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Development of Methodologies for Managing Process Safety Risk Using Hazard and Operability (HAZOP) and Layers of Protection Analysis (LOPA) for Liquefied Natural Gas (LNG) Facilities

Final Technical Project Report

Report to: The U.S. Department of Transportation (DOT), Pipeline and Hazardous Materials Safety Administration (PHMSA)

U.S. Department of Transportation

Date: June 13, 2025

ioMosaic Reference: 23215 Rev. C

"This research was funded in part under the Department of Transportation, Pipeline and Hazardous Materials Safety Administration's Pipeline Safety Research and Development Program. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Pipeline and Hazardous Materials Safety Administration, or the U.S. Government."

Revision History:

Rev.	Date	List of Changes	Prepared by	Reviewed by
A	November 4, 2024	First Issue	David J. Blake R. Pete Stickles, P.E. Judy A Perry, CCPSC	Neil Prophet Kathy Anderson, CCPSC
B	January 24, 2025	Final Technical Report	David J. Blake R. Pete Stickles, P.E. Kathy Anderson, CCPSC Christian Sarno	Neil Prophet
C	June 13, 2025	Footer Update	Skyler Dunn-Sperling	David J. Blake

Notice:

This report was prepared by ioMosaic Corporation for the benefit of The U.S. Department of Transportation (DOT), Pipeline and Hazardous Materials Safety Administration (PHMSA) in response to Solicitation FY23 – Research Announcement #9 ID 693JK323RA0001. The focus of this document addresses a major research need – item 5, Liquefied Natural Gas. This report represents ioMosaic Corporation's best judgment in light of information made available to us. Opinions in this report are based in part upon data and information provided by The U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration and / or The U.S. Department of Transportation (DOT), Pipeline and Hazardous Materials Safety Administration (PHMSA)'s advisors and affiliates. The reader is advised that ioMosaic Corporation has not independently verified the data or the information contained therein. This report must be read in its entirety. The reader understands that no assurances can be made that all liabilities have been identified. This report does not constitute a legal opinion.

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1 Executive Summary

The objective of this project was to develop methodologies for managing Process Hazard Analysis (PHA) techniques, such as the Hazard and Operability (HAZOP) and Layers of Protection Analysis (LOPA) for Liquefied Natural Gas (LNG) facilities.

1.1 Literature Review

A search was initiated to review the relevant literature regarding hazard analysis and risk evaluation, particularly those techniques and methodologies which would be aptly suited for the LNG industry. Approximately one hundred (100) sources were identified for this project. The complete list of literature sources identified are included in Appendix 3-A.

1.2 PHA Techniques

This report examines PHA techniques and how they are used for LNG facilities. These techniques include: Preliminary Hazard Review (PreHA), Hazard Identification (HAZID), Inherently Safer Design Review, Concept Risk Assessment (CRA), Checklist, What-If, Hazard and Operability Study, Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Bow-tie Analysis, Layer of Protection Analysis, and Quantitative Risk Assessment (QRA). The review of PHA techniques is for those designing, operating, and maintaining LNG facilities expecting to perform PHAs.

1.3 Supporting Techniques and Information for Conducting PHAs

The report also explains supporting techniques and provides the information and data needed when it is applied in combination with PHA methodologies. It begins with risk evaluation concepts, such as frequencies, consequences, and risk tolerability, lists of typical hazard scenarios, failure frequencies and conditional modifiers specific to the LNG industry are also contained in the report. The review of supporting techniques and information is for those designing, operating, and maintaining LNG facilities expecting to perform PHAs, as well as those auditing PHAs of LNG facilities.

1.4 Recommended Techniques by Stage

Historically, Process Safety Professionals refer to the life cycle of a project as starting with identification of hazards at the research and development stages, through "Conceptional Design" and pilot plant operations prior to the "Detailed Engineering Design" phase. However, LNG facility construction is based on known chemistries, as well as known hazards. The methodologies to be utilized for a PHA will be dependent on the scope of the project and complexity of the process. This report recommends methodologies for each Life Cycle Stage of an LNG facility. These recommendations are for those designing, operating, and maintaining LNG facilities expecting to perform PHAs.

1.5 How to Conduct a PHA

An LNG facility should have a procedure for it's Process Hazard Analysis (PHA) process. This procedure may be required by local regulations. This report contains information on what the procedure should include, such as: when to perform a PHA, how to prepare for a PHA, how sessions should be run, how to write PHA recommendations, and the PHA training requirements. Checklists specific to LNG facilities can be found in Appendices 5 A/B/C/D. The instructions for how to conduct a PHA are for those designing, operating, and maintaining LNG facilities expecting to perform PHAs, as well as those auditing PHAs of LNG facilities.

1.6 Example PHA(s)

The report describes in detail the steps for conducting a HAZOP and a LOPA. These methodologies were used as examples, but the identification of initiating events, causes, and consequences and the assignment of risk ranking applies to other methodologies independent of how the "deviations" or "initiating events" were identified. Appendix 8-A includes an example HAZOP/LOPA PHA with example P&IDs. The PHA is an example for those designing, operating, and maintaining LNG facilities expecting to perform PHAs.

1.7 How to Use PHA Results

After a PHA is conducted, the PHA Team Leader is usually expected to compile a report of the results. Once the PHA Report is completed, the site should have a system for tracking action plans to resolve the PHA recommendations/findings. The instructions for how to use PHA results is for those designing, operating, and maintaining LNG facilities expecting to perform PHAs, as well as those auditing PHAs of LNG facilities.

1.8 Recommendations

Finally, this report contains a list of recommendations to PHMSA, industry and for further research.

- There are four (4) key recommendations to PHMSA, they can be found in section 10.2.
- There are eight (8) key recommendations for industry consideration, they can be found in section 10.3.
- There are four (4) key recommendations for areas for further research, they can be found in section 10.4.

2 Introduction

2.1 Background

The United States of America is critically dependent on natural gas and petroleum liquids transported through pipelines. The infrastructure that currently transports these energy resources is aging, with a significant fraction being more than fifty years old. While new pipelines are being planned and constructed, pipeline operators typically plan on continued operation of the vast majority of existing pipeline mileage. Assuring the long-term integrity and security of these existing pipelines is essential.

Recognizing these facts, the U.S. Department of Transportation (DOT), Pipeline and Hazardous Materials Safety Administration (PHMSA), Office of Pipeline Safety (OPS) designed a process to emphasize the importance of continuing pipeline-related Research and Development (R&D). States, industry, and other Federal Agencies strongly support PHMSA's initiative.

A 2022 Liquefied Natural Gas (LNG) R&D Public Meeting and Forum was held November 15-16, 2022. The workshop resulted in a common understanding of current research efforts, a listing of key challenges facing government and industry, and a compilation of potential research areas whose exploration would assist with meeting these challenges and should therefore be considered in the development of new research and development applications. PHMSA pipeline safety representatives determined that the following major research areas needed to be addressed:

i. Threat Prevention
ii. Underground Natural Gas/Hydrogen Storage (UNGS)
iii. Anomaly Detection/Characterization
iv. Hazardous Liquid Tanks
v. Liquefied Natural Gas (LNG)
vi. Climate Migration
vii. Materials

On April 12, 2023, PHMSA issued Research Announcement, #693JK323RA0001, to address these areas. This report focuses on the "item v. Liquefied Natural Gas (LNG)" research area.

2.2 Scope / Goals

The objective of this project was to develop methodologies for managing Process Hazard Analysis (PHA) techniques, such as the Hazard and Operability (HAZOP) and Layers of Protection Analysis (LOPA) for LNG facilities.

The anticipated results consist of a detailed and concise guide for LNG production, storage, and transport companies to understand and consistently apply process hazard analysis methodologies, tailored to the LNG industry.

2.3 Intended Audience

For personnel in many industries, a process hazard analysis is a common practice for reviewing a hazardous chemical process. This project assumed that operations and regulatory personnel within the LNG industry might not be as attuned to the PHA process as those in design, where it is included as part of the licensing process. As a result, this project has been written as both an introduction for personnel first being exposed to the concepts and also as a resource for those looking to ensure their facility hazard analyses are comprehensive and complete.

3 Literature Review

3.1 Overview

Upon receipt of the award, a search was initiated to review the relevant literature regarding hazard analysis and risk evaluation, particularly those techniques and methodologies which would be aptly suited for the LNG industry.

The literature search evaluated a wide variety of literature sources for applicability, and broad government and industry acceptability, in applying PHAs for facilities processing LNG. The literature search was not limited to the actual PHA methodologies. It also included the availability of the process safety information (PSI) within the LNG industry needed to support a PHA, and review of previous accidents for hazards that might need to be evaluated in an industry specific PHA.

The literature searched came from a wide variety of sources. U.S. Federal and International regulations were reviewed to understand the current state of affairs both domestically and abroad. Regulations were also reviewed for parallel industries to understand how they have been and could be applied. Domestically, this included regulatory agencies such as the Occupational Safety and Health Administration (OSHA), Environmental Protection Agency (EPA), U.S. Army Corps of Engineers (USACE), and of course, PHMSA and other agencies of the Department of Transportation (DOT). Internationally, regulations from the Nova Scotia Department of Energy and the United Kingdom Health and Safety Executive (UK HSE) were reviewed.

Beyond the actual regulations, the literature search also included government issued information advisory bulletins, directives, general guidance, fact sheets, interpretation letters, failure investigation reports, and National Transportation Safety Board (NTSB) studies and accident reports pertinent to LNG. The literature search also extended to LNG distribution incidents for causal factors that might need to be included in an LNG PHA.

Industry standards were reviewed to understand the practices the LNG industry is expected to be following if it is following best industry practices and Recognized and Generally Accepted Good Engineering Practices (RAGAGEP). Organizations within this area included the National Fire Protection Association (NFPA), American Petroleum Institute (API), American Society of Mechanical Engineers (ASME), American National Standards Institute (ANSI), and the International Electrotechnical Commission (IEC).

Other materials included in the literature search include reference books, magazine articles, and industry guidelines, such as those issued by the American Institute of Chemical Engineers' (AICHE) Center for Chemical Process Safety (CCPS).

Prior to this report, an interim report [1] was issued on March 29, 2024. Approximately ninety (90) sources were identified for this project. Additional sources continued to be added to the search as they were identified. The total count for this project now exceeds one hundred. See Appendix Section 3-A: Bibliography / Literature Reviewed for the complete listing.

3.2 Reference Applicability and Importance Rating

The main objective of the literature review was to extract the most applicable and relevant references from the myriad sources of information available on LNG safety, process hazard analysis, and risk evaluation techniques. To achieve this goal, a list of qualification factors was applied to each literature source reviewed to arrive at an informed impression of the importance of the source to the objectives and goals of the research. The factors applied included:

- Was the source applicable to the Topic (including PHA methodology, risk assessment criteria and failure data, and/or LNG RAGAGEP)?
- Was the source an engineering and design RAGAGEP standard pertinent to LNG facilities?
- Was the source utilizing/demonstrating PHA or LOPA techniques in evaluating risks?
- Was the source providing descriptions of a PHA methodology's application and implementation?

Each reviewer evaluated each of the factors on a Yes/No basis using their knowledge of Industry Best Practices. This was followed by a brief synopsis of subjects in the reference and the quality thereof that was used to determine an importance rating. An important rating scale of 0 to 5 was assigned as shown in Table 1.

Table 1: Projected Activities

Rating	Description
4-5	Literature source has material for basis of further project work
3	Literature source may have some possible additional resource material
1-2	Literature source provides little to no additional insight beyond other sources. A reference with this score is not expected to be considered further
0	Literature source was reviewed and found to have no relevance to the project
N/R	Not rated prior to issue. This includes some sources (such as texts on techniques) that will obviously be used, but reviewers did not rate. It also includes sources that were later additions to the inventory.

Source: ioMosaic Corporation

3.3 Master List

The complete list of literature sources identified is included in Appendix Section 3-A Bibliography / Literature Reviewed. The qualification factors and importance rating values are included for each literature source. The reviewer’s rationale for the importance of rating values is also provided to support the rating. One of the reviews is rather detailed and extended well beyond the confines of a simple spreadsheet. For this entry, further explanation was provided to justify the rating assigned. This explanation is included in Appendix Section 3-B: Handling Failure Data Uncertainty in Risk Assessment.

From the literature search, our reviewers found certain literature sources to appear readily more useful for setting the basis for PHAs for the LNG industry. The following sections have been broken up to provide better relevance.

3.3.1 Preparing for a PHA, Process Safety Information (PSI) Development

Table 2 lists the literature sources expected to be most useful for setting the framework for successful PHAs. OSHA Reference [2] from Table 2 is appealing because it has existing, codified requirements establishing minimums for PSI and PHA team member participation from another regulatory body. The regulation is an established precedent for other industries outside of the LNG industry.

Table 2: Pertinent Literature Sources for Establishment of PHA Requirements

PHA/ Risk Assessment Subject; Preparing for PHA				
Ref	Issuing Organization	Document No.	Title	Desirable Features / Shortcomings
[2]	OSHA	29CFR1910.119	Process Safety Management of Highly Hazardous Chemicals	Existing codified requirements Establishes minimum PSI requirements Establishes minimum team participation requirements for PHAs.
[3]	CCPS	3rd Edition 2008	Guidelines for Hazard Evaluation Procedures	Table 2.2 expands PSI used in PHAs Table 2.3 expands possible team participants. Software recording aids
[4]	British Std. Institute	BS IEC 61882 Ed. 2 2016	Hazard and operability studies (HAZOP studies) – Application Guide	Preparation information doesn't include chemical hazard information. Section 6.4.2 Design Description requirements can be interpreted to include a broad range of information but are less specific on nature of information than the CCPS book.
[5]	Federal Energy Regulatory Commission (FERC)	Commission Staff Guidance Vol. II 2017	Guidance Manual for Environmental Report Preparation	Documentation requirements for LNG applications submitted to FERC contained in Section 11.2.1 of the guidance and Appendices 13E, F and G form a strong compilation of PSI for PHAs during operations. Appendix 13Q covers requirements for Safety Instrumented Systems (SIS) including 13Q.1 Cause & Effect Matrix

FERC Reference [5] was selected as it has provided guidance to the LNG industry on what documentation the Commission expects LNG project applicants to provide during the design and application process. It is comprehensive and detailed covering hazardous chemical properties, process design information and equipment mechanical design specifications. This package of information should be on file at an operating LNG facility and should form the basis for revalidation PHAs once operations have commenced.

3.3.2 Preparing for a PHA, Previous Industry Incidents

CCPS Reference [3] under the previous section 'Preparing for Hazard Evaluation' states: "Before the hazard evaluation actually begins the participants should review previous incidents involving the process to be studied." To begin this process for this project, the literature review included prior Natural Gas (NG) and LNG facility loss of containment accidents, many, but not all, of which resulted in significant casualties and business interruption. The pertinent details regarding these incidents are summarized in Appendix Section 3-C LNG Incident Summary with reviewer comments. Highlights of the summary are shown in Table 3.

Table 3: LNG Incident Lessons Learned Summary

Reference No.	Facility Location	Date	Direct Cause(s)	Lessons Learned
[6]	LNG Peak-Shaving Plant Portsmouth, RI	1/21/2019	Natural Gas (NG) supply outage due to failure to maintain pipeline pressure. The metering system used a remote transfer unit (RTU) to send pressure readings to the Supervisory Control and Data Acquisition (SCADA) control center. The RTU was replaced without checking that it was compatible with the installed pressure sensor meter factor resulting in a faulty pressure signal to the control system.	The root causes were: ▪ Inadequate Management of Change (MOC) management system. ▪ Inadequate communication between maintenance and operations personnel.
[7]	Plymouth LNG Plymouth, WA	3/31/2014	After performing maintenance requiring a line-breaking procedure, NG was used to purge air from the piping prior to restart. The purging did not remove all the oxygen from the system and a flammable mixture ignited causing an internal deflagration which failed the vessel releasing NG. A secondary explosion of released NG injured employees and caused major damage.	▪ The U.S. Chemical Safety and Hazard Investigation Board (CSB) considers air-freeing of process equipment with NG a hazardous operation. ▪ The purge procedure used was a pressure purge, not a sweep purge. ▪ Purge exit gas wasn't monitored for oxygen level.
[8]	Algonquin Compressor Station Weymouth, MA	9/11/2020	Near-miss NG release from a filler/separator during commissioning due to an O-ring not rated for service pressure. The vessel arrived with an underrated O-ring installed and the proper O-ring in a separate package.	▪ Inadequate checking of the bill of material and QC of purchased construction materials against specifications upon receipt. ▪ Unlikely that a Pre-startup Safety Review (PSSR) would have detected fault once vessel was installed. ▪ Demonstrates the importance of pressure testing prior to operation. (See 7 below)
[9]	Freeport LNG Quintana Island, TX	6/08/2022	It appeared that a pressure relief valve (PRV) was isolated and removed for testing. When the PRV was reinstalled, the blocking valve was not reopened. When a demand on the PRV occurred, it was inoperable. The company did not have a formal valve position and car-seal policy for relief devices. Investigation also concluded that there weren't sufficient safeguards for mitigating the initiating overpressure event.	▪ Inadequate mechanical integrity safeguard for reducing human error in handling maintenance of relief devices. ▪ Lack of required operational PHA that could have Identified the need for additional safeguard(s) for overpressure protection.
[10]	Distribution NG Pipeline Lawrence, MA	9/13/2018	The incident occurred at the end of a construction project to replace a cast-iron section of low-pressure NG distribution main with polyethylene pipe. The low pressure (LP) main was protected from upstream overpressure by monitor regulator valves (MRVs) that sensed downstream pressure in the LP main and modulated to control the pressure setpoint. These MRVs did not respond to the increasing pressure in the new LP main because the pressure sensing line was still connected to the old isolated cast-iron line. Engineers discussed the need to relocate the pressure sensing line, but it was not implemented.	▪ The final project construction package didn't address the relocation of the pressure sensing line for the MRVs. ▪ There were several inadequate engineering practices including haphazard filing of prior engineering record documents, cursory constructability reviews, lack of documentation and tracking of corrective action items. ▪ There were at least four PSM system elements that could have prevented this: MOC, PSI, PHA and PSSR, three of which require formal action resolution documentation and tracking.
[11]	Distribution Pipeline Dallas, TX	2/23/2018	NG underground migration into residential customer home due to leak from third party excavation impact.	Not applicable.

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Reference No.	Facility Location	Date	Direct Cause(s)	Lessons Learned
[12]	NG Pipeline San Bruno, CA	9/9/2010	Installation of a substandard and poorly welded section of line on a pipeline constructed prior to 1952. Pipeline ruptured in San Bruno, CA resulting in eight (8) fatalities and many injuries.	▪ A contributing factor was a grandfather exemption from hydrostatic pressure testing (HPT) of pipeline fabrication for lines installed prior to 1970, promoted by the Federal Power Commission and accepted by DOT. ▪ The NTSB concluded that a HPT test would likely have revealed the material and welding flaws.
[13]	LNG Export Algiers, Algeria	1/19/2004	A possible cause was a hydrocarbon (HC) leak in a mixed refrigerant cold box heat exchanger that was ingested by a steam boiler induced draft (ID) fan causing an internal deflagration in the boiler fire box. The explosion ruptured the boiler resulting in a fire ball causing additional damage to surrounding equipment. A secondary larger vapor cloud explosion (VCE) occurred resulting in widespread damage onsite and offsite.	The root causes mentioned include: ▪ Inadequate inspection and maintenance of cold box heat exchanger (HEX). (Such exchangers are inside a structure filled with pearlite insulation and not visually accessible). ▪ Damage was more extensive due to a poor equipment layout and space placing the steam boilers (ignition source) too close to the liquefaction trains and occupied buildings.
[14]	LNG Cleveland OH	10/20/1944	This occurred during the infancy of the commercialization of LNG, when some storage tank design requirements were not well understood. The apparent cause of the loss of containment was structural failure of a steel plate on the bottom of one of the first cylindrical tank designs, releasing its contents. The material of construction was a low alloy 3 ½ % Ni steel. An exact root cause was not determined by the Bureau of Mines investigation report after both external and internal causes were investigated.	▪ A possible cause was the formation of an ice lens underneath the foundation causing upward pressure and deformation of the bottom plate. This problem was not well understood at the time. ▪ This failure revolutionized design aspects of future LNG storage tanks regarding material selection, foundation design, and diking and impoundment areas that are standard practice today and codified in RAGAGEP (e.g., NFPA 59A).

3.3.3 Hazard Analysis and Evaluation Methodology

Table 4 lists the literature sources expected to be most useful for determining when PHAs may be needed for the LNG industry. The OSHA [2], CCPS [3] and British Standard Inst. [references 4] provide continuity for the entire process. IChemE Reference [17] is unique in that it focuses specifically on Revaluations (aka revalidations) of PHAs, which may grow in prevalence as the LNG industry ages.

Table 4: PHA/ Risk Assessment Subject – PHA Application

PHA/ Risk Assessment Subject – PHA Application				
Ref	Issuing Organization	Document No.	Title	Desirable Features / Shortcomings
[2]	OSHA	29CFR1910.119(e)	Process Hazard Analysis	Existing codified requirements Recommended techniques including HAZOP and Failure Modes and Effects Analysis (FMEA) Team Staffing Aspects to cover including prior incidents. Recommendations and action resolution
[3]	CCPS	3rd Edition 2008	Guidelines for Hazard Evaluation Procedures	Applying hazard evaluation techniques including HAZOP and FMEA List of Software recordkeeping aids (Appendix D) Risk Matrix example (section 7) Sample worksheet doesn't have columns for risk ranking
[4]	British Std. Institute	BS EN 61882 2nd Ed. 2016	Hazard and operability studies (HAZOP studies) – Application Guide	
[15]	American Society for Quality (ASQ)	Website	Failure modes and effects analysis procedure description	Methodology combines FMEA and Failure Modes, Effects, and Criticality Analysis (FMECA) techniques. The worksheet format includes risk priority and criticality determination. Severity (S), Occurrence (O), and Detection (D) ranking values not provided.
[16]	U.S. Army Corps of Engineers (USACE Army TM 5-698	Chapter 4	Failure modes, effects, and criticality analysis	Severity, Occurrence and Detection ranking value tables consistent with above methodology provided.
[17]	Institution of Chemical Engineers (IChemE) Safety Centre	Effective Revaluation of Risk Assessments (2021)	Delta HAZOP	Procedure for HAZOP revalidations. Appendix B provides a comprehensive checklist of possible applicable change items. No mention of reranking of modified hazards scenarios

3.3.4 *Risk Assessment Methodology (Layer of Protection Analysis [LOPA])*

Table 5 lists the literature sources expected to be most useful for evaluating Layer of Protection Analysis. There are CCPS books on LOPA which are very useful references on the subject.

Table 5: PHA/ Risk Assessment Subject – Layer of Protection Analysis

PHA/ Risk Assessment Subject: Layer of Protection Analysis				
Ref	Issuing Organization	Document No.	Title	Desirable Features / Shortcomings
[18]	CCPS	Book	Layer of Protection Analysis – Simplified Process Risk Assessment	Defines the factors involved in LOPA. Describes the requirements for each factor. Provides a worked example sequentially covering each factor. Provides some quantitative failure statistics for key factors
[19]	CCPS	Guidelines	Guidelines for Initiating Events and Independent Layers of Protection in LOPA	A more comprehensive and complete evaluation and selection of statistical values for Initiating events and Independent Protection Layers (IPLs)
[20]	CCPS	Guidelines	Guidelines for Enabling Conditions and Conditional Modifiers in LOPA	A more comprehensive and complete evaluation and selection of statistical values for Enabling events and Conditional modifiers.

3.3.5 Safety Tolerability Criteria and Failure Rate Data Sources

Table 6 lists the literature sources expected to be most useful for providing guidance on setting safety tolerability criteria for LNG facilities.

Table 6: PHA/ Risk Assessment Subject – Safety Tolerability Criteria

PHA/ Risk Evaluation Subject: Safety Tolerability Criteria				
Ref.	Issuing Organization	Document No.	Title	Desirable Features / Shortcomings
[21]	British Std. Institute	BS EN 1473 2021	Installation and Equipment for LNG - Design of Onshore Installations	Covers design and operation of LNG facilities. Annexes J, K, L provide an excellent example of a risk matrix basis of societal risk criteria
[22]	NFPA	59A	Standard for the Production, Storage, and Handling of LNG	Societal Risk tolerability region displayed on a F-N domain Figure A19.10.2 (a & b) Tolerable land use zones defined by individual risk criteria, Tables 19.10.1(a & b)
[23]	UK HSE	HSE Books	Reducing Risk, Protecting People (HSE's decision-making process)	Discusses how HSE approaches the management and regulation of risk How risk from work activities is perceived by the public and how HSE address those perceptions Introduces risk tolerance with limited examples of tolerability limits similar to other sources Provides credence to tolerability criteria established in other references

PHA/ Risk Evaluation Subject: Safety Tolerability Criteria				
[24]	CCPS	Guidelines	Guidelines for Developing Quantitative Safety Risk Criteria	Sets tolerable maximum individual risk criteria from all events for workers and public Derives maximum individual risk criteria for each event for workers and public.

3.3.6 Current Status of Hazard Evaluation Requirements in LNG Industry

As part of the Literature Search, the reviewers assessed where hazard evaluations were utilized in the LNG industry over the lifecycle of a facility. The results of this assessment are presented in Table 7. Depending on the stage of the life cycle and the size of facility or modification etc., the LNG industry can choose an appropriate method(s) of Hazard Analysis from Table 7.

Table 7: Recommended Hazard Evaluation Techniques

Recommended Hazard Evaluation Techniques											
Stages of Life Cycle	Quantitative Risk Analysis (Dispersion, Thermal Flux, etc.)	Preliminary Hazard Review / Hazard Identification	Checklist	What-If	HAZOP	Concept Risk Assessment (CRA)	Inherently Safer Design	LOPA Supplement	Failure Mode and Effect Analysis (FMEA)	Bow-tie Analysis	Fault Tree Analysis (FTA) Supplement
Feasibility (FEL-1)		✓	✓	✓			✓				
Conceptual Design (FEL-2)		✓*	✓	✓		✓	✓				
Preliminary Design / Engineering (FEL-3)	✓		✓*	✓*	✓*		✓	✓	✓	✓	✓
Detailed Engineering	✓		✓	✓	✓*		✓	✓*	✓	✓	✓
Construction / Start up			✓	✓	✓			✓	✓	✓	✓
Routine Operation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Expansion or Modification	✓		✓	✓	✓*		✓	✓*	✓	✓	✓
Decommissioning/ Extensive Shutdown			✓	✓				✓	✓		

*Documents such as HAZID, HAZOP or other PHA methods and LOPA are part of the documentation needed for project submission to FERC

4 PHA Techniques

4.1 Preliminary Hazard Review (PreHA)

Preliminary Hazard Review is a special technique derived from the U.S. Military Standard System. PreHA focuses in a general way on the hazardous materials and major process areas of a plant. A PreHA formulates a list of hazards and generic hazardous situations by considering various process characteristics. It is most often conducted early in the development of a process when there is little information on design details or operating procedures and is a precursor to further hazard analyses. Therefore, it is also useful for making site selection decisions. As each hazardous situation is identified, the potential causes, effects, and possible corrective and/or preventive measures are listed. Typical methods for conducting preliminary reviews are HAZID (Hazard Identification), What If? or Checklist but high-level HAZOP technique can also be used. Inherently Safer Design review (ISD) and Concept Risk Analysis (CRA) can be used in this early stage to review location and equipment distancing options to minimize hazards. All of these methods are described in detail later in this section.

4.2 Hazard Identification

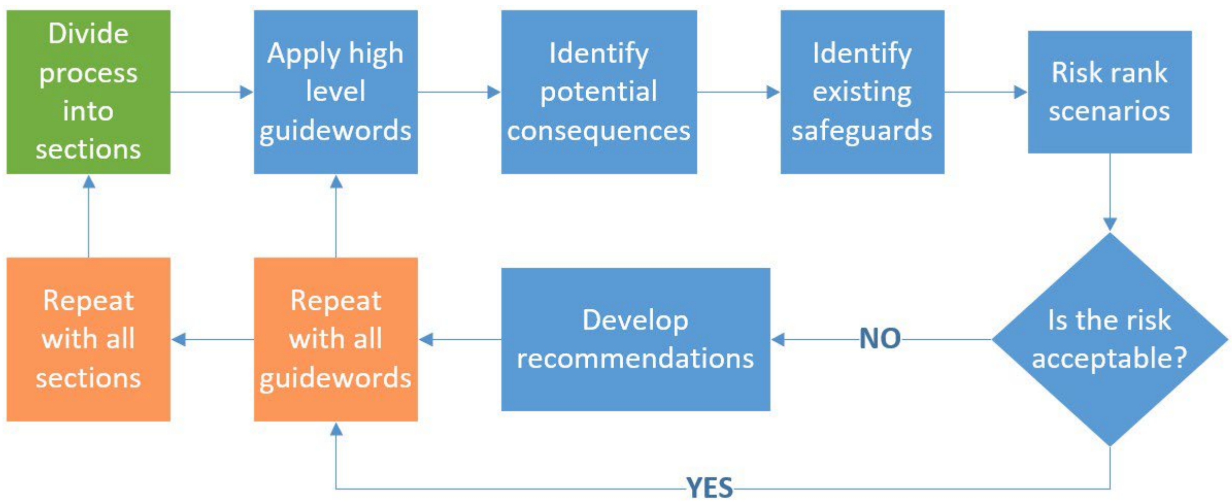
A HAZID is a preliminary assessment of potential hazards and can be conducted in a qualitative or quantitative manner. HAZIDs typically assess inherent hazards and offer general identification, requiring only a design concept. For example, a HAZOP contains details on hazards at specific nodes within the plant, whereas a HAZID may cover all hazards across an area of the plant or geographical location. Completing a HAZID can provide useful information as to where a HAZOP may be applicable, and where a more detailed hazard analysis may be required.

Prior to HAZID development, required information must be gathered, such as drawings and a report of the necessary objectives for the HAZID, to establish the expectations of the HAZID. To conduct the HAZID, a team may participate in a workshop using basic software tools for the HAZID report. As the HAZID relies on human observation and decisions, if HAZID is going to be used for an expansion or modification, plant operators should be involved in the formulation of the HAZID due to their practical experience, and to avoid bias.

HAZIDs can range in detail; however, they must contain: identification of a risk/threat, the potential cause(s) of said event and the consequences of the event, if not addressed. Additional information that can be included are any available safeguards and recommendations. Some HAZIDs may also contain qualitative analysis via a risk matrix but rarely use guidewords (such as ‘no flow’) which are typically associated with HAZOPs.

As previously implied, a HAZID should be discussed within the early stages of hazard analysis to provide a starting point for identifying nodes and the most significant hazards within a process. Bow-tie diagrams can be formed from the content of a HAZID and provide a method to dictate which hazards require higher focus. Other methodologies can be used as well to provide qualitative risk analysis within the ISO 31000 standards [25]. Figure 1 shows steps required to conduct a HAZID and Figure 2 is an example of a HAZID study which includes Qualitative Risk Ranking. Qualitative Risk Ranking involves evaluating the severity (S or S0) of a consequence, then evaluating the likelihood (L or L0) of achieving the consequence. The severity and likelihood are then combined to achieve the risk ranking.

Figure 1: Steps to Conduct a HAZID



Source: ioMosaic Corporation

Figure 2: Example of a HAZID Study Which Includes Qualitative Risk Ranking

Company:
Drawing Numbers:
Unit/Process:
Equipment/Lines:
Description: HAZID
Design Intent:

Date:

System:

LNG Example **HAZID** **Worksheet generated: January 07, 2025**

Deviation #	Deviation	Cause #	Cause	Consequences #	Consequences	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations
1.1	Process Hazard - Design pressure	1.1.1	Upstream pressure in LNG feed system causing overpressure of downstream equipment	1.1.1.1	Release of LNG with fire/explosion causing multiple fatalities	1.1.1.1.1	Downstream overpressure protection	6	1		1.1.1.1.1	Investigate high pressure shutdown for upstream equipment in the LNG feed system
						1.1.1.1.2	Alarm with operator response					
1.2	Process Hazard - Mechanical failure	1.2.1	Tube failure on LNG heat exchanger	1.2.1.1	Overpressure of shell side with release of LNG and multiple injuries or single fatality	1.2.1.1.1	Relief valve on shell side sized for tube failure	5	1			

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

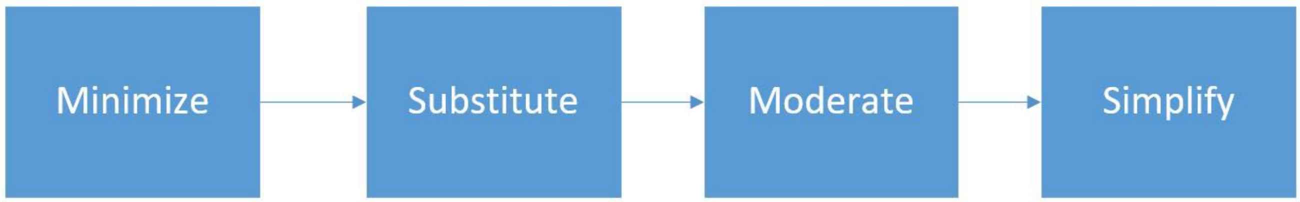
4.3 Inherently Safer Design Review

Inherently safer design review is typically conducted early in the design process to identify possible risk reduction measures by using four (4) strategies:

1. Minimize – lower quantity of material or energy contained in the process
2. Substitute – replace hazardous material or process with less hazardous alternative
3. Moderate – change operating conditions to lower the hazard
4. Simplify – design process with less complexity

An Inherently Safer Design checklist is typically used for this review. For LNG facilities some of these strategies will not apply (i.e. Substitute); however, the review should be conducted as it is required by the latest changes to the EPA RMP regulation 40 CFR Part 68 (see 40 CFR 68.67(c)(9)) [26]. Figure 3 depicts the inherently safer design hierarchy. Figure 4 shows an example of an LNG Inherently Safer Review.

Figure 3: Inherently Safer Design Strategies



Source: ioMosaic Corporation

Figure 4:Example of an LNG Inherently Safer Review

Company:
Drawing Numbers:
Unit/Process:
Equipment/Lines:
Description:
Design Intent:

Date:

System:

LNG Example | ISD | Worksheet generated: January 07, 2025

Item #	Item	Subcategory	Answer	Cause #	Cause	Consequences #	Consequences	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations
6.1	Is process equipment located to minimize length of hazardous material piping?	Minimize	No	6.1.1	LNG piping runs to loading facilities are long runs - possible flange leaks with release of LNG. Shorter runs will introduce higher hazards from exposure to adjacent units	6.1.1.1	Potential flash/jet fire with possibility with possibility of two or more fatalities	6.1.1.1.1	MI inspections	6	1		6.1.1.1.1	Ensure that number of flanges in the piping are minimized
								6.1.1.1.2	Gas detectors with alarms and operator response					
								6.1.1.1.3	Ring joint flanges to minimize leaks					
								6.1.1.1.4	Emergency preparedness (to restrict access)					

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

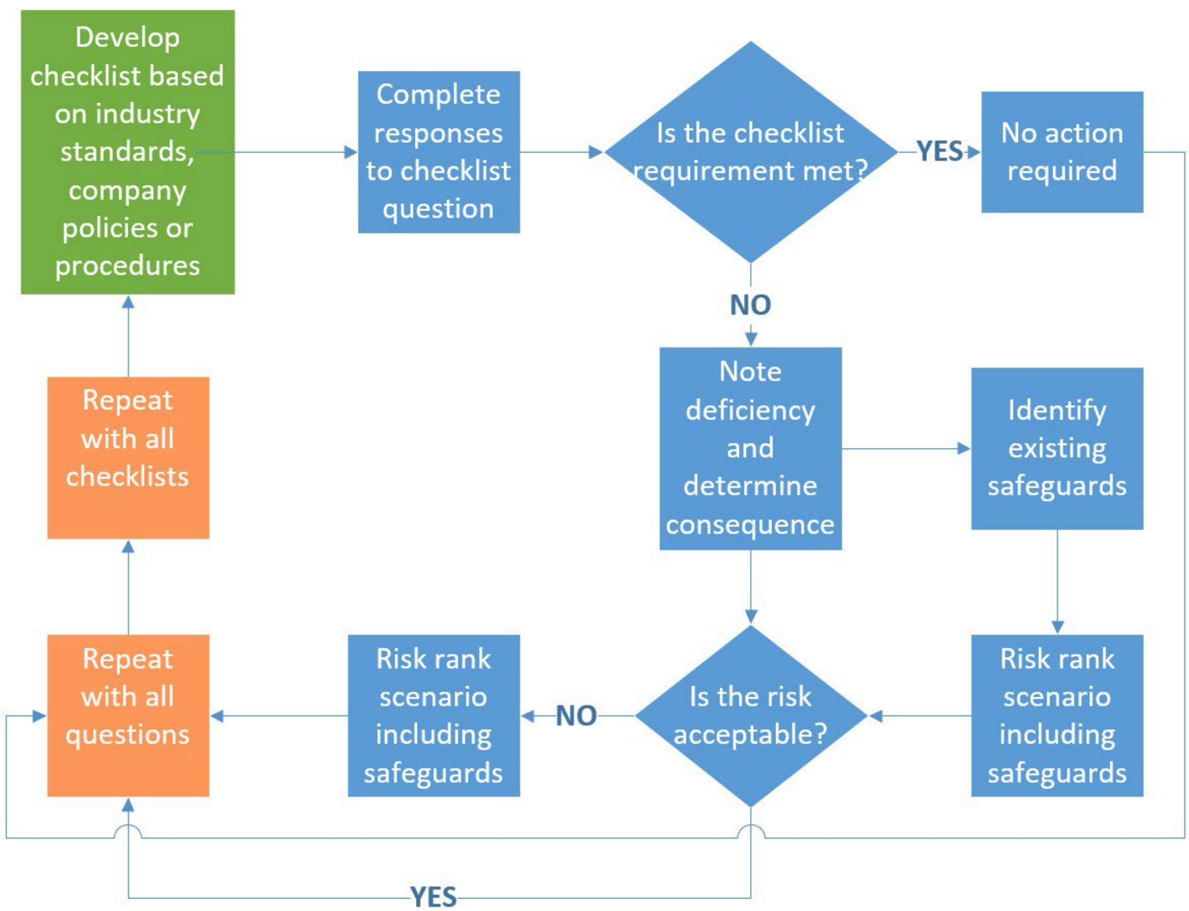
4.4 Concept Risk Assessment (CRA)

The CRAs are used to identify location options with the lowest risk level to local communities. The preliminary Hazard Analysis provides the scenarios that need to be evaluated for potential high impact to community or environment. This is a simplified form of a QRA that uses estimated inventories or generic data; however, it will generate sufficient results to evaluate options for locations of units or plants. Detailed descriptions of QRA are provided later in this section.

4.5 Checklist

The checklist is a structured approach used to identify and evaluate potential hazards associated with a process or facility. It is prepared with a comprehensive list of potential hazards based on industry standards, regulations, past incidents, and expert knowledge. It covers several different areas including equipment failure, chemical hazards, operational procedures, and emergency response. A checklist is typically developed ahead of the study but can be modified by the study team. A checklist can be used as part of a Preliminary Hazard Review or during the reviews at later stages of the process life cycle. Generic checklists are used to review Facility Siting, Human Factors, and Damage Mechanism. Checklists can identify hazards that are missed by other techniques such as HAZOP. Figure 5 shows the steps for using a checklist as a PHA technique. Figure 6 is an example of a hazard analysis using a checklist.

Figure 5: Steps to Conduct Hazard Analysis Using a Checklist



Source: ioMosaic Corporation

Figure 6: Example of a Hazard Analysis Using a Checklist

Company:
Drawing Numbers:
Unit/Process:
Equipment/Lines:
Description:
Design Intent:

Date:

System:

LNG Example | Checklist | Worksheet generated: January 16, 2025

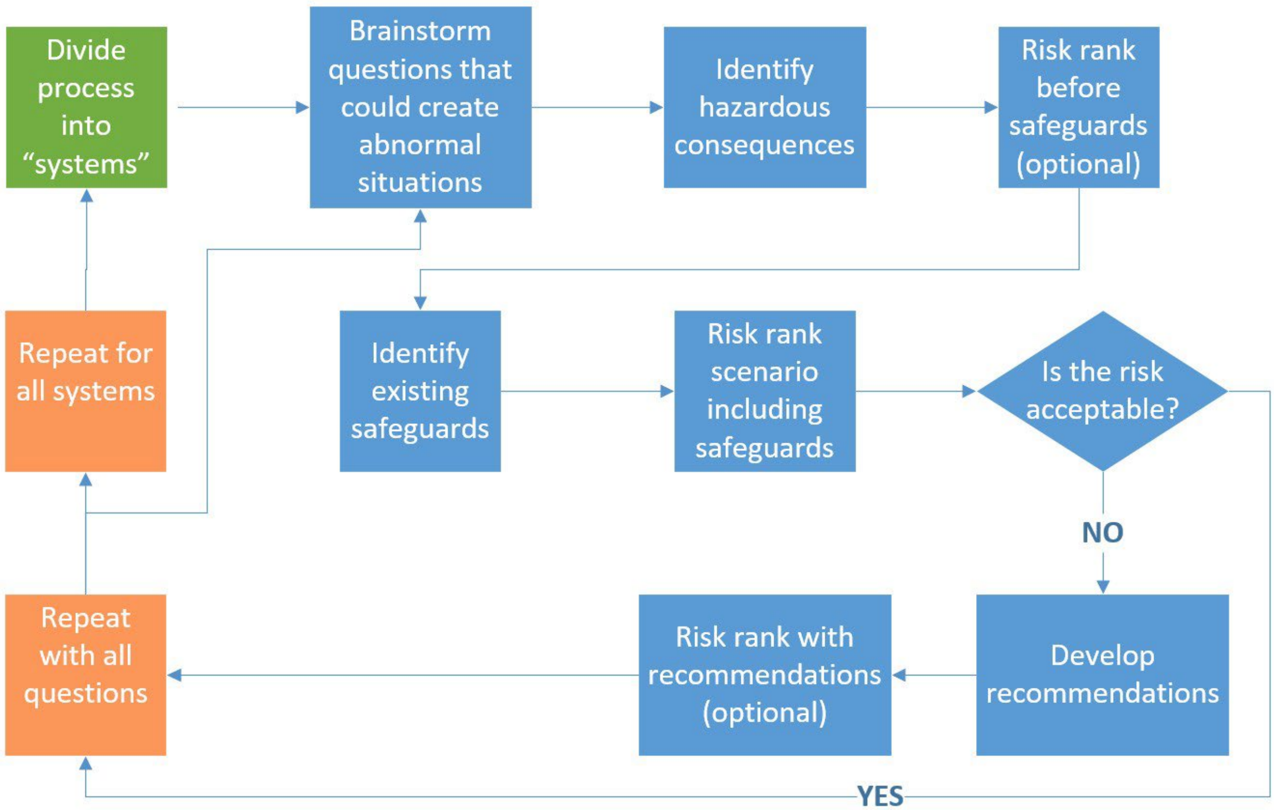
Item #	Item	Answer	Cause #	Cause	Consequences #	Consequences	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations
4.1	Was LNG compressor piping hydrostatically tested?	Yes											
4.2	Was acoustical study of compressor LNG piping completed during detailed design?	No	4.2.1	High compressor vibration - bearing wear	4.2.1.1	Release of LNG with Potential flash/jet fire causing two or more fatalities	4.2.1.1.1	Gas detection with alarms and operator response	6	1		4.2.1.1.1	Complete acoustical piping study on compressor LNG piping
							4.2.1.1.2	MI vibration monitoring					
							4.2.1.1.3	Compressor vibration trip					
							4.2.1.1.4	Basic process control system					
							4.2.1.1.5	Emergency preparedness (to restrict access)					

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

4.6 What-If

What-If Analysis is a brainstorming method for determining what can go wrong and judging the likelihood and consequences of situations. The Team develops a set of questions to identify possible abnormal situations, their consequences, and existing safeguards. Typically, What-if questions are generated based on deviation from operating conditions or defined procedures. The answers to these questions form the basis for judging the acceptability of risks and determining a recommended course of action for risks considered unacceptable or for improvement opportunities. Figure 7 shows the steps required to conduct a What If? analysis. Figure 8 shows an example of a What-if analysis.

Figure 7: Steps to Conduct a What if Analysis



Source: ioMosaic Corporation

Figure 8: Example of a What if Analysis

Company: Date: System:
Drawing Numbers:
Unit/Process:
Equipment/Lines:
Description: What If?
Design Intent:

LNG Example What If Worksheet generated: January 07, 2025

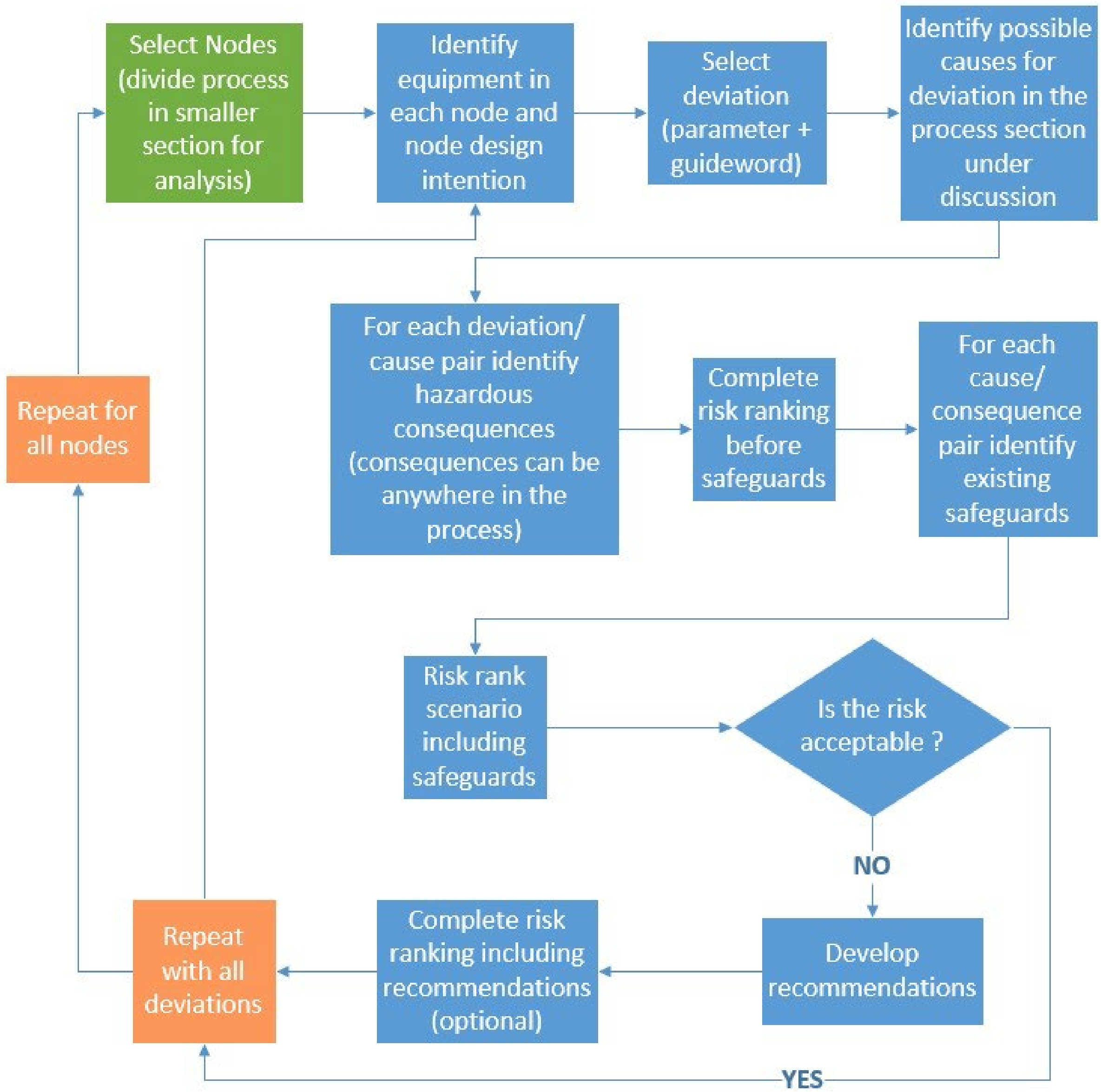
What-If #	What-If	Cause #	Cause	Consequences #	Consequences	S0	L0	R0	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations
3.1	What if compressor vibration is too high?	3.1.1	Compressor bearing wear	3.1.1.1	Potential flash/jet fire with possibility of multiple fatalities	6	5		3.1.1.1.1	Gas detection system with alarm and operator response	6	2		3.1.1.1.1	Install independent high vibration trip on the LNG compressor
									3.1.1.1.2	MI vibration monitoring					
									3.1.1.1.3	Acoustical study of piping during detailed design					
									3.1.1.1.4	Basic process control system					
									3.1.1.1.5	Emergency preparedness (to restrict access)					
				3.1.1.2	Environmental release of LNG contained to site	2	5		3.1.2.1	MI vibration monitoring	2	2			

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

4.7 Hazard and Operability Study (HAZOP)

Hazard and Operability Analysis (HAZOP) is a systematic qualitative technique used to identify potential hazards and operability issues due to deviations from design intent in industrial processes. It is based upon a review of the Piping and Instrument Drawings (P&ID's). The process is divided into sections called "nodes" identified on the P&ID's. It involves a team of experts examining the process systematically, node by node, using a deviation list generated by combining standard process parameters (i.e. flow, temperature pressure, level etc.) with guide words (i.e. less, more, reverse etc.). Based on that list, the team identifies causes of deviations from the intended design conditions that could lead to hazards or operational problems. These are then analyzed to assess their potential consequences and determine the appropriate preventative or mitigating measures. The scenarios can be ranked before safeguards, after existing safeguards and after recommendation(s). Figure 9 shows steps required to conduct a HAZOP study and Figure 10 shows an example of a HAZOP Study.

Figure 9: Steps to Conduct a HAZOP Study



Source: ioMosaic Corporation

Figure 10: Example of a HAZOP Template

Company: Date: System:
Drawing Numbers:
Unit/Process:
Equipment/Lines:
Description:
Design Intent:

LNG Example HAZOP Worksheet generated: January 07, 2025

Deviation #	Deviation	Cause #	Cause	Consequences #	Consequences	S0	L0	R0	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations	S1	L1	R1
5.1	High vibration	5.1.1	Compressor bearing wear	5.1.1.1	Release of LNG with potential flash/jet fire causing two or more fatalities	6	5		5.1.1.1.1	Gas detection alarms with operator response	6	2		5.1.1.1.1	Install independent vibration trip on the compressor	6	1	
									5.1.1.1.2	MI vibration monitoring								
									5.1.1.1.3	Basic process control, system								
									5.1.1.1.4	Acoustical study of piping during detailed design								
									5.1.1.1.5	Emergency preparedness (to restrict access)								
5.2	Low pressure																	
5.3	Vacuum																	
5.4	High temperature																	
5.5	Low temperature																	
5.6	High level																	

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

4.8 Failure Mode and Effect Analysis (FMEA)

FMEA is the process of reviewing as many components, assemblies, and subsystems as possible to identify potential failure modes in a system and their causes and effects. The failure modes and their effects for each component on the rest of the system are recorded in a specific Failure Mode and Effect Analysis worksheet. An FMEA helps identify potential failure modes based on experience with similar products and processes. These steps are depicted in Figure 11 and Figure 12 is an example of an FMEA Study.

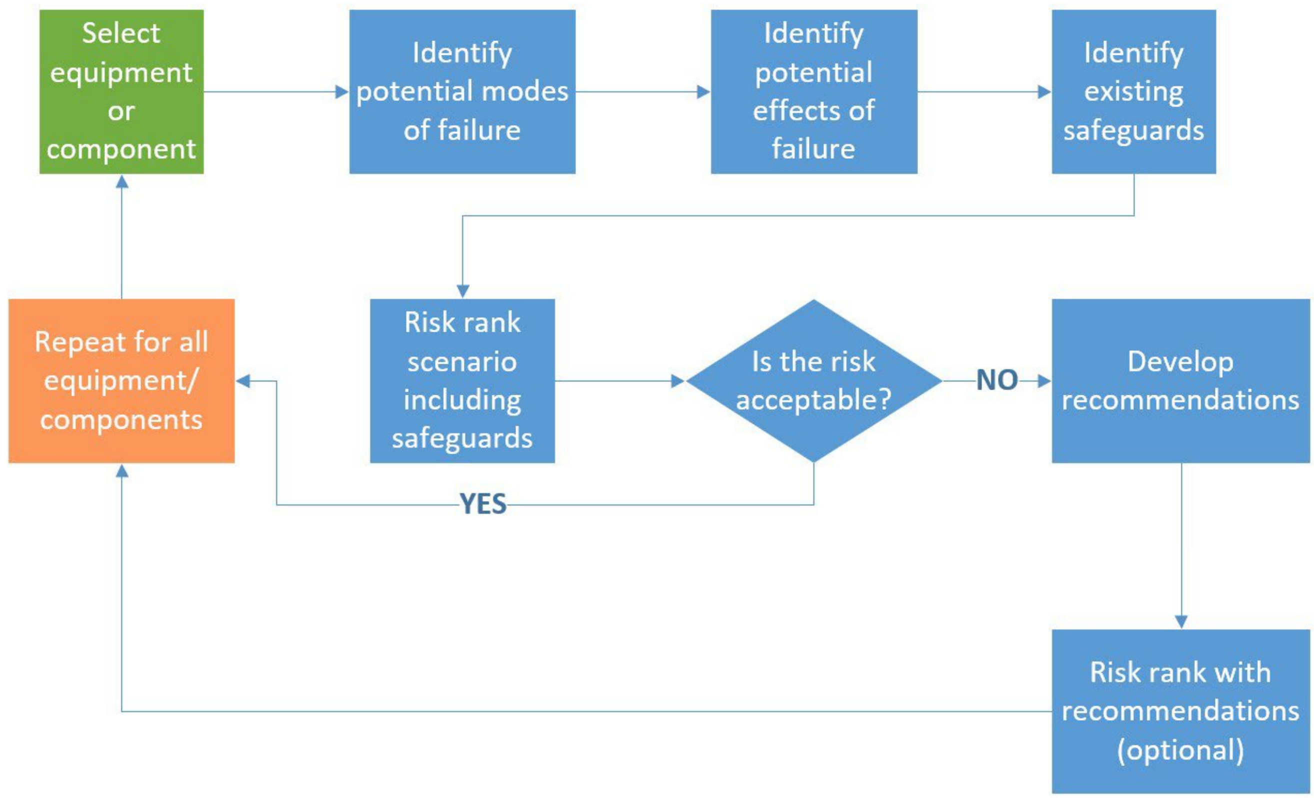
Types of FMEA:

- Functional
- Design
- Process

An FMEA structured approach involves the following steps for complete analysis:

- Select equipment or component
- Identify all potential modes of failure of equipment or component
- Identify potential effects of failure
- Identify existing safeguards
- Risk rank scenarios
- Develop recommendations to lower risk

Figure 11: Steps to Conduct an FMEA Study



Source: ioMosaic Corporation

Figure 12: Example of a FMEA Study

Company:
Drawing Numbers:
Unit/Process:
Equipment/Lines:
Description:
Design Intent:

Date:

System:

LNG Example | FMEA | Worksheet generated: January 07, 2025

Component #	Component	Potential Failure Mode #	Potential Failure Mode	Potential Effects of Failure #	Potential Effects of Failure	Safeguards	S	L	R	Recommendations #	Recommendations
8.1	LNG piping on compressor discharge	8.1.1	Flange leak	8.1.1.1	Release of LNG with flash fire and serious injury	Ring joing flanges	4	2			
						MI inspections					
						Gas detection with alarms and operator response					

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

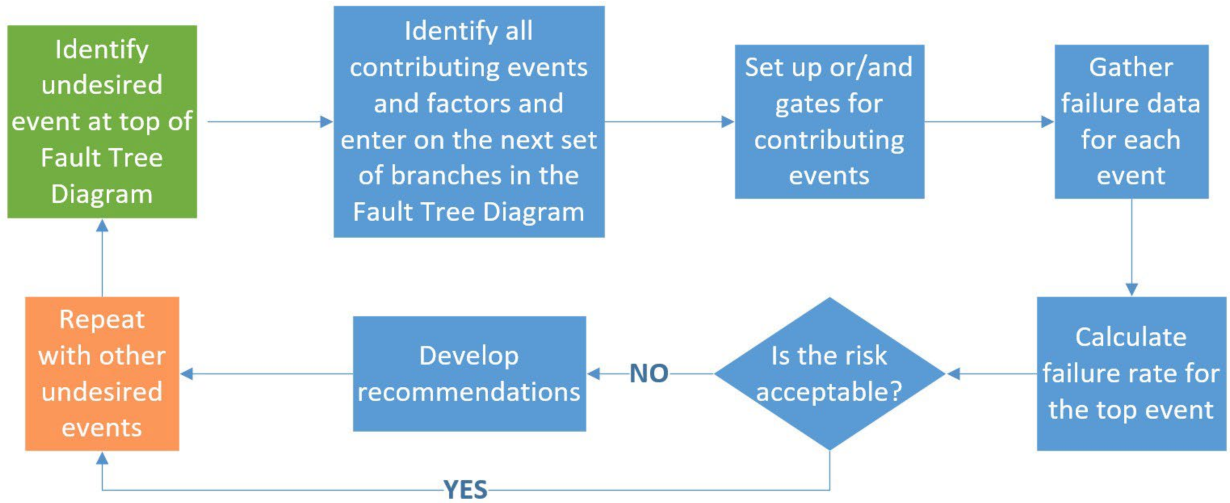
4.9 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a more rigorous form of the LOPA technique that analyzes failures in equipment and processes. It is a visual depiction of contributing factors and events that can lead to a system failure. It is used for very high-risk scenarios to determine different combinations of causes for a single hazardous event. It is useful for incorporating human reliability into failure analysis and evaluating the importance and sensitivity of assigned failure statistics. It is an accepted technique for safety instrumented system (SIS) safety integrity level (SIL) validation. Fault tree analysis can help prioritize the hazards from failures so that teams can identify ways to improve the process.

The steps of an FTA are the following which are depicted in Figure 13.

- Define the undesired (top) event
- Identify the contributing events and factors
- Construct a fault tree
- Gather failure data
- Perform the analysis (determine the probability of the undesired event occurring and its contributing factors)
- Interpret the results
- Make recommendations for improvement
- Implement recommendations and monitor progress

Figure 13: Steps to Conduct a Fault Tree Analysis



Source: ioMosaic Corporation

Figure 14 is an example of an FTA. This figure evaluates the risk of excessive backpressure on relief devices during total loss of power for an LNG liquefaction train. The feed gas to the LNG facility is supplied from a gas field processing plant. The total power failure to a single train scenario resulting in an overpressure release to flare evolves as follows:

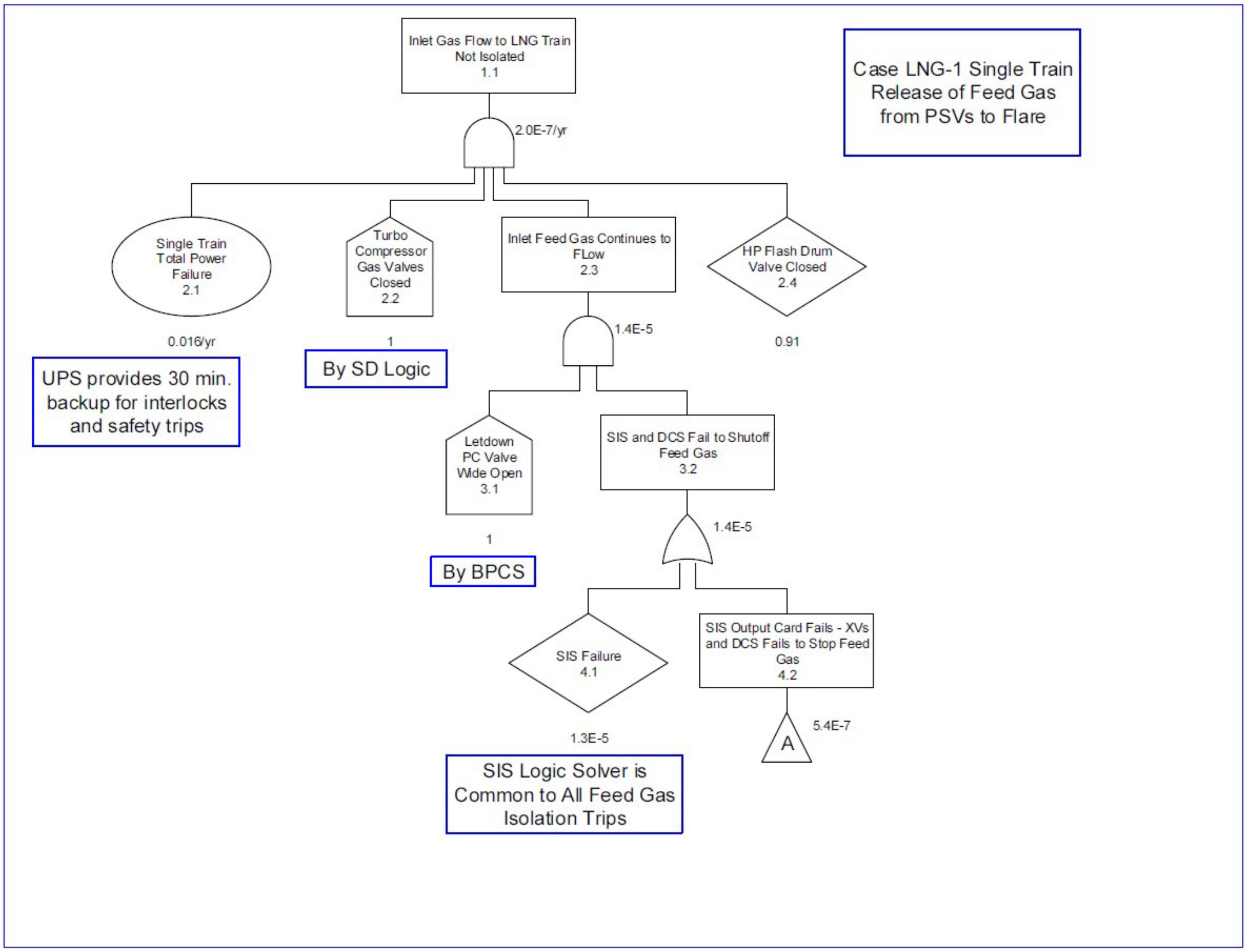
- Initiating (undesired) emergency shutdown (ESD) event is total train power failure (separately evaluated by FTA)
- Enabling events include:
  - Opening of auto-refrigeration pressure letdown valve by basic process control system (BPCS)
  - Shutdown of liquefaction refrigeration compressors by local ESD
- HP flash drum outlet open-close valve closes to prevent back flow from liquefaction
- SIS/SIF and distributed control system (DCS) isolation systems failure allows inlet gas to continue flowing
- Pressure control valves (PCVs) and PRVs relieve overpressure to flare.

Note: Uninterruptible power supply (UPS) provides 30 minutes of backup power for safety instrumented trips and interlocks.

For Figure 14, the fault tree is a graphical depiction of this scenario. The symbols usage is as follows:

- Oval = Initiating event
- Doghouse = Enabling events
- Diamond = Failure events
- Gates include OR (concave bottom) and AND (straight bottom)

Figure 14: Example of a Fault Tree Analysis



Source: Process Safety Office® ioLogic™ - ioMosaic Corporation

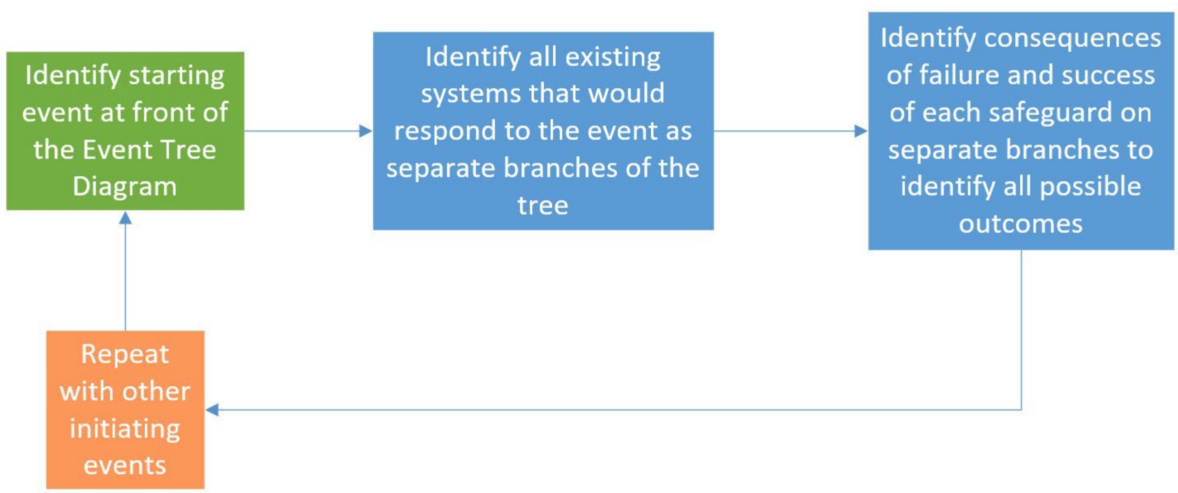
4.10 Event Tree Analysis (ETA)

An Event Tree Analysis is a systematic method used to evaluate potential outcomes following a specific initiating event. It involves creating a graphical representation of possible sequences of events, branching out from the initial event, and analyzing the likelihood and consequences of each outcome. This helps identify potential hazards, assess risk levels, and develop strategies to prevent or mitigate accidents in industrial processes.

The steps in an Event Tree Analysis are depicted in Figure 15 and Figure 16 is an example. The steps of an ETA are the following:

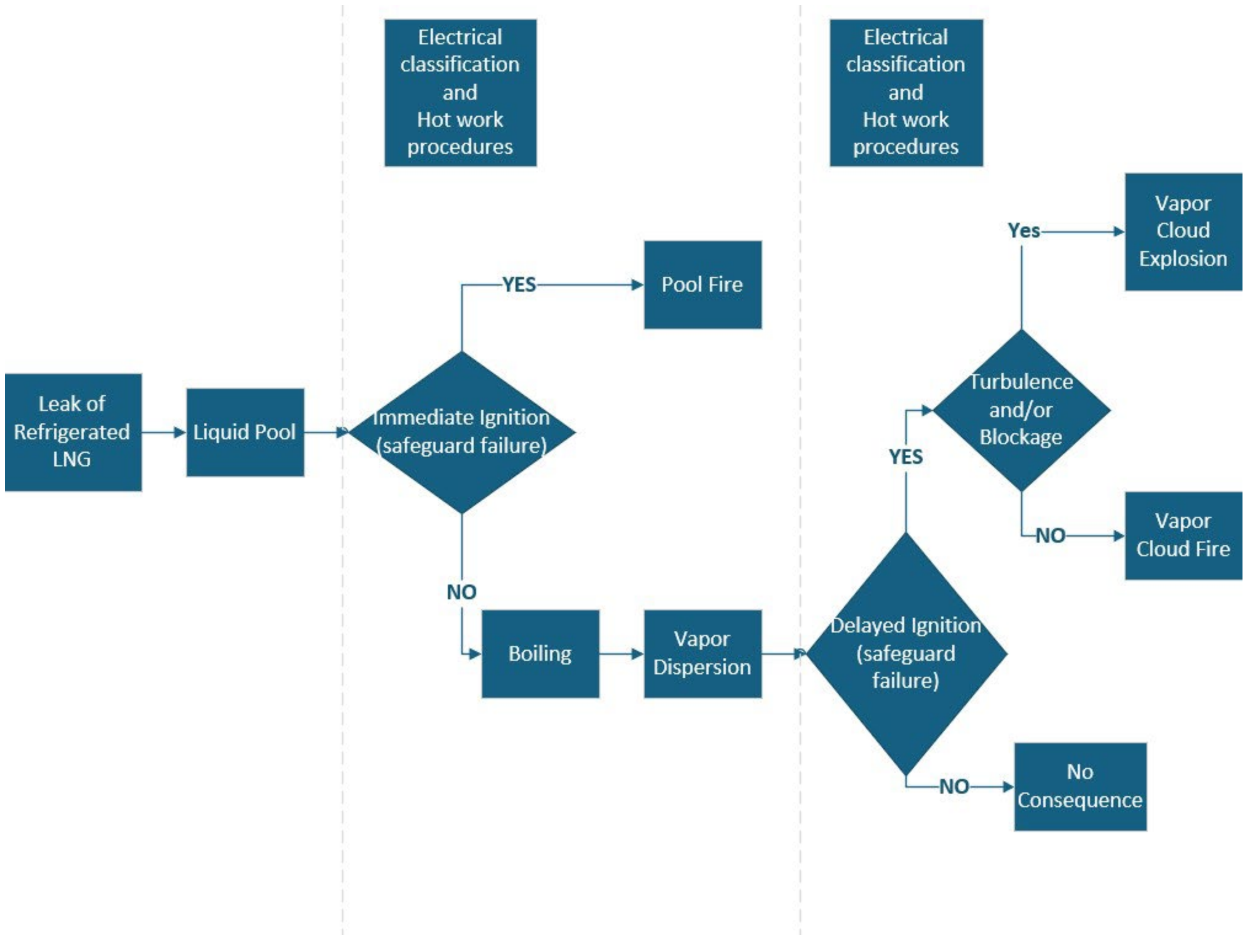
- Identify starting event
- Identify existing mitigating system that would respond to the event
- Identify consequences of failure and success of each of the mitigating systems to construct the Event Tree diagram

Figure 15: Steps to Conduct an Event Tree Analysis



Source: ioMosaic Corporation

Figure 16: Example of an Event Tree Analysis



Source: ioMosaic Corporation

4.11 Bow-tie Analysis

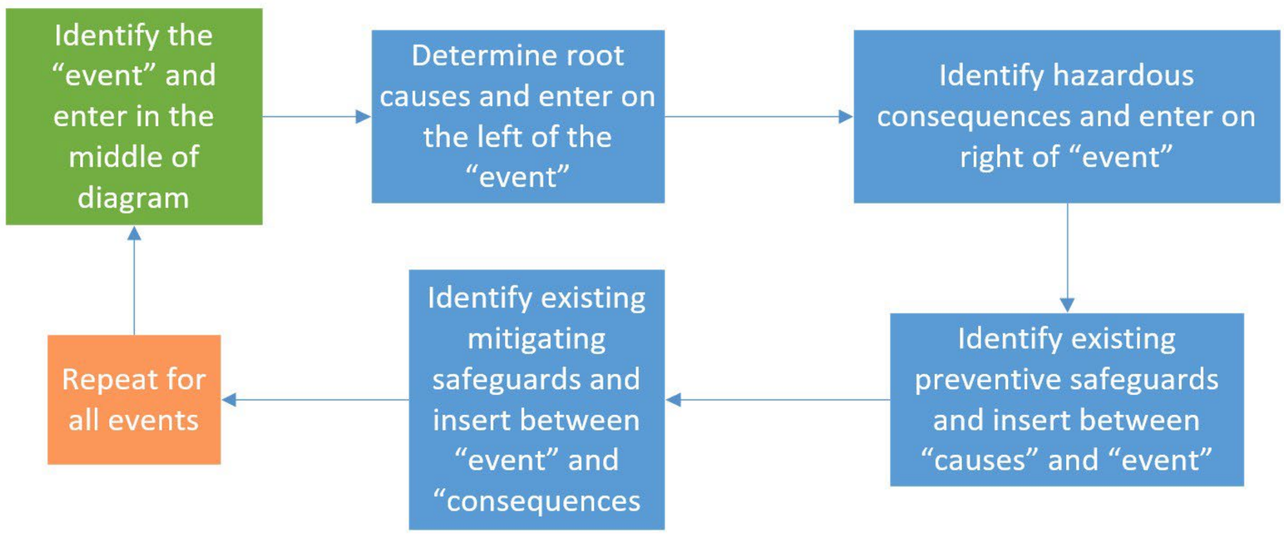
A bow-tie analysis is a risk assessment methodology used to visualize the potential risks and their consequences for hazardous scenarios or events. The name comes from the visual representation of the technique, which consists of three parts: the causes (left), the event (center), and the effects (right).

It consists of the following steps which are depicted in Figure 17 and Figure 18 is an example of a Bow Tie Analysis. The steps of a bow-tie analysis are the following:

- Identify the event in the middle
- Determine root causes that could lead to that hazard/event on the left

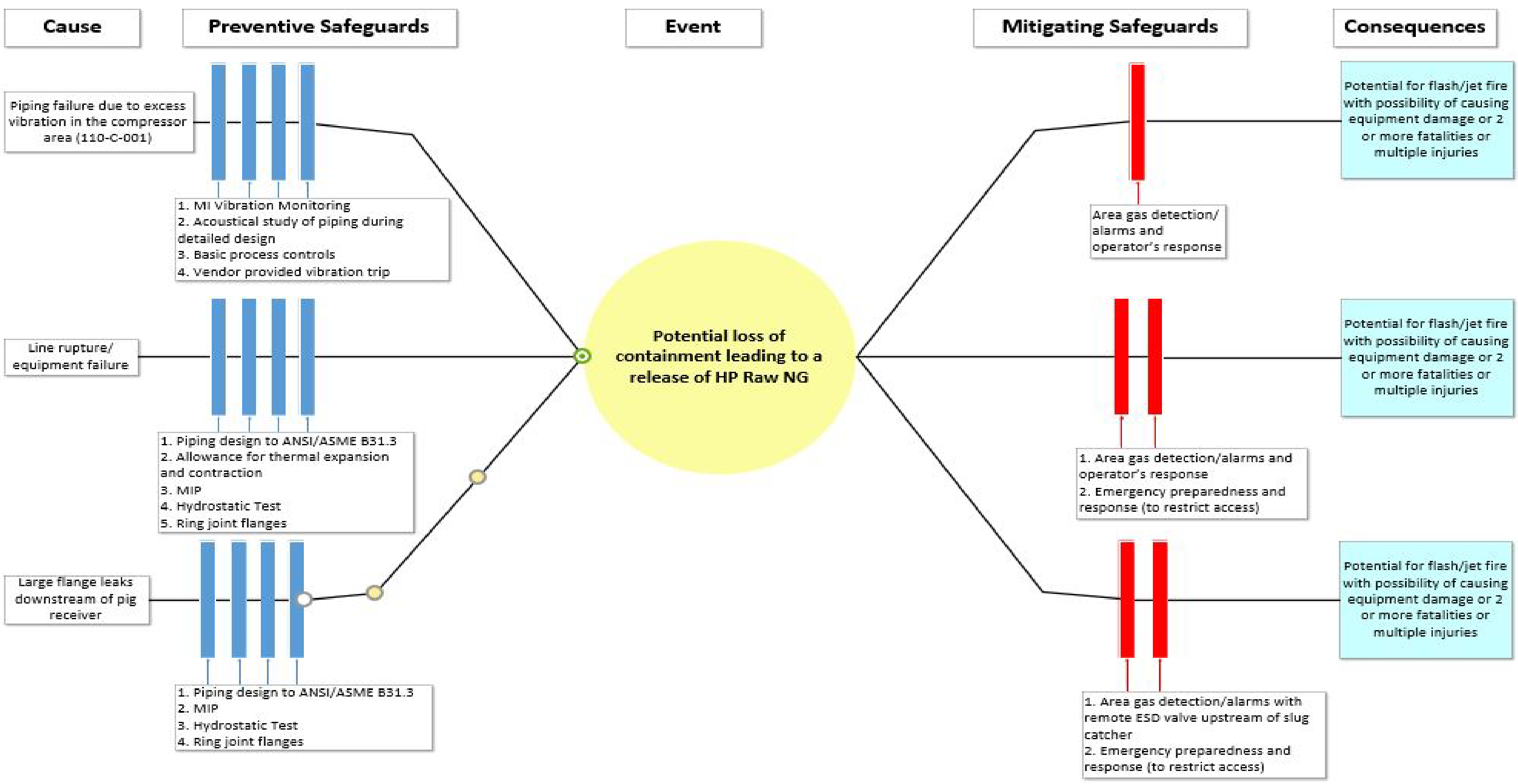
- Recognize the consequences of the hazards and possible damages on the right
- Implement control measures or preventive barriers on the left to lessen the likelihood of the root causes
- Insert recovery or mitigating measures on the right to reduce the possible damages

Figure 17: Steps to Conduce a Bow Tie Analysis



Source: ioMosaic. Corporation

Figure 18: Example of a Bow Tie Analysis



Source: ioMosaic Corporation

4.12 Layer of Protection Analysis (LOPA)

Layer of Protection Analysis (LOPA) is a simple quantitative technique for evaluating the hazards, risks, and protections associated with a system with potential hazards. It allows the team to calculate additional layers of protection needed to meet the organization's risk tolerance. This allows for better definition of the levels of protection needed. LOPA is a simplified form of fault tree analysis that assumes a single-point failure that is typically used to provide quantitative risk values for a large number of risks identified in a HAZOP.

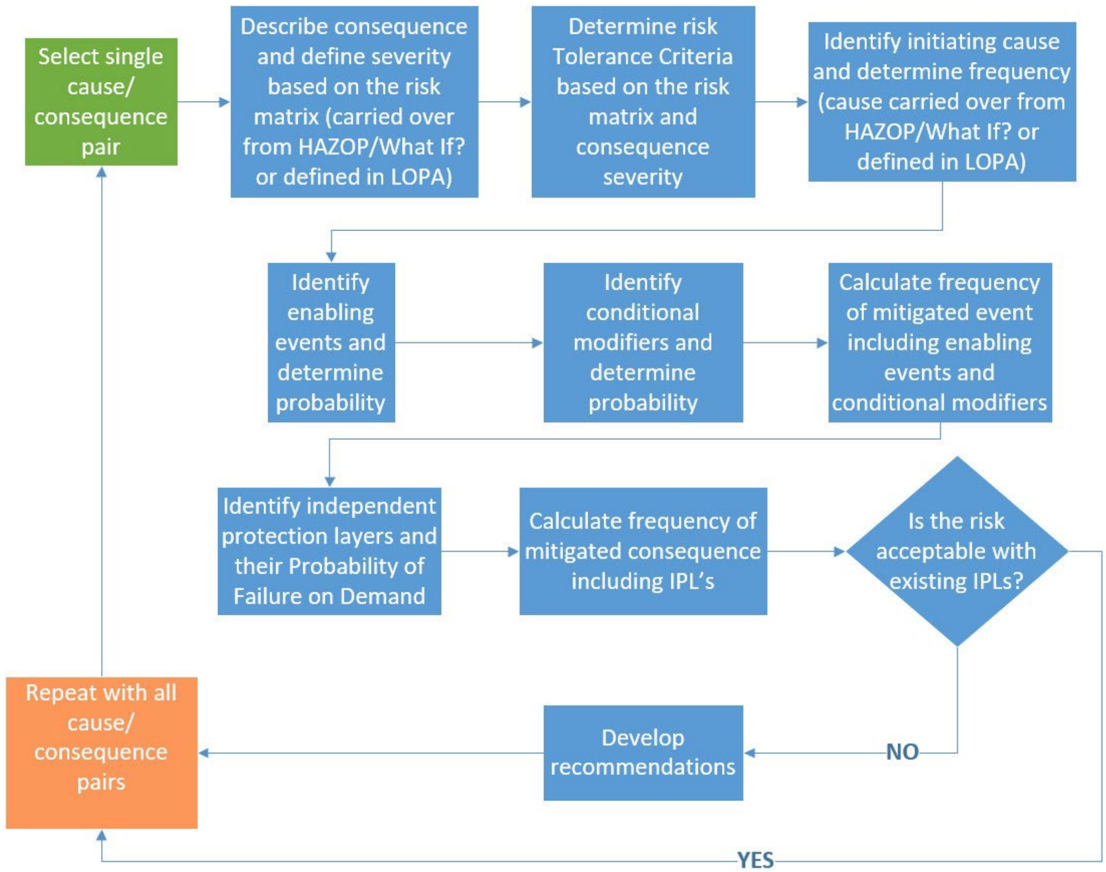
During LOPA the frequency of a mitigated event is compared to the tolerable risk frequency based on the company matrix. If the frequency of the mitigated event is greater than the risk tolerance, then additional risk reduction of the existing scenario is required. Additional recommended independent layers of protection are calculated. LOPA is used to determine quantitatively if a Safety Instrumented System is required and the Safety Integrity Level of the Safety Instrumented Function that is needed.

Mitigated event frequence is calculated using:

- Initiating event frequency
- Enabling events probability (i.e. time at risk)
- Conditional modifiers probability (i.e. probability of ignition, personnel occupancy, etc.)
- Existing independent protection layers probability of failure on demand

LOPA lies between the qualitative end of the scale, characterized by methods such as HAZOP and What-if, and the quantitative end, characterized by Fault Trees and Event Trees and other methodologies. LOPA can be used as an extension of HAZOP analysis to further evaluate the risk of the scenario or can be used as a standalone risk analysis method. In practice, some companies choose to do LOPA on medium to high-risk scenarios as determined in HAZOP. Figure 19 depicts steps required to complete LOPA and Figure 20 is an example.

Figure 19: Steps to Conduct a Layer of Protection Analysis



Source: ioMosaic Corporation

Figure 20: Example of a Layer of Protection Analysis

Company: Date: System:
Drawing Numbers:
Unit/Process:
Equipment/Lines:
Description: LOPA
Design Intent:

LNG Example | LOPA (LOPA) | Worksheet generated: January 17, 2025

PHA Scenario Reference #	PHA Scenario Reference	Scenario Description	Severity Level	Type	Consequence #	Consequence	Target Frequency (per year)	Initiating Event Description	Initiating Event #	Initiating Event	Frequency (per year)	Event Modifier Type	Modifier Factor	Inherent Frequency (per year)	Non-IPL Safeguards	IPL Description	IPL #	IPL	IPL Value	Total Frequency (per year)	R	Required IPL Credits
3.1	Scenario 1.4.1.2	Sudden contact of outer wall with LNG resulting in brittle fracture of plates and a two phase release with flash fire and fatality	5	Safety Criteria	3.1	Single fatality	1E-05	Level transmitter failure LT050	3.1	BPCS instrument loop failure	0.1	Ignition probability	0.1	5.E-3	Level transmitter LT046 with alarm and operator response	Redundant level transmitter LT045 with alarm and operator response	3.1.1	Operator response to alarm with at least 10 minutes response time	1.E-1	5E-05		1
															High level switch LSHH049 stops flow to tank -SIF SIL 1	High level switch LSHH049 stops flow to tank -SIF SIL 1	3.1.2	SIS/SIF SIL-1	1.E-1			
												Personnel presence	0.5									

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

4.13 Quantitative Risk Assessment

Quantitative Risk Analysis (QRA) is the systematic development of numerical estimates of the expected frequency and severity of potential incidents associated with a facility or operation based on engineering evaluation and mathematical techniques. Typically, risk is divided into two categories:

- Individual Risk: risk level to an individual based on an activity that poses the risk
- Societal Risk: function of the total population, workforce or public, present at a given location of interest

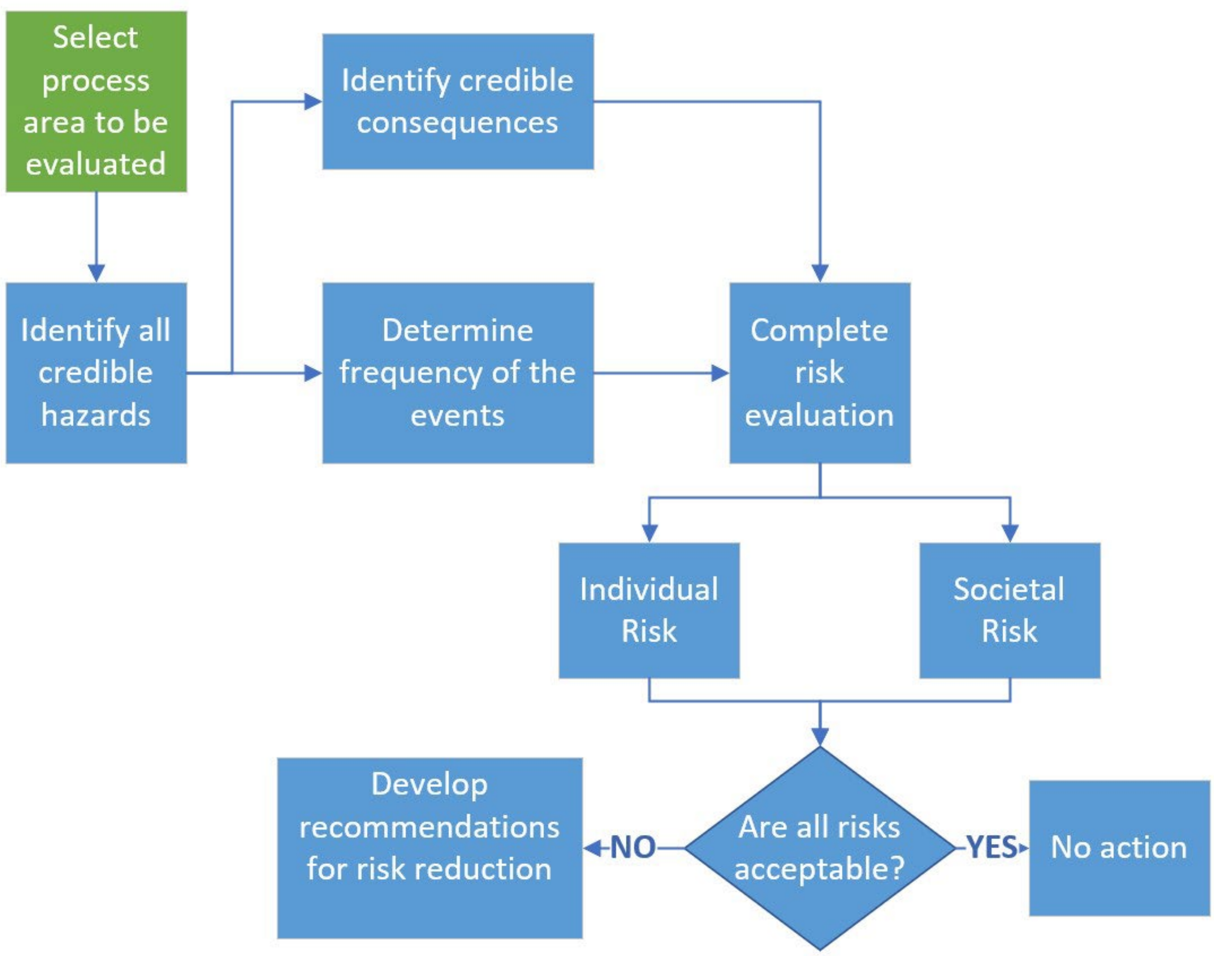
A complete QRA consists of six main steps:

- Hazard Identification – hazards with potential to lead to an explosion, fire or toxic exposure
- Frequency Analysis – estimate of likelihood of occurrence of hazardous events identified
- Consequence Analysis – quantifies the effects and impacts based on damage criteria for fires, explosions and toxic hazards
- Risk Analysis – quantifies the risk levels as a function of likelihood of occurrence and the magnitude of the associated impact

- Risk Tolerability Criteria – compares estimated risk to the worldwide recognized risk tolerability criteria to determine if the risk is acceptable
- Risk Reduction – recommending risk reduction measures to decrease individual and/or societal risk

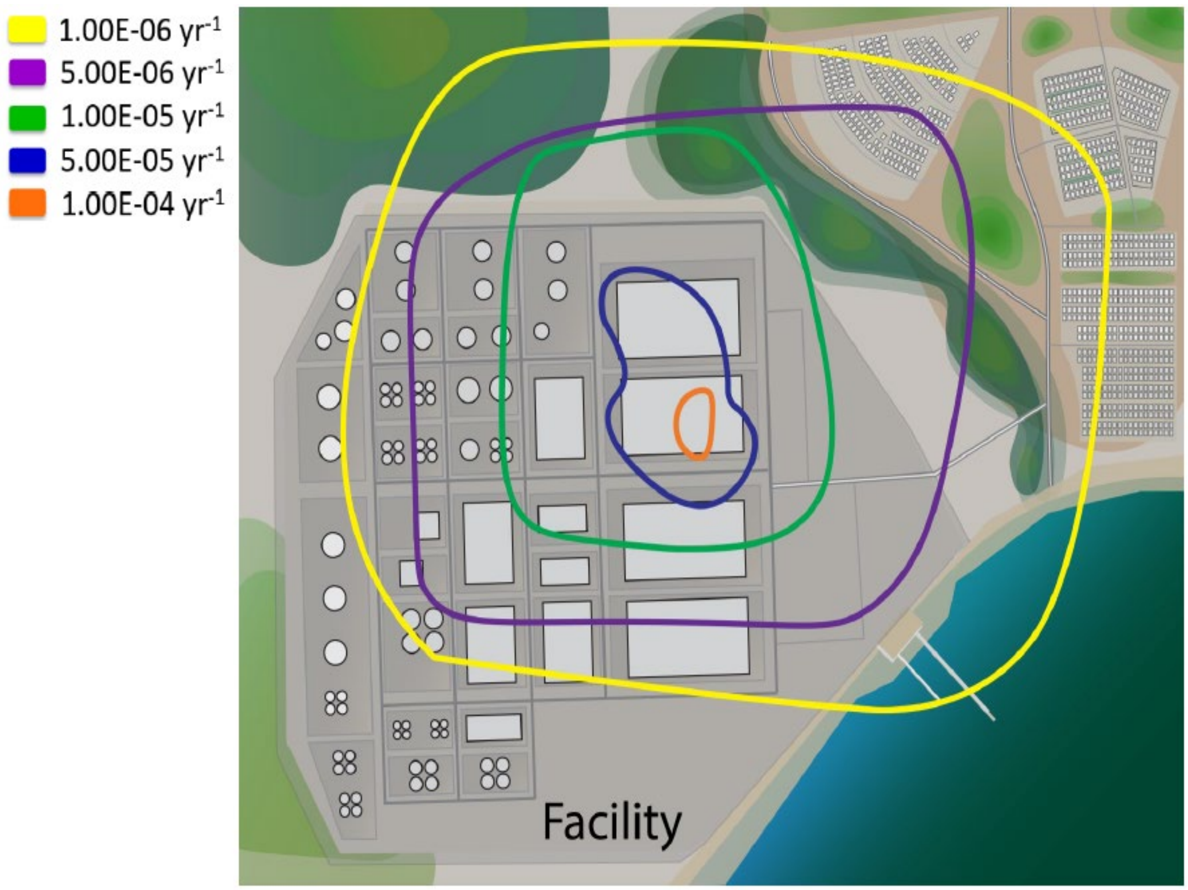
QRA is a good additional tool to pair with traditional analytical methods (HAZOP, LOPA, etc.) to provide a more accurate (numerical) result for specific scenarios. Figure 21 depicts steps required to conduct a QRA. Figure 22 is an example of an individual risk contour. Figure 23 is an example of a predicted FN Curve and Figure 24 is an example of the overpressure exceedance curves (OECs).

Figure 21: Steps to Conduct a QRA



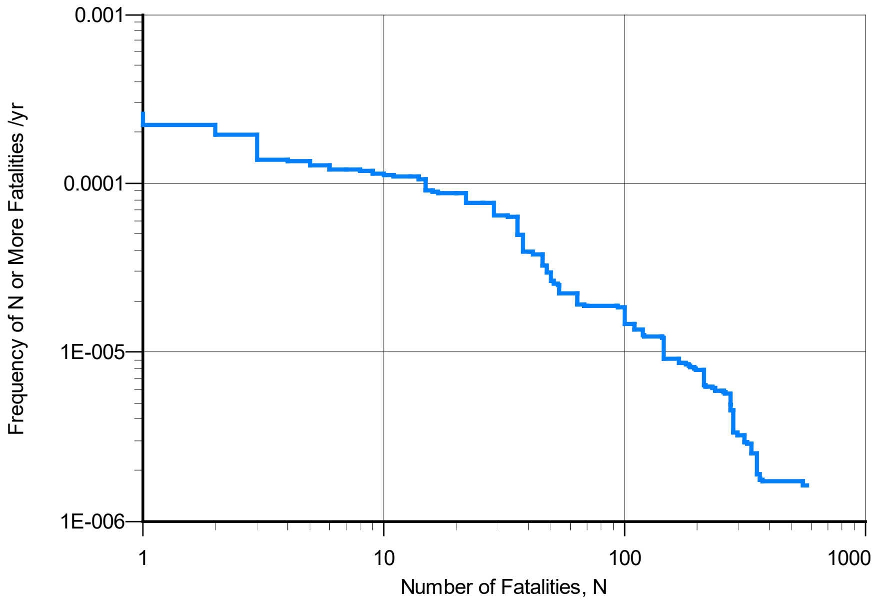
Source: ioMosaic Corporation

Figure 22: Example of Individual Risk Contour



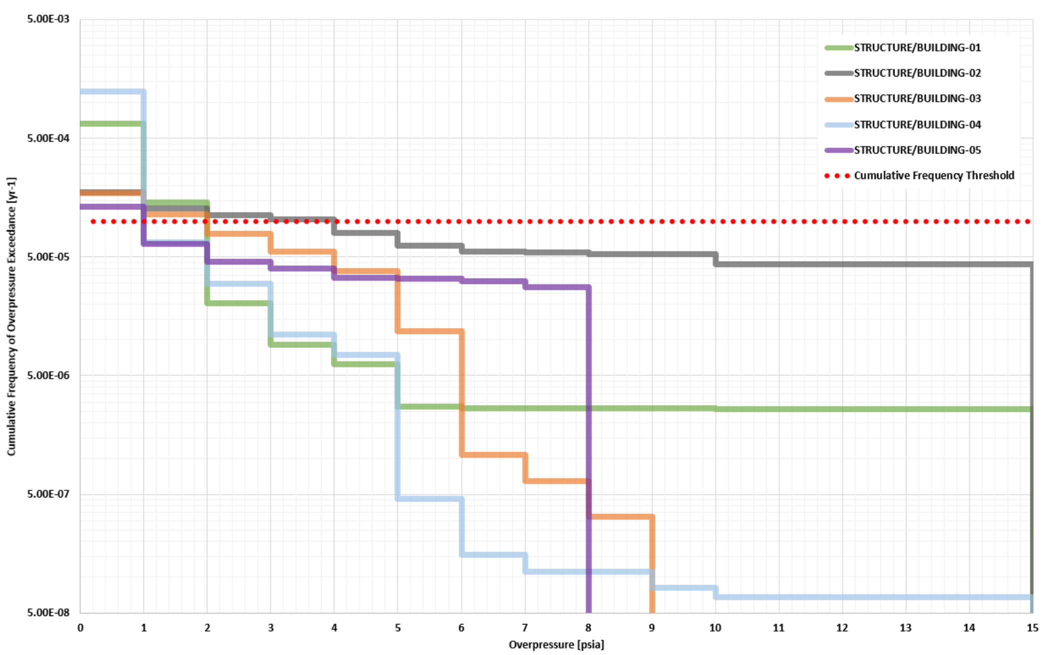
Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Figure 23: Example of predicted FN Curve



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

Figure 24: Example of Overpressure Exceedance Curves (OECs)



Source: Process Safety Office® SuperChems™ - ioMosaic Corporation

5 Supporting Techniques and Information for Conducting PHAs

5.1 Supporting Techniques

This section covers supporting techniques and information that is applied in combination with PHA methodologies. It begins with risk evaluation concepts, continues with checklists specific to LNG facilities, and concludes with lists of typical hazard scenarios, failure frequencies and conditional modifiers specific to LNG industry.

Although the concepts in this section are most associated with the HAZOP methodology and its associated risk matrix, an overall risk tolerance is needed for any PHA methodology to determine whether the risk is tolerable.

5.1.1 Consequence Criteria

Consequences are typically considered for different consequence categories: worker health, public health, environmental impact, and economic loss (ex. production downtime, equipment damage, and company reputation).

Most guidance defines the consequences in terms of numbers of fatalities to worker and public populations; however, these are usually among the worst-case consequence levels. The scenarios that result in fatalities can also lead to further application of LOPA, where a quantitative risk tolerance target is used. This will be discussed later in the report. The consequence criteria for worker and non-worker populations should be defined in a way similar to Table 8.

Table 8: Example Consequence Criteria

Level	Onsite Criteria	Offsite Criteria
1	Reportable Injury	N/A
2	Lost Work Time (LWT)	Public Shelter In-place
3	Multiple LWT Injuries	Public Evacuation
4	Irreversible Injury	Public Hospitalizations
5	Single Fatality	Irreversible Injury
6	Multiple Fatalities	Single Fatality

The consequence criteria for environmental damage and economic losses are subject to the business/organizations' ability to absorb and pay for environmental fines, remediation and economic losses. Examples of Environmental consequence criteria are provided in Table 9.

Table 9: Sample Environmental Consequence Criteria

Consequence Level	Criteria
1	A onetime event, little or no WEC, or other regulatory, fine, <25,000 MT (metric tons; 24,605 long tons) of CO_2 equivalent methane released per year.(1)
2	An environmental incident where contamination is confined to the site and where recovery is complete in 1 year. Release of >25,000 MT of CO_2 equivalent methane per year and WEC fine of $900 per MT in 2024.
3	An environmental incident which could contaminate ground water in the immediate area around the site. Incident affecting public or downstream water users.
4	An environmental incident which could contaminate soil off-site, or contaminate sediments, or ground or surface waters outside site boundaries. Remediation.
5	An environmental incident with significant local or national media attention (reported by national TV, social media)
6	Environmental impact leading to exposure of large population or area, an event that triggers a class action lawsuit by a third party (National resource damages)

(1) Waste Emission Charge (WEC) per EPA Methane Emissions Reduction Program; 1 MT CH_4 = 29.8 MT CO_2 [27]

Typically, mitigation factors such as secondary containment, limiting the number of maintenance personnel in a unit at one time, fire suppression system) are taken into account when determining the consequence.

5.1.2 Frequency Criteria

Definition of the frequency of consequence levels is also required for a PHA. The frequency levels are defined by different orders of magnitude ranging from constantly occurring to negligibly occurring, that are defined semi-qualitatively. Table 10 is an example of frequency criteria. The descriptions in brackets are provided as an alternative approach to understanding the frequencies.

Table 10: Example Frequency Criteria

Level	Frequency	Description
1	<1E-04 /yr	Negligible, Likely to occur less than once per 10,000 years
2	<1E-03 – ≥1E-04 /yr	Improbable, Likely to occur less than once in 1,000 years and up to once in 10,000 years [Once in the life of 100 facilities]
3	<1E-02 – ≥1E-03 /yr	Rare, Likely to occur less than once in 100 years and up to once in 1000 years [Once in the life of 10 facilities]
4	<1E-01 – ≥1E-02 /yr	Possible, Likely to occur less than once in 10 years and up to once in 100 years [Once in the lifetime of a facility]
5	<1 –≥1E-01 /yr	Probable, Likely to occur less than once a year and up to once in 10 years
6	≥1 /yr	Frequent, Likely to occur at least once a year

Frequency can take into account prevention safeguards that reduce likelihood of achieving the consequence in question.

5.1.3 Quantitative Safety Analysis Criteria

The application of quantitative hazard and risk assessment techniques for decision-making requires that some type of acceptance target be set for each individual scenario/PHA item. Target values are generally referred to as threshold or tolerability criteria. There are several types of quantitative safety criteria, depending on the kind of safety that is being evaluated, be it public health, occupational health or safety from hazardous chemical processes. Table 11 summarizes threshold public health criteria for fatality and injury from several US and international sources for comparison. US threshold criteria are generally an order of magnitude lower than for the cited international references.

Table 11: Criteria Examples, Offsite Harm to the Public (Societal Risk), Fatalities / Irreversible Harm

Source	NFPA 59A[1]	SB County[2]	HSE[3]	BS-EN1473[#]
Fatality No.	Frequency/Year			
1	1E-05	1E-05	5E-03	1E-04
10	1E-06	1E-07	1E-04	1E-05
100	1E-07	1E-09	5E-06	1E-06
1000	1E-08		1E-07	
Irreversible Harm				
1	1E-04	1E-03		
10	1E-05	5E-05		
100	1E-06	1E-06		

[#] Approximation from consequence and frequency ranges [21]

[1] Information from 2023 revision of NFPA 59A [22]

[2] Santa Barbara County, California [28]

[3] HSE, 2001. "Reducing Risks, Protecting People; HSE's Decision-Making Process". [23]

Table 12: Criteria Examples, Offsite Harm to the Public (Societal Risk) Fatalities / Injuries

Source	NFPA 59A[1]	CCPS[3]	HSE[4]	BS-EN1473[#]
Consequence Magnitude	Tolerable Frequence, Occurrence/Year			
Reportable Injury[2]		1E-01		
Lost Work Time[2]		1E-02		
2 to 10 Injuries	1E-03	1E-03		
Irreversible Injury	1E-04	1E-04		
Single Fatality	1E-05	1E-05	<5E-03	1E-04
2 to 10 Fatality	1E-06		<1E-04	<1E-05

[#] Approximation from consequence and frequency ranges [21]
[1] Information from 2023 revision of NFPA 59A [22]
[2] Workplace Risk
[3] CCPS [24]
[4] HSE, 2001. "Reducing Risks, Protecting People; HSE's Decision-Making Process". [23]

Tables 11 and 12 are split into two parts to show the fatality and irreversible injury data on the first part and injuries on the second. Some approximation results. However, it is informative in that it shows the societal risk criteria from the 2023 revision of NFPA 59A are representative values compared to values from other well established and recognized sources.

The consequence and frequency criterion from above are usually combined with the threshold criteria to generate a risk matrix. While criterion are published, risk matrices are more difficult to find. The only published data set is from the Center for Chemical Process Safety (CCPS), 2019. The other data sets in Table 12 were constructed using a few anchoring points for consequence and frequency pairs and filling in the values in between. Again, a matrix based on values from the 2023 revision of NPFA 59A is in agreement with the CCPS version.

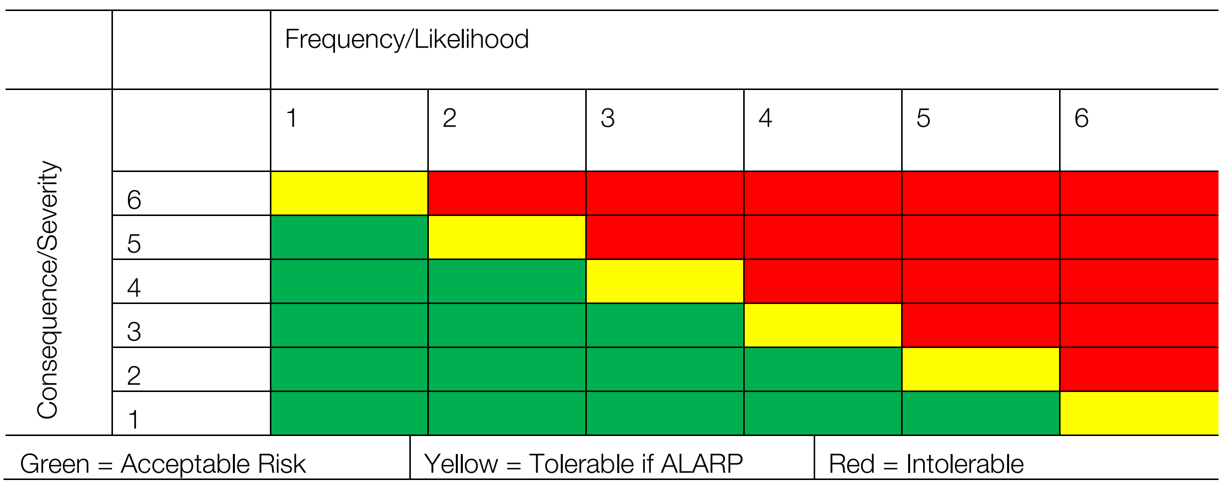
The frequency criteria incorporate some societal risk threshold tolerability data as a benchmark to allow alignment of the other injury/fatality consequence/frequency pairings, which means the results address the risk to the public as well as to workplace employees. If the concern is both onsite and offsite risk, then two sets of frequency criteria would be appropriate with an offset of one order-of-magnitude more frequent for onsite tolerance. Table 13 provides criteria for such a HAZOP risk matrix.

Table 13: Proposed Risk Matrix Frequency Criteria

	Tolerable Frequency/ Year	
Consequence Impact Criteria	Onsite Impact	Offsite Impact
1. Reportable Injury or Public Shelter In-place	≤1E-0	≤1E-01
2. Lost Work Time (LWT) or Public Evacuation	≤1E-01	≤1E-02
3. Multiple LWT Injuries or Public Hospitalizations	≤1E-02	≤1E-03
4. Irreversible Injury	≤1E-03	≤1E-04
5. Single Fatality	≤1E-04	≤1E-05
6. Multiple Fatalities	≤1E-05	≤1E-06

A sample Risk Matrix is presented in Figure 25. The tolerable frequency values would be for the green cells in the risk matrix. The 'as low as reasonably practicable' (ALARP) values (yellow cells) are at one order-of -magnitude higher frequency. Reasonably practicable involves weighing a risk against the difficulty, time and money needed to control it. ALARP describes the highest risk level which is considered tolerable [23].

Figure 25: Sample Risk Matrix



Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

"Reasonably practicable" considers the sacrifice involved in the measures necessary for averting the risk (whether in money, time or difficulty) weighed against the risk reduction benefit. If it can be shown that there is a gross disproportion between them, i.e., the risk reduction being insignificant in relation to the sacrifice, then ALARP is allowable.

In essence, making sure a risk has been reduced ALARP is about weighing the risk against the sacrifice needed to further reduce it. The decision is weighted in favor of health and safety because the presumption is that the enterprise should implement risk reduction measures. To avoid having to make this sacrifice, the enterprise must be able to show that it would be grossly disproportionate compared to the benefit of risk reduction that would be achieved. Thus, the process is not one of balancing the costs and benefits of measures but, rather, of adopting measures except where they are ruled out because they involve grossly disproportionate sacrifices. Extreme examples might be:

- To spend $1M to prevent five employees suffering bruised knees is obviously grossly disproportionate; but
- To spend $1M to prevent a major explosion capable of killing many people is obviously proportionate [29]

Therefore, accepting ALARP as sufficient for risk mitigation will vary depending on the magnitude of the consequence.

Hence, the target frequency for LOPA should be the impact criteria in Table 10 to determine the level of sacrifice needed to achieve a tolerable risk. If that sacrifice is grossly disproportionate (see example) to the benefit achieved in terms of safety and health impacts, then ALARP is permissible.

The risk ranking matrix is also applied during a PHA to estimate a risk level for the identified hazardous events. In this case, the assigned event frequency accounts for the existing safeguards (IPLs) identified.

5.2 Specific Hazard Scenarios for LNG Facilities

The hazards for LNG are primarily a combination of the flammability and physical properties of LNG, combined with undesirable operational events. Table 14 contains the hazards and consequences that may be encountered at LNG facilities.

Table 14: LNG Hazards

Hazard	Source	Notes
Rapid phase transition (RPT)	BS EN 1473 [21], Lee's Loss Prevention in the Process Industries [30]	When quantities of LNG have been introduced into water, over pressurization without combustion can occur due to rapid heat transfer from the water. LNG vaporizes violently. RPTs are more likely to occur for LNG containing high fractions of ethane and propane.
Cold fluid temperature (cryogens)	BS EN 1473 [21], Lee's Loss Prevention in the Process Industries [30]	Cryogenic liquid releases can cause embrittlement if they are exposed to materials not designed to handle such releases, and freeze burns if they expose personnel.
Hot fluid temperature	FERC [5]	Hot vapor releases from turbines, boilers, and engines for power and heat generation.
Asphyxiation and toxic dispersion	BS EN 1473 [21], FERC [5], NFPA 59A [31], Lee's Loss Prevention in the Process Industries [30]	Likely sources are H_2S, NH_3, and methane
Vapor cloud	BS EN 1473 [21], FERC [5], NFPA 59A [31]	Reduced visibility due to unignited vapor clouds, pools, jets
Flammable vapor dispersion / flash fire	BS EN 1473 [21], FERC [5], NFPA 59A [31], Lee's Loss Prevention in the Process Industries [30]	Radiant heat hazards, Gas or liquid releases that form a flammable cloud in an open area, which with ignition, cause a short and intense flash fire that is harmful to personnel. 5-15 vol% flammability limit.
Flame jet	BS EN 1473 [21], FERC [5], NFPA 59A [31]	Radiant heat hazards, Pressurized gas or liquid releases that ignite, creating a high heat flux jet fire.
Pool fire	BS EN 1473 [21], FERC [5], NFPA 59A [31], Lee's Loss Prevention in the Process Industries [30]	Radiant heat hazards, liquid releases that form a pool on the ground or water and with ignition, creates a potentially long-lasting pool fire. The typical surface emissive power of an LNG pool fire lies in the range of 220 +/- 50 kW/m^2.
Fireballs	NFPA 59A [31]	
Vapor cloud explosion (only when confined or when enriched with other hydrocarbons)	BS EN 1473 [21], FERC [5], NFPA 59A [31], Lee's Loss Prevention in the Process Industries [30]	Gas or liquid releases that form a flammable cloud in a congested or enclosed area, and ignition, causing an explosion and a pressure wave.
Boiling Liquid Expanding Vapor Explosions (BLEVE) when LNG is stored in pressure vessels with inadequate relief	FERC [5], NFPA 59A [31]	Projectile and overpressure hazards
Rollover (overpressure)	NFPA 59A [31], SIGTTO [32], Lee's Loss Prevention in the Process Industries [30]	In LNG tank, density of the upper layer increases and/ or the density of the lower-level decreases such that the more dense upper layer sinks and/ or the less dense lower layer rises, causing the two layers to rapidly mix or roll over. This becomes problematic when there also exists a significant temperature difference between the two layers as the rapid mixing will result in a rapid heat transfer and vaporization, which can overwhelm pressure relief valves (PRVs).
Overpressure (e.g. pressure vessel bursts (PVB))	FERC [5], Lee's Loss Prevention in the Process Industries [30]	Projectile and overpressure hazards. Can occur due to insufficient venting or PRV capacity.
Fog or steam	FERC [5]	Visibility hazards due to water condensation (i.e., fog generation from ambient vaporizers or other cooling and heating systems or steam generation).

Table 15 contains a list of initiating events and causes of loss of containment of LNG. These causes are meant to be incorporated into the PHA with any deviations developed by the methodology chosen for the PHA.

Table 15: Initiating Events and Causes

Initiating Event / Cause	Source	Notes
LNG carriers approaching the berth at excessive speed or angle	BS EN 1473 [21], Lee's Loss Prevention in the Process Industries [30]	
Collision with the jetty and/or LNG carrier at berth by heavy displacement vessels passing the berth	BS EN 1473, Lee's Loss Prevention in the Process Industries	
Impact of projectiles	BS EN 1473, Lee's Loss Prevention in the Process Industries	
Consequences of collision (ship, truck, plane, etc.)	BS EN 1473, Lee's Loss Prevention in the Process Industries	
Natural events (hurricane, lightning, flooding, earthquakes, tidal bores, icebergs, tsunamis, seiches, etc.)	BS EN 1473, Lee's Loss Prevention in the Process Industries	
Weather conditions (barometric pressure incl. pressure fluctuation, rain, snow and ice, ambient temperatures)	BS EN 1473	
Ground conditions (weak strata, liquefiable layers, lateral spreading, presence of caverns, voids and defects)	BS EN 1473	
Proximity of airport and/or flight paths	BS EN 1473	
"Domino effect" resulting from fires and/or explosions at adjacent premises	BS EN 1473	
Failure of LNG unloading arm or unloading header and transfer pipeline (during transfer, due to excessive movement between ship and jetty)	Lee's Loss Prevention in the Process Industries	Release during transfer, temporary connections between tank and storage are a weak link
Failure of storage tank	Lee's Loss Prevention in the Process Industries	Release during transfer
Failure of a storage tank outflow line	Lee's Loss Prevention in the Process Industries	Release during transfer
Release due to LNG vaporizer inlet line failure	Lee's Loss Prevention in the Process Industries	Release during transfer
Release due to natural gas line failures	Lee's Loss Prevention in the Process Industries	Release during transfer
Overfilling of containers	Lee's Loss Prevention in the Process Industries	Release at tanker terminals – one of most common accidents
Ignition due to static electricity	Lee's Loss Prevention in the Process Industries	Release at tanker terminals
Maloperation and misidentification	Lee's Loss Prevention in the Process Industries	Release at tanker terminals
Release occasioned by maintenance/construction	BS EN 1473, Lee's Loss Prevention in the Process Industries	

Initiating Event / Cause	Source	Notes
Failure or leak from pipework and fittings: ▪ External Corrosion ▪ Internal Corrosion ▪ Stress Corrosion Cracking ▪ Piping Stress Design for Contraction ▪ Excessive Cool Down Cycling ▪ Manufacturing ▪ Construction Defect ▪ Equipment ▪ Incorrect Operations ▪ Third Party Damage/Mechanical Damage ▪ Excavation Damage Previous Damage (due to Excavation Activity) ▪ Vandalism (includes all Intentional Damage) ▪ Weather Related/Other Outside Force Natural Force Damage (all) ▪ Other Outside Force Damage (excluding Vandalism and all Intentional Damage)	Lee's Loss Prevention in the Process Industries [30], ASME B31.8S [33], PHMSA [34]	
Fire engulfing vessel or tank	Lee's Loss Prevention in the Process Industries	
Explosion in vessel or tank	Lee's Loss Prevention in the Process Industries	
Simultaneous loadings on multi-product jetty	BS EN 1473 [21]	
Poor communication between ship and shore	BS EN 1473	
Traffic within the plant both during construction and operation;	BS EN 1473	
Leakage of other hazardous substances, e.g. flammable refrigerant	BS EN 1473	
Missiles originating from explosion	BS EN 1473	
Elevated tank foundations (flammable mixtures formation below slab)	BS EN 1473	
Security issues (e.g. intrusion, sabotage), arson	BS EN 1473, Lee's Loss Prevention in the Process Industries	
Escalation of accidents	BS EN 1473	
Simultaneous operations during construction.	BS EN 1473	

5.2.1 *Electrical Grounding and Bonding*

Flowing gases and liquids can generate electrostatic discharge. Failure of grounding and bonding may result in the buildup of an electrostatic discharge that can be an ignition source. The following are grounding and bonding requirements per NFPA 59A[31]:

- Grounding and bonding shall be provided. Bonding is not required at transfer areas where both halves of metallic hose couplings or pipe are in contact.
- If stray currents can be present or if impressed currents are used on loading and unloading systems (such as for cathodic protection), protective measures to prevent ignition shall be taken.
- A lightning protection system shall be provided for storage containers supported on nonconductive foundations.

5.3 Failure Frequencies/Probabilities and Conditional Modifiers

5.3.1 *Failure Frequencies*

Failure frequencies are usually compiled from historical records. Failure frequencies for initiating events (IEF) are sourced from CCPS Guidelines for Initiating Events and Independent Layers of Protection in LOPA [19] and CCPS Guidelines for Initiating Enabling Conditions and Conditional Modifiers in LOPA [20] and are for generic processes. The frequencies for the initiating events can be used as a starting point to determine the frequency of the consequences. Initiating events are found in Table 16.

Table 16: Frequency of Initiating Events

Initiating Event	Frequency range (per year)	Suggested Frequency (per year)
Turbine/Diesel engine overspeed with casing breach	1E-03 to 1E-04	1E-04
Third Party intervention (external impact by vehicle, etc.)	1E-02 to 1E-04	1E-02
Crane load drop	1E-03 to 1E-04 per lift	1E-04 per lift
Lightning strike	1E-03 to 1E-04	1E-03
Safety valve opens spuriously	1E-02 to 1E-04	1E-02
Cooling water failure	1 to 1E-02	1E-01
Basic process control system instrument loop failure	1 to 1E-02	1E-01
Regulator failure	1 to 1E-01	1E-01
Small external fire (aggregate causes)	1E-01 to 1E-02	1E-01
Large external fire (aggregate causes)	1E-02 to 1E-03	1E-02
Lock-out tag-out procedure failure (overall failure of a multiple-element process)	1E-03 to1E-04 per opportunity	1E-03 per opportunity
Operator failure (to execute routine procedure, assuming well trained, unstressed, not fatigued)	1E-01 to 1E-03 per opportunity	1E-02 per opportunity
Single circuit loss of power	-	1E-01
Pump, compressor, fan, or blower failure	-	1E-01
Pump Seal Leak	-	1
Single check valve failure	-	1E-01
Hose Leak	-	1E-01
Hose Rupture	-	1E-02
Premature opening of spring-loaded relief valve	-	1E-02

Source Table 5.1 CCPS[18][19]

The range values shown in Table 16 [18] indicate the variability among different data sets. Human error rates can vary depending on stress level, repetitiveness and complexity, for example. Human error IEFs compiled specifically for LOPA calculations are covered in CCPS reference [18] Tables 4.3, 4.4, and 4.5 for different usage frequencies. The referenced tables give context for the recommended values and provide discussion of special considerations and validation methods for guidance on selecting a value appropriate for the existing conditions.

The IEFs are qualified for low-stress operations performed by operators trained in written procedures with periodic refresher training. Table 16 gives a generic IEF for human error of 1E-01 to 1E-03 per opportunity for a LOPA calculation.

Generic loss of containment frequencies for LNG equipment are available in the PHMSA Failure Rate Table (see Table 17).

Table 17: Generic Loss of Containment Frequencies

Typic of Failure	Nominal Failure Rate
Cryogenic Storage Tanks (General)	Failures per year of operation
Rupture of Storage Tank Outlet/Withdrawal Line	3E-05 (Failure Rate Criterion)
Single Containment Atmospheric Storage Tanks	Failures per year of operation
Catastrophic Failure, Release to Atmosphere	5E-06 per tank
Catastrophic Failure of Tank Roof	1E-04 per tank
Release from a hole in inner tank with effective diameter of 1 m (~3 ft)	8E-05 per tank
Release from a hole in inner tank with effective diameter of 0.3 m (~1 ft)	2E-04 per tank
Release from a hole in inner tank with effective diameter of 0.01 m (0.4 in)	1E-04 per tank
Double Containment Atmospheric Storage Tanks	Failures per year of operation
Catastrophic Failure, Release to Atmosphere	5E-07 per tank
Catastrophic Failure of Tank Roof	1E-04 per tank
Release from a hole in inner tank with effective diameter of 1 m (~3 ft)	10-5 per tank
Release from a hole in inner tank with effective diameter of 0.3 m (~1 ft)	3 E-05 per tank
Release from a hole in inner tank with effective diameter of 0.01 m (0.4 in)	1E-04 per tank
Full Containment Atmospheric Storage Tanks	Failures per year of operation
Catastrophic Failure, Release to Atmosphere	1E-08 per tank
Catastrophic Failure of Tank Roof	4E-05 per tank
Release from a hole in inner tank with effective diameter of 1 m (~3 ft)	1E-06 per tank
Release from a hole in inner tank with effective diameter of 0.3 m (~1 ft)	3E-06 per tank
Release from a hole in inner tank with effective diameter of 0.01 m (0.4 in)	1E-04 per tank
Process Vessels, Distillation Columns, Heat Exchangers, and Condensers	Failures per year of operation
Catastrophic Failure (Rupture)	5E-06 per vessel
Release from a hole with effective diameter of 0.01 m (0 .4 in)	1E-04 per vessel
Truck Transfer	Failures per year of operation
Rupture of transfer arm	3E-04 per transfer arm
Release from a hole in transfer arm with effective diameter of 10% transfer arm diameter with maximum of 50 mm (2 in)	3E-03 per transfer arm
Rupture of transfer hose	4E-02 per transfer hose
Release from a hole in transfer hose with effective diameter of 10% transfer hose diameter with maximum of 50 mm (2 in)	4E-01 per transfer hose
Ship Transfer	Failures per year of operation
Rupture of transfer arm	2E-05 per transfer arm
Release from a hole in transfer arm with effective diameter of 10% diameter with maximum of 50 mm (2 in)	2E-04 per transfer arm
Piping (General)	Failures per year of operation
Rupture at Valve	9E-06 per valve
Rupture at Expansion Joint	4E-03 per expansion joint
Failure of Gasket	3E-02 per gasket
Piping: d < 50mm (2-inch)	Failures per year of operation
Catastrophic rupture	1E-06 per meter of piping
Release from hole with effective diameter of 25 mm (1 in)	5E-06 per meter of piping
Piping: 50mm (2-inch) ≤ d < 149mm (6-inch)	Failures per year of operation
Catastrophic rupture	5E-07 per meter of piping
Release from hole with effective diameter of 25 mm (1 in)	2E-06 per meter of piping
Piping: 150mm (6-inch) ≤ d < 299mm (12-inch)	Failures per year of operation
Catastrophic rupture	2E-07 per meter of piping
Release from hole with effective diameter of 1/3 diameter	4E-07 per meter of piping
Release from hole with effective diameter of 25 mm (1 in)	7E-07 per meter of piping
Piping: 300mm (12-inch) ≤ d < 499mm (20-inch)	Failures per year of operation
Catastrophic rupture	7E-08 per meter of piping

Release from hole with effective diameter of 1/3 diameter	2E-07 per meter of piping
Release from hole with effective diameter of 10% diameter. up to 50 mm (2 in)	4E-07 per meter of piping
Release from hole with effective diameter of 25 mm (1 in)	5E-07 per meter of piping
Piping: 500mm (20-inch) ≤ d < 1000mm (40-inch)	Failures per year of operation
Catastrophic rupture	2E-08 per meter of piping
Release from hole with effective diameter of 1/3 diameter	1E-07 per meter of piping
Release from hole with effective diameter of 10% diameter. up to 50 mm (2 in)	2E-07 per meter of piping
Release from hole with effective diameter of 25 mm (1 in)	4E-07 per meter of piping

Source: Gas Technology Institute [35]

Some RAGAGEP specify the leak hole size that should be used (e.g., EN-14620 [36] and API 625[37]). In this case, interpolation of the frequency values will be required to obtain an appropriate value for risk analysis.

5.3.2 Conditional Modifiers

Conditional modifiers can be applied to the scenarios to change the frequency of the ultimate consequence. These modifiers are associated with post-release incident sequencing and are expressed as probabilities. These may include:

- Probability of ignition
- Personnel presence factors or occupancy factors
- Probability of hazardous atmosphere
- Probability of explosion

Ignition probability is the likelihood that a flammable cloud will ignite when it reaches an ignition source. Cox et al [38] estimated immediate ignition probability for gases and liquids based on the leak flow rate. Refer to Table 18 below:

Table 18: Immediate Ignition Probability Criteria

Release Rate	Probability of Ignition		Probability of Explosion given ignition
	Gas	Liquid	
Minor (≤ 1 $kg \cdot s^{-1}$)	0.010	0.010	0.04
Major (1-50 $kg \cdot s^{-1}$)	0.070	0.030	0.12
Massive (≥ 50 $kg \cdot s^{-1}$)	0.300	0.080	0.3

Source: Cox et al. [38]

The probability of delayed ignition caused by an ignition source can be modeled as:

$P(t) = P_{Present} \cdot (1 - e^{-\omega t});$

Where $P(t)$ is the probability of an ignition in the interval time 0 to t (unitless), $P_{Present}$ is the probability that the source is present when the cloud passes (unitless), ω is the ignition effectiveness (s^{-1}), and t is the time (s).

The ignition effectiveness (ω) can be calculated given the probability of ignition for a certain time interval. Table 19 gives the probability of ignition for a time interval of one minute for several sources.

Table 19: Probability of ignition

Point Source	Probability of Ignition Within 60 Seconds
Motor Vehicle	0.4
Flare	1.0
Outdoor Furnace	0.9
Indoor Furnace	0.45
Outdoor Boiler	0.45
Indoor Boiler	0.23
Ship	0.5
Ship Transporting Flammable Materials	0.3
Fishing Vessel	0.2
Pleasure Craft	0.1
Diesel Train	0.4
Electric Train	0.8
Line Source	**Probability of Ignition Within 60 Seconds**
Transmission Line	0.2 per 100 m
Road (i.e., it is a function of the average traffic density)	To Be Determined
Railway (i.e., it is a function of the average traffic density)	To Be Determined
Area Source	**Probability of Ignition Within 60 Seconds**
Chemical plant	0.9 per site
Oil refinery	0.9 per site
Heavy industry	0.7 per site
Light industrial warehousing	as for population
Population Source	**Probability of Ignition Within 60 Seconds**
Residential (i.e., function of the average number of people present in the population source)	0.01 per person
Employment force (i.e., function of the average number of people present in the population source)	0.01 per person

Source: CPR-18E [39]

5.3.3 *Enabling Events*

A condition that is not a failure, error, or protection layer, but makes it possible for an incident sequence to proceed to a consequence of concern is called an enabling event. It consists of a condition or operating phase that does not directly cause the scenario but must be present or active in order for the scenario to produce a loss event. It is expressed as a probability. Examples of some generic types of enabling events are Time at Risk, Seasonal, and Process State are discussed below.

5.3.3.1 *Time at Risk*

Time at Risk is when an incident sequence may only be realized at a certain fraction of the time when conditions are suitable for the event sequence to progress to a loss event. For example, a loading arm fails or decouples while transferring LNG to a cargo carrier. The fractional time at risk is the number of hours per LNG transfer multiplied by the number of cargo carriers that berth per year divided by 8,760 hours per year.

5.3.3.2 *Seasonal Risk*

Seasonal risk is usually associated with weather conditions. A common time-at-risk enabling condition is a sufficiently low ambient temperature to enable process, utility, or instrumentation lines to freeze after failure of designed freeze protection. Enabling conditions may also include extreme high ambient temperatures affecting cooling capacity, or low humidity allowing static accumulation and discharge. Note a seasonal condition should not be an initiating event if it is considered an enabling condition, such as storm flooding that exceeds a 100-year occurrence.

5.3.3.3 *Process State Risk*

This enabling condition is when a process must be in a certain portion of a non-continuous operation when a failure occurs for the incident sequence to be able to proceed to a loss event. For example, a batch chemical reaction may have potential for runaway, but only if cooling loss occurs during the first step of the batch when most of the conversion takes place.

5.3.4 *Independent Layers of Protection*

Independent protection layers (IPLs) are the safeguards that prevent or mitigate consequences. An IPL needs to work upon demand (when there is a hazard scenario that needs to be prevented or mitigated) and like any other component, can fail to perform its function, giving a probability of failure on demand (PFD). The PFD of the IPLs can be used to determine the amount of credit that can be taken for a safeguard, where each negative order of ten can be considered a reduction in the frequency of reaching a consequence in a Risk Matrix (example: 0.01 would reduce a frequency of 5 to 3, assuming the frequency levels are setup similarly to Table 10). Table 20 contains a list of IPLs and their associated PFDs.

Current best practice is to use LOPA to determine the number of IPLs required to reduce the likelihood (risk) of a hazard consequence. The number of IPLs needed will depend on:

- The tolerability target frequency
- The hazard scenario frequency, and
- The frequency reduction value of the IPLs

The tolerability target frequency is defined by the assigned consequence severity and the tolerability threshold region of the risk matrix. The procedure is a risk mitigation gap analysis.

In the case of high severity hazard consequences (i.e., fatalities), the mitigation gap will typically be closed with safety integrity level (SIL) rated safety instrumented system/function (SIS/SIF) IPLs. These systems require validation by RAGAGEP of the probability of failure on demand (PFD), which accounts for diagnostic interval, mean time to replacement (MTTR), mission time, etc. Depending on the required SIL level determined by LOPA, the SIS may be comprised of redundant components (e.g., sensors, SIL rate logic solvers, and final elements).

Table 20: Independent Layers of Protection

Independent Protection Layers Description	Probability of Failure on Demand	Notes
Drainage to dikes, berms, and bunds with remote impoundment	0.01	
Permanent mechanical stop that limits travel (on a valve to prevent complete closure, etc.)	0.01	
Fire-resistant insulation and cladding on vessel	0.01 (IF a relief valve is considered alongside this layer, the total PFD will still be 0.01)	
Single Spring-operated pressure relief valve with rupture disk	0.01 (IF there is an isolation valve upstream or downstream of the relief device, then the PFD is reduced to 0.1)	If there are two or more redundant pressure relief valves (each relief valve can handle the full required relief rate), a PFD of 0.001 can be considered.
Check (non-return) valve	0.1	
Pressure reducing regulators	0.1	
Automatic fire suppression system (within process equipment and local application; can be for spark detection)	0.1	
Automatic explosion suppression system for process equipment	0.1	Works through sensor devices that will detect and inject extinguishing agent.
Human response	0.1	If human response is used as an IPL, an operating/maintenance procedure must exist and the workers must be trained on the procedure. Human response to an abnormal condition with multiple indicators and/or sensors, and the operator has > 24 hours to accomplish the required response action, PFD of 0.01.
An adjustable movement-limiting device, such as strong wire car seal, chain/lock, or an adjustable mechanical stop that is intended to prevent operation of a device or movement of an object beyond the defined limit.	0.1	
Use of personal protective equipment (PPE)	0.1	Only applies if the PPE is specifically designed for the task and potential hazard.
Mechanically activated emergency shutdown / isolation device	0.1	
Continuous pilot	0.1	Serves as an independent ignition source for the main burner to prevent materials from accumulating in fired equipment if flameout occurs.

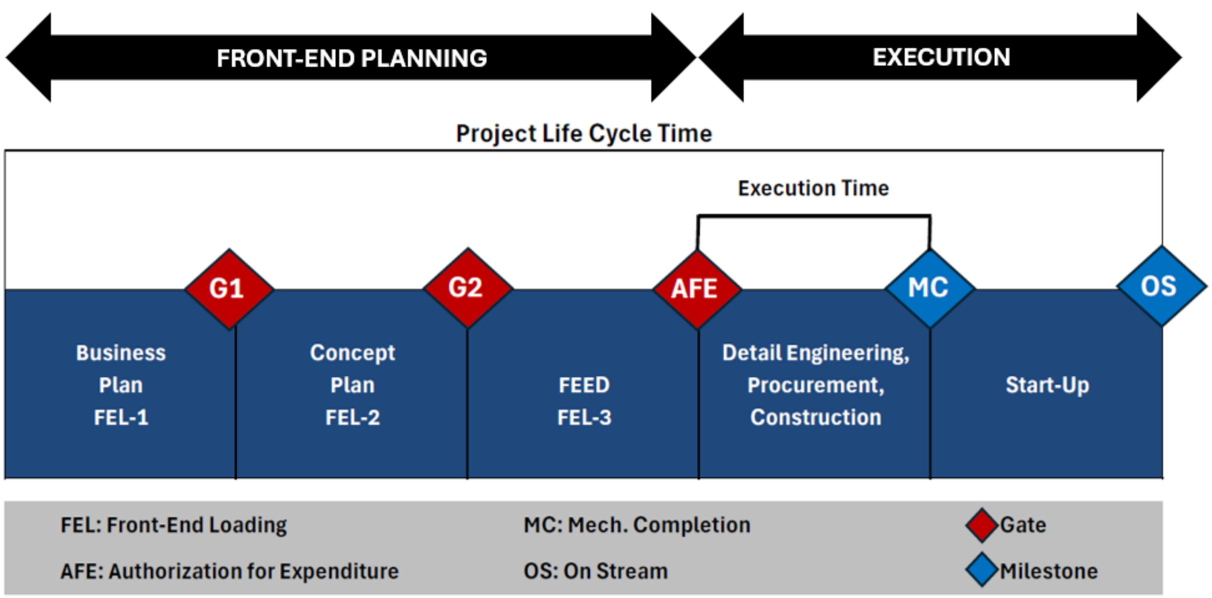
Independent Protection Layers Description	Probability of Failure on Demand	Notes
Restrictive flow orifice	0.01	
Excess flow valve	0.1 (IF the service is clean and/or non-fouling it can be further reduced to 0.01)	Designed to stop flow of material when the predetermined flow rate is reached.
Unstable (overdriven) detonation arrester installed in-line between an ignition source and a source of flammable or combustible vapors.	0.01 – without temperature monitoring and shutdown or isolation response 0.001 – with temperature monitoring and shutdown or isolation response	
In-line stable detonation arrester between a potential ignition source and equipment containing flammable or combustible vapor, where deflagration-to-detonation transition (DDT) cannot be ruled out.	0.1 – without temperature monitoring and shutdown or isolation response 0.01 – with temperature monitoring and shutdown or isolation response	
Deflagration arrester at the end of a pipe (or in line), typically between the location of the ignitable vapors and potential ignition sources	0.01	
SIS loop (which is SIL dependent)	0.1 for SIL 1 0.01 for SIL 2 0.001 for SIL 3	Instrumentation and control systems
Overflow line with no impediment to flow	0.001	

Source: CCPS [20]

6 Recommended Techniques by Stage

Historically Process Safety Professionals refer to the life cycle of a project as starting with identification of hazards at the research and development stages, to "Conceptional Design" and then pilot plant operations prior to the "Detailed Engineering Design" phase. However, LNG facility construction is based on known chemistries, as well as known hazards. It is most appropriate to reference the life cycle in terms utilized by the "Project Management Institute" (PMI.org). The PMI refers to stages in the project as Front-End Loading (FEL) stages (FEL stages can also be called "Appraise-Select-Define" stages), through to "Detailed Design/Engineering". This is the "Front End Engineering Design (FEED)" process. The FEED step is the last phase used for identification of equipment procurement. One example of such a Life cycle is demonstrated in the following Figure: 26

Figure 26: Example of Project Life Cycle



Source: ioMosaic Corporation

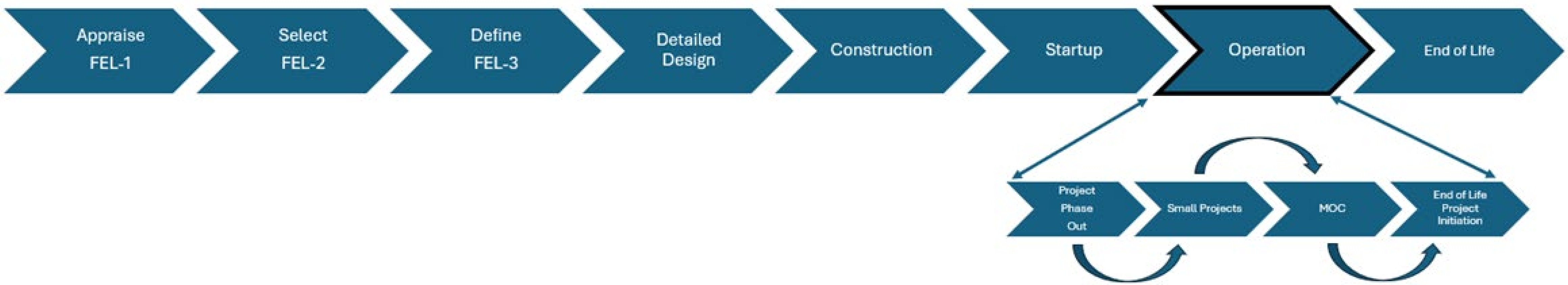
Many consultants and industries have different versions of a Front-End Loading process to properly manage their projects. The stages vary from FEL-0 to FEL-5 and many versions in between. What is more common in the Oil & Gas Industry is a FEL-1 to FEL-3 stage system, therefore this is the model that will be used for demonstration of hazard analysis for the Life Cycle of a project.

Front End Loading (FEL) stages are discussed below, as they relate to PHA methodologies recommended to be utilized for LNG Facilities. The most comprehensive and highest quality approach is to conduct hazard analysis reviews at each FEL stage utilizing a combination of many techniques. Each methodology addresses a specific purpose. The combination approach ensures gaps in design are identified and addressed. A combination of methodologies is also the optimum method for addressing hazards when the plant is fully operational through to the "Decommissioning Stage" in the life cycle.

Many of the same hazard analysis methodologies will be utilized repeatably through each of the Front-End Loading stages, as well as through the remaining life cycle stages. The completed hazard analysis at each stage is considered an iteration of the analysis from the previous stage, once the preliminary analysis is completed. As the design progresses through to the next FEL Stage, often the technique is a revisit of the PHA(s) generated during the previous stages. Each progressive stage typically has developed substantially more details on the process information, scope and design. Therefore, a higher level of rigor can be utilized through the FEL Stages for reviewing potential hazards and risks. It's very important to note the PHA is an iterative process through the FEL Stage Gate reviews. It is also critical to note that once a PHA is completed in FEL-3, the design is considered locked. Any modifications to the final detailed design (during the process lifecycle), once the PHA is completed on that design, must be reviewed through the "Management of Change" process. This may very well include a new hazard analysis, but most certainly a revisit of the existing hazard analyses.

Once the reviews are completed in the FEL/FEED stages, the reviews then progress to the Construction, Startup and the Operations stages. Additional PHAs occur during Operations and a final stage is the End-of-Life decommissioning stage. One common version of this full process life cycle can be represented by Figure 27. (Chemical Center for Process Safety, 2019) [40].

Figure 27: Life Cycle of a Process



Source: ioMosaic Corporation

The methodologies to be utilized for the PHA will be dependent on the scope of the project and complexity of the process. Below in Table 21 are the recommended methodologies for each Life Cycle Stage.

Table 21: Most Appropriate Hazard Evaluation Methodology(s) for each Life Cycle Stage

Stages of Life Cycle	PHA Techniques	Discussion/Strengths
FEL-1- This stage is the "Feasibility" stage where options are generated and filtered. The feasibility of a project is assessed based on commercial viability and risks identified.	Preliminary Hazard Review/HAZID/What-if Analysis	Preliminary Hazard Review does not require detailed information. Typically, at FEL-1, multiple options for the scope of a project are generated. During this stage a preliminary review of hazards occurs to ensure it is feasible to proceed with the project from many perspectives. The feasibility of identifying safe options to address hazards needs to be evaluated and resolved before proceeding to the next stage
	Checklists	Checklists are a good tool for high level hazard identification in the initial stages of a design. They are very beneficial for ensuring key hazards are evaluated and typically have been developed for known designs. With LNG facility design requirements typically well known, the Checklist technique is ideal to ensure each key hazard is evaluated and known risks are being evaluated. Checklists are a good precursor for further analysis during detailed design. Checklists early in the process ensure key items are not overlooked. This could make the project not feasible if discovered later in the design. (Generic high-level Checklists can be found in "Guidelines for Integrating Process Safety into Engineering Projects", Appendix G, among many other publications readily available)..
	Inherent Safer Design Reviews	This stage is the time to incorporate initial thoughts on options for "Inherent Safer Design" (ISD) reviews. If not completed at FEL-1, the changes to accommodate inherent safer design become much more costly. The key hazards and risks are identified and plans to manage or reduce the risks are evaluated through ISD options. High level options are considered; however, more detailed ISD options are generated in FEL-2. The impact on costs during these stages is represented in Figure 28 shown after the conclusion of Table 21

Table 21: Most Appropriate Hazard Evaluation Methodology(s) for each Life Cycle Stage

Stages of Life Cycle	PHA Techniques	Discussion/Strengths
FEL-2- This stage is the "Concept Stage". This stage is utilized to analyze alternatives that remain following FEL-1 reviews. The Team will evaluate and select the best alternatives and concept phase reported.	Preliminary Hazard Review via Brainstorm/HAZID/What-if Analysis	A second iteration of the initial preliminary hazard analysis should occur, particularly on the preferred options the team plans to pursue. Preliminary hazard review is used to identify the major potential hazards in the conceptual design stage that can greatly affect facility design.
	Checklists and ISD iteration	An iteration to the first pass on the Checklists utilized at FEL-1 is generated on the remaining alternatives. Preliminary ISD should be revisited at this stage as well. Some ISD options may be further developed, however not in all cases, at this stage.
	Concept Risk Analysis (CRA)	From a PHA perspective the CRA may be necessary on larger projects to identify if significant safety or environmental impacts impact the feasibility of alternatives or options for the project. The CRAs are used to identify location options with lowest risk level to local communities. The preliminary Hazard Analysis provides the scenarios that need to be evaluated for potential high impact to community or environment. This is a simplified form of a QRA as described in Section 4. At this stage the CRA may be generated on estimates of inventories or generic data as it will generate sufficient results to evaluate options for locations of units or plants. A detailed QRA cannot be generated at this stage due to insufficient information.

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Stages of Life Cycle	PHA Techniques	Discussion/Strengths
FEL-3-This is the stage to outline a detailed scope. At this stage a project manager should be initiating preliminary design/engineering, finalizing scope and obtaining costs. A single concept is selected. This allows for justification and information to further mature the existing hazard evaluations from the earlier stages. In addition, at this stage the basic design has been developed. The preferred options should be identified. Therefore, preliminary PFDs, M&EBs are available and some equipment information. Some organizations merge this stage with the Detailed Design Stage.	What–if/Brainstorming	A What-if can now be initiated at a higher level of rigor, in advance of a HAZOP. This is the 2nd iteration of the What if generated on the identified Scope. Information from the preliminary Hazard Analysis should be utilized.
	Quantitative Risk Analysis (QRA)	At this stage consider offsite major accident risks with results with the more detailed QRAs. QRAs should be utilized to identify location options with lowest risk level to local communities or adjacent units. The level of QRA may vary depending on the complexity of the facility being planned. A simplified quantitative risks assessment (QRAs) will evaluate anticipated risks based on industry data for similar facilities. In addition, at this phase there should be sufficient information to conduct QRAs in line with requirements in the Environmental Report Section 11 requirements FERC. Those results must quantify at this stage multiple scenarios. Those include “Vapor Cloud Overpressure”, “Flammable Vapor Dispersion”, “Asphyxiant Toxic Vapor Dispersion”, “Fire Hazard Analysis”, and others as outlined in FERC Guidelines. In addition, Vapor Overpressure Analysis should be conducted on projectile hazards from boiling-liquid expanding vapor explosions (BLEVE) and pressure vessel bursts. (FERC) once vessel design is determined.
	Checklists	The previous “Checklists” should now be reviewed and developed to cover the identified concept and scope. Any regulatory risks should be evaluated, and checklists are ideal to ensure all regulations are addressed.
	HAZOP	A preliminary HAZOP should now be conducted to identify any gaps in design. HAZOP is a preferred method for hazard identification in the detail engineering stage, especially for continuous processes. Early identification and resolution of hazards through HAZOPs during the detailed engineering phase can result in cost savings as noted by Figure 28. This is accomplished by preventing rework, avoiding delays, and minimizing the need for expensive retrofitting or modifications. The HAZOP may be pre-populated with information from the previous Hazard Analysis conducted. Pre-population will streamline the time required to complete the preliminary HAZOP. This HAZOP will be preliminary to the final HAZOP completed at detailed design stage. The HAZOP study is an iterative process until the design is locked at Final Design (FEED). The first revision of the HAZOP is typically done halfway through the FEL-3 phase, when the P&IDs are at the 95% completion point.
	LOPA	At this stage there should be sufficient information to provide LOPAs as outlined in the Environmental Guidance Manual Volume II, FERC. The LOPAs shall be based on the scenarios identified in the FEL-3 -HAZOP study. In addition, the LOPA analysis will guide the Project team on additional instrumentation or safeguards that are needed to address any gaps in risk levels. The LOPA will guide the design for the critical safety control system interlocks, emergency shutdown system(s) and/or Safety Instrumented System (if applicable for the risks.).

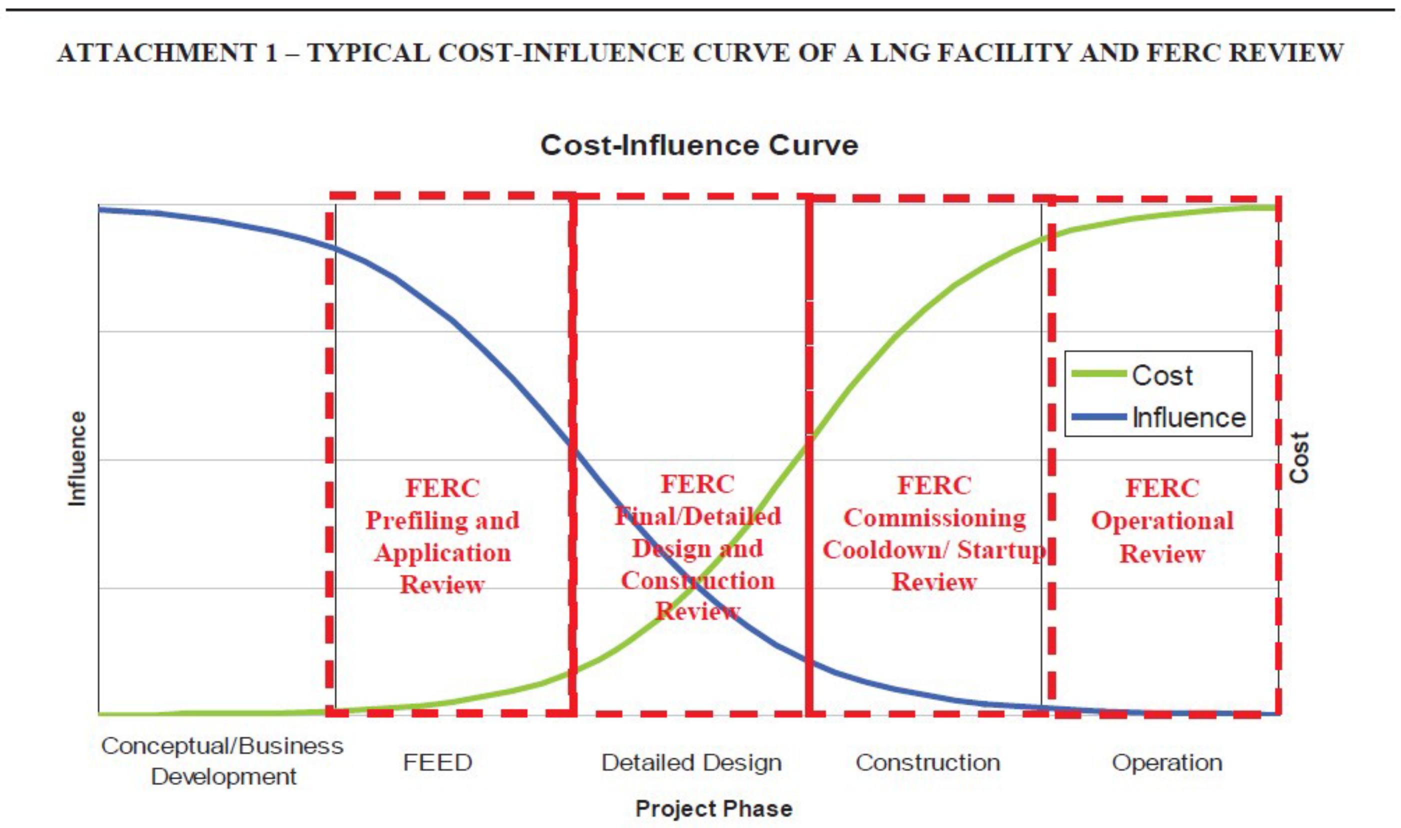
Stages of Life Cycle	PHA Techniques	Discussion/Strengths
Detailed Engineering- Is the final stage where all costing shall be obtained, and a final decision is made to proceed with procurement and construction. This is the stage where the design is frozen from the FEED- Front End Engineering Design (FEED) package.	Checklists	Checklists developed based on standards and regulations are very useful during detailed engineering to ensure that all standards or regulatory requirements are met. These can identify hazards that may not be addressed by methods based on P&ID reviews. Checklists can also be used to identify Human Factors concerns during the detailed design stage. Checklists associated with maintainability of the equipment is also of great benefit to factor integrate Human Factors associated with maintenance activities. There are several checklists that are publicly available for organizations to purchase, or many organizations have a standard checklist that has been developed based on their Companies experiences or lessons learned.
	Hazard and Operability Study (HAZOP)	The HAZOP study from the FEL-3 stage is utilized to ensure any recommendations made by the team have been incorporated into the final design. Once those actions are closed the management of change process must be used to review any further design changes, which includes revisiting the HAZOP and QRAs as appropriate on any changes.
	Layer of Protection Analysis (LOPA)	LOPA analyzes the most critical risks identified by other techniques, ensuring that essential measures are taken to mitigate or eliminate the hazards. The method is flexible to allow for updates if the engineering design changes and it works well with other Process Hazard Analysis techniques. A LOPA provides simplified quantification of the hazards identified by other methods. Scenarios identified by other methods exceeding a hazard threshold should be analyzed further to ensure better definition of level of protection and LOPA is a good technique to accomplish this objective. It is employed to determine whether there is an SIL IPL gap for the safety instrumented systems (SIS) that have been configured. The SIL assessment for potential Safety Instrumented System shall be conducted at this stage. This will also fill the obligation for summarizing the design for the safety instrumented system, as well as provide information that will enable the development of the Cause and Effects Matrices as outlined in the FERC Environmental Report Guidance Manual. (FREC)
	Quantitative Risk Assessment (QRA)	The results of the QRA developed in FEL-3 shall be referenced for capturing consequences in the final HAZOP developed for final design.
	Fault Tree Analysis	The Fault Tree analysis is used for very high-risk scenarios to address evaluate multiple failure events that are not evaluated by HAZOP and LOPA.
	What-if	A What-if study from the earlier stages can be updated for any further design changes

Stages of Life Cycle	PHA Techniques	Discussion/Strengths
Construction/Start Up	Checklists	Checklists are one of the best methods to ensure that equipment is installed per design and standards and all required action items are completed before start-up. These checklists are developed ahead of time and used during completion of different construction phases including Start-up. In addition to the hazard analysis checklists, the Pre-Start Up Safety Review Checklist shall be executed at this stage.
	HAZID	During construction phase HAZID can be used to evaluate certain operations such as lift over live equipment, etc.
	Hazard and Operability Study (HAZOP)	Using a HAZOP structured approach with deviation review makes it easier to update hazard analyses completed in the detailed engineering stage. This should be done after construction completion and before start-up based on as-built information to ensure that previously identified high risk scenarios were properly mitigated, and no new risks were introduced during the construction phase. The HAZOP technique has heavy emphasis on design and equipment; however, it may miss operational issues or human errors that occur executing standard operational procedures.
	What If?	Prior to routine operation it is recommended to supplement the final design HAZOP PHA with a "What-if" analysis on key operational procedures to supplement the HAZOP. The HAZOP of the final design is typically focused on equipment and can miss Human Factors that are easily identified in a "What- if" analysis on a procedure drafted for routine operations. Especially for any situation where there is potential for the procedures not to be followed as drafted.

Stages of Life Cycle	PHA Techniques	Discussion/Strengths
Routine Operation- Full Operation Stage	Hazard and Operability Study (HAZOP)	HAZOP's structured approach is a very good method to identify additional risks during routine operations. Some of these such as events during start-up, shutdown or maintenance may be overlooked during reviews in the detailed engineering stage
	What-If	What If? is a good method to analyze small facilities or procedurals and procedural changes whether temporary or permanent during routine operations. It can be completed quickly and identify hazards if team members have a good understanding and are experienced in the operation that is under review.
	Layer of Protection Analysis (LOPA)	During routine operations, actual data can be obtained, which can be used to determine the risk. During the lifetime of the process or facility, the operators will gain key insight into how the system behaves and what responses can be effective, which can lead to better safety. Probability of failure on demand can be scrutinized relative to assumptions in the initial design, based on actual experience.
Stages of Life Cycle	PHA Techniques	Discussion/Strengths
Expansion or Modification- This stage refers to any change, no matter how small. If it is a change in design on any level a hazard analysis is critical.	Hazard and Operability Study (HAZOP)	HAZOP is a preferred method for hazard identification in the expansion or modification stage, just as it is during final design stage. The structured discussion of specific deviations resulting from any modification or expansion activity minimizes the possibility of omitting hazard scenarios.
	Layer of Protection Analysis (LOPA)	LOPA analyzes the most critical risks identified by other techniques, ensuring that essential measures are taken to mitigate or eliminate the hazards for process expansion and modification. The method is flexible to allow for updates if process changes occur and it works well with other Process Hazard Analyses and techniques. LOPA provides better levels of protection definitions
	Event Tree Analysis (ETA)	Event Tree Analysis allows for the early identification of potential hazards associated with proposed changes, enabling proactive risk management during the design and planning stages. By considering various scenarios

Stages of Life Cycle	PHA Techniques	Discussion/Strengths
		and failure modes, organizations can implement design features or operational controls to mitigate risks before they materialize
Stages of Life Cycle	PHA Techniques	Discussion/Strengths
Decommissioning/Extensive Shutdown	What-If	What-If is a very good method to review procedures during decommissioning. A What if analysis will identify hazards that could be introduced. This brainstorming technique allows for flexibility and is less resource intensive
	Checklists	Checklists are very good tools to use in preparation for decommissioning or after an extended shutdown. These checklists can be developed ahead of time to help focus activities to eliminate hazards

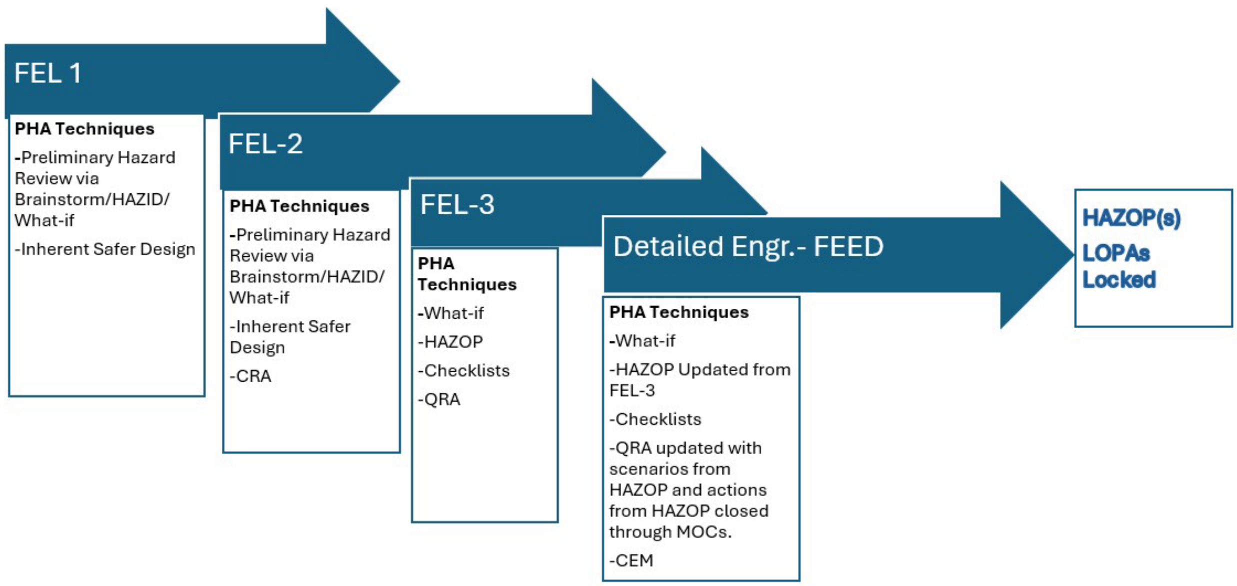
Figure 28: Cost Impact by Project Phase



Source: Federal Energy Regulatory Commission (FERC), 2017

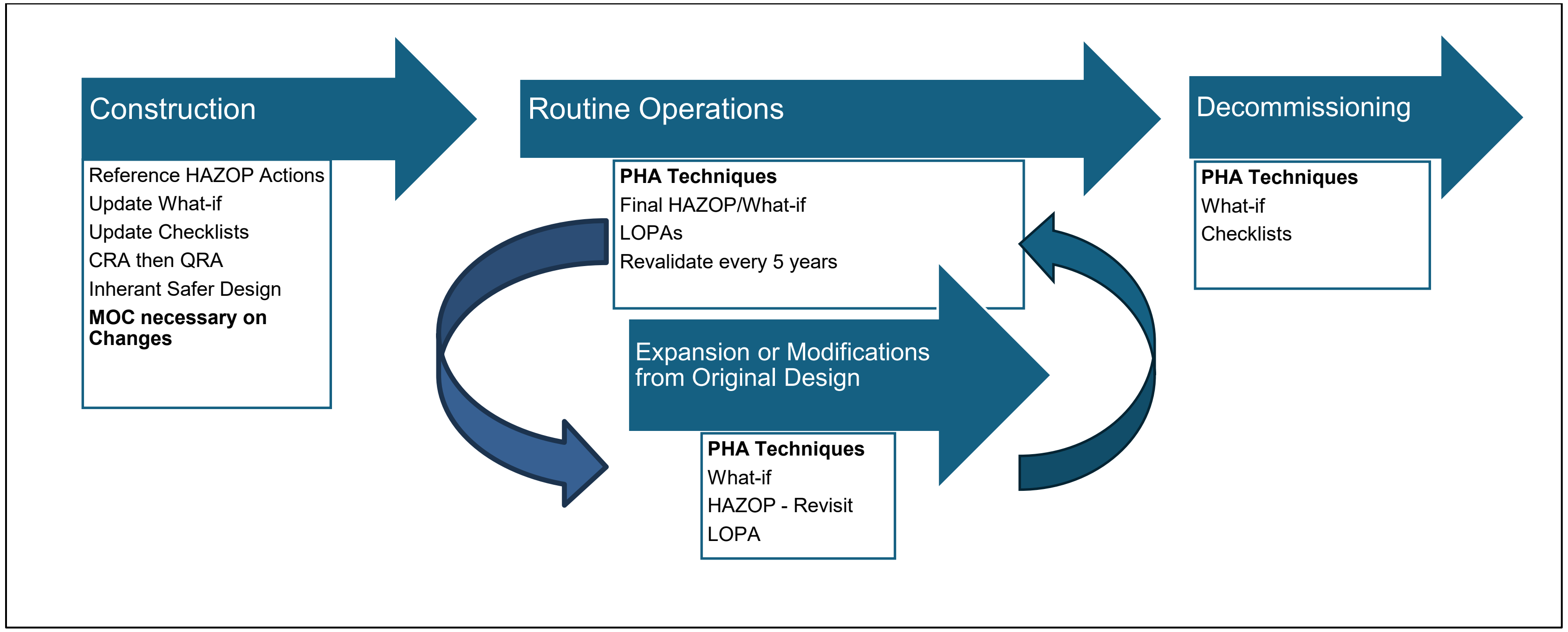
Below is a summary of potential methodologies. Most methodologies are noted as a repeat at each phase. This duplication across each phase is reflective of the iterative process through to the FEED /Final Design Stage for hazard analyses. Figures 29 and 30 summarize techniques discussed above at each Life Cycle Stage.

Figure 29: Optimum Methodologies for Life Cycle Stage through FEED



Source: ioMosaic Corporation

Figure 30: Optimum Analysis Methodologies for Life Cycle Stages after FEED



Source: ioMosaic Corporation

7 How to Conduct a PHA

An LNG facility should have a procedure for their Process Hazard Analysis (PHA) process. This procedure may be required by local regulations. The procedure should state when PHAs are required. This may include:

- Significant modifications to existing facilities or processes (MOC)
- Revalidations of previous PHAs as required by Federal, State and Local regulations.
- New process design and installation

The procedure should include the following sections:

- PHA Preparation
- PHA Sessions
- PHA Recommendations
- Training Requirements

7.1 PHA Preparation

Preparation should begin with the assignment of a PHA Team Leader who should be trained and qualified to serve as a PHA Team Leader. That should quickly be followed by the selection of PHA Team Members according to the PHA procedure.

7.1.1 PHA Team Members

Both the OSHA PSM standard 29 CFR 1910 119 (e) [2] and API RP 750 - 3.5 [41] state that PHAs should be performed by a team of persons knowledgeable in engineering, operations, design, process, and other specialties deemed appropriate. Table 22 provides the recommended skill set for each of the team members that will best ensure a successful PHA study.

Depending on the facility, there may be some overlap between roles. The team should be large enough to have sufficient expertise without becoming too unwieldy. Six to twelve members is common, but can be more for larger, more complex reviews or smaller for support for less complicated management of change reviews.

Table 22: Desired PHA Team Members

Expert Knowledge	Description/Value
Design Engineering	Knowledgeable on how the process is intended to operate Knowledgeable on applicable design standards, codes, specifications equipment design
Process/Instrumentation Engineering	Knowledgeable on process science and technology Knowledgeable to judge the adequacy of existing/new safeguards and equipment design.
Operations and Maintenance	"Hands-on" Operating and Maintenance experience
Health, Safety and Environmental	Knowledgeable on process hazards, safety systems, and related regulations
Other	Specialty areas (This member may be different at times depending upon the needs of the study team, like rotating equipment)
PHA Facilitator/Scribe	Familiar with the PHA techniques being employed and the software being used for recording the PHA

7.1.2 Process Safety Information

Up to date accurate process safety information (PSI) is needed to perform a valid PHA. The following list of PSI combines OSHA's 29CFR1910.119(d) PSI [2] compilation and other best practices. Depending on the project lifecycle stage, not all of this information may be available when the PHA is performed (e.g. at FEED). A PHA conducted during the operating lifecycle stage is expected to have most of this information.

The PHA procedure should designate who is responsible for gathering the PSI prior to the PHA.

- Chemical Hazard Data
    - Toxicity information
    - Permissible exposure limits
    - Physical data
    - Reactivity data
    - Corrosivity data
    - Thermal and chemical stability data
    - Hazardous effects of inadvertent mixing of different materials that could foreseeably occur
    - Safety data sheets
- Process Data
    - Block flow diagram or simplified process flow diagram

- Process chemistry
- Maximum intended inventory
- Standard Operating Procedures
- Safe upper and lower limits for such items as temperatures, pressures, flows or compositions (also basis of operation or operating envelope)
- An evaluation of the consequences of deviations, including those affecting the safety and health of employees
- The results of any previous off-site modeling that has been performed
- Safety Work Practice Information

- Equipment Data
  - Materials of construction / Bill of Materials (BOM)
  - Piping and instrument diagrams (P&ID's, current and updated)
  - Electrical classification
  - Relief system design and design basis
  - Ventilation system design
  - Design codes and standards employed
  - Material and energy balances
  - Safety systems (e.g. interlocks, safety instrumented systems, detection or suppression systems)
  - Demands on safety systems
  - Automated safety system Cause & Effect matrix or description and control narratives
  - Safety critical instrumentation designation
  - Plot plans
- Assumptions Register
  - Ground rules and assumptions listing
  - Risk Matrix and risk tolerance
- Change Related information
  - Management of Change (MOC) documents
  - Site wide changes
  - Staff level changes, where significant
  - Regulatory, industry or company standard changes
  - Procedural changes
  - Process Safety Information (PSI) changes

- Significant Operational Risk Assessments conducted for the plant/unit
- Previous HAZOP reports
- Inspection and Independent Audit Reports
- Near misses and previous incidents on the unit and similar units

- Equipment failures and repairs
- Safety Critical Devices (SCD)
  - Pipeline specific
    - External Corrosion Threat
      - Year of installation
      - Coating type
      - Coating condition
      - Years with adequate cathodic protection
      - Years with questionable cathodic protection
      - Soil characteristics
      - Pipe inspection reports
      - Microbiologically influenced corrosion detected (yes, no, unknown)
      - Leak history
      - Wall thickness
      - Diameter
      - Operating stress level (% SMYS - Specified minimum yield strength)
      - Past hydrostatic test information
    - Internal Corrosion Threat
      - Year of installation
      - Pipe inspection reports
      - Leak history
      - Wall thickness (thinning or pitting indications and minimum wall thickness)
      - Diameter
      - Past hydrostatic test information
      - Corrosion detection devices (instrumented pigs)
      - Operating parameters
      - Operating stress level (% SMYS)
    - Stress Corrosion Cracking Threat (particularly under insulation)
      - Age of pipe
      - Operating stress level (% SMYS)
      - Operating temperature
      - Distance of the segment downstream from a compressor station
      - Coating type
      - Past hydrotest information
    - Manufacturing Threat (pipe and seam)
      - Pipe material
      - Year of installation
      - Fabrication process (age of manufacture as alternative)

    - Seam type
    - Longitudinal weld joint quality factor
    - Operating pressure history
- Construction Threat
    - Pipe material
    - Wrinkle bend identification
    - Coupling identification
    - Post-construction coupling reinforcement
    - Welding procedures
    - Post-construction girth weld reinforcement
    - Non-destructive testing (NDT) information on welds
    - Hydrostatic test information
    - Pipe inspection reports (bell hole)
    - Potential for outside forces
    - Soil properties and depth of cover for wrinkle bends
    - Maximum temperature ranges for wrinkle bends
    - Bend radii and degrees of angle change for wrinkle bends
    - Operating pressure history and expected operation, including significant pressure cycling and fatigue mechanism
- Component Threat
    - Year of installation of failed component
    - Regulator valve failure information
    - Relief valve failure information
    - Flange gasket failure information
    - Regulator set point drift (outside of manufacturer's tolerances)
    - Relief set point drift
    - O-ring failure information
    - Seal/packing information
- Third Party Damage
    - Vandalism incidents
    - Pipe inspection reports (bell hole) where the pipe has been hit
    - Leak reports resulting from immediate damage
    - Incidents involving previous damage
    - In-line inspection results for dents and gouges at top half of pipe
    - On-call records (third party interference)
    - Encroachment records
- Incorrect Operations
    - Procedure review information

        - Audit information
        - Failures caused by incorrect information
    - Weather-related and outside-force threat (earth movement, heavy rains or floods, cold weather, lightning)
        - Topography and soil conditions (unstable slopes, water crossings, water proximity, soil liquefactions susceptibility)
        - Earthquake fault
        - Profile of ground acceleration near fault zones (greater than 0.2g acceleration)
        - Depth of frost line
    - Maintenance records for Safety Critical Devices (SCDs)
- Performance Monitoring Related Information
    - Deviations from processes or systems
    - Key Performance Indicators (KPIs)
    - Staffing arrangements

7.1.3 PHA Meeting Preparation

The PHA Team Leader should determine the type of hazard evaluation technique based on the PHA Procedure or his/her prior knowledge, as appropriate. Once the methodology has been selected, the PHA Leader, in conjunction with the scribe, if used, should set up/prepare any software being used and test the files for operability. The Risk Matrix should be selected by the PHA team leader and entered into the software.

A meeting location should be selected that will minimize the number of interruptions to the participants. If the meeting is expected to extend for more than a few hours, consideration should be made to providing lunch for the participants to minimize downtime. If participants from outside the organization are attending (e.g. equipment vendors, outside facilitators, etc.), ensure appropriate technical connections are available for presentations.

The PHA Team Leader will typically highlight a set of P&IDs indicating the boundaries of the system being studied. From there, the P&IDs will be further divided into nodes. A node is a section of the process where a physical or chemical change occurs. By choosing appropriate nodes that are neither too large nor too small, the leader can organize the analysis so that it is both thorough and efficient. Nodes are also often defined by grouping similar processes that use the same or similar equipment. [42]

An agenda should be made for larger PHAs which may encompass larger areas of a facility so participants can rotate in and out as their expertise is called for. Breaks should be built into schedules, usually every ninety minutes to two hours. Breaks should be limited in length to discourage participants from wandering off.

7.2 PHA Sessions

The PHA Leader should kick off the meeting with a short review/introduction of the PHA methodology being employed during the meeting. This is also a good time to review the scope of the meeting to keep the focus centered. Any software being used should be shown to the participants, so they understand how the data is entered and displayed.

The agenda should be reviewed with the Team so any last-minute conflicts can be adjusted for. This is also a good time to review any assumptions that have been made.

As the team reviews the process, a list of recommendations will be generated. A guide on how to use the recommendations is provided in Section 9 How to Use the PHA Results.

To overcome the shortcomings of some of the methodologies, checklists can be used to verify the design and operation of a process conforms to recognized and good engineering practices (RAGAGEP). Examples of such checklists are reviewed in the next subsection.

7.3 Checklists

The checklist methodology is good for verifying the design and operation of a process conforms to recognized and good engineering practices, which are codified basic design layers of protection, considered to be minimum safety requirements. While many of the other methodologies are based on the review of P&IDs the checklist methodology is more focused on the codes and regulations. They are not considered a substitute for a compliance PHA. They may augment the PHA by helping to identify additional safety hazards and protective systems such as facility siting, human factors and fire and gas detection to obtain full safety coverage. Example checklists, compiled from multiple sources, can be found in the appendices.

A Facility Siting Checklist is used to check if the process facility is laid out so that hazards from one area do not pose a high risk to occupied infrastructure in other areas. An example Facility Siting Checklist can be found in Appendix 7-A. The siting of LNG facilities is regulated by 49 CFR Subtitle B Chapter I Subchapter D Part 193 – LNG Facilities: Federal Safety Standards, Subpart B – Siting Requirements [43]. The checklist contains items that are considered to be relevant for locating LNG facilities including some subjects found in international standards that may be pertinent. It is not the intent that PHMSA should adopt these international standards for the domestic LNG industry. Using certain software, some checklists used during the PHA, (e.g., Facility Siting), may have specific guidewords for referencing each checklist, which can become a separate study node of the PHA. The checklist templates typically have Yes and No checkoff boxes, and column headings for comments, risk ranking and recommendations similar to the other PHA recording spreadsheets.

A Maintenance and Procedures checklist is used to verify the process has the appropriate operating and maintenance procedures for safe operations. An example Maintenance and Procedures checklist can be found in Appendix 7-B.

A Human Factors checklist is used to verify the process, minimizes sources of human error and reviews the environmental conditions operators may encounter. An example Human Factors checklist can be found in Appendix 7-C.

A Facility and Process Modifications checklist is used to verify the design of the process itself conforms to RAGAGEP. An example Facility and Process Modifications checklist can be found in Appendix 7-D.

A Damage Mechanism checklist is used to verify the process design and procedures take into account how the various damage mechanisms (i.e. corrosion, erosion, etc.) affect the equipment. An example Damage Mechanism checklist can be found in Appendix 7-E.

8 Example PHA(s)

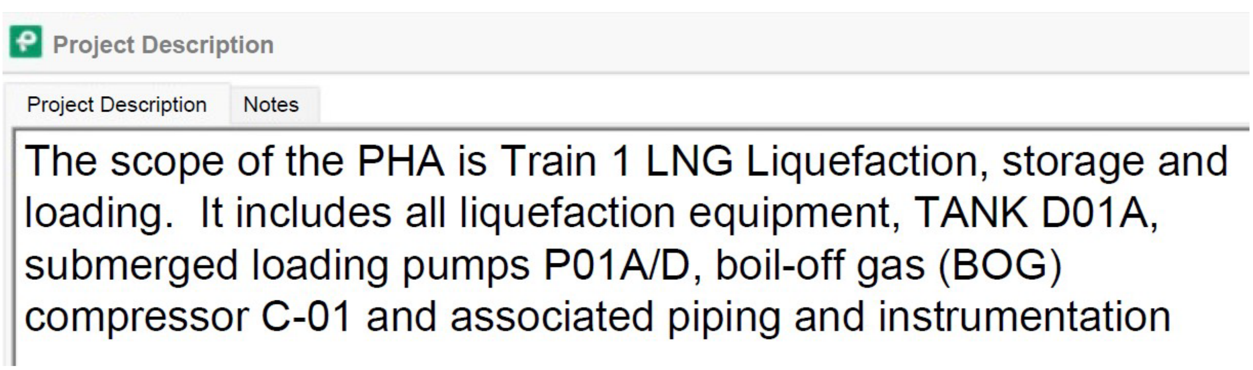
This section describes in detail the steps in conducting HAZOP and LOPA. These methodologies were used as an example, but the identification of initiating events, causes, consequences and risk ranking apply to other methodologies independent of how “deviations” or “initiating events” are identified. Appendix 8-A includes an example HAZOP/LOPA PHA with example P&IDs.

This section uses a software tool to conduct a HAZOP. In the design of a large LNG plant, the PHA is often contracted to an engineering consulting firm that has this software. However, the software is not required to perform a PHA for small upgrade projects or to support a management of change (MOC). The PHA Leader should determine the best way to record the PHA proceedings and recommendations.

Steps in conducting a HAZOP:

- Divide the process into study sections or “nodes” based on the P&ID’s. See P&ID example in Appendix 8-A – Example PHA
- Define Scope of the PHA as shown in Figure 31.

Figure 31: Project Description



Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Create nodes in the recording software by populating the node descriptions. Doing so will can provide a List of Nodes as shown in Figure 32.

Figure 32: Node List

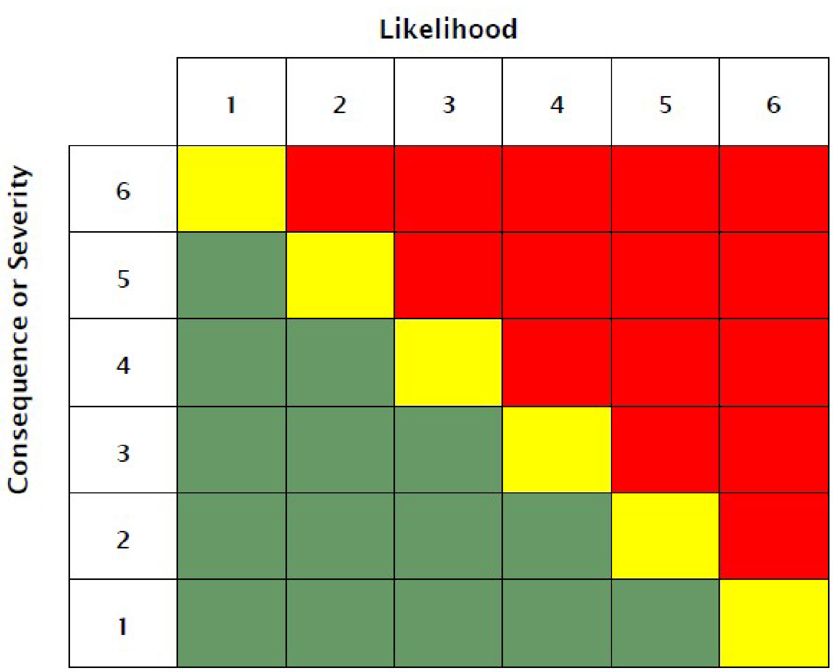
Nodes List

	Node	Description	Template
1	Node 1	Storage Tank D-01A and associated equipment	HAZOP
2	Node 2	LNG feed line from liquefaction to storage	HAZOP

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Clearly highlight each “node” on the P&ID drawings to ensure team members understand what equipment, piping and instrumentation is included
- Ensure the approved Risk Matrix is populated in the software being used. The one being used for this example PHA is shown in Figure 33.

Figure 33: Example Risk Matrix



Likelihood

Level	Events per Year	Impact
1	10-4 to 10-5/yr	Likely to occur less than once per 10,000 years
2	10-3 to 10-4/yr	Likely to occur less than once per 1000 years to once in 10,000 years
3	10-2 to 10-3/yr	Likely to occur between once in 100 up to once in 1000 years
4	10-1 to 10-2/yr	Likely to occur between once in 10 up to once in 100 years
5	1/yr to 10-1/yr	Likely to occur between once a year up to once in 10 years
6	>1/yr	Likely to occur once a year or more

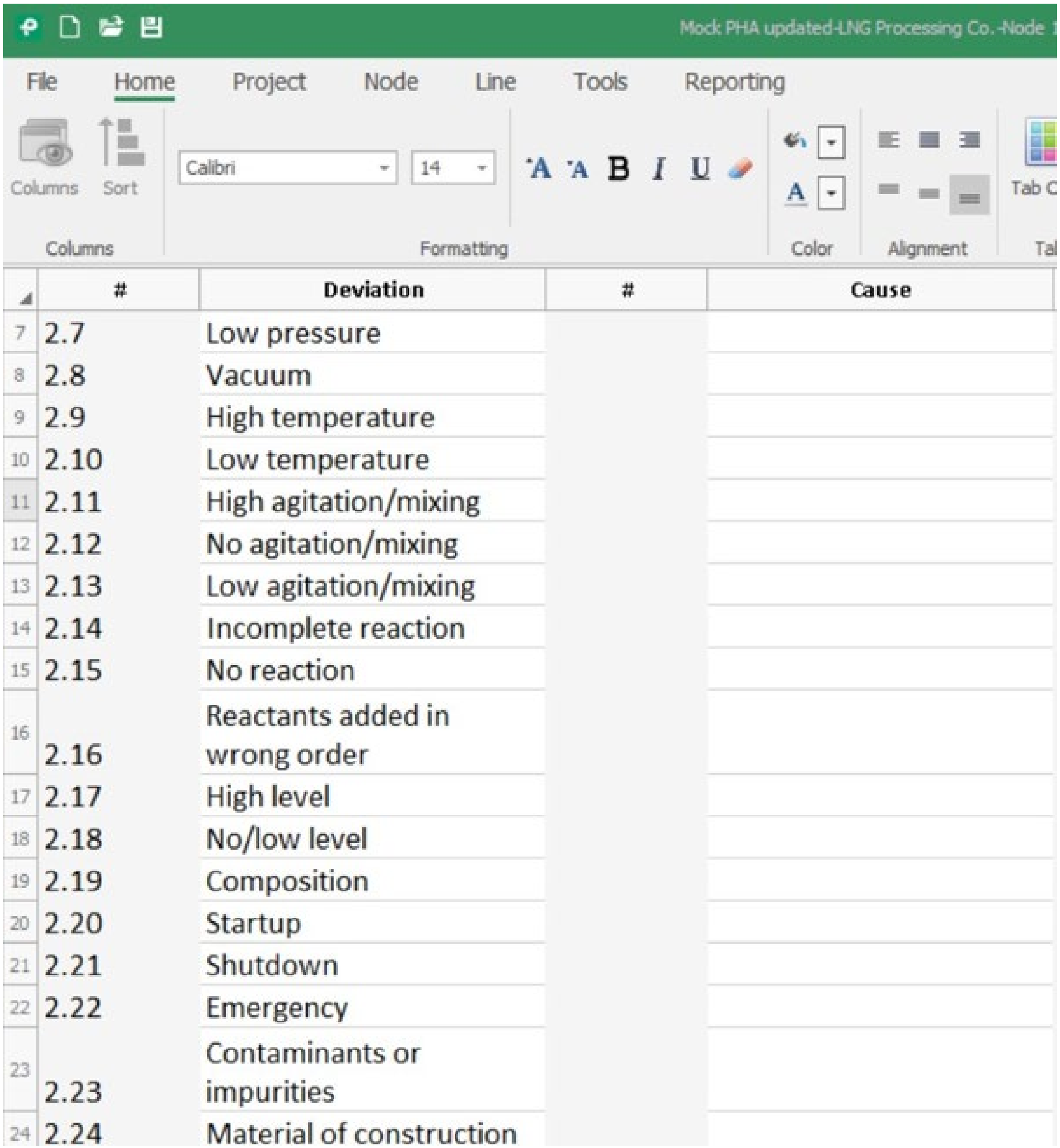
Consequence or Severity

Level	Target Frequency	Safety Criteria	Public Criteria	Environment Criteria	Business Interruption
6	1E-06	Multiple fatalities	Single fatality	An event that triggers a class action lawsuit by a third party	Plant damage/loss over $50 Million
5	1E-05	Single fatality	Irreversible injury	An environmental incident with significant local or national media attention	Plant damage/loss $1Million - $50 Million
4	0.0001	Irreversible injury	Public hospitalization	Remediation of soil off-site, or contaminates sediments, or ground or surface waters outside of site boundaries	Plant damage/loss value in excess of $1,000,000
3	0.001	Multiple lost work injuries	Public evacuation	An environmental incident which could contaminate ground water in immediate area around the site. Incident affecting public or downstream water users	Plant damage/loss value in excess of $500,000 to $1,000,000
2	0.01	Lost work time	Public shelter in place	An environmental incident where contamination is confined to the site and where recovery is complete in 1 year	-Installation seriously damaged/ production is temporarily stopped -Financial losses between $100,000 to $500,000
1	0.1	Reportable injury	No effects	A one time event, little or no WEC fine <25,000 MT of CO2 equivalent methane per year	Limited Damages, Financial Losses $10,000 to $100,000

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Complete the nodes in the software by prepopulating the initial deviations that will be discussed for each node. Enter these in the appropriate column of the worksheet as shown in Figure 34

Figure 34: Node Deviations



	#	Deviation	#	Cause
7	2.7	Low pressure		
8	2.8	Vacuum		
9	2.9	High temperature		
10	2.10	Low temperature		
11	2.11	High agitation/mixing		
12	2.12	No agitation/mixing		
13	2.13	Low agitation/mixing		
14	2.14	Incomplete reaction		
15	2.15	No reaction		
16	2.16	Reactants added in wrong order		
17	2.17	High level		
18	2.18	No/low level		
19	2.19	Composition		
20	2.20	Startup		
21	2.21	Shutdown		
22	2.22	Emergency		
23	2.23	Contaminants or impurities		
24	2.24	Material of construction		

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Populate the software with the team members that will be attending the PHA meetings, and their roles, as shown in Figure 35.

Figure 35: Team Members

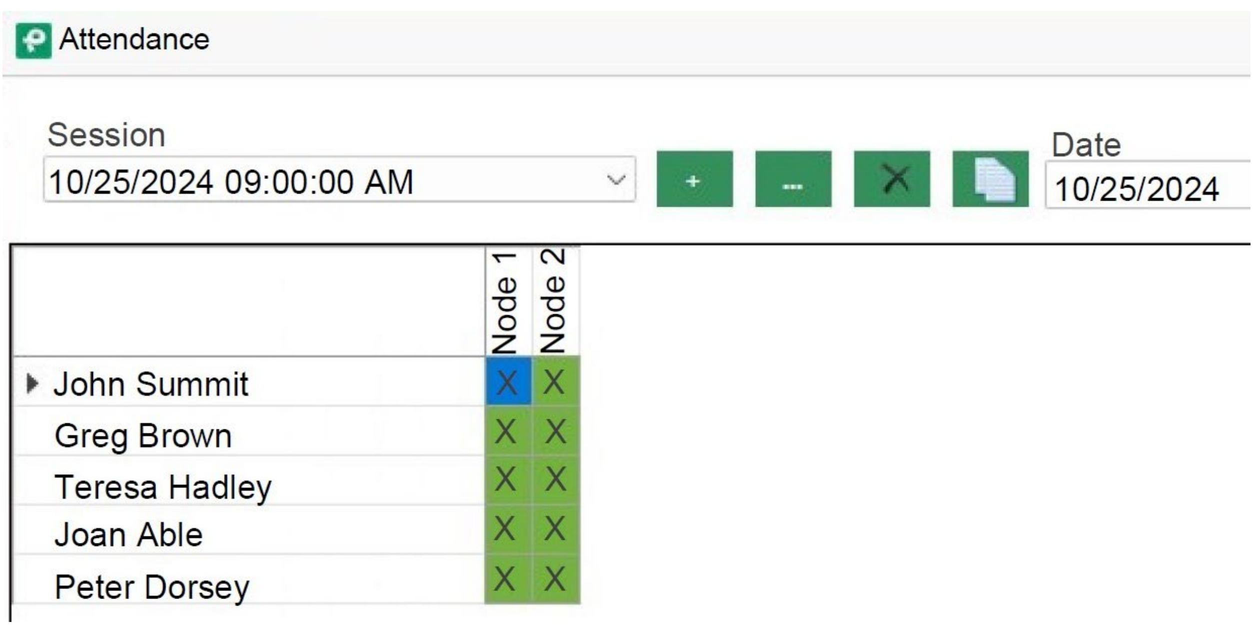
Team

	Name	Role	Company
1	John Smith	Process Engineer	LNG Processing Co.
2	Greg Brown	Maintenance Mechanic	LNG Processing Co.
3	Teresa Hadley	Production Operator	LNG Processing Co.
4	Joan Able	EHS Manager	LNG Processing Co.
5	Peter Dorsey	PHA Leader/scribe	A&Z Consulting
6			

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Review the methodology steps and the Risk Matrix to be used with the PHA Team
- Create a session for the day of study and populate the attendance list tab with team members attending, as shown in Figure 36

Figure 36: Team Attendance

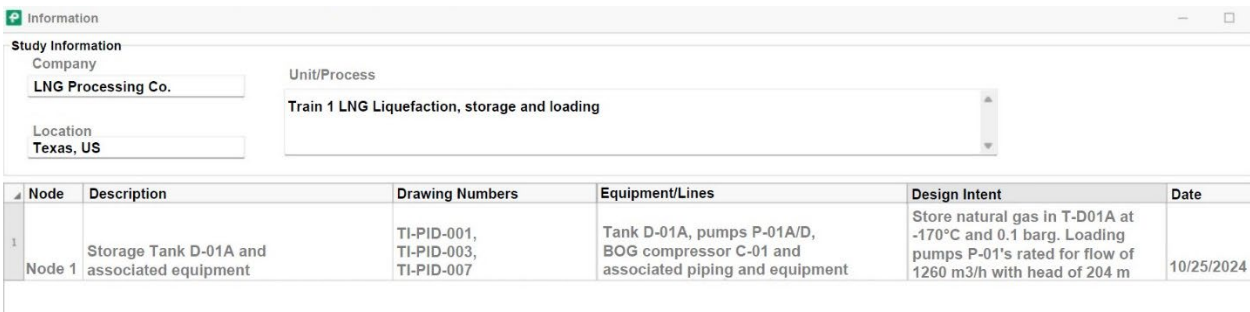


Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- For each node:
    - Review node boundaries with the team
    - Describe “node design Intention” identifying equipment items included, P&ID’s process intent, and normal operating conditions such as flow, temperature, and

pressure. Add the date the node is reviewed. The node intention for one of the nodes is shown in Figure 37

Figure 37: Node Intention



Information

Study Information

Company: LNG Processing Co.

Location: Texas, US

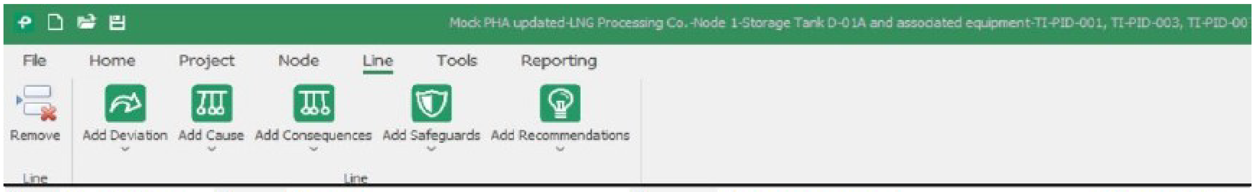
Unit/Process: Train 1 LNG Liquefaction, storage and loading

Node	Description	Drawing Numbers	Equipment/Lines	Design Intent	Date
Node 1	Storage Tank D-01A and associated equipment	TI-PID-001, TI-PID-003, TI-PID-007	Tank D-01A, pumps P-01A/D, BOG compressor C-01 and associated piping and equipment	Store natural gas in T-D01A at -170°C and 0.1 barg. Loading pumps P-01's rated for flow of 1260 m3/h with head of 204 m	10/25/2024

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Start with the first deviation and ask the team to identify all possible causes (initiating events) of that deviation that are in the node boundaries. Enter the causes in the next column of the spreadsheet. Only causes that can be initiated in the node being analyzed should be discussed at this time.
- For each cause identify possible consequences if the initiating event occurs. There may be more than one consequence for each cause (i.e. loss of containment with ignition, loss of containment without ignition) as shown in Figure 38. Consequences identified could be anywhere in the process scope not just in the equipment of the node being reviewed. **NOTE: Consequences are identified assuming there are no safeguards in place to prevent or mitigate the event.**

Figure 38: Causes and Consequences



#	Deviation	#	Cause	#	Consequences	Cons Cat
1.1	Vacuum	1.1.1	BOG (boil-off gas) compressor C-01 failure during loading	1.1.1.1	Vacuum and collapse of inner tank resulting with possible fire in outer tank with casualties	S
1.2	Composition	1.2.1	LNG composition change due to liquefaction process operation outside of specified parameters	1.2.1.1	Tank rollover with rapid vapor generation overwhelming of boil-off system capacity resulting in overpressure and tank damage a large vapor cloud release	E
				1.2.1.2	Tank rollover with rapid vapor generation overwhelming of boil-off system capacity resulting in overpressure and a large vapor cloud release from PSV-002's with flash fire and possible fatality	S
				1.2.1.3	Tank rollover with rapid vapor generation overwhelming of boil-off system capacity resulting in overpressure and tank damage a large vapor cloud release with multiple fatalities	S
		1.2.2	LNG composition change in tank due to unloading of denser material due to boil-off during transit	1.2.2.1	Tank rollover with rapid vapor generation overwhelming of boil-off system capacity resulting in overpressure and tank damage a large vapor cloud release	E

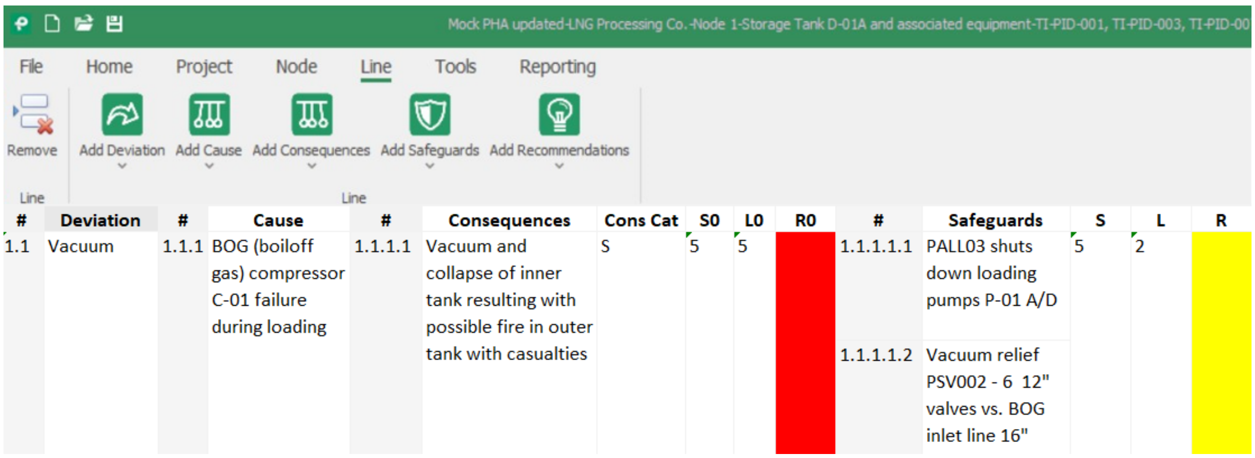
Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- For each cause-consequence pair:
  - Risk rank without taking credit for any safeguards
  - Identify safeguards that apply to the scenario. Ensure that multiple safeguards identified are independent of the cause and each other
  - Risk rank the scenario taking credit for safeguards – during the high level study the safeguard credits are typically accounted for by decreasing

likelihood levels by 1 or 2 orders of magnitude depending on the safeguards as shown in Figure 39

- Based on the risk matrix being used, determine if the risk is acceptable. In the example shown in Figure 39, matrix the Red color in the risk column means the risk remains not tolerable. For our example, the Green color means the risk meets the risk criteria while the Yellow color is ALARP

Figure 39: Safeguards and Risk Ranking

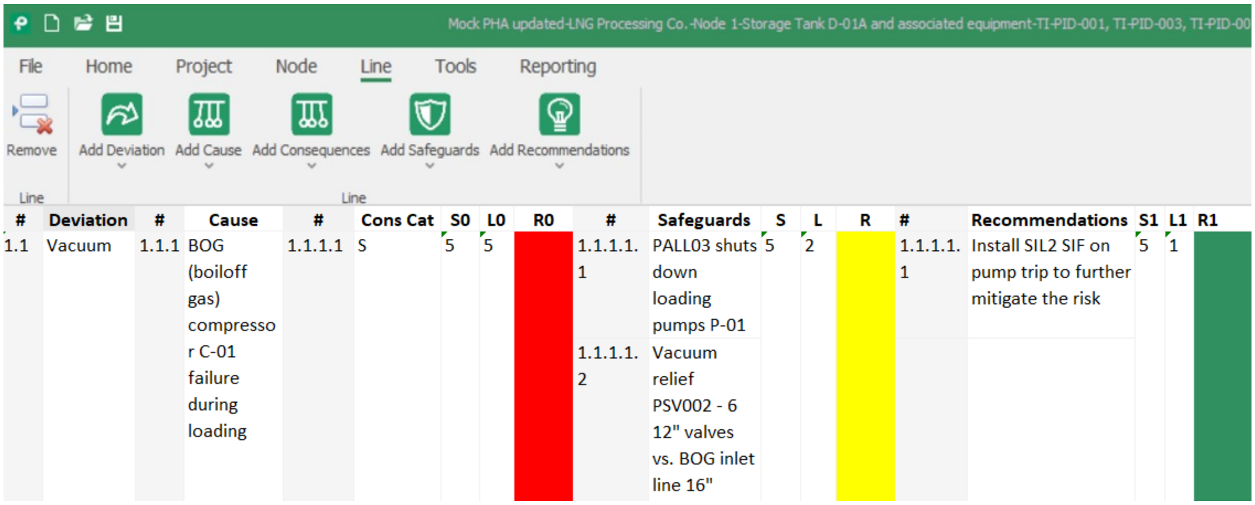


#	Deviation	#	Cause	#	Consequences	Cons Cat	S0	L0	R0	#	Safeguards	S	L	R
1.1	Vacuum	1.1.1	BOG (boiloff gas) compressor C-01 failure during loading	1.1.1.1	Vacuum and collapse of inner tank resulting with possible fire in outer tank with casualties	S	5	5		1.1.1.1.1	PALL03 shuts down loading pumps P-01 A/D	5	2	
										1.1.1.1.2	Vacuum relief PSV002 - 6 12" valves vs. BOG inlet line 16"			

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Make recommendations to lower the risk, if needed, as shown in Figure 40
- Finally, risk rank the scenario taking credit for the recommended safeguards assuming they will be implemented

Figure 40: Recommendations



#	Deviation	#	Cause	#	Cons Cat	S0	L0	R0	#	Safeguards	S	L	R	#	Recommendations	S1	L1	R1
1.1	Vacuum	1.1.1	BOG (boiloff gas) compressor C-01 failure during loading	1.1.1.1	S	5	5		1.1.1.1.1	PALL03 shuts down loading pumps P-01	5	2		1.1.1.1.1	Install SIL2 SIF on pump trip to further mitigate the risk	5	1	
									1.1.1.1.2	Vacuum relief PSV002 - 6 12" valves vs. BOG inlet line 16"								

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

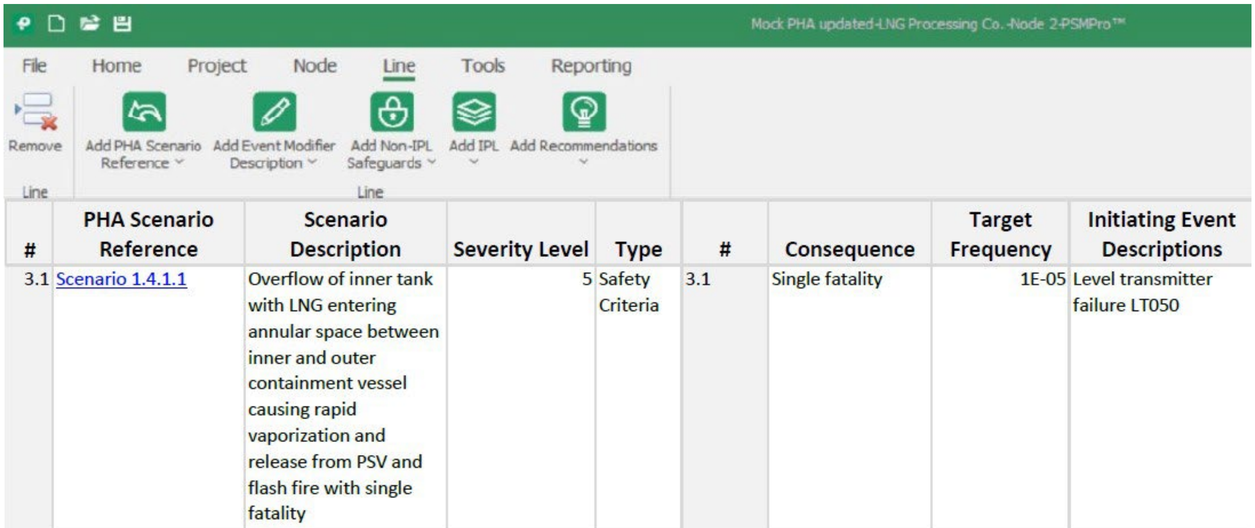
- Repeat for all deviations
- Brainstorm additional deviations that need to be reviewed

- Repeat for all nodes

Steps for conducting a LOPA:

- Select a single cause-consequence pair. See Figure 41, where this has been done by reference to the previous PHA.
- Enter consequence and cause (initiating event) in appropriate columns
- Enter consequence severity ranking
- Based on the Risk Matrix value of the scenario target tolerability frequency for the identified consequence severity will be automatically populated in the typical hazard analysis software

Figure 41: Scenario and Target Frequency



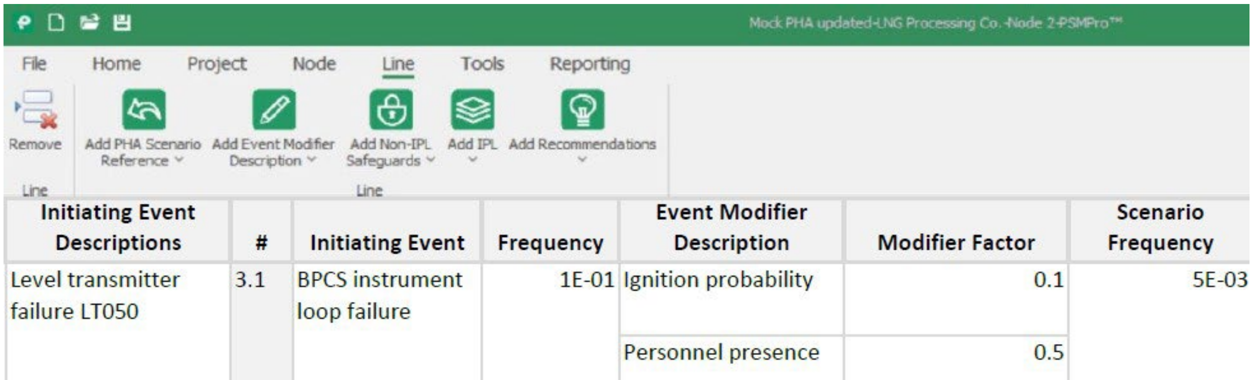
#	PHA Scenario Reference	Scenario Description	Severity Level	Type	#	Consequence	Target Frequency	Initiating Event Descriptions
3.1	Scenario 1.4.1.1	Overflow of inner tank with LNG entering annular space between inner and outer containment vessel causing rapid vaporization and release from PSV and flash fire with single fatality	5	Safety Criteria	3.1	Single fatality	1E-05	Level transmitter failure LT050

*All frequencies in above figure are per year

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Enter initiating event frequency. The data entry continues with Figure 42
- Identify any enabling events and enter their probability
- Identify any conditional modifiers and enter their probability
- Calculate the frequency of the scenario including enabling event and conditional modifiers that apply

Figure 42: Enabling Events and Conditional Modifiers Data Entry



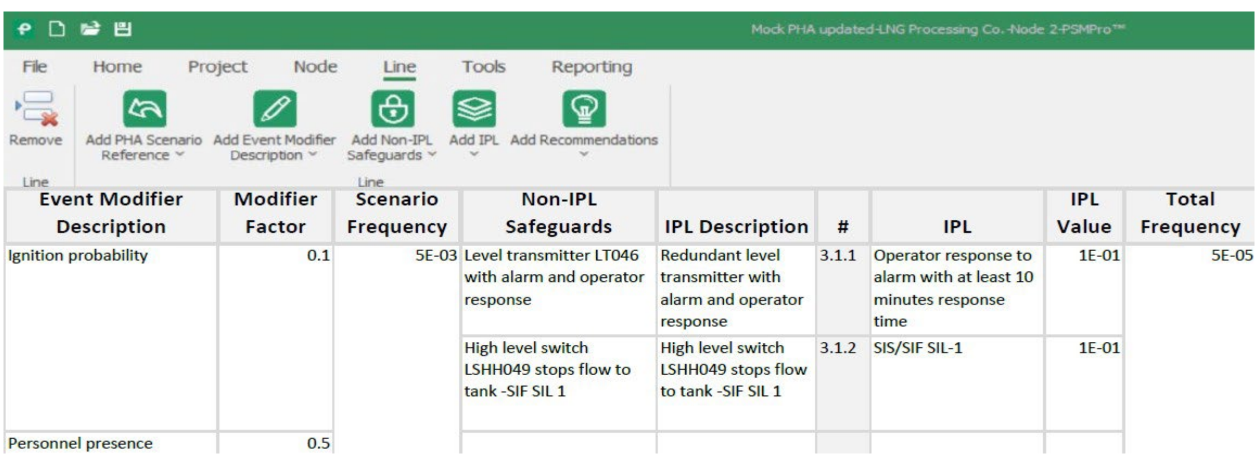
Initiating Event Descriptions	#	Initiating Event	Frequency	Event Modifier Description	Modifier Factor	Scenario Frequency
Level transmitter failure LT050	3.1	BPCS instrument loop failure	1E-01	Ignition probability	0.1	5E-03
				Personnel presence	0.5	

All frequencies in above figure are per year.

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Identify existing safeguards
- Determine which safeguards are independent protection layers
- Enter the Probability of Failure on Demand (PFD) for existing IPL's
- Identify any existing SIFs for the scenario
- Enter calculated PFD for existing SIF's
- Calculate the frequency of the scenario including enabling event and conditional modifiers and all IPL's and SIF's as shown in Figure 43

Figure 43: Scenario Frequency After IPL's



Event Modifier Description	Modifier Factor	Scenario Frequency	Non-IPL Safeguards	IPL Description	#	IPL	IPL Value	Total Frequency
Ignition probability	0.1	5E-03	Level transmitter LT046 with alarm and operator response	Redundant level transmitter with alarm and operator response	3.1.1	Operator response to alarm with at least 10 minutes response time	1E-01	5E-05
			High level switch LSHH049 stops flow to tank -SIF SIL 1	High level switch LSHH049 stops flow to tank -SIF SIL 1	3.1.2	SIS/SIF SIL-1	1E-01	
Personnel presence	0.5							

All frequencies in above figure are per year

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

- Compare the final scenario frequency to the target frequency for the consequence
- Evaluate any additional safeguard PFD or SIL credits needed to meet the target frequency
- Develop recommendation(s) to lower the risk of the scenario as shown in Figure 44

Figure 44: Recommendations

IPL Description	#	IPL	IPL Value	Total Frequency	Required SIL	#	Recommendations
Redundant level transmitter with alarm and operator response	2.4.1	Operator response to alarm with at least 10 minutes response time	1E-01	5E-05	1	3.1.1	Replace SIL 1 SIF with SIL2 SIF on inlet line closure to further mitigate the risk
High level switch LSHH049 stops flow to tank -SIF SIL 1	2.4.2	SIS/SIF SIL-1	1E-01				

All frequencies in above figure are per year

Source: Process Safety Office® PSMPro™ - ioMosaic Corporation

9 How to Use PHA Results

After a PHA is conducted, the PHA Team Leader is usually expected to compile a report of the results. A PHA report typically contains at least the following elements:

- Description of the methodology or methodologies used
- The scope of the PHA
- List of the members of the PHA Team and their expertise
- Identification of the PHA Team Leader and their experience/expertise with the methodologies used
- Listing of all risks identified for the area within the scope
- Listing of all risks regarded as Intolerable (red) and Tolerable if ALARP (yellow) even after the application of safeguards and/or IPL within the scope
- Listing of Initial Findings and Recommendations to reduce the identified risks to tolerable and tolerable if ALARP levels
- List of previous incidents which had a likely potential for catastrophic consequences
- List of Engineering Controls used as safeguards or IPL to reduce the risk and the consequences of their failure
- List of Administrative Controls (i.e. Operations and Maintenance written procedures) used as safeguards to reduce the risk and the consequences of their failure
- Listing of risks associated with any check list used during the study
- Listing of risks associated with other methodologies used
- Any other requirements specified by local regulations

Once the PHA Report is completed, the site should have a system for tracking the findings, recommendations as well as the resolution of addressing the recommendations with closure date.

- The findings and recommendations should be reviewed with Site Management
- All of the findings and recommendations need to be entered into a corrective action system
- Each of the findings and recommendations should be assigned to a responsible person
- Each of the findings and recommendations should be assigned a target completion date
- Progress towards completion should be tracked and managed. Completion should be verified to meet the intent of hazard analysis and necessary mitigation.
- Management may also choose to reject a finding or recommendation. The rationale for rejection of a PHA Finding or Recommendation shall be documented and the appropriate

approvals signature(s) obtained. The CCPS has provided the following additional guidance on when rejecting a PHA recommendation might be justified:

- Detailed engineering analysis determines the finding or recommendation is not feasible
- Additional information not available at the PHA indicates the hazard is not as significant
- There is an error in the data, which when corrected, indicates the finding or recommendation is not needed
- Implementation of other PHA recommendations causes another recommendation to no longer be necessary
- The cost of implementing the recommendation is not justified due to the relatively minor risk reduction compared to other recommendations (ALARP)
- A detailed review shows that the hazard risk is now "as low as reasonably practicable" (ALARP)

- Any rejected finding or recommendation should be tracked to completion showing that the risk was mitigated
- Local regulations may have additional requirements. Consult with local authorities

The results of the PHA Report should also be shared with the employees of the site.

10 Summary of Recommendations

10.1 Introduction

The requirements in the current FERC guidance documents focus on addressing loss of containment due to mechanical integrity of piping, equipment, and natural disasters. Many of the design requirements from recognized and generally accepted good engineering practices (RAGAGEPs) are pulled into the regulations by reference such as ASME B31.8S "Managing System Integrity of Gas Pipelines." Very mature equipment failure rates and prescriptive guidance are provided on how sites are to complete quantitative risk analyses for loss of containment, flashfire, and other catastrophic consequences. Those results are provided to FERC as part of the Environmental Report required under the Natural Gas Act. Even with this level of detailed design, the narrow focus of the requirements leaves a large gap for understanding other potential hazards that could surface from design flaws or operational errors.

The existing PHMSA regulation 49 CFR Part 193, which incorporates NFPA 59A (2001 Edition) by reference, is a prescriptive standard. Prescriptive standards work well for small plants that have a limited number of processes (e.g. LNG liquefaction, LNG storage and LNG loading). Performance-based standards like the OSHA Process Safety Management Standard (PSM) are used where multiple processes, complex processes and large plants make writing a prescriptive set of regulations infeasible. According to communication with PHMSA, industry feedback, based on Process Safety Analyses conducted, indicate that the 49 CFR Part 193 regulation does not provide full safety review coverage for large scale LNG facilities.

10.2 Recommendations for PHMSA

Recommendations for PHMSA include the following:

10.2.1 PHMSA Recommendation #1

It is recommended for PHMSA to consider adding the following requirement to 49 CFR Part 193:

29 CFR 1910.119 Process Safety Management is adopted by reference for LNG plants that meet specific conditions … [ex. process exceeds selected threshold quantities, proximity to other facilities, etc.]

19 USC 60102(b)(5) Secretarial decision making, sets a high barrier for new regulations by stating: "Except where otherwise required by statute, the Secretary shall propose or issue a standard under this chapter only upon a reasoned determination that the benefits, including safety and environmental benefits, of the intended standard justify its costs."

However, since the safety record for the industry has been historically good, there has not been large numbers of fatalities, millions of dollars of commercial damage, or millions of dollars of environmental damage to justify additional regulation.

10.2.2 PHMSA Recommendation #2

In lieu of PHMSA Recommendation #1 above, it is recommended for PHMSA to consider renegotiating their Memorandum of Understanding (MOU) with OSHA which currently exempts all LNG plants from the 29 CFR §1910.119 regulation. A revised MOU could eliminate the PSM exemption for LNG facilities built prior to March 31, 2000, that are currently exempted by 49 CFR §193.2005(b) from many of the Part 193 provisions.

10.2.3 PHMSA Recommendation #3

It is well known that loss of containment within the LNG industry can be catastrophic. As the infrastructure within the LNG industry ages, the risk of failure from older equipment will naturally increase. PHA revalidations would allow this risk to be mitigated as the initial evaluations would be revised to account for the aging infrastructure. This report outlines how the use of PHAs could be extensively expanded to further prevent incidents from multiple initiating events. It is important for a thorough PHA to assess the risks of deviations well beyond mechanical failure. It is recommended for PHMSA to consider reaching out to the NFPA Technical Committee on Liquefied Natural Gas (the committee responsible for NFPA 59A) to consider adopting the standards for PHAs, including LOPAs and QRAs, from the Center for Chemical Process Safety (CCPS) publications, including:

- Guidelines for Hazard Evaluation Procedures
- Guidelines for Chemical Process Quantitative Risk Analysis
- Guidelines for Initiating Events and Independent Protection Layers in Layer of Protection Analysis
- Guidelines for Initiating Enabling Conditions and Conditional Modifiers in LOPA

10.2.4 PHMSA Recommendation #4

It is recommended that PHMSA consider amending 49 CFR Part 93 through the adoption of NFPA 59A Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG) 2023, and more specifically, Chapter 19, Performance-Based LNG Plant Siting Using Quantitative Risk Analysis (QRA) to bring the regulation up to current industry standards.

10.3 Recommendations for Industry

Below is a list of key recommendations for industry consideration:

10.3.1 Industry Recommendation #1

It is well known that loss of containment within the LNG industry can be catastrophic. As the infrastructure within the LNG industry ages, the risk of failure from older equipment will naturally increase. PHA revalidations would allow this risk to be mitigated as the initial evaluations would be revised to account for the aging infrastructure. This report outlines how the use of PHAs could be extensively expanded to further prevent incidents from multiple initiating events. It is important for a thorough PHA to assess the risks of deviations well beyond mechanical failure. It is recommended for the NFPA Technical Committee on Liquefied Natural Gas to consider including a chapter on PHAs into NFPA 59A. The committee could also consider making the following PHA standards from the Center for Chemical Process Safety (CCPS), including LOPAs and QRAs, , into referenced publications, some of which are already included as informational references:

- Guidelines for Hazard Evaluation Procedures
- Guidelines for Chemical Process Quantitative Risk Analysis
- Guidelines for Initiating Events and Independent Protection Layers in Layer of Protection Analysis
- Guidelines for Initiating Enabling Conditions and Conditional Modifiers in LOPA

10.3.2 Industry Recommendation #2

An expanded risk assessment is very important during Front End Engineering Design (FEED) of a new facility, and during start up, normal operation and decommissioning of existing operations. See section 6 - Recommended Techniques by Stage. It is recommended for industry to consider starting the detailed risk assessment process during Front End Engineering Design as outlined in section 6 of this report. It has high potential to save investment funds and drive inherent safer decisions for the LNG industry. This will not only ensure lower risks to operators, it will also lower risks to the communities and environments these facilities reside in.

- Initiating detailed risk assessments during the early FEED stages will enable identification of Inherent Safer Designs (ISD) (see Section 4.3 PHA Techniques - Inherent Safer Design). ISD assessments will help the industry continue to reduce hazards at all new facilities, future expansions, and existing facilities. Two key publications to reference for risk assessment during the FEED stage are as follows:
  - CCPS Guidelines for Inherently Safer Chemical Processes: A Life Cycle Approach
  - CCPS Guidelines for Integrating Process Safety into Engineering Projects

10.3.3 Industry Recommendation #3

The guidance for the PHAs in this report (see section 4 PHA Techniques) is based on a long history of success with the methodologies that are universally utilized in many other industries, most notably the Chemical and Petroleum industries. More details on PHAs are readily available with the multiple CCPS publications. Most notable is the previously mentioned. "Guidelines for Hazard Evaluation Procedures". A true life-cycle PHA is an iterative process. It is recommended for industry to begin utilizing these recognized methodologies at the different life cycle stages of an LNG Facility.

10.3.4 Industry Recommendation #4

It is recommended for industry to adopt the HAZOP methodology to be the cornerstone for conducting PHAs on high hazard facilities such as LNG. As noted above, the PHA guidance provided in this report is based on current best industry practices. The most universally accepted and applied PHA technique is the Hazard and Operability (HAZOP) study (see section 4.7). It is a process design and operation deviation analysis conducted by a multidisciplinary team. It can be applied to the range of project life-cycle stages. For the conceptual project stage, a modified format referred to as Hazard Identification (HAZID) (see section 4.2) is often used. It applies the same principles but does not carry out the analysis as far due to the preliminary nature of the project information at that stage. See section 8 – Example PHAs for an example.

10.3.5 Industry Recommendation #5

A variety of PHA methodologies at the different life cycle stages is beneficial to help identify additional design gaps. These gaps in design will be uncovered with the synergy of multiple methodologies. It will be inclusive of items such as instrumentation failures, human factors, facility siting and other potential detailed design flaws. Not only will this prevent incidents, but it will also be a more cost-effective way to ensure a proper design is employed as noted in Figure 28. It is recommended that industry adopt the use of multiple PHA methodologies at the different life cycle stages of each facility.

10.3.6 Industry Recommendation #6

It is recommended for industry to consider adopting a management of change (MOC) philosophy into operations. This process is best initiated once the final design is locked (after the FEED stage is completed). Once the final design is locked, any additional changes made during construction or start-up should be reviewed using the MOC process.

Once startup of operation occurs, the management of change PHA files would only need to be maintained until the next PHA revalidation occurs and they are incorporated into the revalidation

PHA, irrespective of the methodology used. Process safety information derived from the MOC would be maintained.

10.3.7 Industry Recommendation #7

It is recommended for industry to consider a five (5) year revalidation PHA for all LNG operating facilities, similar to other industries handling hazardous materials.

10.3.8 Industry Recommendation #8

It is recommended for industry to consider adopting a tracking system for their PHA recommendations. It is critical to track every recommendation from a PHA with full documentation to understand how each recommendation is addressed or closed.

10.4 Recommendations for Future PHMSA Funded Studies

Below is a list of key recommendations for areas for further research:

10.4.1 Research Recommendation #1

It is recommended that PHMSA fund a study to create a set of pre-populated checklists. These could be used by both PHMSA and industry to evaluate completeness of a PHA for various processes within the LNG industry.

10.4.2 Research Recommendation #2

It is recommended that PHMSA fund a study to create a set of generic PHA/LOPA documentation packages for three types of small LNG facilities: an LNG compression facility, an LNG storage facility and an LNG peak shaving facility. These packages could be a modification of, or an addition to, the "Gusher LNG" document package currently used by the PHMSA Training and Qualification Center. These packages could be used for four specific purposes:

- The documentation package could be used by PHMSA to review the prescriptive 49 CFR 193 regulation and the NFPA 59A standard for safety gaps
- The documentation package could be used by small LNG plants as a model and provide encouragement for completing a PHA for their specific sites
- The generic list of risks and consequences from the documentation package could be directly used by small LNG plants to initiate internal risk and consequence discussions, even if the facilities choose not to create a PHA for their specific sites
- The documentation package could be used as training documents by the PHMSA Training and Qualification Center

10.4.3 Research Recommendation #3

It is recommended that PHMSA fund a study to review the prescriptive 49 CFR 193 regulation and the NFPA 59A standard against the PHA/LOPA generic models to identify any safety gaps not currently covered by the regulation. Part of this study would determine the boundary between small, simple LNG plants that are adequately covered by the Part 193 regulation and the larger facilities for which an additional PHA/LOPA might be recommended.

10.4.4 Research Recommendation #4

It is recommended that PHMSA fund an initiative to provide a variety of newly developed prepopulated "Checklists" for the use by PHMSA and industry (see section 4.5). These can be easily developed based on the depth of industry knowledge and experience that already exists. Each LNG operation could utilize design, human factors, maintenance, and reliability, as well as Pre-Start Up Safety Review checklists to ensure all items that should be considered in design, startup and continued operation have been addressed.

10.5 Impact from the Research Results

As noted in Section 1.1 Background, the United States of America is critically dependent on natural gas and petroleum liquids transported through pipelines. The infrastructure that currently transports these energy resources is aging, with a significant fraction being more than fifty years old. As the LNG infrastructure ages, it is prudent to look forward and evaluate the risk of continued usage of the pipelines and LNG handling equipment. Assuring the long-term integrity and security of this existing infrastructure is essential. It is well known that loss of containment within the LNG industry can be catastrophic. As the infrastructure within the LNG industry ages, the risk of failure from older equipment will naturally increase. PHA revalidations would allow this risk to be mitigated as the initial evaluations would be revised to account for the aging infrastructure. This report outlines how the use of PHAs could be extensively expanded to further prevent incidents from multiple initiating events.

The research from this project is expected to provide PHMSA with an opportunity for consensus standards strengthening. By working with NFPA and other industry associations, standards such as NFPA 59A can be strengthen.

The research gives auditors tools to check PHAs of LNG facilities to confirm that they are following RAGAGEP. These tools include: Failure frequencies, conditional modifiers, independent layers of protection, and quantitative safety analysis criteria.

11 Final Financials

The project prices for each activity/deliverable, both federal and cost-sharing of items, were considered fixed price. The original Technical and Deliverable Milestone Schedule from Agreement #693JK32310005POTA is shown in Table 23. The actual project schedule is shown in Table 24. A final Project financial report that summarizes the status of Government and Team contributions for the Project and reconciles any prior discrepancies or variances in contributions is provided in Table 25.

Table 23: Milestone Schedule

Technical and Deliverable Milestone Schedule								
Item No	Task No (per proposal)	Activity/Deliverable	Quarter No.	Expected Completion Date/Mos	Payable Milestone	Federal Payment	Resource-Share	-
1	1	Project discussion with PHMSA / TAP to see addition input	1	1 month	Submit Discussion Results Meeting Minutes	20,000.00	4,000.00	24,000.00
2	2	Kickoff Meeting	2	1 month	Submit Kickoff Meeting Minutes	4,400.00	880	5,280.00
		First Payable Milestone	1	1 month	SUBTOTAL	24,000.00	4,880.00	29,280.00
3	3	Literature Review	1	3 months	Provide Interim Report summarizing literature reviewed and conclusions drawn	57,600.00	11,520.00	69,120.00
4	8	First Quarterly Status Report	1	3 months	Submit 1st quarterly report	12,000.00	2,400.00	14,400.00
		Second Payable Milestone	2	3 months	SUBTOTAL	69,600.00	13,920.00	83,520.00
5	4	Identification of Process Hazard Analysis Techniques	3	6 months	Provide interim report summarizing each PHA methodology, strengths and weaknesses, and	57,600.00	11,520.00	69,120.00
6	8	Second Quarterly Status Report	3	6 months	Submit 2nd quarterly report	12,000.00	2,400.00	14,400.00

Technical and Deliverable Milestone Schedule								
Item No	Task No (per proposal)	Activity/Deliverable	Quarter No.	Expected Completion Date/Mos	Payable Milestone	Federal Payment	Resource-Share	-
		Third Payable Milestone	3	6 months	SUBTOTAL	69,600.00	13,920.00	83,520.00
7	5	Develop Criteria and Methodologies for Conducting PHAs	3	9 months	a. Provide interim report summarizing the key components comprising any type of PHA b. Development of checklists specific to LNG facilities (Facility Siting, Human Factors, Maintainability Review, Facility and Process Modification, Damage Mechanism Review) c. Development of list of typical hazard scenarios related to LNG production, storage and transportation d. Development of list of failure frequencies /probabilities and conditional modifiers specific to the LNG industry	57,600.00	11,520.00	69,120.00
8	8	Third Quarterly Status Report	3	9 months	Submit 3rd quarterly report	12,000.00	2,400.00	14,400.00
		Fourth Payable Milestone	4	9 months	SUBTOTAL	69,600.00	13,920.00	83,520.00
9	9	Prepare and submit Draft and Technical Project Report	4	12 months	Draft Technical Project Report	57,600.00	11,520.00	69,120.00
10	8	Fourth Quarterly Status Report	4	12 months	Submit 4th Quarterly report	12,000.00	2,400.00	14,400.00
		Fifth Payable Milestone	5	12 months	SUBTOTAL	69,600.00	13,920.00	83,520.00
11**	11	Prepare & Present Paper at public event or publish paper in journal/magazine	N/A	N/A	Prepare & Present Paper at public event or publish paper in journal/magazine	0	TBD	0
12***	10	Final Dissemination Meeting	N/A	N/A	Final Dissemination Meeting	0	TBD	0
13****	9	Address Comments and Submit Final Report	N/A	12 months	Submit final report	0	TBD	0

Technical and Deliverable Milestone Schedule								
Item No	Task No (per proposal)	Activity/Deliverable	Quarter No.	Expected Completion Date/Mos	Payable Milestone	Federal Payment	Resource-Share	-
14*****	9	Public Version of Final Report	N/A	N/A	Submit public version of final report	0	TBD	0
					SUBTOTAL	0	0	0
					GRAND TOTALS	302,800.00	60,560.00	363,360.00

Notes:
* The Draft Final Report must be submitted 30 days prior to the period of performance end for the project.

** This requirement as described in the Research Announcement will be at zero gov costs but can have associated cost sharing.

*** This requirement as described in the Research Announcement will be at zero gov costs but can have associated cost sharing.

**** The Final Report should be submitted by the project period of performance end. All Final Reports containing no Intellectual Property or Trade Secret information will be publicly posted.

***** A Public Final Report is required when the Final submitted Report contains Intellectual Property or Trade Secret information. It should be submitted as soon as possible after submittal of the Final Report

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Table 24: Actual Schedule

Technical and Deliverable Actual Schedule									
Item No	Task No (per proposal)	Activity/Deliverable	Quarter No.	Expected Completion Date/Mos	Actual Completion Date/Mos	Actual Payable Milestone	Federal Payment	Resource-Share	-
1	1	Project discussion with PHMSA / TAP to see addition input	1	1 month	3 months	Submit Discussion Results Meeting Minutes	20,000.00	4,000.00	24,000.00
		First Payable Milestone	1	1 month	3 months	SUBTOTAL	20,000.00	4,000.00	24,000.00
2	2	Kickoff Meeting	2	1 month	4 months	Submit Kickoff Meeting Minutes	4,400.00	880	5,280.00
3	3	Literature Review	1	3 months	6 months	Provide Interim Report summarizing literature reviewed and conclusions drawn	57,600.00	11,520.00	69,120.00
4	8	First Quarterly Status Report	1	3 months	3½ months	Submit 1st quarterly report	12,000.00	2,400.00	14,400.00
		Second Payable Milestone	2	3 months	6 months	SUBTOTAL	74,000.00	14,800.00	88,800.00
6	8	Second Quarterly Status Report	3	6 months	6 months	Submit 2nd quarterly report	12,000.00	2,400.00	14,400.00
		Third Payable Milestone	3	6 months	9 months	SUBTOTAL	12,000.00	2,400.00	14,400.00
5	4	Identification of Process Hazard Analysis Techniques	3	6 months	9½ months	Provide interim report summarizing each PHA methodology, strengths and weaknesses, and	57,600.00	11,520.00	69,120.00

Technical and Deliverable Actual Schedule									
Item No	Task No (per proposal)	Activity/Deliverable	Quarter No.	Expected Completion Date/Mos	Actual Completion Date/Mos	Actual Payable Milestone	Federal Payment	Resource-Share	-
7	5	Develop Criteria and Methodologies for Conducting PHAs	3	9 months	9½ months	a. Provide interim report summarizing the key components comprising any type of PHA b. Development of checklists specific to LNG facilities (Facility Siting, Human Factors, Maintainability Review, Facility and Process Modification, Damage Mechanism Review) c. Development of list of typical hazard scenarios related to LNG production, storage and transportation d. Development of list of failure frequencies /probabilities and conditional modifiers specific to the LNG industry	57,600.00	11,520.00	69,120.00
8	8	Third Quarterly Status Report	3	9 months	9 months	Submit 3rd quarterly report	12,000.00	2,400.00	14,400.00
		Fourth Payable Milestone	4	9 months	12 months	SUBTOTAL	127,200.00	25,440.00	152,640.00
9	9	Prepare and submit Draft and Technical Project Report	4	12 months******	13 months	Draft Technical Project Report	57,600.00	11,520.00	69,120.00
10	8	Fourth Quarterly Status Report	4	12 months	12 months	Submit 4th Quarterly report	12,000.00	2,400.00	14,400.00
		Fifth Payable Milestone	5	12 months******	13 months	SUBTOTAL	69,600.00	13,920.00	83,520.00
11**	11	Prepare & Present Paper at public event or publish paper in journal/magazine	N/A	N/A		Prepare & Present Paper at public event or publish paper in journal/magazine	0	TBD	0
12***	10	Final Dissemination Meeting	N/A	N/A		Final Dissemination Meeting	0	TBD	0
13****	9	Address Comments and Submit Final Report	N/A	12 months		Submit final report	0	TBD	0
14*****	9	Public Version of Final Report	N/A	N/A		Submit public version of final report	0	TBD	0

Technical and Deliverable Actual Schedule									
Item No	Task No (per proposal)	Activity/Deliverable	Quarter No.	Expected Completion Date/Mos	Actual Completion Date/Mos	Actual Payable Milestone	Federal Payment	Resource-Share	-
						SUBTOTAL	0	0	0
						GRAND TOTALS	302,800.00	60,560.00	363,360.00

Notes:

* The Draft Final Report must be submitted 30 days prior to the period of performance end for the project.

** This requirement as described in the Research Announcement will be at zero gov costs but can have associated cost sharing.

*** This requirement as described in the Research Announcement will be at zero gov costs but can have associated cost sharing.

**** The Final Report should be submitted by the project period of performance end. All Final Reports containing no Intellectual Property or Trade Secret information will be publicly posted.

***** A Public Final Report is required when the Final submitted Report contains Intellectual Property or Trade Secret information. It should be submitted as soon as possible after submittal of the Final Report

****** On September 17, 2024, Modification 0002 to Award Number 693JK32310005POTA extended the period of performance to October 31, 2024.

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Table 25: Cost Summary Report

Project and Subcases List Summary								
Project #	Type	Status	Time Cost	Expense	Adjustment	Total Cost	Contract	Currency
23215-00	Government	Case	0	0	0	0	0.00	U.S. dollar
23215-01	Government	Case	19,902.50	0	0	19,902.50	19,902.50	U.S. dollar
23215-02	Government	Case	3,732.50	0	0	3,732.50	3,732.50	U.S. dollar
23215-03	Government	Case	66,007.50	1,964.04	0	67,971.54	67,971.54	U.S. dollar
23215-04	Government	Case	4,136.25	0	0	4,136.25	4,136.25	U.S. dollar
23215-05	Government	Case	62,001.25	0	0	62,001.25	62,001.25	U.S. dollar
23215-06	Government	Case	980	0	0	980	980.00	U.S. dollar
23215-07	Government	Case	66,027.50	0	0	66,027.50	66,027.50	U.S. dollar
23215-08	Government	Case	1,041.25	0	0	1,041.25	1,041.25	U.S. dollar
23215-09	Government	Case	132,922.50	0	0	132,922.50	133,279.71	U.S. dollar
23215-10	Government	Case	4287.50	0	0	4287.50	4,287.50	U.S. dollar
23215-11	Government	Case	0	0	0	0	0.00	U.S. dollar
		Total:	351,305.00	1,964.04	0.00	353,269.04	363,360.00	
Project Overrun and Subcases List Summary								
23215-99	Government	Case	25,635.00	0	0	25,635.00	0.00	U.S. dollar
		Total:	351,305.00	1,964.04	0.00	388,637.79	363,360.00	

Notes:

All financial data reported through January 17, 2025.

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Appendix A: Acronyms and Definitions

Appendix A-1: Glossary of Acronyms

AIChE	American Institute of Chemical Engineers
ALARP	As Low as Reasonably Practicable
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
API	American Petroleum Institute
ASQ	American Society for Quality
BLEVE	Boiling Liquid Expanding Vapor Explosion
BOG	Boil-off Gas
BOM	Bill of Materials
BOM	Bureau of Mines
BPCS	Basic Process Control System
BSI	British Standards Institution
CCPS	Center for Chemical Process Safety
CFR	Code of Federal Regulations
CRA	Concept Risk Analysis
CSB	U.S. Chemical Safety and Hazard Investigation Board
DCS	Distributed Control System
DDT	Deflagration-to-Detonation Transition
DOT	The U.S. Department of Transportation
Dow F&E Index	Dow Fire and Explosion Index
EN	European Norma
EPC	Engineering Procurement and Construction
ESD	Emergency Shutdown
ETA	Event Tree Analysis
EPA	Environmental Protection Agency
FEED	Front End Engineering Design
FEL	Front End Loading
FERC	Federal Energy Regulatory Commission
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects, and Criticality Analysis
FSV	Flow Safety Valve/Devices
FTA	Fault Tree Analysis
GIIGNL	International Group of Liquefied Natural Gas Importers
GTI	Gas Technology Institute

HAZOP	Hazard and Operability Study
HC	Hydrocarbon
HEP	Human Error Probability
HEX	Heat Exchanger
HIPPS	High Integrity Pressure Protection System
HIRA	Hazard Identification and Risk Analysis
HPT	Hydrostatic Pressure Testing
HSE	Health and Safety Executive (UK)
IChemE	Institution of Chemical Engineers
ID	Induced Draft
IEC	International Electrotechnical Commission
IEF	Failure Frequencies for Initiating Events
IPL	Independent Protection Layer
ISA	International Society of Automation
ISD	Inherently Safer Design
ISO	International Standardization Organization
KPI	Key Performance Indicator
LEL	Lower Explosive Limit
LFL	Lower Flammable Limit
LNG	Liquefied Natural Gas
LOPA	Layer of Protection Analysis
LP	Low Pressure
LWT	Lost Work Time
MI	Mechanical Integrity
MOC	Management of Change
MOU	Memorandum of Understanding
MRV	Monitor Regulator Valve
NDT	Non-Destructive Testing
NG	Natural Gas
NFPA	National Fire Protection Association
NTSB	National Transportation Safety Board
OPS	PHMSA Office of Pipeline Safety
OREDA	Offshore Reliability Data database
OSHA	The Occupational Safety and Health Administration
P&ID	Piping and Instrumentation Diagram
PCV	Pressure Control Valve
PFD	Process Flow Diagram

PFD	Probability of Failure on Demand
PHA	Process Hazard Analysis
PHMSA	United States Pipeline and Hazardous Materials Safety Administration
PMI	Project Management Institute
PreHA	Preliminary Hazard Analysis
PPE	Personal Protective Equipment
PRV	Pressure Relief Valve
PSI	Process Safety Information
PSM	Process Safety Management
PSSR	Pre-startup Safety Review
PVB	Pressure Vessel Bursts
QC	Quality Control
QRA	Quantitative Risk Analysis/Assessment
R&D	Research and Development
RAGAGEP	Recognized and Generally Accepted Good Engineering Practices
RC	Root Cause
RCA	Root Cause Analysis
RP	Recommended Practice
RPT	Rapid Phase Transition
RTU	Remote Transfer Unit
SCADA	Supervisory Control and Data Acquisition
SCC	Stress Corrosion Cracking
SCD	Safety Critical Device
SDD	Shut Down Device
SDV	Shut Down Valve
SIF	Safety Instrumented Function
SIGGTO	Society of International Gas Tanker and Terminal Operators
SIL	Safety Integrity Level
SIS	Safety Instrumented System
SMYS	Specified Minimum Yield Strength
UNGS	Underground Natural Gas/Hydrogen Storage
UPS	Uninterruptible Power Supply
USACE	U.S. Army Corps of Engineers
UVCE	Unconfined Vapor Cloud Explosion
VCE	Vapor Cloud Explosion
WEC	Waste Emission Charge

Appendix A-2: Definitions

MSCF	Thousand standard cubic feet
MT	Metric Tons
Node	A section of the process where a physical of chemical change occurs.

Appendix Section 3-A: Bibliography / Literature Reviewed

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
CCPS Process Safety in Upstream Oil and Gas	Yes	N/R				
CCPS Guidelines for Revalidating a Process Hazard Analysis, 2nd Edition	Yes	4	No	Yes	Yes	
Occupational Safety and Health Administration (OSHA) 29 CFR §1910.119	Yes	N/R				
NFPA 59A – Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG) – 2023	Yes	3	No	No	Yes	Chapters 5 Plant Siting and 19 Performance Based LNG Siting using Quantitative Risk Analysis are very relevant. Chapter 5 is prescriptive using design basis release rate and calculation of hazard zones of activity exclusion. This Chapter was in prior editions. Chapter 19 is new and involves a full blown QRA. It covers hole size frequencies, piping failure rates, individual and societal risk tolerability criteria and exclusion Zone allowed activities. A lot of stuff that is good fodder for inclusion in a CFR. The standard does not allow combining some sections of 5 and other of 19. Regarding Transportation, items 19.1.6 and 7 accounts for transportation releases outside and inside the plant that can impact the plant. I assume this would apply to LNG trucks or rail cars. An event on a docked ship could also qualify presumably.
NFPA 59A – Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG) – 2001	Yes	0	Yes	No	Yes	2001 edition is currently referenced in 49CFR193.
API Recommended Practice (RP) 1173: Pipeline Safety Management Systems, First Edition	YES	4	No	Yes	No	The TOC shows a series of elements like PSM for pipelines. Risk Management element is Section 7. Section 7.2 is Data Gathering. Section 7.3 Risk Identification and Assessment states "Risks to pipeline safety that could result in an unintended release or abnormal operating conditions shall be identified, based on data and information, as well as knowledge and experience with similar facilities." The operator shall maintain a process to identify threats that are posed by operations and the operating environment, including changes in conditions that could occur between assessments. Risk assessment shall consider the likelihood and severity of threats using any one of a variety of risk management tools. Risk assessments shall be performed periodically to identify and understand the collective threats and support the selection of prevention and mitigation measures to minimize the likelihood of the occurrence and consequences of an unintended release and the likelihood of abnormal operating conditions. Section 7.3 requirements are mostly performance based without specifics on methods. While the RP is for application to pipelines the concepts are broadly applicable.
49 CFR Part 191: Transportation of Natural and Other Gas by Pipeline; Annual, Incident, and Other Reporting	No	0	No	No	NA	
PHMSA Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards, 49 C.F.R. §192.	Yes	4	Yes	Yes	Yes	(a) This regulation prescribes minimum safety requirements for pipeline facilities and the transportation of gas, including pipeline facilities and the transportation of gas within the limits of the outer continental shelf (inclusive of compressors). Requirement of 49 CFR 192 - B31-8S focuses on piping and distribution with high emphasis on Risk assessment (Pinpointing mostly piping/distribution systems). Outlines four prescriptive options and needs to be referenced for final documentation finalized by ioMosaic Team - Has direct application to project. Four methodologies outlined as required risk assessment based on consequence and likelihood multipliers. "The ASME B31.8 and B31.8S codes have offered a variety of risk assessment approaches to ensure the safety of gas pipelines by continually adding and updating design, construction, operational prevention, mitigation, and assessment language and guidance. The Section Committee has adopted prescriptive and performance approaches to pipeline safety and also has evaluated and drafted life cycle and reliability based methodologies". ..."An operator shall utilize one or more of the following risk assessment approaches consistent with the objectives of the integrity management program. These approaches are listed in a hierarchy of increasing complexity, sophistication, and data requirements. These risk assessment approaches are subject matter experts, relative assessments, scenario assessments, and probabilistic assessments."
49 CFR Part 193: Liquefied Natural Gas Facilities: Federal Safety Standards	No	1	Yes	No	No	NFPA 59A included as regulatory reference. Has RAGAGEPs stated to some degree, however incorporates NFPA 59A extensively. No direct reference to risk assessment requirements at all.
49 CFR Part 194: Response Plans for Onshore Oil Pipelines	No	0	No	No	No	Focus is Emergency Response.

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
PHMSA Advisory Bulletin ADB-12-09 Pipeline Safety: Communication During Emergency Situations	No	0	No	No	No	Bulletin associated with requirement to communicate to government, including local authority upon a release.
PHMSA Advisory Bulletin ADB-11-03 Pipeline Safety: Updates to Pipeline and Liquefied Natural Gas Reporting Requirements	No	0	No	No	No	Focus is on reporting requirements for Operators to PHMSA (Incidents and other operating IDs - Non PHA or RAGAGEPs related.)
PHMSA Advisory Bulletin ADB-10-07 Liquefied Natural Gas Facilities: Obtaining Approval of Alternative Vapor-Gas Dispersion Models	Yes	1	No	Yes	Yes	Pure focus on dispersion models, which is certainly a direct tie to Risk Assessment, however not PHA/LOPA.
PHMSA Advisory Bulletin ADB-06-04 Pipeline Safety: Lessons Learned From a Security Breach at a Liquefied Natural Gas Facility	No	0	Yes	No	No	Focus is on Security and a breach of cutting a fence. N/A to this project, however some minimal design considerations for security.
Chemical Safety Board (CSB) Case Study Enterprise Products Gas Plant Explosion	Yes	5	Yes	No	Yes	Demonstrated inconsistencies in PHA Teams on assumed consequences between revalidation cycles. Also example of (rate of temperature change set point), a safeguard assumed to be in place on DCS, however, a set point was not right. Auditing of safeguards should be part of PHA standard. Specific template on these Heat Exchangers for a PHA and credible failure scenarios should incorporate this report. (Thermal fatigue in a HE causes catastrophic failure.)
IFO Group RCFA Freeport LNG Incident Final Redacted Report	Yes	2	No	No	NA	Incident Investigation report demonstrates the need for LNG facilities to conduct PHAs on processes (since operators ignored alarm).
API RP 1171: Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs		N/R				
LNG Plant Requirements: Frequently Asked Questions page on PHMSA site		N/R				FAQ example on subject "Many toxic substances stored above certain quantities are regulated under Appendix A of the EPA's "Risk Management Program for Chemical Accidental Release Prevention" (RMP, 40 CFR 68) and OSHA's "Process Safety Management of Highly Hazardous Chemicals" (PSM, 29 CFR §1910.119). Compliance with EPA's RMP and OSHA's PSM regulations is a sufficient approach to comply with NFPA 59A Paragraph 2.1.1(d). PHMSA does not have authority to enforce EPA or OSHA regulations, but requires operator compliance with NFPA 59A Paragraph 2.1.1(d)"
Bayesian-LOPA Methodology Development for LNG Industry	Yes	2	No	Yes	Yes	Rather complicated methodology using probability distributions with database failure rates to refine the failure statistics. Rather involved for not much gain. See Appendix Section 3-B: Handling Failure Data Uncertainty in Risk Assessment for additional details.
Control of Major Accident Hazards Regulations (COMAH)		N/R				
Control of Major Accident Hazards Regulations (COMAH) amendment - transport and directly related temporary intermediate storage activities and transport in pipelines		N/R				
UK HSE Pipeline Safety Regulations		N/R				
UK HSE L82 A guide to the Pipelines Safety Regulations		N/R				
UK HSE Gas Safety (Management) Regulations		N/R				
UK HSE Gas Safety (Management) (Amendment) Regulations		N/R				
2012 Safety in the LNG Value Chain_H.Ozog		N/R				

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
API RP 14C: Analysis, Design, Installation, and Testing of Safety Systems for Offshore Production Facilities		5				
ISA 84: Instrumented Systems to Achieve Functional Safety in the Process Industries		3				
ISA 84: Instrumented Systems to Achieve Functional Safety in the Process Industries		N/R				ANSI/ISA-84 standard has been harmonized with IEC 61511. The standards essentially have the same requirements except for a “grandfather” clause. This clause allows installations to use the 1996 version of S84, provided the safety equipment is designed, maintained, inspected, tested and operated in a safe manner.
IEC 61511: Functional safety - Safety instrumented systems for the process industry sector - Part 1: Framework, definitions, system, hardware and application programming requirements		5				
PHMSA Inspection Question set (based on NFPA 59A, but lags the current standard) [PHMSA-LNG-LNG-2024-01-IA-Question-Set-January-2024]		N/R				
OSHA Interpretation Letter - PSM Coverage of LNG Facilities - 04272021	No	0	No	No	No	PSM does not apply to PHMSA-covered facilities by the law that created the agency. However, any LNG facility exempted from PHMSA authority would be covered by OSHA.
OSHA Interpretation Letter - PSM Standard Coverage of LNG Facilities (Runyon) - 12091998_rescinded	No	0	No	No	No	Rescinded per OSHA Interpretation Letter from 04272021. Provided as historical reference.
Nat Gas Trans Line Risk List	No	0	No	No	No	Document provides indication of regulatory structure. Not a source document.
ASME, B31.8S - Managing System Integrity of Gas Pipelines, 2022.	Yes	5	No	Yes	Yes	Ranked as 5, as all storage locations will have piping and distribution from storage. Requirement of 49 CFR 192 - B31-8S focuses on piping and distribution with high emphasis on Risk assessments. Outlines four prescriptive options and needs to be referenced for final documentation finalized by ioMosaic Team - Has direct application to project. Four methodologies outlined as required risk assessment based on consequence and likelihood multipliers. "The ASME B31.8 and B31.8S codes have offered a variety of risk assessment approaches to ensure the safety of gas pipelines by continually adding and updating design, construction, operational prevention, mitigation, and assessment language and guidance. The Section Committee has adopted prescriptive and performance approaches to pipeline safety and also has evaluated and drafted life cycle and reliability based methodologies". **"An operator shall utilize one or more of the following risk assessment approaches consistent with the objectives of the integrity management program.**" These approaches are listed in a hierarchy of increasing complexity, sophistication, and data requirements. These risk assessment approaches are subject matter experts, relative assessments, scenario assessments, and probabilistic assessments." All Risk assessments must have the following components: identify events, evaluate likelihood, risk rank, identify options, provide feedback loop, provide structure and updating. Also indicates risk assessments required to be redone annually (See 5.8).
Report to the Federal Energy Regulatory Commission (FERC); Evaluation of the Cryogenic Design Review Process and Inspection Program [ioMosaic Report]		N/R				
GTI Project 22423 "Performance Comparison of Process Safety Management Consensus Standards and Regulatory Requirements for LNG Facilities"	Yes	4	No	Yes	No	Paper is great summary of identifying gaps between LNG PHA requirements of NFPA 59A, like what is needed. (Focus of our work) Worth the read for section on PHA to get high level summary of gap and what LPG industries feel about addressing the gap.

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
Freeport LNG Incident and Regulatory Response PHMSA / FERC / USCG	Yes	5	No	Yes	No	Isolated relief device led to BLEVE - Loss of Containment. Consequences - Vapor cloud Explosion, fireball, secondary pool fire, short term release from 3" piping. Root causes: 1) Pressure Safety Valve Testing Procedure and Car Seal Program; 2) Safeguards to Warn Operators of Increasing Vacuum Insulated Piping Temperature and/or Pressure for Lines Routinely Isolated by Procedure; 3) Operating Procedures Allowed for Operators to Routinely Isolate a Section of LNG Line
U.S. regulator releases report blaming Freeport LNG blast on inadequate processes	Yes	0	No	Yes	No	See Freeport LNG Incident and Regulatory Response PHMSA / FERC / USCG.
June 8, 2022 - Loss of Primary Containment Incident Investigation Report Freeport LNG Quintana Island, Texas (redacted)	Yes	0				See Freeport LNG Incident and Regulatory Response PHMSA / FERC / USCG.
PHMSA LNG Interpretations		N/R				
Process Hazards Analysis. Ian Sutton. swbooks.com. 2001		N/R				Introduction to PHA according to book review.
Process Risk Management. Ian Sutton. Whitepaper		N/R				
Process Risk Management - Risk Tree Analysis Methods. Ian Sutton.		N/R				
EN 1473 Installation and equipment for liquefied natural gas - Design of Onshore Installations	Yes	5	Yes	Yes	Yes by reference to EN/IEC 31010 & ISO/TS 16901	Section 6.0 Risk Assessment introduction states that "Safety shall be considered throughout all the project phases: engineering, construction, start-up, operation and decommissioning including plant modifications. Risk assessments shall be carried out and the required safety measures implemented to ensure acceptable risk levels". However the focus is mainly on design phase. This section is comprehensive covering hazard ID and risk evaluation, LNG release characterization, and consequence modeling. Two of the consequence scenarios to be considered are related to the Skikda and Plymouth LNG incident root causes. Appendices I, J and K - Contain advice on defining frequency ranges, classes of consequence, levels of risk and acceptance criteria. The risk assessment is often part of a hazard and operation study (HAZOP), but approaches such as failure mode effect analysis (FMEA), event tree method (ETM) or fault tree method (FTM) are also permitted. Overall a very worthy standard.
Nova Scotia DOE Code of Practice - Liquified Natural Gas Facilities	Yes	3	Yes	Yes	No	3.1.1.5 Preliminary Hazard and Operability (HAZOP) Study: A preliminary HAZOP shall be conducted based on the process safety information developed during the FEED. 3.1.2.2 HAZOP Study Based on Detailed Engineering Design The preliminary HAZOP study shall be updated based on the final detailed engineering design. Table 3-1: Risk Ranking Matrix (based on ioMosaic's table). It References NFPA 59A
CSA Z276:22 Liquefied Natural Gas (LNG) - Production, Storage, and Handling	Yes	3	Yes	Maybe	No	Didn't find a free copy of the standard to review. Typically Canadian Standards are "harmonized" to match US codes or standards committees like NFPA. This is a reference in Nova Scotia DOE LNG Code of Practice.
GTI Project 21873 for PHMSA "Statistical Review and Gap Analysis of LNG Failure Rate Table" 1/11/2017	Yes	3	No	No	Yes	Paper has outlined FTA on failures and rates for fixed equipment on and off shore, also inclusive of manufacturing (i.e. HEs, Pressure Vessels, Storage Tank, cryogenic and non cryogenic". PHMSA has very mature failure rate tables developed.
EPA Risk Management Program Fact Sheet	Yes	3	No	No	No	Program Level 1 Plan covers processes that would not affect the public in situations of a worst-case release. Limited hazard assessment requirements. Program Level 3 Plan covers processes not eligible for Level 1 and subject to OSHA PSM standard as well as additional hazard assessment management. Example of another government agency recognizing OSHA PSM Standard.
EPA General Guidance on Risk Management Programs for Chemical Accident Prevention	Yes	4	No	No	Yes	Hazard Analysis: RMP Guidance for Offsite Consequence Analysis for worst-case and alternate releases. Exhibit 4-1 Hazard Modeling Methods. Options include EPA Lookup Tables, EPA models, and third-party models. Exhibit 4-2 Sources of Assistance for Modeling Includes reference to CCPS Guidance for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVES (1994) Exhibit 4-3 Required Parameters (input) for Modeling Worst-Case Scenarios.
CCPS Layer of Protection Analysis: Simplified Process Risk Assessment, 2001.	Yes	5	No	Yes	Yes	This is the first CCPS book on the topic of Layer of Protection Analysis (LOPA). Covers the basic steps involved in applying the methodology. Uses worked example of using LOPA, and has a table of some suggested failure statistics.

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
CCPS Guidelines for Initiating Events and Independent Layers of Protection in LOPA	Yes	5	No	Yes	Yes	As the title suggests, this book greatly expands on providing statistical data on initiating events and Independent Protection Layer (IPL) credits for use with LOPA. Each datum value is thoroughly referenced and committee peer reviewed, with a recommended consensus value.
CCPS Guidelines for Enabling Conditions and Conditional Modifiers in LOPA	Yes	5	No	Yes		This is the companion book for referenced data on enabling conditions and conditional modifiers for use with Layer of Protection Analysis. Conditional modifiers include, but are not limited to: probability of a hazardous atmosphere, probability of ignition, probability of explosion, probability of personnel presence, probability of injury or fatality, and probability of equipment damage or other financial impact. These three books provide an essential library for applying LOPA methodology that meets RAGAGEP. There are some other referenced Recommended Practices (RP) that may contain additional data such as API RP Risk Based Inspection, that could enhance the compendium of available data.
FERC - GUIDANCE MANUAL FOR ENVIRONMENTAL REPORT PREPARATION - For Applications Filed Under the Natural Gas Act 59.Volume II - Liquefied Natural Gas Project Resource Reports 11 & 13 Supplemental Guidance	Yes	5	Yes	Yes	Yes	The FERC is responsible for authorizing the siting and construction of onshore and near-shore LNG import or export facilities under Section 3 of the Natural Gas Act. Facilities must file a Resource report. Within the Resource report is a section on PHAs/LOPAs/Dispersion Analysis. Guidance states "PROVIDE a summary of the basic design and various layers of protection and associated codes and standards to mitigate the risk of an incident impacting the safety or reliability of the plant's design, construction, operation, maintenance, and management. Also requires [operators] "PROVIDE copies of preliminary process hazard analysis (PHA) design reviews. The PHA should include lists of the recommendations and status of implementation. The design reviews should, at a minimum, include the requirements for siting, equipment layout and spacing, process controls, and ignition controls applicable during all phases of commissioning, startups, shutdowns, operation and maintenance. "
CCPS Guidelines for Hazard Evaluation Procedures, 3rd Edition	Yes	5	No	Yes	Yes	Chapter listings include: 3 Hazard Identification Methods 5 Scenario- Based Hazard Evaluation Procedures 6 Selection of Hazard Evaluation Techniques 7 Risk- Based Determination of the Adequacy of Safeguards 12 Detailed Engineering- Fault Tree and Event Tree Analysis. I presume that Chapter 7 describes LOPA, but refers the reader to the LOPA books. This would be a primary reference for HAZOP methodology.
NTSB, Safety Recommendation, In reply refer to: P-11-8 through -20 and P-11-1 and P-11-2 (Reclassification)	Generically Yes	2	No	No	No	Installation of a substandard and poorly welded section of line on a NG transmission pipeline constructed prior to 1952 by PG&E. Pipeline ruptured in San Bruno, CA resulting in eight (8) fatalities and many injuries. Pipeline was grandfathered from requirement to perform hydrostatic pressure test during construction for a repair. See Appendix Section 3-C: LNG Incident Summary for further details.
NTSB Pipeline Accident Report - Over pressurization of Natural Gas Distribution System, Explosions, and Fires in Merrimack Valley, Massachusetts September 13, 2018	Generically Yes	4	No	No	No	The incident occurred at the end of a construction project to replace a cast-iron section of low-pressure (LP) NG distribution main with polyethylene pipe. The cast-iron main was isolated and the new line was being activated by introducing NG from a HP main which over pressured the LP network causing multiple fires and some explosions at customer locations. The pressure sensing line to protective monitor regulator valves remained connected to the abandoned cast-iron main allowing high pressure NG to the LP network. See Appendix Section 3-C: LNG Incident Summary for further details.
NTSB Pipeline Accident Report - Atmos Energy Corporation Natural Gas-Fueled Explosion Dallas, Texas February 23, 2018	No	1	No	No	No	Underground gas line leak migrated into a house producing a flammable atmosphere which ignited. The leakage came from a crack in the NG pipeline believed to have been caused during previous excavation for a sewer line some years prior to the explosion. This is a delayed third-party intervention related incident that is not particularly applicable to the PHMSA scope.
NTSB Safety Study Integrity Management of Gas Transmission Pipelines in High Consequence Areas	Marginal	1	By Reference	No	Yes	This manual provides additional details for complying with 2004 Integrity Management regulations in 49 Part 192, Subpart O. There is a section on Risk Assessment which allows for Scenario-Based Models and Probability Models. The descriptions are broad enough to encompass any PHA methodology we would likely recommend. High level incident statistic for NG transmission lines are also discussed and summarized in Table 4 for various cause categories. Highest percentage of all causes is for Equipment (27.7%) and second is Excavation (16.0%). The data is sliced and diced by other parameters like age, length, and year installed. It is interesting but specific to pipelines. The individual reports are more useful for identifying root causes that are more generic.
PHMSA FAILURE INVESTIGATION REPORTS (Purging with N/G)	Yes	1	No	No	No	Vessel and piping internal deflagration to detonation transition (DDT) caused by autoignition of a gas-air mixture present in equipment due to a pressure purge that failed to remove the air from the system prior to start up. This is another case of a mishap due to using NG to purge air from a system after a repair requiring line-breaking. Investigation concluded the procedure was faulty. See Appendix Section 3-C: LNG Incident Summary for further details. This one happened well after the fiasco at Clean Energy that destroyed a power plant before it even ran.

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
ROOT CAUSE FAILURE ANALYSIS INVESTIGATION Loss of Primary Containment, Freeport LNG Quintana Island, Texas	Yes	3	No	No	No	This report is highly redacted, apparently LNG became superheated in a line due to atmospheric heating. There was a problem with a blocked PSV device and eventually the overpressure caused the piping to rupture resulting in a BLEVE which knock-on effects. A PSV may have been taken out of service for testing, When it was returned and reinstalled, the isolating block valve was not reopened. There was no formal program for managing the placement of car seals on PSV block valves in the correct position. See Appendix Section 3-C: LNG Incident Summary for further details.
ROOT CAUSE FAILURE ANALYSIS INVESTIGATION REPORT Weymouth Compressor Station September 11, 2020 Closure Seal Failure Algonquin Gas Transmission, LLC	Generically Yes	2	No	No	No	Incident occurred during commissioning of the compressor station for pressure containment. The Root Cause Analysis (RCA) Report does not indicate whether there were any impacts other than release of 169 MSCF of NG. A filter/separator vessel with a Sentry(TM) closure rated for 2,035 psig was shipped with an O-ring not rated for that pressure. The in-service O-ring was shipped separately. The shipped vessel was installed with the O-ring that it came with, unaware that it was not properly rated. See Appendix Section 3-C: LNG Incident Summary for further details.
Technical Root Cause Analysis of Delmont Line 27 Failure - April 29, 2016 - Spectra	No	1	Yes	No	NA	Cause was corrosion under a piping coating. Lack of recognition of accelerated corrosion under pipe coating at weld.
PHMSA incident Detailed Report for LNG from Database search on PHMSA website		N/R				Results of search of NGL transportation incidents on PHMSA web site. See Column AI for description of each incident. If more information desired, contact Dave with report # (column A) and I can download it. Based on Incident report form 5800.1 submitted by industry.
CCPS G/L for Developing Quantitative Safety Criteria	Yes	5	No	No	Yes	This is a comprehensive and authoritative reference book that reviews the status of available knowledge on the topic of hazard and risk assessment tolerability criteria that is broadly accepted. Basically the CCPS committee has done the literature research on this topic and provided guidelines for developing appropriate criteria. For guidance in performing LOPA and QRA studies, this is a long overdue reference.
IEC 31010: 2019 Risk Management - Risk Assessment Techniques 2d Ed.	Yes	2	No	Yes	Yes	Referenced a review copy of a Singapore Safety Standard SS IEC 31010 2021 which is essentially the same as the IEC Standard, with a few org. name changes. The techniques covered in the TOC include HAZOP and LOPA. I don't know how extensively the methodology is described since the page count per each of the 30 plus techniques covered is not that much. I have a 3 pg. table that summarizes all the techniques. CCPS book is still probably the best reference.
ANSI/ASSE Z690.3 Risk Assessment Techniques 2011	Yes	4	No	Yes	Yes	This is an adopted version by the American Society of Safety Engineers (ASSE) of the IEC 31010 2009 Standard. See above for the latest edition of IEC 31010.
29 CFR §1910.119(e) Process Safety Management [See also, OSHA]	Yes	3	No	Yes	No	While LNG facilities are not covered by OSHA PSM regulations, PSM Element (e) is a pretty good summary of the requirements for conducting a compliance PHA. Namely, (e)(2) methodologies to employ, (e)(3) what needs to be considered including (3)(ii) prior incidents, and (e)(4) team composition. It is already codified in the Code of Federal Regulations (CFR). It would be a good template for developing a PHA regulation specific to LNG, with some modification.
API, API RP 750 : MANAGEMENT OF PROCESS HAZARDS, 1990.	Yes	3	N/A	Yes	No	Section 3 3 PHA Methodology refers to CCPS Guidelines (G/L) for Hazard Evaluation Procedure book. Section 3.5 Team Analysis expands the requirements of OSHA PSM somewhat, as follows. Analysis performed by a team of persons knowledgeable in engineering, operations, design, process, and other specialties deemed appropriate. The participants should have detailed knowledge of the specifics of the process being evaluated and have access to that knowledge.
Mannan, S., & Lees, F. P. Lee's Loss Prevention in the Process Industries: Hazard Identification, Assessment, and Control. Butterworth-Heinemann; Elsevier, 2012.	Yes	2	Maybe	Yes	General	This book was sourced and edited by Sam Mannan of Texas A&M. Like Lee's prior books it covers the universe of loss prevention and safety topics like Perry's Chemical Engineering Handbook. But the depth of coverage is only enough to make the reader aware of the substance of the science. You need to follow the reference pointers if you need to apply the analytical procedures. There are some tables summarizing major incidents involving hazardous chemicals. The online text was small, so can't comment on whether some involve LNG.
29 CFR §1910.119(d) Process Safety Information (PSI) [See also, OSHA]	Yes	5	Refers	Related	No	Like paragraph (e), this OSHA PSM element is a fairly complete listing of process and design information needed to conduct a quality PHA.
British Standard BS IEC 61882 Hazard and Operability Study (HAZOP)	Yes	2	No	Yes	No	This is a standard that is specific to HAZOP. HAZOP was developed at Imperial Chemicals Industry (ICI) in the UK by Trevor Kletz!
CCPS Guidelines for Risk Based Process Safety	Yes	1	Refers	Yes	Yes	This CCPS Book is long on prose and short on specificity. In general, it provides little of value for our assignment.
OSHA Information directive CPL-02-01-065	Yes	1	Refers	Yes	No	This directive provides OSHA's answers to interpretation questions. Answers to QE-16/17 give OSHA's guidance on what they expect for the verification of the effectiveness of any mitigation safeguards during a PHA. This includes the reliability of supporting systems such as electric power. Also the preventative maintenance (PM) requirements.

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
PHMSA Report: Outage at LNG Peak-Shaving Plant, Portsmouth, RI	Yes	4	No	No	No	Natural Gas supply network outage due to failure to maintain pipeline pressure. The problem was traced to an inverted meter factor which incorrectly monitored gas flow. No releases, fire or unconfined vapor cloud explosion (UVCE). The metering system used a remote transfer unit (RTU) to send readings to the Supervisory Control and Data Acquisition (SCADA) control center. There are two types of RTUs and the meter K-factor for one type is the inverse of the factor for the other. At some point the RTU was changed out, but the meter K-factor was not checked for compatibility with the replaced RTU. Example of inadequate MOC policy! See Appendix Section 3-C: LNG Incident Summary for further details.
API RP 581 Risk Based Inspection Technology 3rd Ed.	Yes	3	No	No	Yes	This publication provides quantitative procedures to establish an inspection program using risk-based methods for pressurized fixed equipment, including pressure vessel, piping, tankage, pressure relief devices, and heat exchanger tube bundles. The API Risk-Based Inspection (API RBI) methodology may be used to manage the overall risk of a plant by focusing inspection efforts on the process equipment with the highest risk. API RBI provides the basis for making informed decisions on inspection frequency, and the extent of inspection. Of interest to PHA/LOPA is table 7.2 Default Initiating Event Frequencies that can result in over pressuring equipment. A companion Table 7.3 Overpressure Scenario Logic uses these initiating events to project the demand factors (0.1 to 1.0) for a protective pressure relief device (PRD) and describes the consequence (rupture, etc.) if the PRD fails to open. The scenarios are specific to different type of equipment (e.g., vessels, heat exchangers, columns, etc.)
Chemical Engineering Progress, Is Rollover Possible in an Ammonia Storage Tank?, Dharmavaram, Daugherty, and Duisters, pp. 35-42		N/R				I have flagged this article, not so much for the article, but for the references to LNG that it contains.
Center for Liquefied Natural Gas (CLNG) Website	Yes	2	No	No	No	CLNG is largely a trade organization for LNG export commerce for information on business activities and trade statistics. It monitors regulatory actions that can impact the industry such as the recent pause in permitting of new export LNG plants. The website had one item of interest on modernization of regulations. CLNG is working with the Pipelines and Hazardous Materials Safety Administration (PHMSA) and other stakeholders to address modernization of its LNG regulations – 49 CFR Part 193. Modernization of PHMSA's LNG regulations would: •Allow PHMSA and LNG facilities to identify and deploy the latest in safety best practices. •Ideally, incorporate a risk-based approach that goes hand-in-hand with a focus on continuous improvement and enables the industry to focus on the technologies and areas that make the greatest impact. Did not find any publications of a recommended practice nature.
BRITISH STANDARD BS EN 1473 Installation and Equipment for Liquefied Natural Gas — Design of Onshore Installations	Yes	5	Yes	Yes (except LOPA)	Yes	This is the European equivalent of NFPA 59A. Section 4.4 Hazard Assessment covers methodologies and risk assessment. Annexes J,K,L provide frequency, consequence severity criteria and risk matrices that are based on an F-N plot format. One for on-site harm and another for off-site harm. Very complete treatment.
UK Health & Safety Executive, Reducing Risks, Protecting People HSE's decision-making process, 1st Edition, 2001.	Yes	1	No	No	Yes Criteria	This reference expounds for 88 pages of text on reducing risk and very little on hard quantitative risk criteria. The quantitative information given on individual and societal criteria is pretty consistent with other sources including comparison with NFPA 59A criteria.
Design and Construction of LNG Storage Tanks, Josef Rotzer, Ernst & Sohn, 2020, Berlin.		N/R				
Reliability Analysis Center, CRTA-FMECA Failure Modes, Effects, and Criticality Analysis	Yes	2	No	No	FMECA	The subject of this reference is MIL-Std 1628A FMECA, which is a legacy document that has a lot of original thinking on the subject. It covers both quantitative and qualitative approaches. The example worksheets are outdated by current practice. Appendix A of document provided failure mode distributions (e.g., open, closed, stationary) for a compilation of common system components and parts.
USACE Army TM 5-698-4 Chapter 3 FMEA Methodology	Yes	2	No	No	FMEA	Chapter 3 of this reference covers standard FMEA methodology. There is a severity ranking table, but none for occurrence. Worksheets include more aspects, but not to the level of best practice.
USACE Army TM 5-698-4 Chapter 4 FMECA Methodology	Yes	3	No	No	FMECA	Chapter 4 of this reference covers FMECA methodology. There are ranking tables for severity, occurrence, and detection. Qualitative Worksheets include severity (S), occurrence (O) and PRN (S x O). Detection (D) factor is not used.
American Society for Quality Website	Yes	4	NO	No	FMEA	This website has a good description of current practice of combining FMEA and FMECA methodologies into one analysis. The worksheet allows for listing existing safety controls (safeguards) followed by calculating RPN and criticality. It also allows re-ranking the risk after applying mitigation recommendations. Additional notes available.

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
Explosion at Sonatrach's Skikda LNG Complex	Yes	2	Related	No	No	A hydrocarbon leak suspected from a cold box was ingested by a boiler ID fan resulting in an internal deflagration that ruptured the fire box. The resulting explosion caused knocking effects producing a large vapor cloud and secondary explosion that caused widespread damage on and off site. The impact was 27 fatalities and many injuries plus > $500M in property damage. Inadequate plant equipment layout placing a boiler too close to the processing area was considered one of the root causes (RC) for the massive impacts. Poor equipment inspection was the other RC for the initiating event. One RC happened during design, the other during operation.
BoM Report R.I. 3867 Investigation of the Fire at the LNG Plant of East Ohio Gas Co.	Yes	0	Related	No	No	A catastrophic failure occurred to one of the first cylindrical LNG storage tanks installed. Failure of a tank bottom plate was determined to be at fault. The material of construction was a 3.5 % Ni alloy steel, that was marginally accepted for this low temperature service. The failure resulted in a massive surge of LNG and cool vapor that almost immediately found an ignition source. A probable root cause was not identified, but structural failure was suspected. This incident revolutionized the design of LNG tanks including material selection (9% Ni alloy), spill drainage and impoundment, and foundation design. It is only of historical significance now due to standardization of LNG tank design.
IChemE Safety Centre Guidance, Effective Revalidation of Risk Assessments - Delta HAZOP	Yes	5	No	No	Yes	This is a pretty good reference for a revalidation HAZOP. Appendix B of document is consolidated checklist of change items that might be applicable.
Sandia Report - Using Bayesian Methodology to Estimate Liquefied Natural Gas Leak Frequencies, Garrett W. Mulcahy, Dusty M. Brooks, Brian D. Ehrhart	Yes	3	No	Yes	No	Used various sources to produce a table of LNG leak frequencies from various equipment.
Canadian Standards Association (CSA) Z767:17 Process Safety Management	Yes	2	Yes	Yes	No	"The purpose of this Standard is to identify the performance requirements for organizations that plan to implement, or have implemented, a PSM system. PSM is the application of management principles and systems for the identification, understanding, avoidance, and control of process hazards to prevent, mitigate, prepare for, respond to, and recover from process-related incidents. The Standard was prepared by the Technical Committee on Standards for PSM, which has representation from different Canadian industrial sectors, regulators, academics and government."
Storage Incident Frequencies, 434-03, International Association of Oil & Gas Producers	Yes	5	0	Yes	0	See title.
Evaluation of the Cryogenic Design Review Process and Inspection Program, Report to the Federal Energy Regulatory Commission (FERC), ioMosaic Corp., September 22, 2005.	Yes	1	No	No	No	ioMosaic evaluation of the FERC design review process and inspection program to determine if there are any additional measures that could be used to enhance the program.
Consistency Review of Methodologies for Quantitative Risk Assessment [filename: 693JK31810006__Public_Final_Report__26 Oct20]	Yes	2	No	Yes	Yes	This research project developed a standard methodology and guidelines for performing a Quantitative Risk Assessment (QRA) for Liquefied Natural Gas (LNG) facilities, with the objective to support the US Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) if it considers permitting risk-based approaches and regulations for evaluating potential impacts to life and property. In comparison, PHMSA's current requirements contained in 49 CFR Part 193 for ensuring safety associated with LNG facilities are primarily prescriptive in nature.
US DOT PHMSA Research Project #731: Consistency Review of Methodologies for Quantitative Risk Assessment; Final Virtually Held Information Dissemination Meeting, November 16, 2020 [filename: PHMSA 693JK31810006 LNG QRA Consistency Review Final Virtually-Held Info Dissem Mtg 16Nov20]	Yes	2	No	Yes	Yes	Presentation of previous entry.

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
Memorandum of Understanding Between The Department of Transportation and The Federal Energy Regulatory Commission Regarding Liquified Natural Gas Transportation Facilities	Yes	5	Yes	No	No	Memorandum of Understanding (MOU) between agencies defines responsibilities for each agency in the regulation of LNG facilities.
CCPS, Inherently Safer Chemical Processes Life Cycle Approach - Second Edition	Yes	4	Yes	Yes	Yes	Description of Inherently Safer Design
Adapting cause and effects methodology to your Safety Instrumented System (SIS) to reduce human errors from engineering, operations and beyond, Charles M. Fialkowski, CFSE & Luis M. F. Garcia, CFSE Siemens Industry Inc., Presentation, 2017 MKOPSC Process Safety Symposium, 2017	Yes	4	Yes	Yes	Yes	See title.
Effective Implementation of Inherently Safer Design during Design Phase of Modularized Onshore LNG Projects, Masayuki Tanabe and Atsumi Miyake, Chemical Engineering Transactions, The Italian Association of Chemical Engineering Online (www.aidic.it.cet), Vol. 48, 2016, pp. 535-540.	Yes	4	Yes	No	Yes	Article on Inherently Safe Design during Design Phase of LNG Plants
Society of International Gas Tanker and Terminal Operators (SIGTTO), Guidance for the Prevention of Rollover in LNG Ships, SIGTTO, 1st edition, 2012.	Yes	5	Yes	No	No	Some material here can go into the checklist section in 5b and is very focused on rollover and how it is not usually accounted for in relief sizing exercises.
33 CFR Part 127 - Waterfront Facilities Handling Liquefied Natural Gas and Liquefied Hazardous Gas	Yes	5	Yes	No	No	Some material here can go into the checklist section regarding transfer requirements.
Statistical Review and Gap Analysis of LNG Failure Rate Table	Yes	5	No	Yes	Yes	Discusses PHAs and their conduct.
CCPS, Guidelines for Integrating Process Safety into Engineering Projects, 1st edition, AIChE Publications, New York, 2019.	Yes	5	No	Yes	No	The primary focus of this Transport Canada report's research was to identify information gaps on understanding the physical phenomena of LNG hazards in the transport of LNG; to recommend additional research to improve the knowledge; and hence to support improvements to LNG emergency response guidelines. An initial step of this research was to gather and assimilate a representative sample of LNG incidents, which includes the ones listed above and several additions. The hazards are classified by types and consequences. The three main LNG hazards are characterized as Flammability, Explosivity, and Cryogenics. (Table 1 of Section 3.5.1 Representative Sample of Historical LNG Incidents)
CSN EN 14620-1 Design and manufacture of site built, vertical, cylindrical, flatbottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0 °C and -165 °C - Part 1: General	Yes	5	No	Yes	Yes	As previously implied, a HAZID should be discussed within the early stages of hazard analysis to provide a starting point for identifying nodes and the most significant hazards within a process. Bow-tie diagrams can be formed from the content of a HAZID and provide a method to dictate which hazards require higher focus. Other methodologies can be used as well to provide qualitative risk analysis within the ISO-31000.
API, API 625 - Tank Systems for Refrigerated Liquefied Gas Storage, First Edition, 2021.	Yes	5	Yes	No	No	To avoid LNG 'rollover' are LNG tankers alternatingly filled from the top and bottom depending on the densities of the incoming LNG relative to the stored LNG?
Perry, Judy A. and Myers, Molly R. P.E., "Streamline Your Process Hazard Analysis", Chemical Engineering Progress, January 2013, pp. 29-33.	Yes	5	No	Yes	Yes	Discusses PHAs and their conduct.

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
Huffman, Mitchell, Wang, Qingsheng PhD, Baxter, Christina M. PhD, Noll, Gregory G., and Hildebrand, Michael S., "Validation of Recommended Emergency Actions for Liquefied Natural Gas (LNG) in the Emergency Response Guidebook (ERG)", by the Fire Protection Research Foundation under contract with Transport Canada, February 2023	Yes	5	No	Yes	No	The primary focus of this Transport Canada report's research was to identify information gaps on understanding the physical phenomena of LNG hazards in the transport of LNG; to recommend additional research to improve the knowledge; and hence to support improvements to LNG emergency response guidelines. An initial step of this research was to gather and assimilate a representative sample of LNG incidents, which includes the ones listed above and several additions. The hazards are classified by types and consequences. The three main LNG hazards are characterized as Flammability, Explosivity, and Cryogenics. (Table 1 of Section 3.5.1 Representative Sample of Historical LNG Incidents)
International Organization for Standardization (ISO). (2018). Risk Management - Guidelines, edition 2, (ISO 31000:2018).	Yes	5	No	Yes	No	As previously implied, a HAZID should be discussed within the early stages of hazard analysis to provide a starting point for identifying nodes and the most significant hazards within a process. Bow-tie diagrams can be formed from the content of a HAZID and provide a method to dictate which hazards require higher focus. Other methodologies can be used as well to provide qualitative risk analysis within the ISO-31000.
Cahill, J. and Athanasiou, V. "Preventing LNG Stratification and Roll-Over Events", July 3, 2024, AspenTech Optimize 24 conference.	Yes	5	Yes	Yes	No	To avoid LNG 'rollover' are LNG tankers alternatingly filled from the top and bottom depending on the densities of the incoming LNG relative to the stored LNG?
U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Investigation Report – AGT/National Grid LNG	Yes	5	Yes	Yes	No	LNG Accident Investigation
PHMSA, Failure Report- Williams Partners Operating LLC	Yes	5	Yes	Yes	No	LNG Accident Investigation
California Energy Commission, Algerian LNG Plant Explosion (Fact Sheet), 4/20/2004.	Yes	5	Yes	Yes	No	LNG Accident Investigation
U.S. Army Corps of Engineers, Failure Modes, Effects And Criticality Analysis (FMECA) for Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) Facilities, Army TM 5-698, September 29, 2006.	Yes	5	No	Yes	Yes	PHA Methodology
NFPA., "NFPA 59A: Standard for Production, Storage, and Handling of Liquefied Natural Gas (LNG)", National Fire Protection Association, Massachusetts, 2001.	Yes	5	Yes	No	No	NFPA Standard, Basis for existing PHMSA Rulemaking
EPA Chemical Accident Prevention Provisions, 40 C.F.R. §68. 67(c)(9).	Yes	5	No	Yes	No	Intrinsic Safe regulation
42 U.S. Code § 7436 - Methane emissions and waste reduction incentive program for petroleum and natural gas systems.	Yes	5	Yes	Yes	No	LNG Risk requirements
County of Santa Barbara, Planning and Development, Environmental Thresholds and Guidelines Manual, January 2021.	Yes	5	No	Yes	No	Risk criterion
UK Health & Safety Executive, ALARP "At a Glance", https://www.hse.gov.uk/enforce/expert/alarpglance.htm, 1/20/2025.	Yes	5	No	yes	No	ALARP

Relevant Literature & Regulations			LNG PRODUCTION			
Literature/Regulation Title	Is Item Applicable to Topic?	Prioritization - (5-High; 1-Low)	LNG Design RAGAGEP	Risk Assessment - PHA/LOPA Requirements	Risk Assessment Methodology Details	Reviewer Notes
Gas Technology Institute, GTI PROJECT NUMBER 21873, Statistical Review and Gap Analysis of LNG Failure Rate Table, 2017.	Yes	5	No	Yes	No	LNG Failure Rates
Cox, A.W., Lees, F. P., and Ang, M.L., “Classification of Hazardous Locations”, Rugby: Institution of Chemical Engineers, 1990.	Yes	5	No	Yes	No	Risk criterion
VROM. “Guidelines for Quantitative Risk Assessment”, Publication Series on Dangerous Substances (PGS3); (CPR-18E), 2005.	Yes	5	No	Yes	No	Risk criterion

Appendix Section 3-B: Handling Failure Data Uncertainty in Risk Assessment

Handling Failure Data Uncertainty in Risk Assessment

Nature of Databases

Those who have been engaged in the practice of reliability or failure analysis are aware of the variability in component and system failure rate data. This is mainly a result of how such data is compiled. Some data is actually based on run-to-failure testing of components where the environmental conditions are known and controlled and where the scatter in the data is less. However, the majority of failure data is collected from operational field data where the environmental conditions are less well known and considerably more variable. For example, the Offshore Reliability Data (OREDA) database which is collected for a focused type of equipment in one industry, still exhibits one or two orders-of-magnitude variability between lower and upper failure rate values[1]. Databases with homogeneous data sets present the failure rate upper and lower values as reported, and the range can be more than two orders of magnitude. Most databases do provide a Mean or Median value.

Dealing with Failure Data Uncertainty

There are procedural approaches to manage the data uncertainty when applying fault tree analysis and LOPA. The analysis should tend to err on the side of conservatism. That means accessing several databases to understand the range of failure statistics for a particular item, and determine if there is some level of agreement. One warning here is to make sure alternate databases aren't based on the same referenced data. Next, when assigning frequencies and event probabilities, start by selecting values that are mean or above. The usual objective of the FTA/ LOPA output is a frequency or PFD that is less than a target tolerability criteria. If the target can be met using more conservative failure statistics, that should increase the confidence in the analysis.

This type of hazard likelihood evaluation can also be used to establish the importance of the scenario events and failure pathways. Once that is established, the sensitivity of the assignment of certain failure rates to the overall likelihood can be computed by adjusting the rates.

> Extreme precision is not required (and is not believed!) in a fault tree evaluation; it is the order of magnitude size of the failure rate that is of concern, i.e., is the failure rate 10^{-6} per hour or 10^{-5} per hour. To this "order of magnitude" precision, detailed environments and detailed component specifications are often not important in obtaining gross estimates of the failure rate. The analyst, however, should of course use all the available information in obtaining as precise an estimate as he can for λ for each component or basic event on his tree.

Fault Tree Handbook NUREG-0492

Bayesian-LOPA

Recently, Bayesian estimation to refine the failure data inputs to LOPA has been suggested. While a worthy endeavor to determine what additional data accuracy might be obtained, the additional effort makes the methodology (which is supposed to be Simplified Risk Assessment) more complex. As the

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[1] After normalization of variations in different company data sample sets using a gamma distribution function with Chi-Square percentage points .

figure in the paper shows, the difference between the prior and posterior frequency values are not an order of magnitude different for 6 of the 7 scenarios tested. As the quotation for the NUREG Fault Tree Handbook states, extreme precision is not warranted.

Conclusions

Bayesian LOPA adds complexity to an established and widely utilized methodology without providing a substantial safety improvement. It should not be the basic LOPA procedure. It could be cited as an approved option for all who choose to apply it.

References

1. Offshore Reliability Data Handbook, OREDA Participants, 4th edition (2002)
2. Fault Tree Handbook, NUREG-0492, Nuclear Regulatory Commission, (Jan-1981)
3. Guen Woong Yun, Bayesian-LOPA Methodology Development for LNG Industry, Texas A & M University

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Appendix Section 3-C: LNG Incident Summary

Reference	Facility/Location	Data	Incident Description	Root Cause
PHMSA Incident Database	LNG Peak-Shaving Plant Portsmouth, RI	1/21/2019	Natural Gas supply outage due to failure to maintain pipeline pressure. The problem was traced to an inverted meter factor which incorrectly monitored gas flow. No release, fire or unconfined vapor cloud explosion (UVCE). Crashed the NG piping network in three RI towns including some power plants. The consequences could have been worse. Initiator was cold weather.	The metering system used a remote transfer unit (RTU) to send readings to the Supervisory Control and Data Acquisition (SCADA) control center. There are two types of RTUs and the meter K-factor for one type is the inverse of the factor for the other. At some point the RTU was changed out, but the meter K-factor was not checked for compatibility with the replaced RTU. Root cause (RC) was inadequate MOC policy. Also, inadequate communication between maintenance and operations personnel.
PHMSA Incident Database	Plymouth LNG Plymouth, WA	3/31/2014	Vessel and piping internal deflagration to detonation transition (DDT) caused by autoignition of a gas-air mixture present due to a purge that failed to remove the air from the system prior to start up. A catastrophic vessel failure and subsequent external deflagration injured five employes and caused widespread damage to the facility including penetration of the outer shell of an LNG-1 storage tank, which led to a precautionary evacuation of Plymouth.	Following line-breaking maintenance work, three rounds of pressure purging of air with NG between 100 and 5 psig was completed. Recognized Industry standard calls for < 1 psig at the end of each depressurization. Startup proceeded by repressuring the system to 685 psig with NG, which also caused heating due to adiabatic compression. When the flammable mixture was allowed to flow into the salt-bath heater it auto-ignited. In this case, there was no mention of checking the vented purge gas for oxygen content. Incident Investigation Report identified inadequate purge following maintenance procedure.
DNV GL USA, Inc. RCA Report 10263555-1	Algonquin Compressor Station Weymouth, MA	9/11/2020	Incident occurred during commissioning of the compressor station for pressure containment. The Root Cause Analysis (RCA) Report does not indicate whether there were any impacts other than release of 169 MSCF of NG.	A filter/separator vessel with a Sentry™ closure rated for 2,035 psig was shipped with an O-ring not rated for that pressure. The in-service O-ring was shipped separately. The shipped vessel was installed with the O-ring that it came with, unaware that it was not properly rated. During pressure testing, the O-ring blew out causing the release. Reviewer believes inadequate checking of the Bill of Material (BOM) and quality control (QC) of purchased construction materials against specifications upon receipt was root cause. The report mentions mechanical integrity and Pre-startup safety review (PSSR).
IFO Group Report	Freeport LNG Quintana Is, TX	6/08/2022	This report is highly redacted. LNG became superheated in a line due to atmospheric heating. There was a problem with a blocked PRV device and eventually the overpressure caused the piping to rupture resulting in a Boiling Liquid Expanding Vapor Explosion (BLEVE). The released vapor found an ignition source (damaged wiring) resulting in a Vapor Cloud Explosion (VCE). A lot of physical damage to the plant.	Literally reading between the redacted lines, a PRV may have been taken out of service for testing. When it was returned and reinstalled, the isolating block valve was not reopened. There was no formal program for managing placement of car seals on PRV block valves in the correct position. And for this scenario, the PRV was the only IPL. The RCA recommended providing other means to identify and respond to the initiating event.
NTSB Columbia Gas	LP Distribution System Lawrence, MA	9/13/2018	The incident occurred at the end of a construction project to replace a cast-iron section of low-pressure (LP) NG distribution main with polyethylene pipe. The cast-iron main was isolated, and the new line	The LP main is protected from upstream overpressure by monitor regulator valves (MRVs) that sense downstream pressure in the LP main and modulate to control the pressure setpoint. These MRVs did not respond to the increasing pressure in the LP main. The reason they did not

Reference	Facility/Location	Data	Incident Description	Root Cause
			was being activated by introducing NG from the high-pressure distribution main. The pressure in the LP distribution suddenly increased and fires and one house explosion occurred. There was one fatality and numerous burn injuries requiring hospitalization.	properly respond was that the sensing line for the MRVs was still connected to the abandoned cast-iron main. The MRVs actually opened more because they sensed no pressure in the cast-iron main further exacerbating the overpressure. Root causes: The final project construction package did not address the relocation of the sensing line to the MRVs. There were several inadequate engineering practices including haphazard filing of prior engineering record documents, cursory constructability reviews, lack of documentation and tracking of corrective action items. The NTSB cited "weak engineering management that did not adequately plan, review, sequence and oversee the project construction …" There were at least four PSM element programs that could have prevented this, MOC, PSI, PHA and PSSR, three of which require formal resolution documentation and action tracking. The need to relocate the sensing line was known and verbally discussed, but implementation fell through engineering management cracks.
NTSB Atmos Energy Corp	Residential House Explosion Dallas, TX	2/23/2018	Underground gas line leak migrated into a house producing a flammable atmosphere which ignited. The leak came from a crack in the NG pipeline believed to have been caused during previous excavation for a sewer line some years prior to the explosion.	This is a delayed third-party intervention incident not particularly applicable to the PHMSA scope.
PG&E	NG transmission line rupture San Bruno, CA	9/9/2010	Installation of a substandard and poorly welded section of pipeline constructed prior to 1952. Pipeline ruptured in San Bruno, CA resulting in eight (8) fatalities and many injuries.	A contributing factor was a grandfather exemption from hydrostatic pressure testing (HPT) of pipelines installed prior to 1970, promoted by the Federal Power Commission, and accepted by DOT. The NTSB concluded that such a test would likely revealed the material and welding flaws. It is customary practice to perform HPTs of plant piping and equipment during construction prior to commissioning.
Sonatrach	Skikda LNG Terminal, Algeria	1/19/2004	A possible cause was a hydrocarbon (HC) leak into a mixed refrigerant cold box heat exchanger (HEX) that was ingested by a steam boiler induced draft (ID) fan causing an internal deflagration in the boiler fire box. The explosion ruptured the boiler resulting in a fire ball causing additional damage to the surrounding equipment. A secondary larger VCE occurred resulting in widespread damage onsite and offsite. The Unit 40 steam boiler was sited very close to the LNG liquefaction and separation sections of the Unit 40 process train.	The root causes mentioned include: ▪ Inadequate inspection and maintenance of cold box HEX. (Such exchangers are inside a structure filled with pearlite insulation and not visually accessible). ▪ Damage was more extensive due to a poor equipment layout and spacing plan placing the steam boilers (ignition source) too close to the liquefaction trains and occupied buildings.
East Ohio Gas Company / Transport Canada	Cleveland, OH LNG Facility	10/20/1944	This occurred during the infancy of LNG commercialization, when some tank design requirements were not well understood. Failure of a tank bottom plate was determined to be at fault. The material of construction was a 3.5 % Ni alloy steel, that was marginally accepted	A probable root cause was not identified, but structural failure was suspected. This incident revolutionized the design of LNG tanks including material selection (9% Ni alloy), spill drainage and impoundment, and foundation design. It is only of historical significance now due to standardization of LNG tank design.

Reference	Facility/Location	Data	Incident Description	Root Cause
			for this low temperature service. The failure resulted in a massive surge of LNG and cool vapor that almost immediately found an ignition source.	
Transport Canada	Includes both fixed facilities and transportation incidents	February 2023	The primary focus of this Transport Canada report's research was to identify information gaps on understanding the physical phenomena of LNG hazards in the transport of LNG; to recommend additional research to improve the knowledge; and hence to support improvements to LNG emergency response guidelines. An initial step of this research was to gather and assimilate a representative sample of LNG incidents, which includes the ones listed above and several additions. The hazards are classified by types and consequences. The three main LNG hazards are characterized as Flammability, Explosivity, and Cryogenics. (Table 1 of Section 3.5.1 Representative Sample of Historical LNG Incidents)	▪ Incident history reveals there are no incidents with containers constructed to North American LNG transport standards that can clearly be attributed to BLEVE. ▪ There is currently a lack of consensus within research into Rapid Phase Transition (RPT) from spills of LNG on water. The uncertainties revolve around whether or not a RPT will occur in a spill event, and how many, the strength of the overpressure explosion, and the ignition potential.

Appendix Section 7-A: Facility Siting Checklist

#	Item	Source(s)
1.1	Have the geotechnical factors been considered including the geo-mechanical characteristic of the sub-soil for the site assessment?	BS EN 1473:2021
1.2	Have the marine geotechnical characteristics for jetty design and marine access been considered for the site assessment?	BS EN 1473:2021
1.3	Has harbor dredging been discussed and/or arranged with the responsible harbor authority?	BS EN 1473:2021
1.4	Does the site study include sea water quality, temperature, tidal, wave, wind conditions, and the risks of flooding from rain or seaside?	BS EN 1473:2021
1.5	Does the site study consider the air temperature, relative humidity, atmospheric stability, corrosive characteristic of the air?	BS EN 1473:2021
1.6	Have the risk, consequences and mitigation of lightning been considered?	BS EN 1473:2021 (CCPS Hazard Evaluation 3rd Edition, Appendix B)
1.7	Is climate data, including forecasted frequency and strength of severe storms, rainfall, snow, icing relevant to the duration of the facilities life expectancy readily available to site personnel?	BS EN 1473:2021
1.8	Have all potential emissions from the plant been identified?	BS EN 1473:2021
1.9	Does the plant facilitate controls/abatement of harmful emissions that are either solid/liquid/gaseous?	BS EN 1473:2021
1.10	Have potential waste stream(s) been minimized to ensure low utilization of emergency flare system?	BS EN 1473:2021
1.11	Is process water effluent discharging directly to the environment in any way monitored and minimized when possible?	BS EN 1473:2021
1.12	Have the nearest traffic routes (through land, sea and/or air) to/from the LNG plant been assessed?	BS EN 1473:2021
1.13	Has the local land been surveyed to identify surrounding infrastructure, types of terrain, potential ignition sources and/or fire risks?	BS EN 1473:2021
1.14	Has the marine ecosystem been studied within the surrounding of the LNG port?	BS EN 1473:2021
1.15	Has there been planning to ensure safe distances and adequate maneuvering area is provided whilst LNG carriers are in transit within the port and at berth?	BS EN 1473:2021

#	Item	Source(s)
1.16	Has earthquake analysis been carried out for the site and presented in an appropriate seismic report?	BS EN 1473:2021 33 CFR Part 127 Subpart B: §127.103
1.17	Has there been studies relating to the ground water tables?	BS EN 1473:2021
1.18	Has the suitability of the location been assessed considering the current and future social/industrial/transportation developments and their impacts on the plant operation and maintenance philosophy?	BS EN 1473:2021
1.19	Does the siting of the plant provision for safe releases of unignited process fluid (i.e LNG) to potentially populated areas?	NFPA 59A Section 5.3.2.7/8
1.20	Does the siting/layout/feature of the plant minimize the radiative effect of ignited LNG?	NFPA 59A Section 5.3.2.10
1.21	Are there precautionary measures (inherent to the siting) to maintain the overpressure level due to potential deflagration/detonation of LNG vapor cloud to as low as possible?	NFPA 59A Section 5.3.2.9
1.22	Do containers/vessels containing ignitable fluid (other than LNG) exist within an LNG tank impounding area?	NFPA 59A
1.23	Is LNG plant control center located on site and is it accessible at all times to responsible/authorized personnel?	49 CFR Part 193: §193.2441
1.24	Are outdoor areas within the LNG plant well-lit between sunset and sunrise and are light sources located on average, 1 m above the walking surface?	33 CFR Part 127 - Subpart B: §127.319/1109
1.25	Are motor vehicles permitted to be on site of the LNG plant and are they situated at least 15 m (49.2 ft) away from any storage tank or loading flange?	33 CFR Part 127 - Subpart B: §127.311
1.26	Is there a building or facility alarm or communication system to warn building-occupants (of an emergency)?	(CCPS Hazard Evaluation 3rd Edition, Appendix B)
1.27	Are there safe exit routes from the LNG facility?	(CCPS Hazard Evaluation 3rd Edition, Appendix B)
1.28	Is all auxiliary electrical gear (e.g. transformers, breakers) located in safe areas (e.g. away from flooding, hazardous materials)? (CCPS Hazard Evaluation 3rd Edition, Appendix B)	(CCPS Hazard Evaluation 3rd Edition, Appendix B)
1.29	Are all buildings intended for occupancy (including change rooms, conference rooms, lunchrooms) included in the siting assessment?	API 752, 2009 Ed.
1.30	Is there at least one portable fire extinguisher in the parking area of the LNG plant?	33 CFR Part 127 Subpart B: §127.603
1.31	If the portable extinguisher provided is a dry chemical extinguisher, does it contain a minimum nominal agent capacity of 20 lb (9kg) and is it capable of discharging a minimum of 1 lb/s of said agent?	NFPA 59A Section 16.6.1.3

Appendix Section 7-B: Maintenance and Procedures

#	Item	Source(s)
2.1	Is there a startup and shutdown procedure documented for all aspects of the LNG facility which include purging, component inerting and cooldown?	29 CFR 1910.119 (OSHA) NFPA 59A
2.2	Are there procedures available for maintaining process parameters (temperature, pressure differentials, flow rates) to within the maximum allowable operating limit for all plant equipment? This includes screening and response for the existence of any abnormal conditions.	NFPA 59A Section 18.3.8
2.3	Are equipment and areas of the plant actively maintained to minimize fire hazard (debris, etc.) and ice formation (which can impede performance)?	CSA Z276 §13.4.3.2 and 13.4.3.3
2.4	Has a contingency plan been developed internally that highlights potential hazards of upsets relative to LNG which includes descriptions and locations of firefighting equipment, nearest exits and emergency response (dos/don'ts) procedures?	NFPA 59A 49 CFR Part 192: Subpart M CSA Z276 §13.4.3.4
2.5	Have security procedures been reviewed and revalidated in the last 27 months of operations?	NFPA 59A Section 18.5.2
2.6	On site, is there provision for daily monitoring to ensure that the 32 F isotherm does not penetrate the soil below a tank in contact with the ground?	NFPA 59A Section 18.6.2.1 CSA Z276 §13.3.5.2.1
2.7	Prior to commissioning AND decommissioning an LNG vessel, has the containment been purged thoroughly with inert (or non-flammable / non-toxic medium)?	NFPA 59A Section 18.6.5.3 and 18.6.5.6.4/5
2.8	During purging or loading of LNG equipment, is oxygen level inside monitored using an oxygen analyzer or similar equipment to ensure the oxygen level inside does not exceed 2 vol%?	NFPA 59A Section 18.6.5.8
2.9	LNG transfer into a static/transportation vessel is properly grounded to Earth for the duration of the filling process?	CSA Z276 §10.7.2
2.10	Have high level inspections been made, and review of transfer sequence agreed upon with vessel operator before each transfer of LNG/processing of LNG?	49 CFR part 193 - §193.2623
2.11	Is the LNG facility clearly segmented into distinct areas that are accessible?	49 CFR Part 192: Subpart M
2.12	Is there a program in place where all operators are assigned a routine patrol to ensure the transmission lines (dependent on sizes and locations) are in satisfactory conditions and activities around the site are not beyond the norm?	49 CFR Part 192: Subpart M

#	Item	Source(s)
2.13	(Bookkeeping) Responsible plant personnel store records of each repair/modification in the least 5 years, including locations, dates and descriptions?	49 CFR Part 192: Subpart M ASME B31.8S-2022 Section A-3.8
2.14	Responsible plant personnel store records of assessment results that are aimed to maintain the integrity of LNG equipment such as hydrotesting in Stress Corrosion Cracking (SCC) detection?	ASME B31.8S-2022 Section A-3.8
2.15	Are redundancies provided as part of the facility design being inspected regularly every calendar year (or at least every 15 months)?	49 CFR Part 192: Subpart M
2.16	Are all hoses used for transfer of LNG and flammable refrigerant being inspected at least once every 15 months?	49 CFR Part 193: §193.2621
2.17	Leak surveys are completed at least semi-annually (quarterly if static pipeline is unprotected)?	49 CFR Part 192: Subpart O
2.18	When a pipeline is taken out of service, are operators familiar with inspections of the pipe internals and externals before reinstating?	49 CFR Part 192: Subpart I
2.19	Are all aspects of the LNG pipelines being maintained to the same, high quality and in a safe condition? This includes but is not limited to the valves, bridles, primary attachments, and out-of-service pipelines.	UK HSE L82 A guide to the Pipelines Safety Regulations
2.20	Is the procedure for surface water removal in the aftermath of adverse weather documented and available?	NFPA 59A
2.21	Are LNG-related plant equipment operated in accordance with their respective operating manuals?	
2.22	Do all transfer hoses and loading arms have permanently attached nameplates/markings that indicate the grades of LNG in service, and its operating and design conditions?	33 CFR Part 127 - Subpart C: §127.1102 CSA Z276 §9.3.5
2.23	Are all relief devices in service of LNG (and their respective safety system in place) inspected and tested in the interval of once every 30 months?	CSA Z276 §13.4.6.2
2.24	Are generally accepted procedures for tank and piping cooldown used to minimize stress due to system contraction?	

Appendix Section 7-C: Human Factors Checklist

#	Item	Source(s)
3.1	Have shift work and overtime schedules been designed to minimize operator fatigue/stress?	PSMPro™ - Human Factor Template - CCPS
3.2	Are operators enrolled in a recognized written/hands-on qualification program related to LNG handling in land or in marine environment (which shall include examinations) or similar?	49 CFR Part 192: Subpart N: Qualifications of Pipeline Personnel 33 CFR Part 127 - Subpart B: §127.501/503 NFPA 59A Section 18.11.5
3.3	Are there ways of maintaining training records from the last 5 years that can be reviewed regularly by qualified personnel (i.e supervisors) or the individual whom it belongs?	49 CFR Part 192: Subpart N: Qualifications of Pipeline Personnel
3.4	Are new personnel who have yet to complete the LNG training program working under tight supervision of a trained personnel?	NFPA 59A Section 18.11.4
3.5	Has the facility allocated time and resources to address human factor issues?	PSMPro™ - Human Factor Template - CCPS
3.6	Are critical controls operated in the same manner they are purposed/intended (e.g., up/down/push/pull)?	PSMPro™ - Human Factor Template - CCPS
3.7	Is there a procedure in place to evaluate an individual/groups' competency should an operator believe that the individual's performance had contributed to a minor/major incident?	49 CFR Part 192: Subpart N: Qualifications of Pipeline Personnel
3.8	Are changes within the plant frequently and thoroughly communicated with the responsible personnel in the forms of formal proceedings?	49 CFR Part 192: Subpart N: Qualifications of Pipeline Personnel
3.9	Is human factors support and expertise available within the organization?	PSMPro™ - Human Factor Template - CCPS
3.10	Have actions been taken to reduce the likelihood and impact of potential human errors?	PSMPro™ - Human Factor Template - CCPS
3.11	Has there been efforts in familiarizing the public with the risks and hazards of all operations pertinent to LNG so that they are aware of the emergency response plans in the event of an incident?	49 CFR Part 192: Subpart L API RP 1162
3.12	Has refresher training (and its frequency) been mandated as part of company policy to ensure high working standards are maintained (every 2 years)?	29 CFR 1910.119 (OSHA) NFPA 59A Section 18.11.6.1

#	Item	Source(s)
3.13	Are critical operating procedures clearly identified as such?	PSMPro™ - Human Factor Template - CCPS
3.14	Are all personnel familiar with damages/threats pertinent to all things LNG?	PSMPro™ - Human Factor Template - CCPS
3.15	Can personnel/operators competently select appropriate repair methods when necessary?	ASME B31.8S-2022 Chapter 7 - Table 7.1-1
3.16	Are all personnel working with LNG able to identify signs of process upsets/causes of failures and prevent further deterioration of process equipment?	ASME B31.8S-2022 Chapter 7 - Table 7.1-1
3.17	Is there adequate space to access system elements for normal operations and maintenance?	PSMPro™ - Human Factor Template - CCPS UK HSE L82 A guide to the Pipelines Safety Regulations
3.18	Are supervisors trained in detecting the effects of substance abuse/stress on the performance of personnel?	PSMPro™ - Human Factor Template - CCPS
3.19	Are there training programs and support services to help with controlled substance use or abuse or mental health problems?	PSMPro™ - Human Factor Template - CCPS
3.20	Are two-way communication systems available for personnel on land (in charge of transfer for the facility) and on-board of the transfer vessel (truck, ship)?	33 CFR Part 127 - Subpart C: §127.1111
3.21	Warning signs are present in LNG transfer area and writings are legible at all times?	33 CFR Part 127 - Subpart C: §127.613/1113 NFPA 59A Section 16.8.6
3.22	Are operators aware that welding work or any hot work is generally prohibited unless authorized by the responsible personnel through a granted permit (e.g. *Captain of the port* (COTP) in waterfront sites)	33 CFR Part 127 Subpart B: §127.617
3.23	A cybersecurity vulnerability assessment of the process control systems and safety instrumented systems is conducted every 2 years or at least every 27 months?	NFPA 59A Section 11.7.2
3.24	Are all personnel entering and leaving the plant identifiable through means of ID card or picture badges?	NFPA 59A Section 17.14 and 18.5.1

Appendix 7-D: Facility and Process Modification Checklist

#	Item	Source(s)
4.1	Spill and leak detection system is installed on relevant equipment?	NFPA 59A Section 5.2.3 and 5.3 49 CFR Part 192: Subpart M
4.2	Are LNG containers with capacity greater than 125 gallon (0.5 cubic meter) located only outdoors?	NFPA 59A Section 6.3.4 CSA Z276 §5.2.4.4
4.3	Are vaporizers, using ignitable fluid as its medium, located at least 50 ft (15 m) from any known source(s) of ignition AND are at least 100 ft (30 m) away from the designated property lines?	NFPA 59A Section 6.4.1/4
4.4	Is the volume of the impounding area equivalent to 110% of the LNG tank's available liquid capacity?	NFPA 59A Section13.1 49 CFR Part 193 - §193.2181 BS EN 1473:2021 CSA Z276 §5.2.2.1
4.5	For a shared impounding area, is the volume capacity equal to the cumulative volume of the LNG containers it is designated to?	NFPA 59A Section 13.2
4.6	As well as containing for leaks and spills, are the impounding area floors graded to prevent hazardous LNG accumulation?	NFPA 59A Section 13.2.2
4.7	Has the containment(s) been designed to withstand the maximum hydrostatic pressure of the impounded LNG in case tanks within it are fully drained?	NFPA 59A Section 13.6
4.8	Has the mechanical integrity of the impounding walls been assessed so that it can tolerate extreme impact such as loading under windborne missiles?	NFPA 59A Section 13.6
4.9	Has a secondary container system been designed and constructed to accommodate LNG spills during a secondary container fire?	NFPA 59A Section 13.7
4.10	Are impounding areas equipped with water removal systems capable of transporting a minimum of 25% of the rate of precipitation due to storm of a 10-year frequency for at least 1 hour?	NFPA 59A Section 13.12.1 49 CFR Part 193 - §193.2173
4.11	If water removal system is automated, does it offer redundant automatic shutdown control to prevent operation when LNG is present at large?	NFPA 59A Section 13.2.2 49 CFR Part 193 - §193.2173
4.12	Is a minimum of 3 ft (0.9 m) clearance provided along the pipelines to access all isolation valves in service?	NFPA 59A Section 6.3.3

#	Item	Source(s)
4.13	Redundancies (spares) provided for plant critical equipment, which includes emergency power supply/system that is rated to provide enough power for the operation of the Emergency Shutdown (ESD), communications equipment, firefighting, and emergency lighting?	49 CFR Part 193: §193.2445 33 CFR Part 127 Subpart B: §127.107
4.14	Has the design of the plant been optimized to reduce the effect of noise incoming from equipment?	BS EN 1473:2021
4.15	If the facility is to process/receive various grades of LNG (i.e. various densities), has the effort been made in segregating different grades of LNG into their individual containment to best avoid stratification?	SIGTTO - Guidance for the prevention of rollovers in LNG ships
4.16	If the latter is not possible, are storage tanks on site retrofitted with a closed-loop recirculation system (through a top fill line) that will promote break-ups of stratified liquid layers? Acceptable also is to run the in-tank pump on spill back mode to recirculate LNG until the top and bottom layer density variation is less than 2 kg/m3 and 2 °C for temperature variation	SIGTTO - Guidance for the prevention of rollovers in LNG ships GIIGNL - Rollover in LNG Storage Tanks
4.17	(For waterfront sites) Are substructures except moorings and breasted dolphins that support or are within 5 meters (16.4 ft) of any pipe or equipment containing LNG, or are within 15 meters of a loading flange made out of concrete or steel AND have a fire endurance rating of not less than 2 hours?	33 CFR Part 127 Subpart B: §127.103
4.18	(For waterfront sites) Are impounding areas located such that the heat flux from a fire over the impounding space does not cause structural damage to LNG vessels moored or berthed at waterfront facilities?	33 CFR Part 127 Subpart B: §127.105
4.19	Are LNG containers equipped with a level device (if smaller than 1,000 gal), or at a minimum of 1 liquid level device (for containers between 1,000 and 30,000 gal) or 2 liquid level devices (for containers larger than 30,000 gal) that can provide continuous level indication from 0-100%	NFPA 59A Section 11.3.1.1
4.20	Is each LNG container equipped with at least 2 independent pressure gauges that are connected at a point above the maximum liquid level?	NFPA 59A Section 11.4.1
4.21	Are flow safety devices (FSV) in the incoming pipeline provided immediately upstream from the process station and are FSV on the departing pipeline located as far downstream as reasonably practical but upstream of a block valve?	API RP 14C - Annex A: A.9.3.2
4.22	Are shut down devices (SDV) located in a way that minimizes or eliminates the extent of unprotected systems within the processing facility?	API RP 14C - Annex A: A.9.3.3
4.23	Are PSV installed on pipelines located on the downstream of input sources and installed in a way that prevents them from being isolated from the inlet sources?	API RP 14C - Annex A: A.9.3.1
4.24	To avoid LNG 'rollover' are LNG tanks alternatingly filled from the top and bottom depending on the densities of the incoming LNG relative to the stored LNG?	AspenTech Optimize 24 Conference – *Prevent LNG Tank Stratification and Rollover Events Through Operator Training*

Appendix Section 7-E: Damage Mechanism Checklist

#	Item	Source(s)
5.1	(To control internal corrosion) Does the production/storage process limit the concentration of corrosive species (i.e. CO_2, H_2S) flowing through the pipelines OR alternatively introduce inhibitors/scrapers to address these constituents?	49 CFR Part 192: Subpart L
5.2	Is there potential for accelerated corrosion to equipment installed in a naturally high pH/corrosive environment?	49 CFR Part 192: Subpart I
5.3	Do LNG vessels and containers undergo a recurring pressure test (at 1.1x MAWP held for 30 mins) every calendar year or at least once every 15 months?	33 CFR Part 127 - Subpart B: §127.407
5.4	Is there a clear audit plan outlining the preferred method of testing for Cathodic Protection?	
5.5	For each pipeline under Cathodic Protection, are there sufficient test stations to determine the adequacy of cathodic protection?	49 CFR Part 192: Subpart I - §192.463 (and see Appendix D) ASME B31.8S-2022 Chapter 13
5.6	Is there capacity internally for analyzing potential brittle damages/crack formations or development on equipment strained from cold LNG service or natural wear?	49 CFR Part 192: Subpart M - §192.712
5.7	Is there a response schedule to tackle indications of third-party damages and mechanical damages? Indications may include known pipelines operating at or above 30% Specified Minimum Yield Strength (SMYS), mechanical damages with/without concurrent visible indentation, dents that affect ductile girth or seam welds if depth is in excess of 2%, etc.?	ASME B31.8S-2022 Chapter 7.2.3
5.8	Is atmospheric corrosion being controlled by means of construction using resistant material or suitable coating/jacket?	49 CFR Part 193: §193.2627
5.9	Is external corrosion controlled for buried or submerged components?	49 CFR Part 193: §193.2629
5.10	Is internal corrosion controlled for buried or submerged components?	49 CFR Part 193: §193.2631
5.11	When cooldown stabilization is reached, are cryogenic piping systems being checked for leaks in vulnerable areas such as flanges, valves and seals?	49 CFR Part 193: §193.2505
5.12	To avoid LNG rollover, are tankers, carriers and terminals fitted with stratification detection systems? This may include temperature instruments capable of at least an accuracy to the nearest 0.1 °C and/or density measuring instruments capable of detecting variations to the nearest 0.1%	SIGTTO - Guidance for the prevention of rollovers in LNG ships
5.13	For storage tanks only, are there *active* safety mechanisms in place to prevent LNG 'rollover' such as mixing (jet) nozzles or multi orifice tube at the inlet feed line(s) to the tank?	SIGTTO - Guidance for the prevention of rollovers in LNG ships GIIGNL - Rollover in LNG Storage Tanks
5.14	Are there ways to detect the vapor contents in LNG containers to determine the rate of vaporization? Subsequent offset below the expected boil-off rate will indicate LNG stratification that can lead to 'rollover'	SIGTTO - Guidance for the prevention of rollovers in LNG ships

#	Item	Source(s)
5.15	Are LNG tanks/containers fitted with appropriate pressure relief devices such as vent or PSV to alleviate the consequence of vessel overpressure? (relief devices should be sized for a minimum capacity of <= 3 mass% of full tank contents in 24 hours)	GIIGNL - Rollover in LNG Storage Tanks NFPA 59A Section 7.8.5.3
5.16	If pressure relief in accordance with the requirements of API STD 521 is not technically or economically practical, is there at least a High Integrity Instrumented approach (such as HIPPS) to protect the system?	API RP 14C - Annex E: E.1.1 and E.1.5
5.17	Further to relief sizing, is there an appropriate and validated model that can be used to calculate the boil-off rate due to 'rollover'? Conservatively, this flowrate can be assumed to be 100x the maximum flowrate of a tank boil-off due to heat input during normal operation based on observed past rollover incidents	GIIGNL - Rollover in LNG Storage Tanks
5.18	In the emergency response documentation, does the LNG plant/site provision for remote shutdown of sources of ignition that are potentially in the path of the dispersing gas in case of a leak?	GIIGNL - Rollover in LNG Storage Tanks
5.19	Are emergency shutdown (ESD) manual control stations located strategically throughout the facility for complete shut in of all hydrocarbon sources?	API RP 14C - Annex G: G.2.1.1
5.20	Are ESD systems designed to permit continued operation of emergency paramount systems such as firefighting equipment (and other support systems)?	API RP 14C - Annex G: G.2.1.1
5.21	Are transfer and enclosed areas equipped with at least 2 gas detection systems that are capable of detecting 0-100% of the lower flammable limit (LFL) of methane?	NFPA 59A Section 16.7.4 33 CFR Part 127 - Subpart B: §127.203 API RP 14C - Annex G: G.2.3.2
5.22	Is the fire water supply able to feed water to the fire protection system (which includes the monitor nozzles) at the rate of the design flow and pressure PLUS an allowance of 1,000 gpm (63 L/s)?	NFPA 59A Section 16.5.2
5.23	Are indoor LNG facilities ventilated and capable of handling a venting rate of at least 1 cfm of air per ft^2 (5 L/s of air per m^2) of floor area? Alternatively, these vents are adequately sized to prevent accumulation of combustible gas above 25% of the lower explosive limit (LEL)?	NFPA 59A Section 12.7.3 CSA Z276 §5.3.2.3 API RP 14C - Annex G: G.2.4
5.24	If there are basements or depressed floor levels, is there an additional mechanical ventilation system in place?	CSA Z276 §5.3.2.2 (d)
5.25	Are pumps and compressors in an LNG facility fitted with vents or PSVs, or both, to ensure safe working pressure is attainable?	CSA Z276 §6.1.4
5.26	The installed insulation on LNG vessels are noncombustible and will not decompose at temperatures up to 538 °C (1, 000 °F)?	CSA Z276 §7.6.3.3.2 (a)
5.27	For PSVs installed to protect the LNG vaporizers, are they installed at a location where they will not be subjected to temperatures exceeding 60 °C (140 °F)?	CSA Z276 §8.4.2
5.28	Are liquid lines connected to LNG containment/equipment that have the potential to release large quantities of LNG made out of any material whose melting point is below 1,093 °C (exception made for liquid lines protected against fire exposure)?	CSA Z276 §9.2.2.3

Appendix Section 8-A: Example PHA

Node 1 2
Node 2 7
Risk Matrix 14
P&IDs – Node 1 16

Deviation #	Deviation	Cause #	Cause	Consequences #	Consequences	S0	L0	R0	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations	S1	L1	R1
1.1	Vacuum	1.1.1	BOG (boiloff gas) compressor C-01 failure during loading	1.1.1.1	Vacuum and collapse of inner tank resulting with possible fire in outer tank with casualties	5	5		1.1.1.1.1	PALL03 shuts down loading pumps P-01 A/D	5	2		1.1.1.1.1	Install SIL2 SIF on pump trip to further mitigate the risk	5	1	
									1.1.1.1.2	Vacuum relief PSV002 - 6 12" valves vs. BOG inlet line 16"								
1.2	Composition	1.2.1	LNG composition change due to liquefication process operation outside of specified parameters	1.2.1.1	Tank rollover with rapid vapor generation overwhelming of boiloff system capacity resulting in overpressure and tank damage a large vapor cloud release	3	4		1.2.1.1.1	Conitnuous density measurement on rundown line and DT039 density measurement in the tank with differential alarm and operator response	3	2						
									1.2.1.1.2	Loading line recirculation provides continuous mixing in the tank with FT004A/D low flow alarm with operator response								
									1.2.1.1.3	Redundant pumps P-01A/D available								
				1.2.1.2	Tank rollover with rapid vapor generation overwhelming of boiloff system capacity resulting in overpressure and a large vapor cloud	5	4		1.2.1.2.1	Conitnuous density measurement on rundown line and DT039 density measurement in the tank with differential alarm and operator response	5	2						

Deviation #	Deviation	Cause #	Cause	Consequences #	Consequences	S0	L0	R0	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations	S1	L1	R1
					release from PSV-002's with flash fire and possible fatality				1.2.1.2.2	Loading line recirculation provides continuous mixing in the tank with FT004A/D low flow alarm with operator response								
									1.2.1.2.3	Redundant pumps P-01A/D available								
				1.2.1.3	Tank rollover with rapid vapor generation overwhelming of boiloff system capacity resulting in overpressure and tank damage a large vapor cloud release with multiple fatalities	6	4		1.2.1.3.1	Conitnuous density measurement on rundown line and DT039 density measurement in the tank with differential alarm and operator response	6	1						
									1.2.1.3.2	Loading line recirculation provides continuous mixing in the tank with FT004A/D low flow alarm with operator response								
									1.2.1.3.3	Redundant pumps P-01A/D available								
									1.2.1.3.4	Relief devices on storage tank PSV004 A/F (sized for rollover scenario)								
		1.2.2	LNG composition change in tank due to unloading of denser material due to boiloff during transit	1.2.2.1	Tank rollover with rapid vapor generation overwhelming of boiloff system capacity resulting in overpressure and tank damage a large vapor	3	5		1.2.2.1.1	Conitnuous density measurement on rundown line and DT039 density measurement in the tank with differential alarm and operator response	3	3						

Deviation #	Deviation	Cause #	Cause	Consequences #	Consequences	S0	L0	R0	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations	S1	L1	R1
					cloud release				1.2.2.1.2	Loading line recirculation provides continuous mixing in the tank with FT004A/D low flow alarm with operator response								
									1.2.2.1.3	Redundant pumps P-01A/D available								
				1.2.2.2	Tank rollover with rapid vapor generation overwhelming of boiloff system capacity resulting in overpressure and a large vapor cloud release from PSV's with flash fire and possible fatality	5	5		1.2.2.2.1	Conitnuous density measurement on rundown line and DT039 density measurement in the tank with differential alarm and operator response	5	3						
									1.2.2.2.2	Loading line recirculation provides continuous mixing in the tank with FT004A/D low flow alarm with operator response								
									1.2.2.2.3	Redundant pumps P-01A/D available								
				1.2.2.3	Tank rollover with rapid vapor generation overwhelming of boiloff system capacity resulting in overpressure and tank damage a large vapor	6	5		1.2.2.3.1	Conitnuous density measurement on rundown line and DT039 density measurement in the tank with differential alarm and operator response	6	2						

Deviation #	Deviation	Cause #	Cause	Consequences #	Consequences	S0	L0	R0	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations	S1	L1	R1
					cloud release with multiple fatalities				1.2.2.3.2	Loading line recirculation provides continuous mixing in the tank with FT004A/D low flow alarm with operator response								
									1.2.2.3.3	Redundant pumps P-01A/D available								
									1.2.2.3.4	Relief devices on storage tank PSV004 A/F (sized for rollover scenario)								
1.3	Low temperature	1.3.1	Temperature controller TC034 failure on foundation heaters - single controller with 11 temperature sensors	1.3.1.1	Deep ground frost penetration under foundation causing soil upheaval resulting in foundation failure and possible buckling of tank bottom plates with spill of LNG and flash vapor fire and possible fatality	5	5		1.3.1.1.1	None - cannot risk rank scenario without additional detailed information								
1.4	High level	1.4.1	Level transmitter failure LT050	1.4.1.1	Overflow of inner tank with LNG entering annular space between inner and outer containment vessel causing rapid vaporization and release from PSV and flash fire with single fatality	5	5		1.4.1.1.1	Level transmitter LT046 with alarm and operator response	5	3		1.4.1.1.1	Install SIL2 SIF on inlet line closure to further mitigate the risk	5	2	
									1.4.1.1.2	High level switch LSHH049 stops flow to tank -SIF SIL 1								
				1.4.1.2	Sudden contact of outer wall with LNG resulting in brittle fracture of plates and a two phase release with flash fire and fatality	5	5		1.4.1.2.1	Level transmitter LT046 with alarm and operator response	5	3		1.4.1.2.1	Install SIL2 SIF on inlet line closure to further mitigate the risk	5	2	
									1.4.1.2.2	High level switch LSHH049 stops flow to tank -SIF SIL 1								

Deviation #	Deviation	Cause #	Cause	Consequences #	Consequences	S0	L0	R0	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations	S1	L1	R1
1.5	Loss of containment	1.5.1	Piping failure due to contraction stresses (cool down) - system cooled down too rapidly - temperature cycling	1.5.1.1	Significant flange leak or weld failure resulting in LNG realease with possible confined vapor explosion and multiple fatalities	6	3		1.5.1.1.1	Design to ASME standards for temperature cycling	6	1						
									1.5.1.1.2	Flange torquening procedure								
									1.5.1.1.3	Tightness testing at operating pressure and temperature								
1.6	High vibration	1.6.1	Geysering in LNG tank rundown riser (surging due to two phase flow)	1.6.1.1	Excessive vibration resulting in loss of containment due to flange failure. Possible release with flash fire and single fatality	5	3		1.6.1.1.1	Piping and supports designed to ASME standards	5	1						
									1.6.1.1.2	Use of flanges minimized								
									1.6.1.1.3	Flange torquing procedure								
1.7	Maintenance	1.7.1	Crane cable issues during submerged pump P-01A/D maintenance	1.7.1.1	Crane load dropped over roof of storage tank resulting in roof puncture and flammable vapor release with delayed ignition at ground level with one fatality	5	2		1.7.1.1.1	Heavy lift plan approved	5	1						
									1.7.1.1.2	Crane maintenance PM								
									1.7.1.1.3	Crane operator training								
1.8	High pressure																	
1.9	Low pressure																	
1.10	High temperature																	
1.11	Low/No level																	

Deviation #	Deviation	Cause #	Cause	Consequences #	Consequences	S0	L0	R0	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations	S1	L1	R1
1.12	High flow																	
1.13	Low/No flow																	
1.14	Reverse flow																	
1.15	Misdirected flow																	
1.16	High agitation/mixing																	
1.17	Low agitation/mixing																	
1.18	No agitation/mixing																	
1.19	Incomplete reaction																	
1.20	No reaction																	
1.21	Composition																	
1.22	Reactants added in wrong order																	
1.23	Steps out of order																	
1.24	Startup																	
1.25	Shutdown																	
1.26	Emergency																	
1.27	Contaminants or impurities																	
1.28	Material of construction																	
1.29	Sampling																	
1.30	Corrosion/ erosion																	

Deviation #	Deviation	Cause #	Cause	Consequences #	Consequences	S0	L0	R0	Safeguards #	Safeguards	S	L	R	Recommendations #	Recommendations	S1	L1	R1
1.31	Impact																	
1.32	Effluent																	
1.33	Service/utilities failure																	
1.34	Facility siting																	
1.35	Human factors																	
1.36	External fire																	

Company: LNG Processing Co. **Date:** 10/25/2024 **System:**
Drawing Numbers:
Unit/Process: Train 1 LNG Liquefaction, storage and loading
Equipment/Lines:
Description: LOPA
Design Intent:

Example PHA **Node 2 (LOPA)** **Worksheet generated: January 17, 2025**

PHA Scenario Reference #	PHA Scenario Reference	Scenario Description	Severity Level	Type	Consequence #	Consequence	Target Frequency (per year)	Initiating Event Description	Initiating Event #	Initiating Event	Frequency (per year)	Event Modifier Description	Modifier Factor	Scenario Frequency (per year)	Non-IPL Safeguards	IPL Description	IPL #	IPL	IPL Value	Total Frequency (per year)	R	Required SIL	Recommendations #	Recommendations
2.1	Scenario 1.2.2.2	Tank rollover with rapid vapor generation overwhelming of boiloff system capacity resulting in overpressure and a large vapor	5	Safety Criteria	2.1	Single fatality	1E-05	LNG composition change in tank due to unloading of denser material due to boiloff during transit	2.1	Initiating event level 1	0.1	Ignition probability	0.1	0.005	Conitnuous density measurement on rundown line and DT039 density measurement in the tank with differential alarm and operator response	Density measurement with alarm with operator response	2.1.1	Operator response to alarm with at least 10 minutes response time	1.E-1	5E-05		1		

PHA Scenario Reference #	PHA Scenario Reference	Scenario Description	Severity Level	Type	Consequence #	Consequence	Target Frequency (per year)	Initiating Event Description	Initiating Event #	Initiating Event	Frequency (per year)	Event Modifier Description	Modifier Factor	Scenario Frequency (per year)	Non-IPL Safeguards	IPL Description	IPL #	IPL	IPL Value	Total Frequency (per year)	R	Required SIL	Recommendations #	Recommendations
		cloud release from PSV's with flash fire and possible fatality													Loading line recirculation provides continuous mixing in the tank with FT004A/D low flow alarm with operator response	Loading line recirculation provided continuous mixing - no operator response required	2.1.2	IPL level 1	1.E-1				2.1.1	Replace SIL 1 SIF with SIL2 SIF on inlet line closure to further mitigate the risk
															Redundant pumps P-01A/D available									
												Personnel presence	0.5											

PHA Scenario Reference #	PHA Scenario Reference	Scenario Description	Severity Level	Type	Consequence #	Consequence	Target Frequency (per year)	Initiating Event Description	Initiating Event #	Initiating Event	Frequency (per year)	Event Modifier Description	Modifier Factor	Scenario Frequency (per year)	Non-IPL Safeguards	IPL Description	IPL #	IPL	IPL Value	Total Frequency (per year)	R	Required SIL	Recommendations #	Recommendations
2.2	Scenario 1.2.2.3	Tank rollover with rapid vapor generation overwhelming of boiloff system capacity resulting in overpressure and tank damage a large vapor cloud release with multiple fatalities	6	Safety Criteria	2.4	Multiple fatalities	1E-06	LNG composition change in tank due to unloading of denser material due to boiloff during transit	2.2	Initiating event level 1	0.1	Ignition probability	0.1	0.005	Conitnuous density measurement on rundown line and DT039 density measurement in the tank with differential alarm and operator response	Density measurement with alarm with operator response	2.2.1	Operator response to alarm with at least 10 minutes response time	1.E-1	5E-08		0		
															Loading line recirculation provides continuous mixing in the tank with FT004A/D low flow alarm with operator response	Loading line recirculation provided continuous mixing - no operator response required	2.2.2	IPL level 1	1.E-1					

PHA Scenario Reference #	PHA Scenario Reference	Scenario Description	Severity Level	Type	Consequence #	Consequence	Target Frequency (per year)	Initiating Event Description	Initiating Event #	Initiating Event	Frequency (per year)	Event Modifier Description	Modifier Factor	Scenario Frequency (per year)	Non-IPL Safeguards	IPL Description	IPL #	IPL	IPL Value	Total Frequency (per year)	R	Required SIL	Recommendations #	Recommendations
															Relief devices on storage tank PSV004 A/F (sized for rollover scenario)	Relief devices on storage tank PSV004 A/F (sized for rollover scenario)	2.2.3	Pressure relief device (multiple redundant PRDs in clean service and/or contains in-line valves under proper management system)	1.E-3					
															Redundant pumps P-01A/D available									
												Personnel presence	0.5											
2.3	Scenario 1.4.1.1	Overflow of inner tank with LNG entering annular space between inner and	5	Safety Criteria	2.9	Single fatality	1E-05	Level transmitter failure LT050	2.3	BPCS instrument loop failure	0.1	Ignition probability	0.1	0.005	Level transmitter LT046 with alarm and operator response	Redundant level transmitter with alarm and operator response	2.3.1	Operator response to alarm with at least 10 minutes response time	1.E-1	5E-05		1	2.3.1	Replace SIL 1 SIF with SIL2 SIF on inlet line closure to further mitigate the risk

PHA Scenario Reference #	PHA Scenario Reference	Scenario Description	Severity Level	Type	Consequence #	Consequence	Target Frequency (per year)	Initiating Event Description	Initiating Event #	Initiating Event	Frequency (per year)	Event Modifier Description	Modifier Factor	Scenario Frequency (per year)	Non-IPL Safeguards	IPL Description	IPL #	IPL	IPL Value	Total Frequency (per year)	R	Required SIL	Recommendations #	Recommendations
		outer containment vessel causing rapid vaporization and release from PSV and flash fire with single													High level switch LSHH049 stops flow to tank -SIF SIL 1	High level switch LSHH049 stops flow to tank -SIF SIL 1	2.3.2	SIS/SIF SIL-1	1.E-1					
												Personnel presence	0.5											
2.4	Scenario 1.4.1.2	Sudden contact of outer wall with LNG resulting in brittle fracture of plates and a two phase release with flash fire and fatality	5	Safety Criteria	2.11	Single fatality	1E-05	Level transmitter failure LT050	2.4	BPCS instrument loop failure	0.1	Ignition probability	0.1	0.005	Level transmitter LT046 with alarm and operator response	Redundant level transmitter with alarm and operator response	2.4.1	Operator response to alarm with at least 10 minutes response time	1.E-1	5E-05		1	2.4.1	Replace SIL 1 SIF with SIL2 SIF on inlet line closure to further mitigate the risk
															High level switch LSHH049 stops flow to tank -SIF SIL 1	High level switch LSHH049 stops flow to tank -SIF SIL 1	2.4.2	SIS/SIF SIL-1	1.E-1					
												Personnel presence	0.5											

Severity Criteria

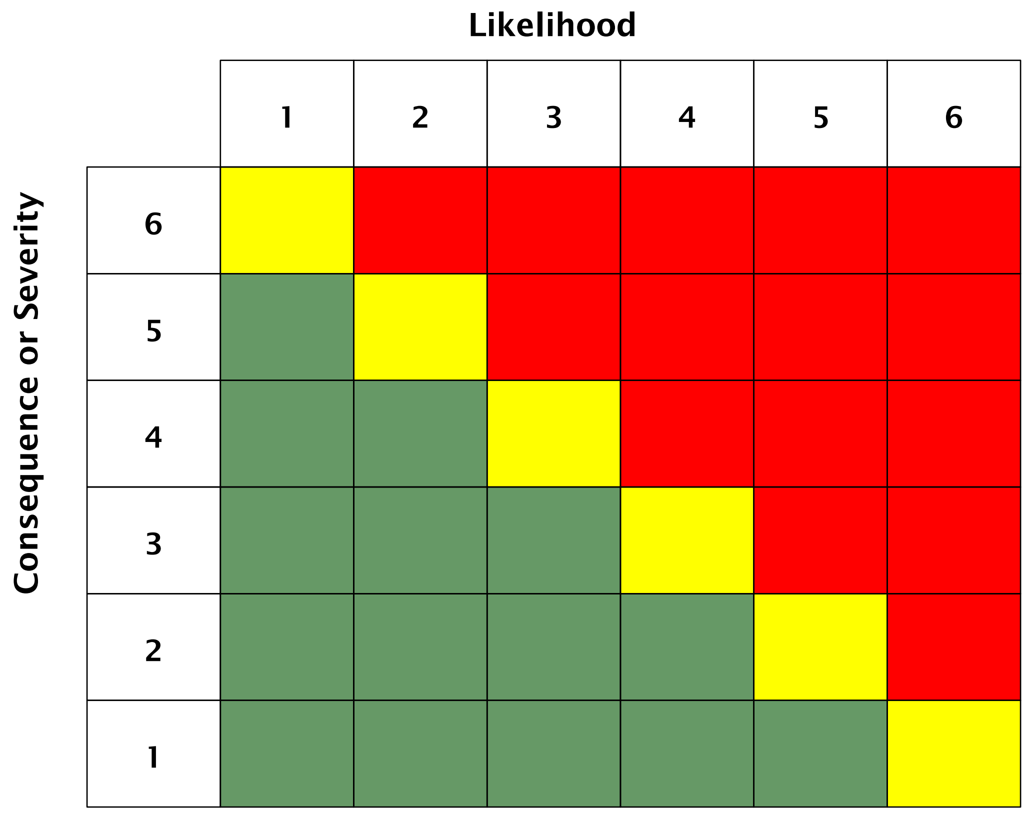
Description
Safety Criteria
Public Criteria
Environment Criteria
Business Interruption

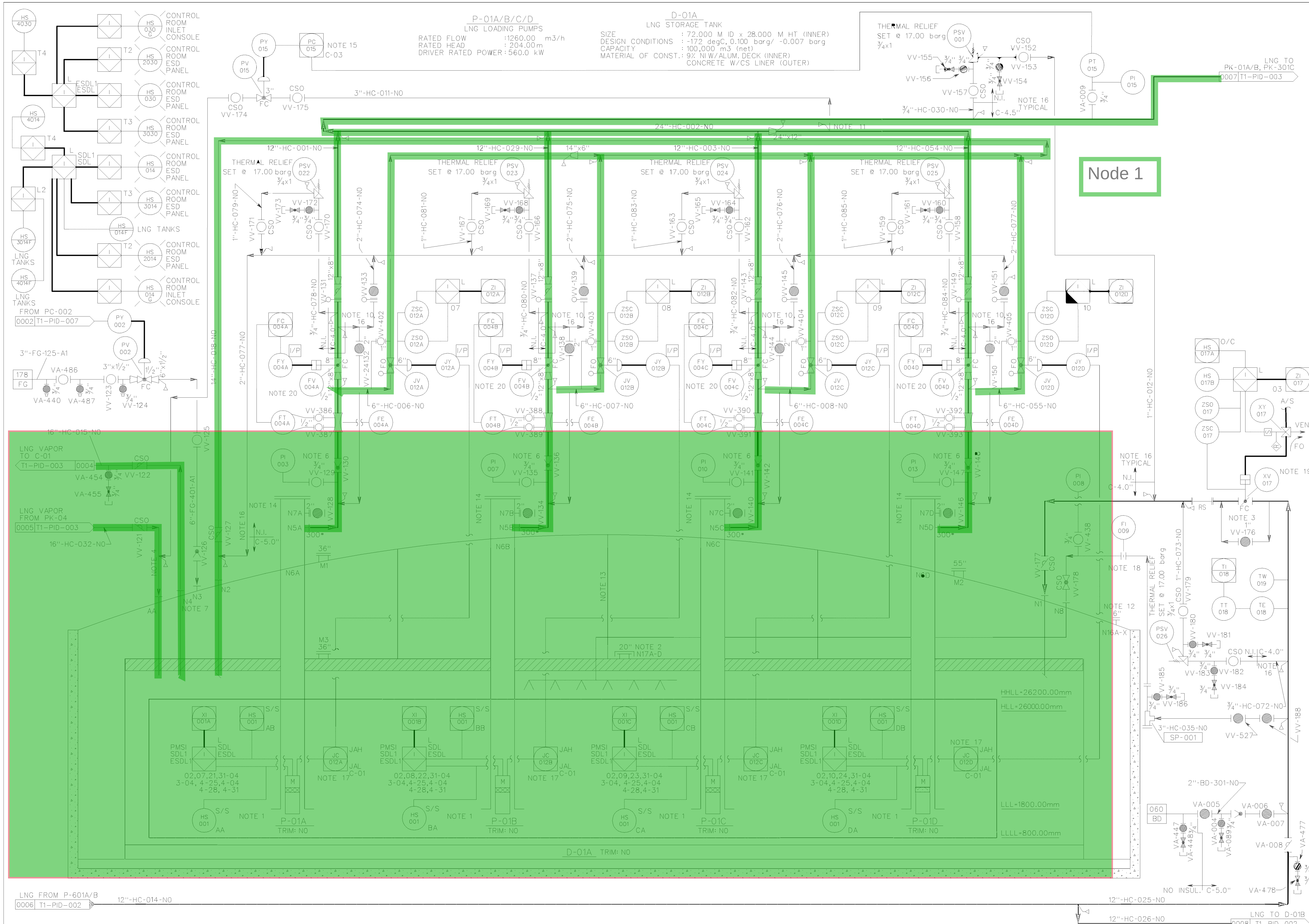
Likelihood

Level	Events per Year	Impact
1	10-4 to 10-5/yr	Likely to occur less than once per 10,000 years
2	10-3 to 10-4/yr	Likely to occur less than once per 1000 years to once in 10,000 years
3	10-2 to 10-3/yr	Likely to occur between once in 100 up to once in 1000 years
4	10-1 to 10-2/yr	Likely to occur between once in 10 up to once in 100 years
5	1/yr to 10-1/yr	Likely to occur between once a year up to once in 10 years
6	>1/yr	Likely to occur once a year or more

Consequence or Severity

Level	Target Frequency	Safety Criteria	Public Criteria	Environment Criteria	Business Interruption
6	1E-06	Multiple fatalities	Single fatality	An event that triggers a class action lawsuit by a third party	Plant damage/loss over $50 Million
5	1E-05	Single fatality	Irreversible injury	An environmental incident with significant local or national media attention	Plant damage/loss $1Million - $50 Million
4	0.0001	Irreversible injury	Public hospitalization	Remediation of soil off-site, or contaminates sediments, or ground or surface waters outside of site boundaries	Plant damage/loss value in excess of $1,000,000
3	0.001	Multiple lost work injuries	Public evacuation	An environmental incident which could contaminate ground water in immediate area around the site. Incident affecting public or downstream water users	Plant damage/loss value in excess of $500,000 to $1,000,000
2	0.01	Lost work time	Public shelter in place	An environmental incident where contamination is confined to the site and where recovery is complete in 1 year	-Installation seriously damaged/ production is temporarily stopped -Financial losses between $100,000 to $500,000
1	0.1	Reportable injury	No effects	A one time event, little or no WEC fine <25,000 MT of CO2 equivalent methane per year	Limited Damages, Financial Losses $10,000 to $100,000


Likelihood
1
2
3
4
5
6
Consequence or Severity
6
5
4
3
2
1



NOTES:

1. FOOT VALVE FOR COLUMN ISOLATION.
2. DECK VENT N17 (4 REQUIRED).
3. CLOSURE SPEED TO BE ADJUSTED TO MEET SAFETY REQUIREMENTS AND SURGE LIMITS.
4. LOCATE 3" TIE-IN BELOW HIGH POINT TO ENSURE LIQUID DRAINAGE INTO TANK AND NOT INTO VAPOR LINE.
5. ELEVATION BASIS: 0.00 m = MEAN SEA LEVEL.
6. NON-SLAM NON-RETURN VALVE WITH 5 MM DRILLED HOLE ON FLAPPER.
7. NOZZLE N4 (BOIL-OFF GAS COMPRESSOR SUCTION) TO BE LOCATED AT LEAST 90 DEGREES FROM NOZZLE AA (SHIP VAPOR RETURN).
8. DELETED
9. LOW POINT BLOW-DOWN CONNECTION.
10. LOCATE TAKE-OFF FROM BOTTOM OF PIPE.
11. LOCATE TAKE-OFF FROM TOP OF PIPE AT HIGH POINT.
12. PERLITE FILL NOZZLE N16 (24 REQ'D).
13. SUSPENDED DECK HANGERS.
14. SEE DETAIL 1 ON T1-PID-007.
15. COMPLEX LOOP [C-03]: INTERLOCK 03 ACTION PLACES PC-015 IN MANUAL AND RAMPS PV-015 CLOSED.
16. COLD INSULATE PIPES 1.5 m VERTICALLY FROM THE COLD END. TYPICAL FOR ALL PSV'S.
17. COMPLEX LOOP [C-01]: LNG STORAGE TANK (D-01A) LOADING PUMPS SHUTDOWN.
18. COOL DOWN LINE INSTALLED ONLY DURING START-UP.
19. VALVE PROVIDED WITH ADJUSTABLE SPEED CONTROL. DO NOT MODIFY CLOSURE TIME DUE TO POTENTIAL WATER HAMMER IMPLICATIONS. VALVE FULL STROKE CLOSURE NO FASTER THAN 90 SECONDS TO MEET SAFETY REQUIREMENT.
20. VALVE PROVIDED WITH ADJUSTABLE SPEED CONTROL. DO NOT MODIFY CLOSURE TIME DUE TO POTENTIAL WATER HAMMER IMPLICATIONS. VALVE FULL STROKE CLOSURE NO FASTER THAN 30 SECONDS TO MEET SAFETY REQUIREMENT.

L SDL SDLI	HANDSWITCH HS-014/2014/4014/3014/014F INITIATES SDL/SDLI/014G/3014F/4014F.
L ESDL ESDLI	HANDSWITCH HS-030/2030/4030/3030/030G INITIATES ESDL/ESDLI.
L 02	LNG STORAGE TANK D-01A LOW-LOW LEVEL STOPS LNG LOADING PUMPS P-01A THRU D.
L 03	LNG STORAGE TANK D-01A HIGH-HIGH PRESSURE OR HIGH-HIGH LEVEL CLOSES XV-017 & PV-015 (THRU PC-015).
L 07	RECIRC. VALVE JV-012A OPEN AND HV-608A/B FULLY OPEN OR CLOSED PERMISSIVE TO START PUMP P-01A.
L 08	RECIRC. VALVE JV-012B OPEN AND HV-608A/B FULLY OPEN OR CLOSED PERMISSIVE TO START PUMP P-01B.
L 09	RECIRC. VALVE JV-012C OPEN AND HV-608A/B FULLY OPEN OR CLOSED PERMISSIVE TO START PUMP P-01C.
L 10	RECIRC. VALVE JV-012D OPEN AND HV-608A/B FULLY OPEN OR CLOSED PERMISSIVE TO START PUMP P-01D
L 21	P-01A NOT RUNNING, JC-012A CONTROLLER TO MANUAL CLOSE VALVE.
L 22	P-01B NOT RUNNING, JC-012B CONTROLLER TO MANUAL CLOSE VALVE.
L 23	P-01C NOT RUNNING, JC-012C CONTROLLER TO MANUAL CLOSE VALVE.
L 24	P-01D NOT RUNNING, JC-012D CONTROLLER TO MANUAL CLOSE VALVE.
PMS1 L	PMS TRIPPED STOPS LNG LOADING PUMPS P-01A THRU P-01H.

NO.	DATE	REVISION	PROJ. ENGR.	PROC. ENGR.	MECH. ENGR.	CS. LEAD	PD&P LEAD	EGS	AREA ENGR.	PEM	CLIENT
00	30/09/2024	As Built	AB	CD	EF	GH	IJ	KL	NO	PQ	RS

NO.	DATE	REVISION	PROC. LEAD	INST. LEAD	ELEC. LEAD	MECH. LEAD	ENG MNGR.	PLANT MNGR.

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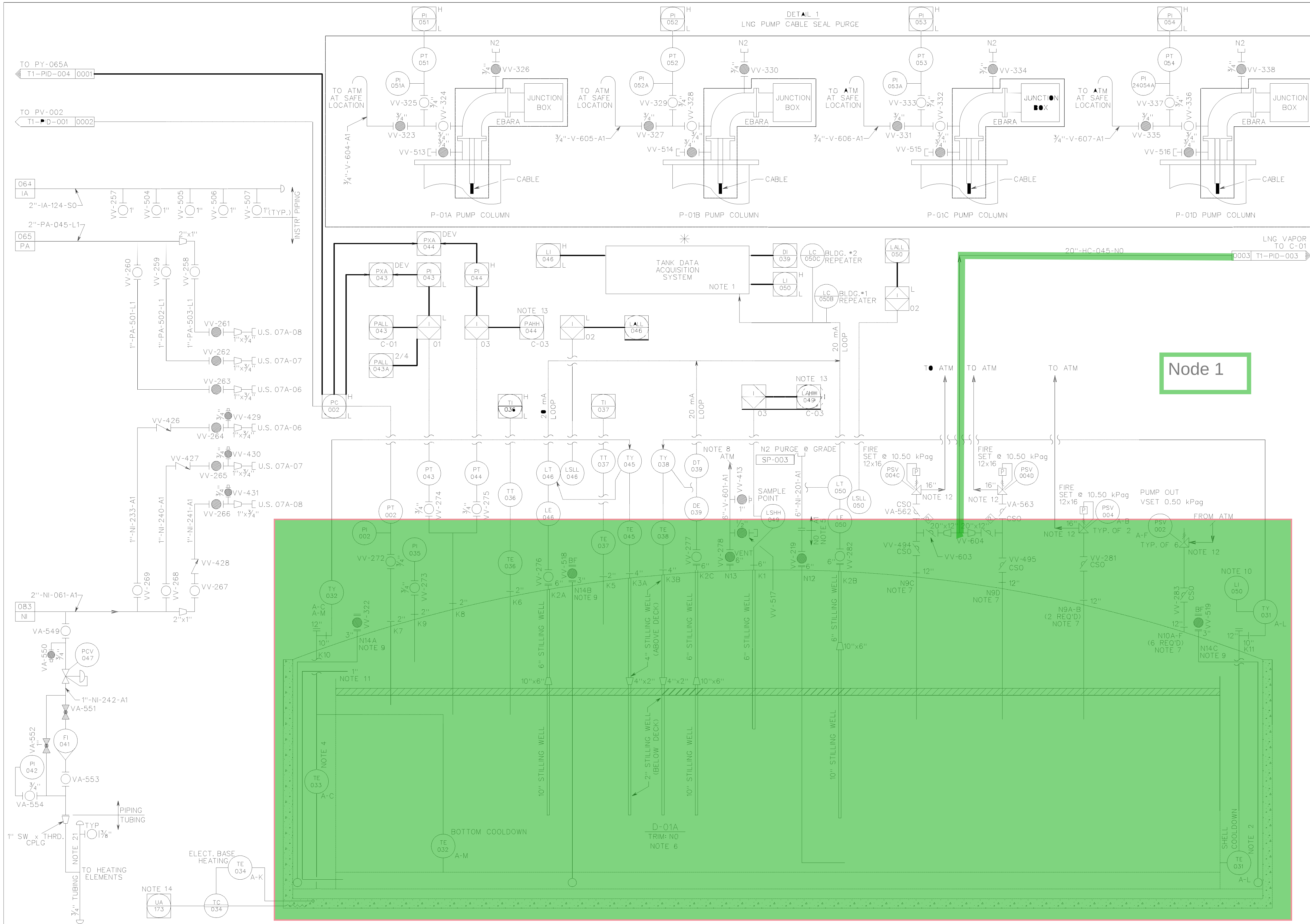
LNG TRAIN 1

PIPING AND INSTRUMENTATION DIAGRAM
LNG STORAGE TANK "A"
& LOADING PUMPS

CAD DATE:	09/30/2024
CAD FILE:	T1-PID-001.dwg
DRAWING NO.	T1-PID-001
SCALE:	NONE



NOTES:

1. COMBINED LEVEL, TEMPERATURE AND DENSITY MEASURING SYSTEM.
2. SKIN TYPE TEMP POINTS ATTACHED TO OUTER SURFACE OF INNER TANK SPACED EQUALLY OVER SHELL HEIGHT.
3. ALL TE'S ARE WIRED TO AND TERMINATED IN A JUNCTION BOX FOR USE AS REQUIRED.
4. THREE RTD'S FOR LEAK DETECTION SPACED EQUALLY AROUND CIRCUMFERENCE OF TANK AND LOCATED ON THE TANK FLOOR IN ANNULAR SPACE.
5. LOCATE SPEC BREAK 0.61 m MIN. DISTANCE FROM BLOCK VALVE.
6. REFERENCE P&ID T1-PID-001 FOR ADDITIONAL TANK INFORMATION.
7. NOT MORE THAN ONE PSV CAN BE TAKEN OUT OF SERVICE AT ANY ONE TIME. QUANTITY INCLUDES ONE SPARE.
8. VENT TO ATMOSPHERE AT SAFE LOCATION AT LEAST 3.048 M ABOVE NEAREST OPERATING LEVEL.
9. 3 REQ'D FOR ANNULAR SPACE PURGE DURING START-UP.
10. LOCAL LEVEL/TEMPERATURE INDICATION AT BASE OF TANK.
11. BASE INSULATION VENT PIPE (2 REQ'D).
12. PSV INLET AND OUTLET INFORMATION:

PSV NO.	INLET BLOCK VALVE	OUTLET LINE NO.	TE NO.
02A	VV-83	-	
02B	VV-88	-	
02C	VV-89	-	
02D	VV-90	-	
02E	VV-91	-	
02F	VV-92	-	
04A	VV-81	16"-V-13-022A/B	
04B	VV-93	16"-V-14-023A/B	
04C	VV-94	16"-V-15-024A/B	
04D	VV-95	16"-V-16-025A/B	

13. COMPLEX LOOP [C24-03]: D-01A/B SHUT DOWN PC-015 AND PC-215 ON HIGH-HIGH LEVEL OR HIGH-HIGH PRESSURE.
14. BASE HEATING SYSTEM COMMON TROUBLE ALARM.
15. NITROGEN PURGE TO BASE HEATER CONDUIT TUBING TO BE SYMMETRICAL.

I L 02 — LNG STORAGE TANK D-01A LOW-LOW LEVEL STOPS LNG LOADING PUMPS P-01A THRU D.

I L 03 — LNG STORAGE TANK D-01A HIGH-HIGH PRESSURE OR HIGH-HIGH LEVEL CLOSES XV-017, PV-015 (THRU PC-015)

NO.	DATE	REVISION	PROJ. ENGR.	PROC. ENGR.	MECH. ENGR.	CS. LEAD	PD&P LEAD	EGS	AREA ENGR.	EM	CLIENT
00	30/09/2024	As Built	AB	CD	EF	GH	IJ	KL	NO	PQ	RS

NO.	DATE	REVISION	PROC. LEAD	INST. LEAD	ELEC. LEAD	MECH. LEAD	ENG MNGR.	PLANT MNGR.

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TRAIN 1

PIPING AND INSTRUMENTATION DIAGRAM
LNG STORAGE TANK INSTR./N2 PURGE

CAD DATE:	09/30/2024
CAD FILE:	T1-PID-007.dwg
DRAWING NO.	T1-PID-007
SCALE:	NONE