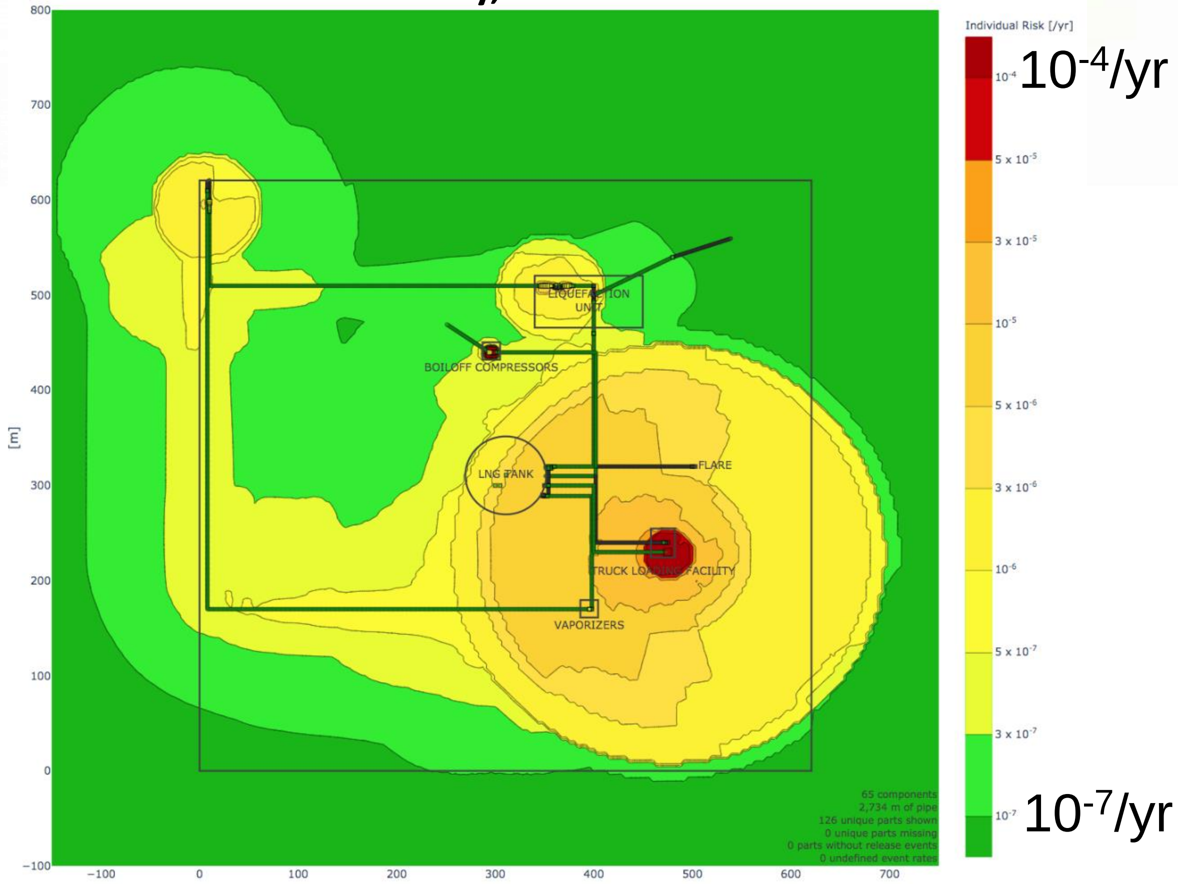
Individual Risk | Export

Export Facility, Gulf Coast Location



Individual Risk | Peak Shaver

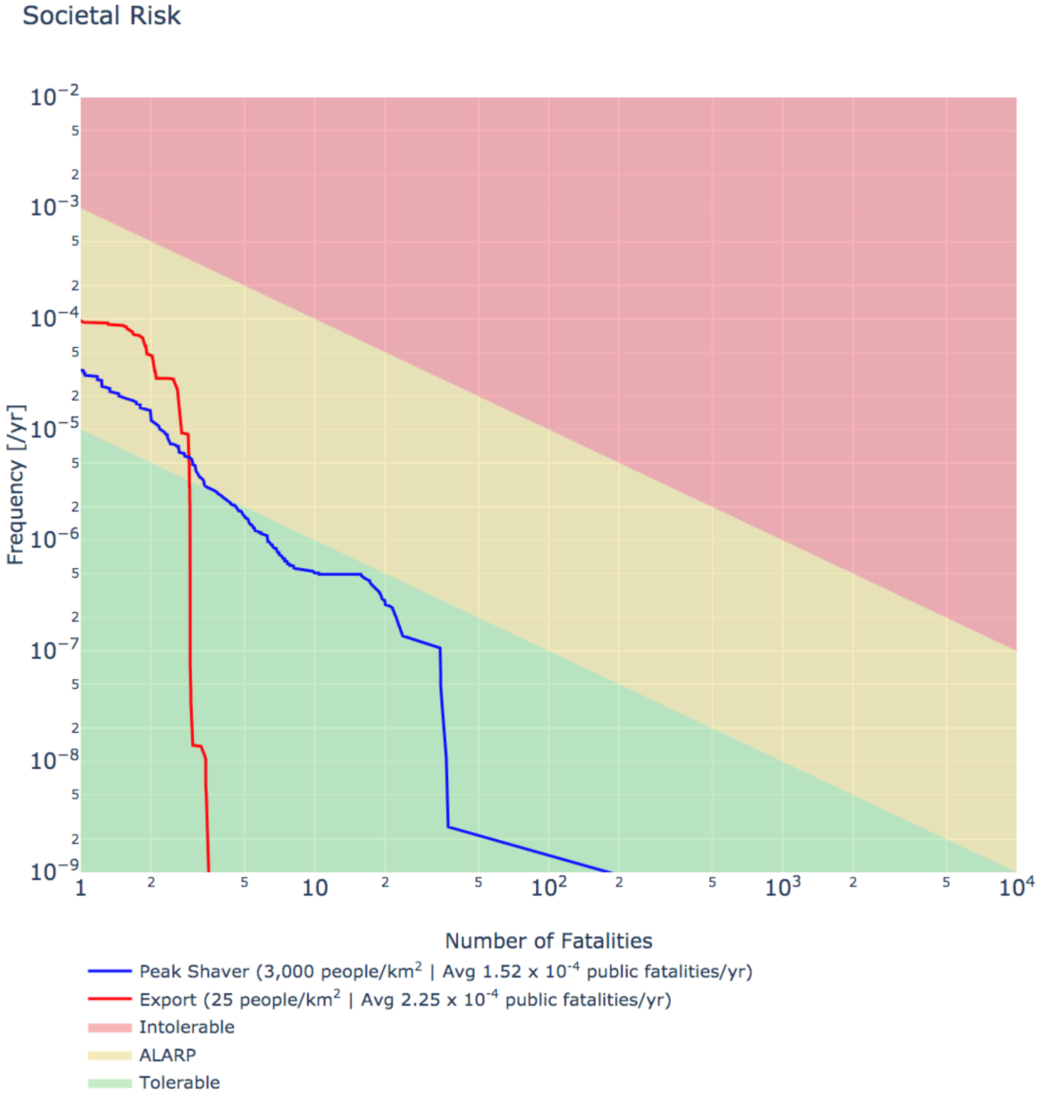
Peak Shaver Facility, Northeast US Location



Individual risk outside of facility boundary meets mostly Zone 2 criteria of NFPA 59A

Individual risk outside of facility boundary meets mostly Zone 3 criteria of NFPA 59A

Task 4 Results: Baseline Societal Risk



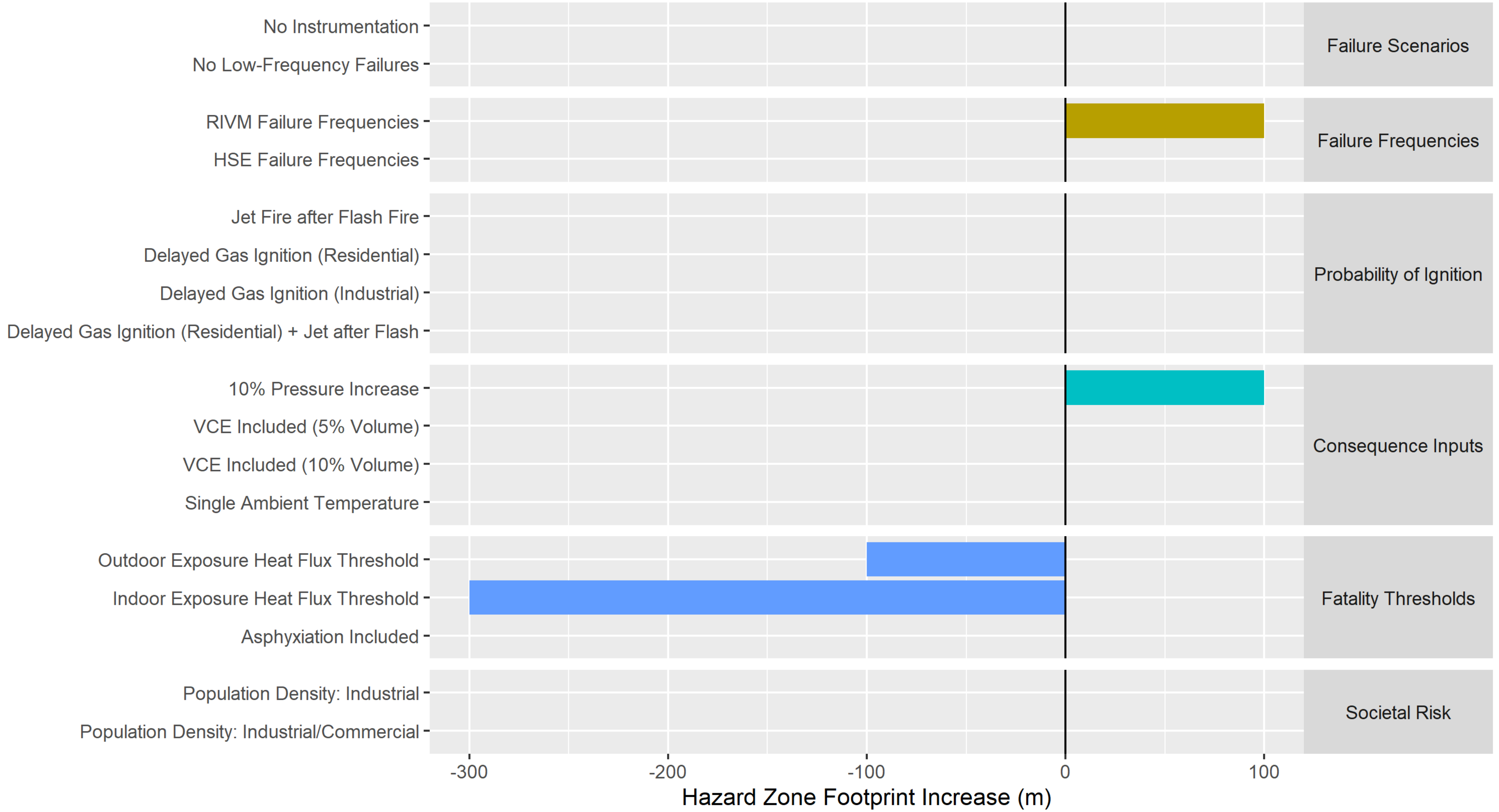
- Assumed population densities accounting for likelihood of receptor presence
  - Peak shaver facility – 3,000 people/km^2
  - Export facility – 25 people/km^2
- Results in ALARP (as low as reasonably practicable) region could be addressed through more detail design and QRA

Task 5: Perform Sensitivity Analysis to Refine/Probe QRA Methodology

- 17 sensitivity cases were chosen:
  - 8 for frequency
  - 4 for consequence
  - 5 for risk estimations
- The results of each case were compared against the “baseline” case to determine the effect of the input change.
- See Appendix D.7 of Public Final Report for more details

Task	Category		Sensitivity Case
5.1 Frequency Estimation	Failure Scenarios	1	No Instrumentation
		2	No Low-Frequency Failures
	Failure Frequencies	1	RIVM Failure Frequencies
		2	HSE Failure Frequencies
	Probability of Ignition	1	Jet Fire after Flash Fire
		2	Delayed Gas Ignition (Residential)
		3	Delayed Gas Ignition (Industrial)
		4	Delayed Gas Ignition (Residential) + Jet after Flash
5.2 Consequence Estimation	Consequence Inputs	1	10% Pressure Increase
		2	VCE Included (5% Volume)
		3	VCE Included (10% Volume)
		4	Single Ambient Temperature
5.3 Risk Estimation	Fatality Thresholds	1	Outdoor Exposure Heat Flux Threshold
		2	Indoor Exposure Heat Flux Threshold
		3	Asphyxiation Included
	Societal Risk	1	Population Density: Industrial
		2	Population Density: Industrial/Commercial

Task 5: Perform Sensitivity Analysis to Refine/Probe QRA Methodology - Export Facility Sensitivity Results

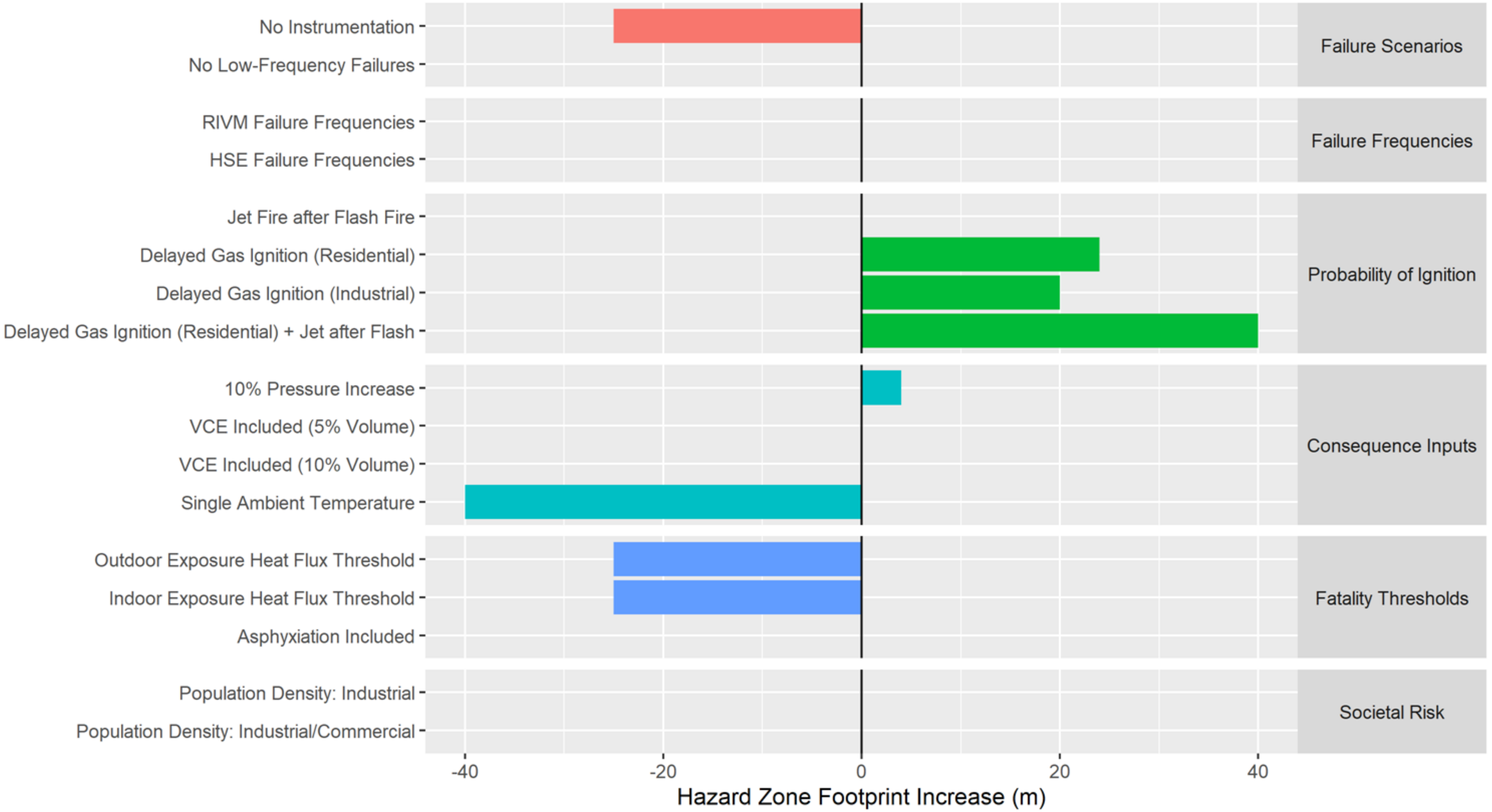


RIVM failure frequencies results in larger than baseline footprint distance

10% increase in release pressure increases hazard footprint distance

Increased heat intensity thresholds reduced hazard footprint distance

Task 5: Perform Sensitivity Analysis to Refine/Probe QRA Methodology – Peak Shaver Facility Sensitivity Results



Removing instrumentation failures results in lower than baseline footprint distance

Considering delayed ignition increases hazard footprint distance due to pipeline at site boundary

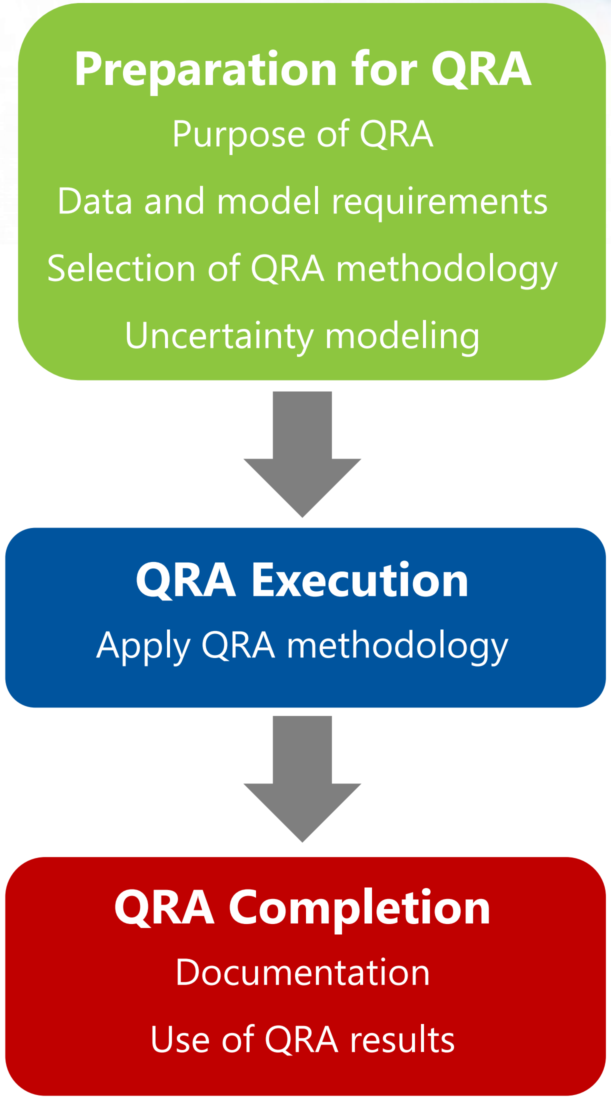
Ambient temperature variability at Peak Shaver location is greater

Task 6: Compare Proposed QRA Methodology to NFPA 59A 2019

- Comparisons were evaluated and provided by category of QRA framework:
  - System Description
  - Hazard Identification
  - Release Event Scenarios
  - Frequency Analysis
  - Consequence Modeling
  - Risk Estimation
  - Risk Evaluation
- See Appendix C of Public Final Report or Appendix of this presentation for more detail
- The proposed guidelines are largely consistent with NFPA 59A (2019) for all risk analysis steps but offer more flexibility and detailed guidance on application depending on the QRA classification

Task 7: Develop Guidelines for QRA Methodology – Process Framework

- Preparation for QRA
  - Define purpose
  - Define data requirements
  - Select methodology
  - Define handling of uncertainties
- QRA Execution
  - Approach defined by QRA methodology
- QRA Completion
  - Documentation
  - Use of results



Task 7: Develop Guidelines for QRA Methodology – Preparation

Purpose

- Depends on the functional stage of the facility and *intended use of QRA results*
- Level of detail for the QRA will be determined at this stage. Remainder of the guidelines address QRA execution steps according to the level of detail.

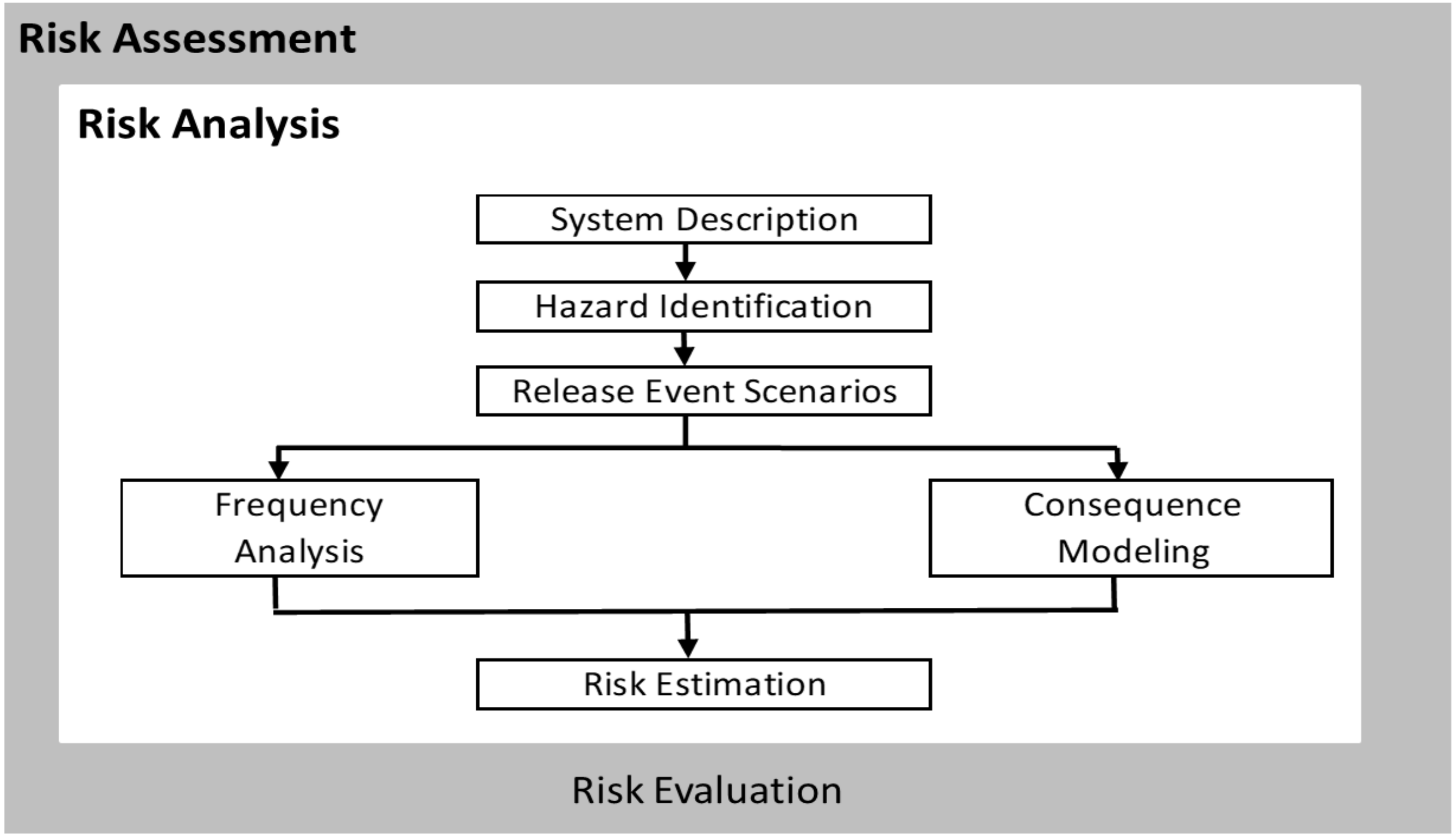
Data and Model Requirements

- Data collection and model selection are informed by the level of detail required to meet the purpose of the QRA
- Can be an iterative process to ensure the input data and models are suitable for the application

Uncertainty Modeling

- Guidance for handling uncertainties:
  - Incomplete system description
    - Unknowns can be approximated from standards or domain expertise
    - Uncertainty decreases as details of facility description increase
  - Lack of data
    - Use a range of possible values to bound unknown inputs, i.e. sensitivity analyses
  - Inherent randomness
    - Address using probabilistic representations

Task 7: Develop Guidelines for QRA Methodology – Execution



- Recommendations provided for performing each step of risk analysis
- Comments provided for risk evaluation

Task 7: Develop Guidelines for QRA Methodology – System Description

- QRA is classified as 'preliminary-design', 'detailed-design' or 'operational-facility' based on the availability of facility-specific details
  - These levels of detail are **illustrative;** if more or less detail is available, the QRA can be scaled accordingly.
- Minimum system description requirements are shown below

Preliminary-design QRA	Detailed-design QRA	Operational-facility QRA
Design-basis documents	Documents required for preliminary-design QRA	Documents required for detailed-design QRA
Process flow diagrams (PFDs)	Isometric design drawings	As-built construction drawings
Heat and material balances (HMBs)	Piping and instrumentation diagrams	Facility incident data
Site layout	Facility operational states	Equipment maintenance status
Site location	Process safety plans	Process safety records and near-misses
Surrounding land usage	Inspection and maintenance plans	Records of facility modifications
	Emergency response plans	Population data and land usage
	Topographic maps for surrounding area	

Increasing level of detail

Task 7: Develop Guidelines for QRA Methodology – Hazard Identification

Hazards for LNG facilities are due to ignition of flammable gas, vapor or liquids, which result in:

- Jet Fires
- Flash Fires
- Pool Fires
- Toxic or Asphyxiating vapor clouds (from unignited releases)
- Overpressure (from vapor cloud explosions, pressure vessel ruptures, and boiling liquid expanding vapor explosions)

Task 7: Develop Guidelines for QRA Methodology – Release Event Scenarios

- Total risk is a sum of the risks from each release event scenario
- Minimum set of conditions that are required to define release event scenarios:
  - Release from each piece of equipment that forms a part of isolatable inventory
  - Modes of failure (defined based on release hole sizes); minimum of two representative failure modes recommended:
    - Catastrophic release or full-bore rupture, and leaks that may remain undetected for a period before activating automated emergency shut-down devices (ESD)
    - Additional failure modes considered depending on the equipment type
  - Location and direction of release
  - Facility and equipment operational status
  - Functional status of emergency shut-down systems
  - External conditions

Task 7: Develop Guidelines for QRA Methodology – Release Event Scenarios (cont.)

- Available details to define the minimum conditions will vary based on QRA classification
- Preliminary-design QRA
  - Full listings of equipment may not be available; major equipment in the PFDs and release scenarios consistent with applicable standards are recommended
- Detailed-design QRA
  - May consider cascading events with the availability of detailed isometric design
- Operational-facility QRA
  - May consider additional human factors scenarios, triggering events, and simultaneous multi-system failures

Task 7: Develop Guidelines for QRA Methodology – Frequency Analysis

- Three components:
  - Frequency of release event
  - Probability of weather conditions corresponding to the release event scenario
  - Probability of ignition
- Frequency estimation approach categorized into three levels based on use of objective data and engineering models
  - Level 1: Subject Matter Expert (SME) Opinion
  - Level 2: Historical Data
  - Level 3: Probabilistic Models

Task 7: Develop Guidelines for QRA Methodology – Frequency Analysis (cont.)

Recommended Release Event Frequency Estimation Approaches:

Release Event Frequency Component	Preliminary-design	Detailed-design	Operational-facility
Facility equipment failure frequency ('failure rate')	Historical failure rates	Historical failure rates, and probabilistic modeling	Facility-specific data, historical failure rates, and probabilistic modeling
Probability of the operational status of the facility	Probability not considered	Historical data and SME opinion	Facility-specific data and SME opinion
Probability of the location of failure within the equipment	Probabilistic modeling with simplified assumptions	Probabilistic modeling based on design documents	Probabilistic modeling and facility-specific data

Task 7: Develop Guidelines for QRA Methodology – Frequency Analysis (cont.)

Recommended Release Event Frequency Estimation Approaches (cont.):

Release Event Frequency Component	Preliminary-design	Detailed-design	Operational-facility
Probability of the release direction	Probabilistic modeling with simplified assumptions	Probabilistic modeling based on design documents	Probabilistic modeling and facility-specific data
Probability of failure of emergency shutdown systems	Historical data	Historical data	Probabilistic modeling, historical and facility-specific data
Probability of an external triggering event	Probability not considered	Historical data	Historical data and probabilistic modeling

Task 7: Develop Guidelines for QRA Methodology – Consequence Modeling

- Quantifies the potential safety hazards due to release events, including:
  - Thermal radiation due to jet fires and pool fires
  - Flammable, toxic or asphyxiating concentrations of vapor due to vapor cloud dispersion
  - Overpressure due to explosions or rapid combustion of confined flammable vapors
- Due to the complexity of the consequence modeling process, a wide range of software packages are available
  - PHMSA provides a list of approved software packages for analysts to choose from; alternative models may have to be approved by regulators

Task 7: Develop Guidelines for QRA Methodology – Risk Estimation

- Calculate location-specific individual risk (LSIR) and societal risk (SR) measures
- Consequence thresholds for heat flux, product concentration, and overpressure are defined for fatality
  - Thresholds are related to risk criteria and should be selected together

Hazard Type	NFPA 59A	RIVM	Singapore Guidelines
Radiant heat flux	9 kW/m^2 (30 s exposure)*	35 kW/m^2 (20 s exposure)	15.3 kW/m^2 21.6 kW/m^2 (30 s exposure)
Flash fire extent	LFL**	LFL – 20 s exposure	LFL
Overpressure	3 psi	4.35 psi (0.3 bar)	5, 7, 10 psi***

*as implied in 19.8.4.2.2 of NFPA 59A

**Lower Flammability Limit

***implied 3%, 10% and 50% fatality

Task 7: Develop Guidelines for QRA Methodology – Risk Estimation (cont.)

- Selection of consequence thresholds needs consideration of risk acceptance criteria and consistency within a selected standard
  - Low-consequence threshold with high-risk tolerance implies a similar level of public safety as high-consequence threshold with low-risk tolerance
- SR estimation requires information on presence and exposure of the neighboring population
  - Preliminary-design QRA population data may be obtained from surrounding land use characterization and census data
  - Detailed-design QRA and operational-facility QRA population data may be obtained from maps of land usage, footprint of the built-up areas, aerial maps of houses and other facilities

Task 7: Develop Guidelines for QRA Methodology – Risk Evaluation

- Risk criteria for LSIR are divided into three zones:
  - Tolerable without restrictions
  - Tolerable with restrictions
  - Not tolerable under any conditions

- SR criteria are divided into three zones (NFPA 59A)
  - Tolerable
  - As low as reasonably practicable (ALARP)
  - Intolerable

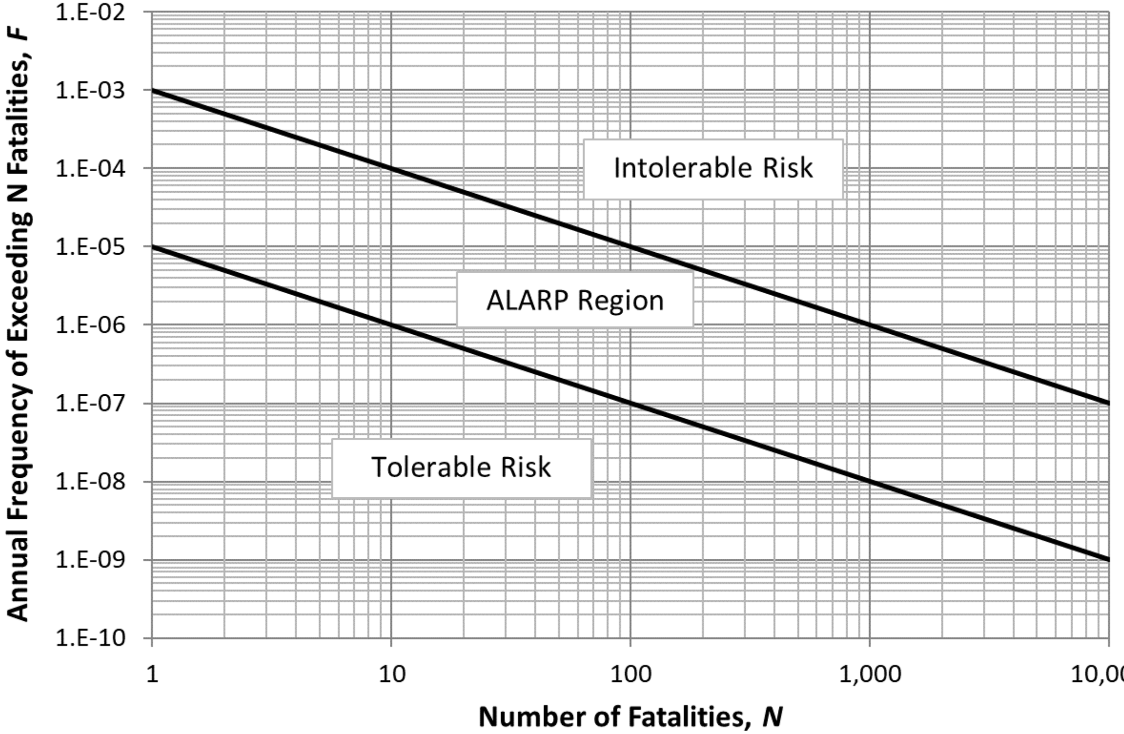
	Zone	NFPA 59A	RIVM*	Singapore Guidelines
1	**Minimum intolerable**	5×10^{-5}	1×10^{-5}	5×10^{-5}
2	**Some restrictions**	5×10^{-5} to 3×10^{-7}	–	5×10^{-6}
3	**Maximum tolerable**	3×10^{-7}	1×10^{-6}	1×10^{-6}

*The Dutch criteria has only intolerable and tolerable risks for existing and the new facilities

Task 7: Develop Guidelines for QRA Methodology – Risk Evaluation (cont.)

- Risk tolerance criteria
  - Consistent with consequence thresholds
  - Consistent with other assets regulated by PHMSA (e.g. pipelines)
  - Consideration of combined public safety risks
- Risk mitigation actions can be considered in the QRA; the resulting risk reduction can be quantified and evaluated in accordance with the ALARP principle
- Cost of risk reduction activities may be disproportionate to the magnitude of risk reduction; ALARP accounts for this
  - Demonstration of ALARP needs a quantification of the safety benefit for comparison against the costs of the risk reduction activities

Societal Risk Criteria for Fatalities in NFPA 59A (2019)



Task 7: Develop Guidelines for QRA Methodology – Documentation and Use

Documentation

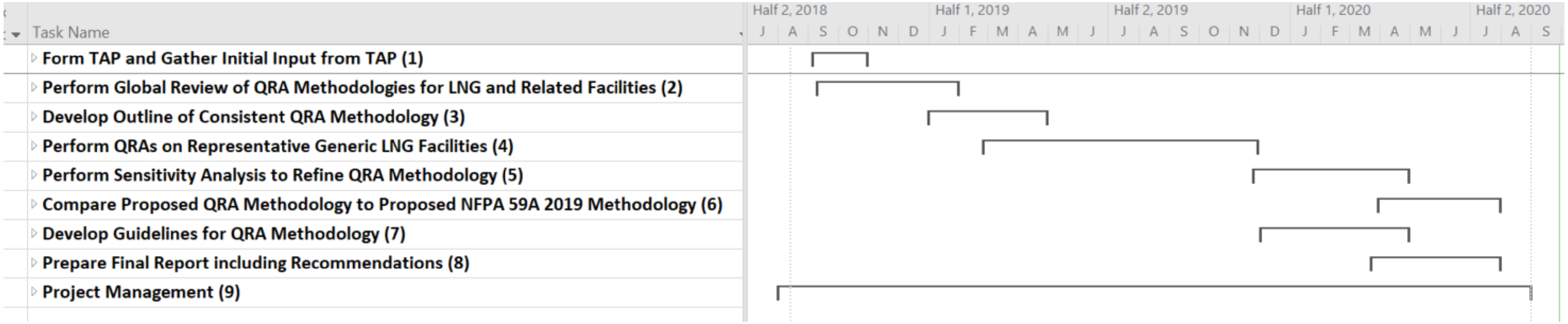
- Purpose of the QRA
- Data sources and modeling approach to handle uncertainties
- QRA components:
  - System description and hazard identification
  - List of release event scenarios
  - Modeling approach for frequency analysis and consequence estimation
  - Risk estimation approach
  - Risk measures used
- Results of sensitivity analyses

Use

- Two potential outcomes to a QRA Process:
  - Risk is tolerable; no further assessment required
  - Risk is intolerable; refinement is required to reduce conservatism or demonstrate ALARP
- Additional QRA to assess the sensitivity of the estimated risk to the assumptions and limitations is recommended
  - These additional analyses can be used to bound the estimated risk

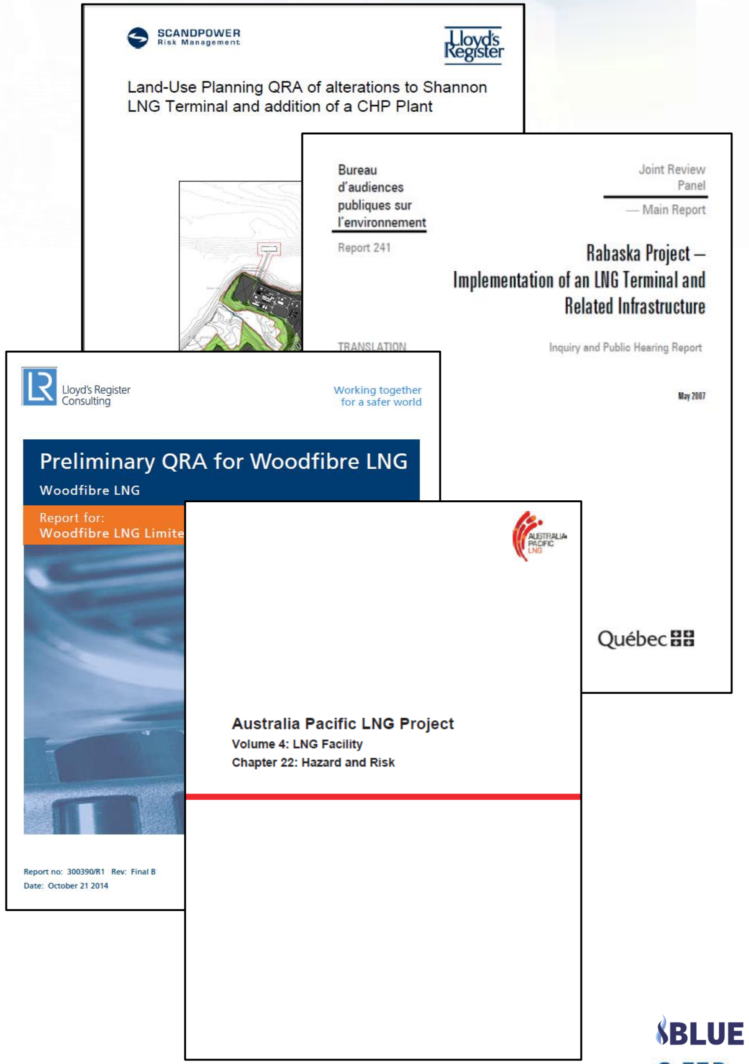
Task 8: Develop Final Report with Recommendations
Task 9: Project Management

- All project tasks and deliverables were completed on schedule, including Draft Final Report submitted on July 31, 2020
- No requests for additional funding or schedule were submitted
- No changes occurred in project team members throughout the project



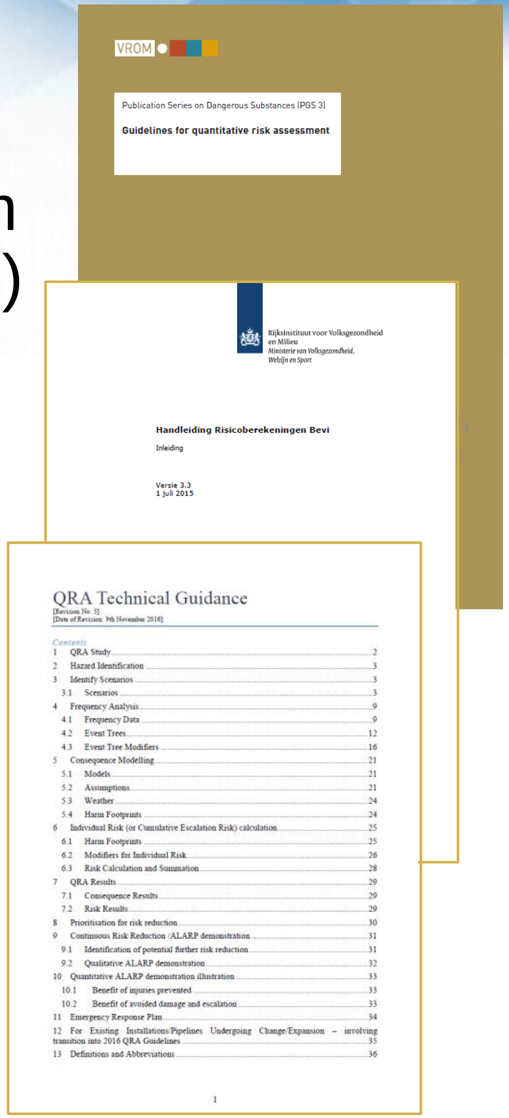
Project Results and Conclusions

- A literature review of the public domain QRA reports, supplemented by a review of international standards for QRA of LNG facilities, has shown that the application of QRA methodology has a large degree of consistency.
  - However, this finding (with respect to public domain QRAs) is limited to preliminary-design QRAs for export facilities
  - The limited number of QRAs for LNG export or peak shaving facilities in the public domain creates a knowledge gap and lack of public consensus on detailed requirements for QRA.



Project Results and Conclusions (cont.)

- A comparison of the QRA approaches used in regulations from the UK, the Netherlands, and Singapore with NFPA 59A (2019) showed these methodologies to be generally consistent.
  - Hazard types, equipment failure modes and rates, risk measures, and risk quantification criteria are similar.
  - Key areas of difference included the definition of the thermal radiation hazard thresholds, the implied probability of fatality associated with the hazard thresholds, and the risk acceptance criteria.
  - Most regulations require modeling cascading failures (or domino effects) but lack details on the release event scenarios and casual factors that result in cascading failures.



Project Results and Conclusions (cont.)

- Guidelines to perform QRA of LNG facilities were developed to ensure consistency with respect to the level of rigor of the approaches selected to estimate different components of QRA, e.g. frequency, consequences and risk.
  - They address data and model requirements, uncertainty modeling, and make recommendations on minimum requirements for each analysis step.
  - They address both new designs and existing facilities, and account for differing levels of available detail at three levels of an LNG facility: preliminary-design, detailed-design and operational phase. By including an operational phase, the guidelines can support PHMSA's potential consideration of QRAs as a means to more quantitatively measure an operator's ongoing improvements to manage risk through metrics.
  - The proposed guidelines are largely consistent with NFPA 59A (2019) for all risk analysis steps but offer more flexibility and detailed guidance on application depending on the QRA classification.

Project Results and Conclusions (cont.)

- As a benchmarking and demonstration exercise, preliminary-design QRAs using the guidelines were conducted for both a generic export and a generic peak shaver LNG facility. Documentation was provided.
  - The results of the QRAs for the two selected facility types show that safety risk does not reach intolerable levels for either facility when designed according to the existing standards.
  - Sensitivity analyses showed that the estimated risk can be sensitive to a few parameters such as hazard thresholds and population density surrounding the facilities. Compared to these factors, assumptions corresponding to equipment failure rates and exclusion of minor instrumentation failures had little effect on the risk metrics. However, these results are specific to the benchmark facilities analyzed and the specific assumptions made about the facility design and location. These results cannot be generalized without additional detailed QRA studies.

Knowledge Transfer / Potential Next Steps

- The project results provide a resource to:
  - PHMSA as it considers **potential revisions to 49 CFR Part 193**
  - The NFPA 59A Technical Committee and others to help inform **potential consensus revisions to future editions to NFPA 59A**
    - Multiple TAP members, project members and organizations who were involved in this project serve on the NFPA 59A Technical Committee
    - Public input period for 2022 edition is open through Jan. 6, 2021
- An additional public presentation of the project results is scheduled at the Transportation Research Board's 100th Annual Meeting to occur virtually in Jan. 2021, in a session entitled "New Developments in North American Transport of Liquefied Natural Gas (LNG)"

Additional Potential Next Steps: Future Research

- Perform a study of the preliminary-design benchmark LNG QRAs to a detailed-design facility QRA and to an operational facility QRA
- Compare the differences of the QRA results conducted according to available international and the US standards is recommended
- Expand consideration of hazard mitigation options for detailed-design or operational-facility QRAs
- Develop more accurate modeling approaches for overload and triggering events such as blast and impact loads, as well as more sophisticated probabilistic models for equipment failure frequencies, to enable more practical and accurate modeling of potential cascading events
- Further consider potential combined risks due to infrastructure surrounding the LNG facility

Thank You / Closing Discussions

PHMSA
Pipeline and Hazardous Materials Safety Administration

Project public webpage: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=731

- Public Final Report
- This Presentation

Researchers Contact Info:

- GTI: Rich Kooy, PE | rkooy@gti.energy
- BLUE: Filippo Gavelli, PhD, PE | FGavelli@blueeandc.com
- C-FER: Smitha Koduru, PhD, PEng | S.Koduru@cfertech.com
- INL: Bob Youngblood, III, PhD | robert.youngblood@inl.gov

Appendix: Additional Details / Information

- Task 3 Nomenclature
- Task 5 Sensitivity Results Examples
- Task 6 Additional Information

Task 3: Develop Outline of Consistent Methodology

Nomenclature Definitions

Probability of Fatal Event

Probability of Hazard Intensity given an event

Probability of Hazard Events

Probability of Each Weather Combination

Frequency of Release Events

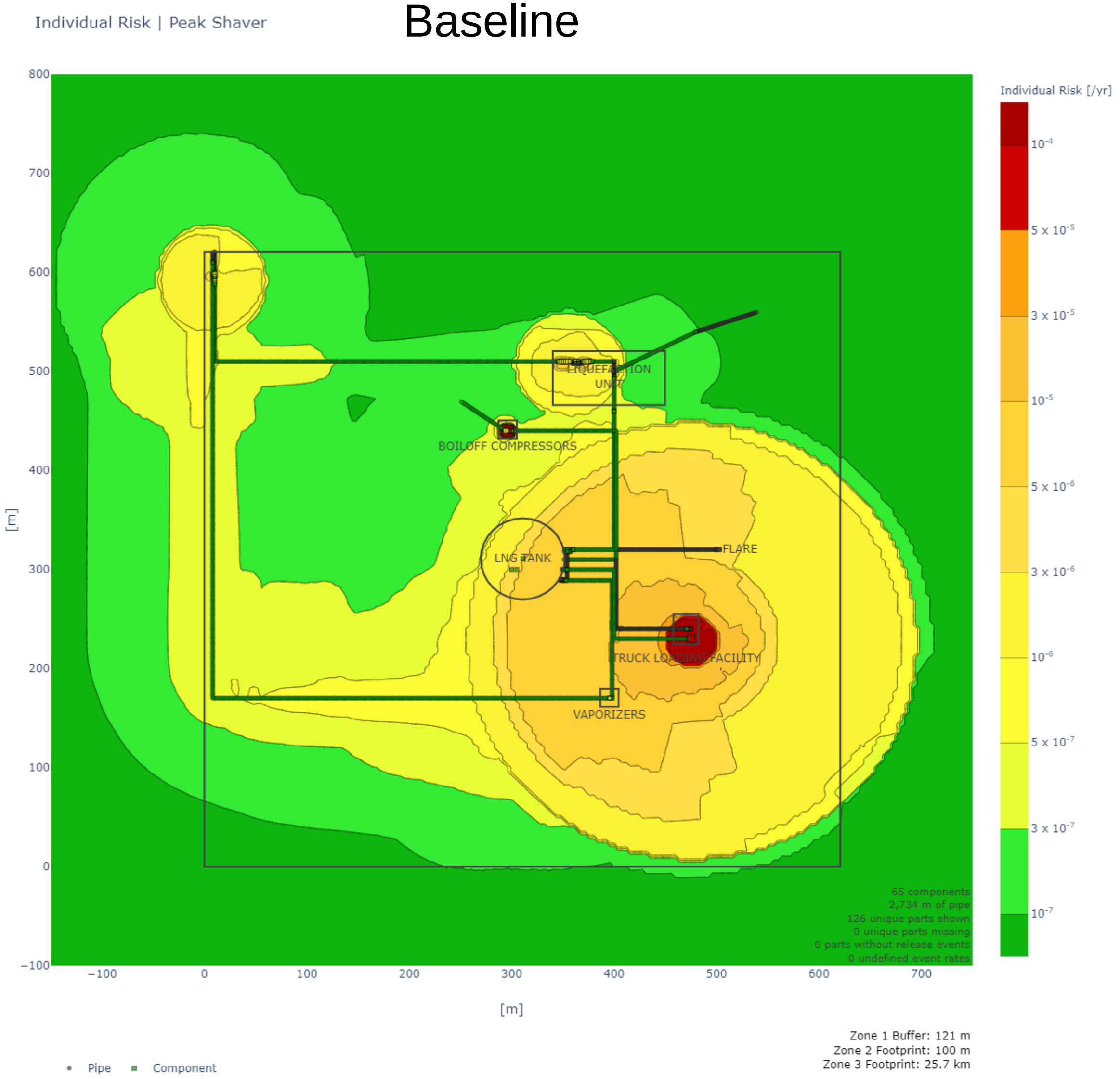
$$IR_{(x,y)} = \sum_{i=1}^{n} \left(\sum_{j=1}^{J} P\left[I_i | H_j\right] \cdot \left(\sum_{l=1}^{L} \sum_{k=1}^{K} P\left[H_j | HE_k, W_l, E_i\right] \cdot P\left[HE_k | W_l, E_i\right] \cdot P\left[W_l\right] \right) \cdot P\left[E_i\right] \right)$$

$IR_{(x,y)}$	Individual risk at a location	Any point (x, y) on grid
E_i	Release event	Set of all release scenarios
I_i	Fatal event	An event where the intensity (e.g. heat flux, concentration) exceeds the fatal limit
H_j	Hazard intensity	The intensity of a hazard (e.g. heat flux, concentration)
HE_k	Hazard event	The type of hazard event that occurs (e.g. jet fire, flash fire, toxicity)
W_l	Weather combination	Combo of: (1) temperature, (2) humidity, (3) wind speed, (4) stability class, (5) wind direction, (6) irradiance

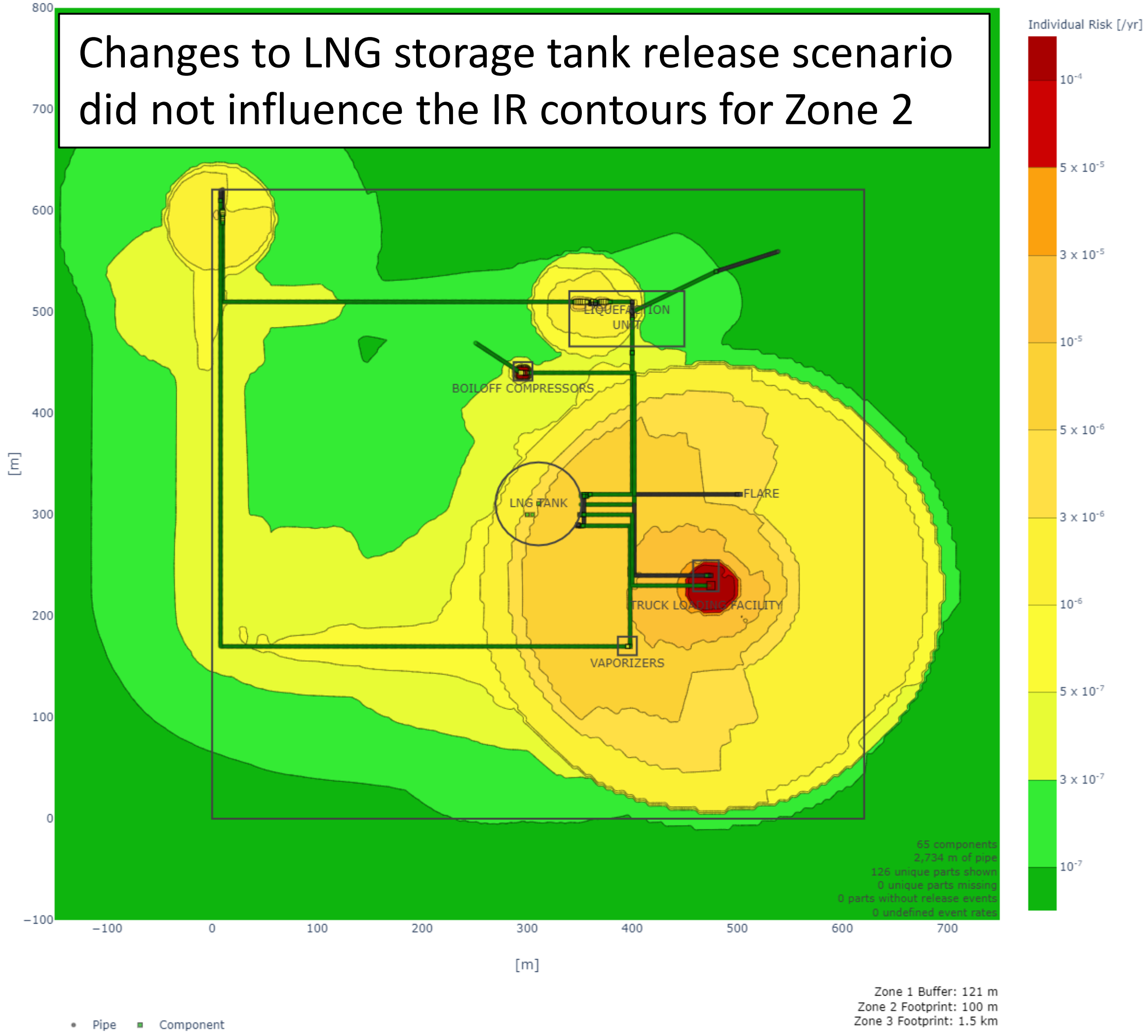
- The individual risk equation served as the road map for the analyses conducted in Task 4

Task 5: Perform Sensitivity Analysis to Refine/Probe QRA Methodology – Example Peak Shaver IR Sensitivity Result

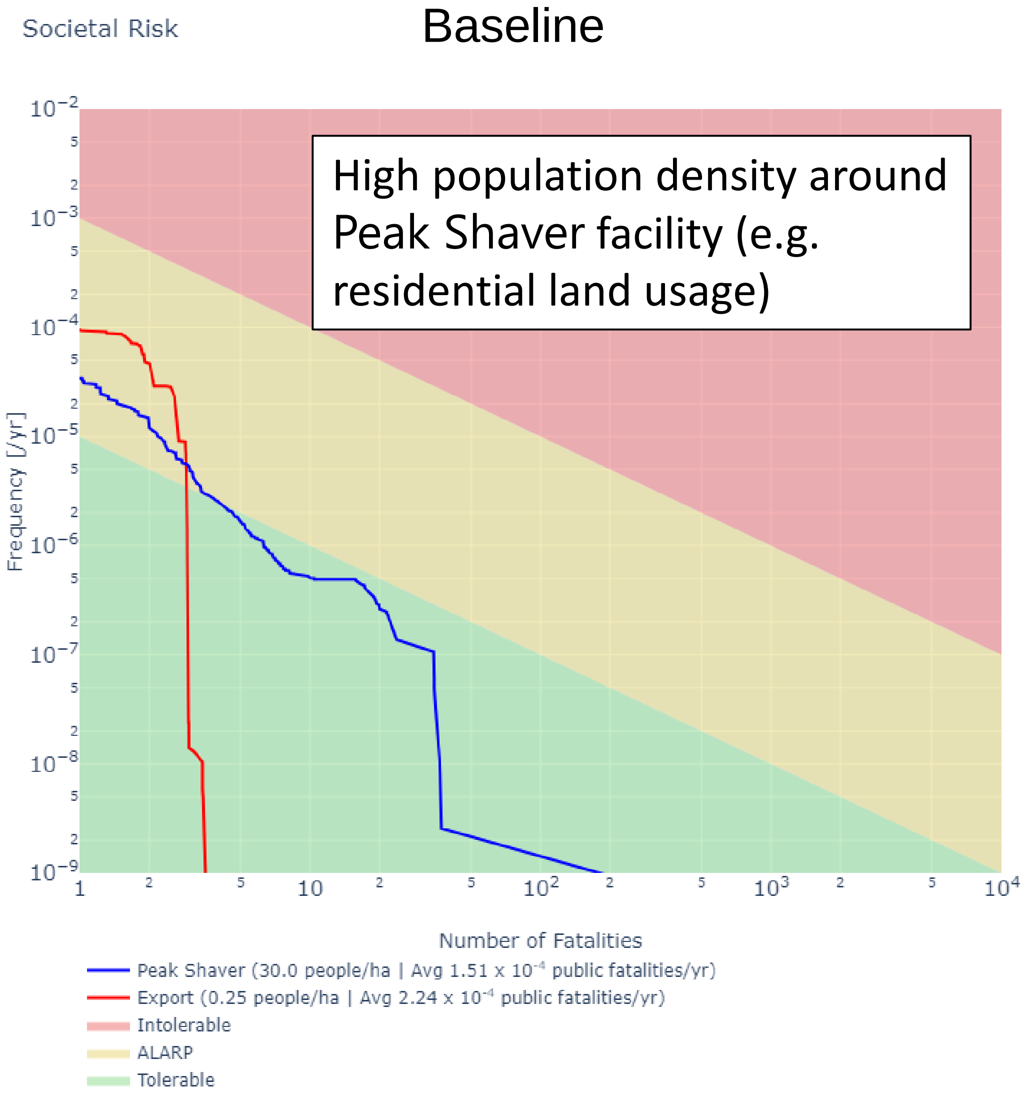
Baseline

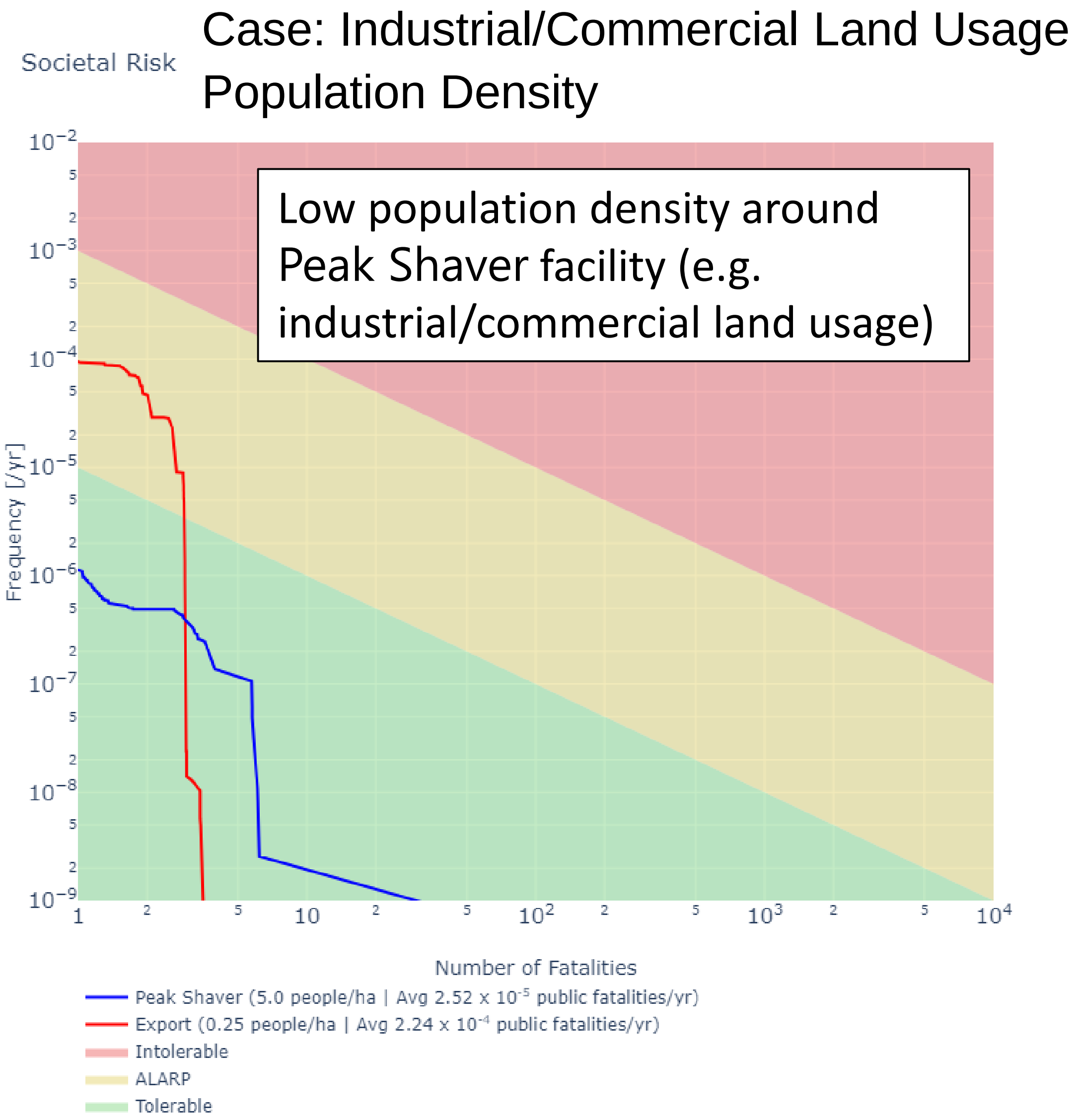


Case: Remove Low-Frequency Failures



Task 5: Perform Sensitivity Analysis to Refine/Probe QRA Methodology – Example Peak Shaver SR Sensitivity Results





Task 6: Compare Proposed QRA Methodology to NFPA 59A 2019

Category	Examples of how the Proposed Guidelines compare to NFPA 59A 2019
System Description	Consistent with the relevant content of NFPA 59A (2019) including clauses 19.5.1 and 19.5.2, but provides more detail with respect to the levels of detail for system description.
Hazard Identification	Consistent with relevant clause 19.5.1.2 of NFPA 59A (2019), but allows for hazard identification for preliminary-design QRAs (due to the lower level of detail available in the design basis documents).
Release Event Scenarios	Consistent with the list in Clause 19.5.2.1 of NFPA 59A (2019), but provides a minimum set of requirements and includes consideration for external conditions such as weather and extreme events. Also, recommends at least two representative failure modes: one to account for a catastrophic release or full-bore rupture, and a second for leaks that may remain undetected for a period of time before activating automated emergency shut-down devices. And also recommends that additional failure modes based on the equipment type should be considered.

Task 6: Compare Proposed QRA Methodology to NFPA 59A 2019 (cont.)

Category	Examples of how the Proposed Guidelines compare to NFPA 59A 2019
Frequency Analysis	Offer more detailed guidance on the specific inputs for frequency estimation; but do not prescribe a failure rate source. The proposed QRA guidelines divide the frequency estimation into three components - - frequency of the release event, probability of weather conditions corresponding to the release event, and probability of ignition. Also, the approach for determining the release event frequency of these three components is further subdivided into 3 levels: 1) subject matter expert opinion, 2) historical data, 3) probabilistic models. The proposed guidelines also outline a more detailed approach, including probabilistic modeling to determine release event frequencies and weather condition modeling. The frequency estimation approach in NFPA 59A (2019) can be used according to the proposed QRA guidelines; but adherence to the proposed guidelines results in more flexibility when determining release event frequencies.

Task 6: Compare Proposed QRA Methodology to NFPA 59A 2019 (cont.)

Category	Examples of how the Proposed Guidelines compare to NFPA 59A 2019
Consequence Modeling	Offers more guidance by outlining the levels of detail and general approaches for consequence modeling, and remain consistent with the requirements in NFPA 59A 2019.
Risk Estimation	Consistent with the relevant clauses of NFPA 59A (2019) such as 19.9.1 and 19.9.2, but the discussion on uncertainty in the QRA in the proposed guidelines is more detailed than in NFPA 59A (2019). The proposed guidelines also recommend sensitivity analyses to reduce uncertainty in the QRA.
Risk Evaluation	Consistent with the requirement of clause 19.11 of NFPA 59A (2019), but notes that the concept of as low as reasonably practicable (ALARP) can be difficult to establish in practice because it would require defining the concept of ‘gross disproportion’ and monetization of fatalities and irreversible harm.

End Slide

Thank You