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FINAL REPORT

GTI PROJECT NUMBER 21873

Project Title: Statistical Review and Gap Analysis of LNG Failure Rate Table

Contract Number: DTPH56-15-T-00008

Date Issued:
Jan. 11, 2017

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Summary of Research and Impact from Research Results

This report summarizes the results of U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) contract #DTPH56-15-T-00008 to review and consider recommendations for potential refinements of the LNG Failure Rate Table ("FRT"), which establishes the criteria for Design Spills into impounding areas at LNG facilities serving only vaporization, process or LNG transfer areas in order to comply with US 49 *Code of Federal Regulation* Part 193. US 49 CFR Part 193 incorporates by reference specific sections of the 2001 and 2006 editions of NFPA 59A *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG).*

Unfortunately, neither NFPA 59A (2001 edition) or US 49 CFR Part 193 define Single Accidental Leakage Sources ("SALS") for a Design Spill in this impounding area. This resulted in the U.S. Federal Energy Regulatory Commission (FERC) receiving a wide variety of interpretations for a Design Spill for these impounding areas in applications proposed for LNG facilities during the 2010-11 timeframe.

FERC and PHMSA established the FRT and its threshold criteria methodology in 2012 in order to establish a consistent approach to determine SALS for this Design Spill in LNG facility applications. FERC and PHMSA established a threshold criteria of 3×10^{-5} failures per year for equipment and piping segments located in this impounding area, as a level of the risk associated with the rupture of a LNG storage tank (i.e. container) outlet line (i.e. a Design Spill specified for containment by NFPA 59A 2001 edition). FERC's and PHMSA's determination of this criteria of 3×10^{-5} failures per year was based in part on a review of five references from 1979-1984.

Accurate estimates of equipment failure rates are important. Specifying "conservative" equipment failure rates greater than those supported by actual representative field data can have unintended impacts. The goals of this research effort were to:

- Review the basis for the baseline threshold failure rate criterion of 3E-5 failures per year.
- Develop additional foundational basis for PHMSA's current LNG FRT, by applying a rigorous statistical analysis and expanding the data set analyzed.
- Identify gaps in PHMSA's current LNG FRT, such as equipment items not addressed and gaps in available failure rate data.
- Propose potential specific revisions to the FRT, as appropriate.
- Identify key follow-on research desirable for further refinements.

The scope of this research did not include generating any new statistical data or estimates of equipment leak or rupture failure rates.

The project team reviewed more than 150 references sources listed in the References and Bibliography and considered in detail more than 20 additional data sources beyond those identified in FERC's issuance #201203010016. These data sources were identified through the combined efforts of the project literature review efforts, Technical Advisory Panel (TAP), and contacts to more than 50 Subject Matter Experts beyond the TAP.

The project team found limited LNG- or cryogenic-specific failure rate data beyond that previously identified by FERC in its 2012 issuance #20120301-0016. For example:

- The last survey of LNG equipment failure rates in the U.S. was conducted 35 years ago. FERC and PHMSA referenced this study in their establishment of the FRT.
- The most recent equipment failure rate data from The Society of International Gas Tanker and Terminal Operators (SIGTTO) identified in this research issued 20 years ago.
- The International Group of LNG Importers Ltd. (GIIGNL) presented a technical paper at the LNG17 conference in 2013 that provided failure/leak rate statistics, but it analyzed LNG terminal subsystems and provided no break-out data for specific components.
- British Compressed Gases Association reviewed failure rates of cryogenic tanks in Technical Information Sheet 23 issued in 2012, but this yielded a comparative minimum failure rate from the industrial gas industry (since no failures were observed) and only for a combination of equipment categories in the FRT.
- The results of two phases of fatigue and crush tests of cryogenic truck transfer hoses performed in Europe in 2016 were summarized and compared to the truck transfer hose failure rate specifications in the FRT.
- Three fault tree analysis estimates of predicted membrane tank failure rates were identified and included for PHMSA's and FERC's information.

The project team also identified and included other non-LNG-specific failure rate data sets for review and consideration. These included: PHMSA's natural gas transmission and hazardous liquid pipeline rupture data, and comparable data from European natural gas pipeline operators; the *Handbook Failure Frequencies* used by the Flemish Environment, Nature and Energy Department; two Release Frequency Manuals from the International Oil and Gas Producers Association (IOGP); API Recommended Practice 581 *Risk Based Inspection Methodology*; failure rate data for chemical processing plant equipment and nuclear power plant components developed by Idaho National Laboratory; and other data as summarized in Section 3.2.

The project team also reviewed key LNG-specific equipment failure rate references produced during 1979 – 1984. This review indicated that some of the Mean Time Between Failure data applied as leak or rupture failures was apparently actually failure to operate, and in some cases minimum rates were apparently applied as actual rates. This understanding further limited the LNG-specific equipment failure data content in this project's database, as detailed in Section 4.

The project team also gathered available failure rate data of atmospheric LNG storage tanks (i.e. containers) for PHMSA's and FERC's information. The Design Spill for atmospheric LNG storage containers is already specified in Table 2.2.3.5 of NFPA 59A 2001 edition specified by US 49 CFR Part 193.

Some of the available generic equipment failure rate data is quite dated and not necessarily reflective of modern design practices. Section 7 includes a quote by representatives of the Dutch National Institute of Public Health and the Environment (RIVM) commenting that the set of available failure frequencies was not up-to-date in 2006, not only in the Netherlands but all over Europe and in fact worldwide. Recent efforts by RIVM include a review of its failure rates specified for double walled LNG storage tanks (with an apparent focus on LNG pressure vessels) and those results are pending, as noted in Section 4.3.

Some of the underlying data could not be evaluated. European regulatory bodies such as the UK Health and Safety Executive (HSE) have developed detailed guidelines for evaluating risks and detailed Quantitative Risk Assessments (QRAs) for significant land planning, such as in the

HSE's *Failure Rate and Event Data for use within Risk Assessments* (FRED) document. While the FRED document provides very good high-level information about the basis of its failure rate specifications, many of its citations are confidential.

One modern equipment failure rate database that is publicly available and has significant content and pedigree is the UK's Hydrocarbon Release Database (HCRD) System, which contains failure rate data continuously collected from UK off-shore oil and gas operations since 1992. This data provides the basis for DNV GL's LEAK commercial software that estimates leak frequencies for piping and process equipment, including many of the equipment categories listed in the FRT. Appendix L illustrates this database and Appendix M provides cumulative probability failure rate distributions developed by the project team from this database to help PHMSA and FERC better understand this resource.

Despite the age and limited amount of underlying LNG or cryogenic failure rate data, FERC's and PHMSA's consideration in 2011-12 of the UK HSE FRED and Dutch RIVM equipment failure rate frequency guidance documents (and additional references cited) is consistent with other leading global regulatory authorities and appears to be properly included as "best available" data, including for LNG facilities as highlighted below. Also included below is information from IOGP and a relevant 2015 ISO standard.

- The UK HSE's FRED document specifically defines failure rates for "LNG Refrigerated Vessels" in its Item FR 1.1.2.1. Its specification for failure rates for "Pipework" (in Item FR 1.3) has 44 citations, which include one confidential analysis of pipework associated with bulk storage of liquid oxygen and two gas terminal studies.
- Singapore requires using HSE's FRED document for Fixed Installations in its *QRA Technical Guidance Manual* issued August 2016.
- ISO Technical Specification ISO/TS16901:2015 *Guidance on performing risk assessment in the design of onshore LNG installations including the ship/shore interface* in its section A.3 lists many of the same references considered in this analysis and concludes "It should be noted that there are no publicly available incident databases for LNG plants that can be available to derive leak frequencies and therefore should rely on the above more general data."
- The Dutch government agency RIVM in its *Reference Manual Bevi Risk Assessment* 2009 document stipulates on page 3 of its Introduction that the "SAFETI-NL" calculation package by DNV London is "stipulated for carrying out the Quantitative Risk Assessment (QRA) calculations for establishments that fall under the Bevi". "SAFETI-NL" contains equipment failure rate data based apparently in large part on the UK HCRD.
- The European Industrial Gas Association in its guidance document 60/15 to apply SEVESO Directives to cryogenic industrial gas facilities in Europe also highlights on p. 21 that the standardized version of DNV's PHAST/Risk software named "SAFETI-NL" must be used in the Netherlands.
- IOGP's comments regarding the applicability of the recommendations in its *Risk Assessment Data Directory: Process Release Frequencies* document #434-1 dated March 2010 include: "We therefore recommend use of the same frequencies for LNG installations as given in Section 2.0" [i.e. for other oil & gas facilities]. IOGP bases its release frequencies for process equipment and piping on DNV's analysis of the HCRD.

As an additional point of comparison, a representative of Korea Gas Corp. (KOGAS) indicated that KOGAS primarily uses IOGP data for its QRAs.

Because the consideration of a significant amount of equipment failure data from related but different (non-LNG or non-cryogenic) service was required, the project team used a Bayesian Network statistical methodology to assess the data. The project team built a framework and database, and applied the data using a commercial Bayesian risk analysis software coupled with a custom input/output script. The project team considered the following two scenarios in its sensitivity analysis, in addition to considering various Bayesian prior distributions:

1. “Perceived Relevancy” Scenarios:

   The project team analyzed failure rate data by its source, its applicability, its site location, and type (using analyst judgement). Twelve variations of analysis factors were provided in order to help illustrate various impacts on results for different scenario examples. This analysis was informative but the lack of specific LNG or cryogenic data limited the ability to apply new LNG-specific data to the existing generic prior data. Additional Percieved Relevancy scenarios can also be considered and evaluated in future analysis, if PHMSA and FERC would like to see future refinements of this analysis.

2. “Wisdom of the Crowd” Scenarios:

   The project team analyzed failure rate references by illustrating Wisdom of the Crowd scenarios, and developed examples that sought to reduce duplication of underlying source data and put an increased weighted importance on the more well-known or commonly-used international references or failure rate regulatory guidance documents. Reviewing the Wisdom of the Crowd example results provided another useful way to quantitatively compare the overall data sets and develop the results and the recommendations, in conjunction with the qualitative analysis and conclusions. Additional Wisdom of the Crowd scenarios can also be considered and evaluated in future analysis, if PHMSA and FERC would like to see future refinements of this analysis.

Appendix B concisely summarizes the recommendations from this project regarding specific categories and failure rates specified in the FRT, and which are also intended to support the strengthening of consensus standards. A summary of key findings and recommendations for FERC’s and PHMSA’s consideration is:

- The leak and guillotine rupture failure rates specified for piping in the FRT directly match those in HSE’s FRED guidance document (with only two small exceptions). The guillotine rupture failure rates specified for piping in the FRT are slightly less than, or greater than, the guillotine rupture failure rates specified by Dutch regulators (depending on pipe diameter), and also appear reasonable with compared to the actual rupture rates observed in PHMSA’s onshore natural gas and hazardous liquid pipeline database (2010-2015). The single actual data point for LNG piping leak rates identified in this analysis (from the 1981 survey of LNG peak shaving plants) also matches up favorably with the FRT’s current specifications for piping. It is recommended to consider retaining the current piping failure rate specifications in the FRT, but to also consider eliminating the smallest piping size category (d < 2”) and the current 40”D maximum limit of the largest piping size category (in order to enhance clarity to end-users of the FRT). Section 6.9 provides more details regarding piping-related findings and recommendations.
- The FRT currently does not address pipe-in-pipe piping such as the vacuum-jacketed

piping that is sometimes used in LNG facilities. It is recommended to consider specifying failure rate reduction factors of 0.01 and 0.1 to modify piping failure rates when one of either two different types of pipe-in-piping is used. These reduction factors are based on a review of a 1982 analyses by Pacific Northwest Laboratory (PNL), a 2012 analysis of double containment piping by Idaho National Laboratory, and a relevant Center for Chemical Process Safety reference.

- The FRT currently does not address potential modification factors in piping failure rates for long transfer lines or inter-unit piping (as commonly exist in LNG terminals). Some relevant information was identified for PHMSA's and FERC's review and future consideration on a generalized basis, beyond those engineering analyses submitted for FERC's and PHMSA's consideration on a case-by-case project application basis.
- The leak and guillotine rupture failure rates for LNG transfer hoses and arms specified in the FRT were compared to other references in this study, and also to results of recent tests in Europe and other developments. There are significant technology developments underway on LNG transfer hoses and arms for both ships and trucks (trailers and trailer-mounted ISO containers). This equipment category was identified as an important watch area for PHMSA and FERC to seek new failure rate data in the future, because for example results of crush and fatigue tests on cryogenic hoses in Europe in 2016 indicates that the truck hose leak rate specified in the FRT may be about 100 times too conservative, and also that a guillotine rupture of a truck transfer hose may not be a credible event. However, at the present time it is recommended that: 1) if FERC and PHMSA want to retain the current basis of "Failures per year of operation", then they may consider making no changes to the FRT's specification; and 2) that PHMSA and FERC review this new cryogenic test data and consider removing the rupture frequency specifically for multi-composite hoses. If FERC and PHMSA want to consider changing the FRT's basis of specification from "Failures per year of operation" to "Failures per hour of operation", then they could consider applying the failure frequency rates specified by Dutch and Flemish regulators. Sections 6.4 and 6.5 provide more details.
- The failure rate for valves specified in the FRT was compared to other references in this study. It is recommended to retain the FRT's currently-specified rupture rate for valves, but to also add a leak rate consistent with that specified in HSE's FRED guidance Item FR 1.2.1 for valves, using the 2 mm hole size considered in Section 4.6 of this report.
- The failure rate for gaskets (i.e. flanges) specified in the FRT was compared to other references in this study. It is recommended to consider eliminating the "Failure of Gasket" terminology and specify failure rates consistent with those specified in HSE's FRED guidance item FR 1.2.4 for gaskets (and flanges), using the 25 mm and 50 mm hole sizes considered in Sections 4.8 of this report.
- The failure rate for expansion joints specified in the FRT was compared to other references in this study and to underlying references. It is recommended to consider revising the specified failure rate from 4×10^{-3} to 1×10^{-4} failures/year in order to better align it with the 1975 risk analysis performed by Science Applications Inc. (excerpts shown in Appendix I) and to also clarify that it applies to single ply expansion joint; both the existing and recommended rates are greater than the 3×10^{-5} FRT threshold criterion. In addition, it is recommended to specify a rupture failure rate for double ply expansion joints.

- The guillotine rupture failure rate specified for "Process Vessels, Distillation Columns, Heat Exchangers and Condensers" in the FRT aligns well with the rate specified for Pressure Vessels in HSE's FRED guidance document and also with the rates specified by Dutch and Flemish regulators for Process Vessels. The 10 mm hole leak failure rate specified in the FRT also aligns well with the 10 mm hole leak failure rates specified by Dutch and Flemish regulators for process vessels, and is more conservative than than the 10 mm hole leak failure rates specified for Pressure Vessels in HSE's FRED guidance document. This research also reviewed and summarized the lower failure rates assigned to Pressure (Storage) Vessels (vs. Process Vessels) by Dutch and Flemish regulators than the rates specified by the UK HSE's FRED guidance document for Pressure (Storage) Vessels, but it was recommended that FRT retain its more conservative basis and not specify lower failure rates specifically for Pressure (Storage) Vessels as different than those rates for Process Vessels. This research also explored, accumulated and analyzed for PHMSA and FERC a number of potential equipment subcategories within this overall category. In summary it was recommended that the FRT retain this existing category name and its currently-specified rupture and leak failure rates.
- The FRT currently specifies leak and rupture rates for cryogenic atmospheric storage tanks. For determination of single accidental leakage sources for process facilities this information does not appear to be relevant because the Design Spill for LNG tanks (i.e. containers in NFPA 59A) is already specified in Table 2.2.3.5 of the NFPA 59A (2001 edition) specified by US 49 CFR Part 193. However, if DOT allows for design spills to be selected using a failure rate or risk based approach (e.g., NFPA 59A 2016 edition) then this information may be relevant. Therefore, it is recommended that PHMSA consider eliminating this category or clarify the use of this information for single accidental leakage sources in impounding areas serving only vaporization, process or LNG transfer areas.

This research also reviewed the threshold criterion of 3×10^{-5} failures per year used in FRT. The 3×10^{-5} failures per year criterion appears to be based on two key analyses conducted by Pacific Northwest Laboratories (PNL) in 1982, which are among five references cited by FERC in the derivation of the FRT Criterion. The two PNL studies used fault tree analysis to estimate a number of failure rate frequencies for various LNG plant components and subsystems. The project team confirmed that the 3×10^{-5} to 5×10^{-5} failure rate threshold criterion was contained in the historical references, and their observations of these and other references in Section 2.3 also included that:

- The 3×10^{-5} failures per year criterion refers to an estimated failure rate for an equipment component failure, and not the resulting level of risk to society or an individual as is analyzed in some other risk assessment methodologies.
- The criterion appears to be derived from the failure rate associated with the failure of one of the most critical plant components, i.e. the LNG container liquid withdrawal line. The failure rate criteria associated with the failure of line connection penetrations to the primary container may or may not set an equivalent risk level required for all other equipment component failure rates.
- The 3×10^{-5} failures per year criterion appears to be associated with the failure rate of an LNG container liquid withdrawal line isolated with an internal shutoff valve, while US 49 CFR Part 193 also permits evaluation of events with other consequences such as the nearly complete emptying of the LNG container.

- While for example the failure rates in the FRT for process piping exactly match HSE's FRED document (with two small exceptions), the FRT's threshold criteria methodology appears to be a somewhat unique risk assessment methodology.
- A risk assessment prepared in 1975 by Science Applications Inc. for the Western LNG Terminal Company for a LNG terminal proposed for Oxnard, CA also prepared a number of FTAs and estimated the probability of a "Leak Occurs in Storage Tank or Tank Outlet" as 1×10^{-6} failures/year and a "Leak Occurs in Outlet of Tank" as 9.8×10^{-11} failures/year (when the isolation systems were considered).
- No direct analysis was made to compare the current FRT criterion of 3×10^{-5} failures per year to other regulated risk criteria in the U.S., since such an analysis of the risks to individuals and society of applying the FRT's methodology and criterion to vaporization, process, or LNG transfer components versus the risks associated with failure of a primary LNG container outlet line was beyond the scope of this analysis. This analysis may include a comparison of a 1-hour spill versus a complete loss of containment.

Recommendations regarding the FRT criterion are:

- No direct basis was identified to propose revising current the FRT Criterion of 3×10^{-5}, for the reason identified in the prior bullet above. Therefore it is recommended to retain the FRT Criterion of 3×10^{-5}.
- FERC and PHMSA should further consider whether methodologies other than the current FRT criterion methodology would be suitable for defining a SALS for impoundment areas serving only vaporization, process, or LNG transfer areas.

Recommendations regarding subsequent research and related efforts are:

- PHMSA and FERC should consider funding research to conduct a new survey of LNG facilites in the US, in order to update and expand upon the most recent survey study completed in 1981. It was "the opinion of GRI that the failure rate data base should be periodically updated, at about 5-year intervals" as stated in that survey, but unfortunately no industry or federal funding was made available for this purpose.
- PHMSA and FERC should consider supporting the coordination of any new industry-government consortium efforts to create a national database of information related to in-service performance of LNG piping and components.

This research performed in this project was led by and substantially performed by Gas Technology Institute (GTI). CH-IV International Inc. was a project subcontractor and contributed end-user perspective and insights, based on their experience working with many LNG facility developers to use the LNG FRT and submit design engineering submittals to FERC. The recommendations provided in this report are solely for PHMSA's and FERC's consideration.

The research project team also expresses their sincere thanks to PHMSA and to the members of this project's Technical Advisory Panel for their comments, input and insights:

- Ari Flores and Howard Goldberg, Consolidated Edison, Inc.
- Jon Huddleston, NW Natural
- Brandon Jones, Paiute Pipeline Co./Southwest Gas Corp.
- Andrew Kohout, FERC
- Roy Lucas, PHMSA consultant
- Jeff Marx, Quest Consultants Inc.
- Frank Su and Skip Doucette, National Grid
- Mike Wardman and Jill Willday and their colleagues, UK HSL

1. Introduction

1.1 Project Overview

This report summarizes the results of U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) contract #DTPH56-15-T-00008 to review and consider potential refinements to PHMSA's LNG Failure Rate Table[1] ("FRT"), which is referenced by the answers to question #DS1 and #DS2 of PHMSA's current information resource webpage "LNG Plant Requirements: Frequently Asked Questions"[2] and also in Volume II of U.S. Federal Energy Regulatory Commission's (FERC's) *Guidance Manual for Environmental Report Preparation* draft version issued December 2015. The current FRT is shown in Table 1. The FRT establishes the criteria for Design Spills from vaporization, process or LNG transfer areas at LNG plants in order to comply with US 49 *Code of Federal Regulation* Part 193.

Gas Technology Institute (GTI) led and substantially performed the research in this project. CH-IV International Inc. served as a project subcontractor and contributed valuable end-user perspective and insights (in addition to the project's Technical Advisory Panel), based on their experience working with many LNG facility developers to use the FRT and submit design engineering submittals to FERC.

1.2 Project Context

FERC's and PHMSA's introduction of the LNG Failure Rate Table in 2012 coincided with a number of subsequent significant changes in the U.S. LNG industry, including:

- A large increase in activity in the U.S. to develop LNG as an export commodity, as a transportation fuel, for utility peak shaving service (both upgrades to existing facilities and new facilities), and other purposes.
- The 2013 and 2016 editions of NFPA 59A *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)* incorporate Quantitative Risk Assessments (QRA) content in new Chapter 15, as an alternative to the prescriptive requirements in Chapter 5. Table 15.6.1 of NFPA 59A 2013 and 2016 editions specify equipment failure rates that differ from those in the FRT. This project's analysis can hopefully help efforts to harmonize future standards and regulations.
- The 2016 edition of NFPA 59A introduced membrane tanks. This development is not directly relevant to the FRT since US 49 CFR Part 193 recognizes the 2001 and 2006 editions of NFPA 59A (specific respective sections), but the project team summarized membrane tank failure rate data for PHMSA's and FERC's information since FERC and PHMSA may receive applications that consider membrane tanks.

Accurate estimates of equipment failure rates are important. Specifying equipment failure rates that are higher than those supported by actual representative field data can have unintended impacts. For example:

- If a catastrophic guillotine rupture of a hose used to load or unload a LNG trailer or ISO shipping container becomes a probable event as determined by the FRT, then designers may need to propose locating the loading/unloading station near the center of an LNG facility in order to meet the exclusion zone requirements in US 49 CFR Part 193. This can conflict with a common overall safety (and security) goal by plant designers and operators to keep most vehicular traffic at the perimeter of a site. This may particularly impact a number of new or existing sites that are constrained in size and for which LNG-related improvements have been considered (e.g. for the development of LNG as a marine vessel bunker fuel as one way for U.S. ship operators to meet low-sulfur Emission Control Area requirements).

- If a catastrophic guillotine rupture of a long transfer line or other component becomes a probable event as determined by the FRT, then designers may need to implement measures to meet exclusion zone requirements that may have unintended impacts. Examples of design case rupture analyses that have been required using the current FRT as recorded in public filings on FERC's website include these related to LNG export plant applications:
  - Freeport LNG – 8.67" diameter hole in LNG rundown line; 26" hole diameter in marine transfer line
  - Trunkline LNG – 6.7" diameter hole and 8" diameter hole in LNG rundown lines
  - Magnolia LNG – 10" diameter hole in LNG rundown line
  - Corpus Christi LNG – 10" diameter hole in marine transfer line; 10" diameter hole in LNG rundown line
  - Oregon LNG – 10.67" diameter hole in marine transfer line; 8" diameter hole in LNG rundown line
  - Downeast LNG – 12" diameter hole in marine transfer line
  - Jordan Cove LNG – 36" diameter hole in marine transfer line; 8" diameter hole in LNG rundown line
  - Golden Pass LNG – 18" diameter hole in LNG rundown line

  While these types of failures and events have not been observed at LNG facilities in the U.S. or at LNG import/export terminals worldwide, LNG-specific piping failure rate data is known to be limited due in part to the relatively small cumulative operating history of the LNG industry when compared for example to the chemical process industry or overall oil and gas industry. This research seeks to consider piping failure rate data from other industries using a Bayesian analysis and also to review the FRT threshold criterion used to determine required release scenarios.

This research is also consistent with PHMSA's continued emphasis to update guidance on critical components of risk assessment approaches, including appropriate risk metrics and methods.[34]

1.3 Project Goals

The goals of this research effort were to:

- Review the basis for the baseline threshold failure rate criterion of 3E-5 failures per year.
- Develop additional foundational basis for PHMSA's current LNG FRT, by applying a rigorous statistical analysis and expanding the data set analyzed.

- Identify gaps in PHMSA's current LNG FRT, such as equipment items not addressed and gaps in available failure rate data.
- Propose potential specific revisions to the FRT, as appropriate.
- Identify key follow-on research desirable for further refinements.

This research effort identified, reviewed, and analyzed existing leak and rupture equipment failure rate data or references that may be potentially relevant to the FRT. The scope of this research did not include generating any new statistical data or estimates of equipment leak or rupture failure rates.

Type of Failure	Nominal Failure Rate
Cryogenic Storage Tanks (General)	Failures per year of operation
Rupture of Storage Tank Outlet/Withdrawal Line	3E-5 (Failure Rate Criterion)
Single Containment Atmospheric Storage Tanks	Failures per year of operation
Catastrophic Failure, Release to Atmosphere	5E-6 per tank
Catastrophic Failure of Tank Roof	1E-4 per tank
Release from a hole in inner tank with effective diameter of 1m (~3ft)	8E-5 per tank
Release from a hole in inner tank with effective diameter of 0.3m (~1ft)	2E-4 per tank
Release from a hole in inner tank with effective diameter of 0.01m (0.4in)	1E-4 per tank
Double Containment Atmospheric Storage Tanks	Failures per year of operation
Catastrophic Failure, Release to Atmosphere	5E-7 per tank
Catastrophic Failure of Tank Roof	1E-4 per tank
Release from a hole in inner tank with effective diameter of 1m (~3ft)	1E-5 per tank
Release from a hole in inner tank with effective diameter of 0.3m (~1ft)	3E-5 per tank
Release from a hole in inner tank with effective diameter of 0.01m (0.4in)	1E-4 per tank
Full Containment Atmospheric Storage Tanks	Failures per year of operation
Catastrophic Failure, Release to Atmosphere	1E-8 per tank
Catastrophic Failure of Tank Roof	4E-5 per tank
Release from a hole in inner tank with effective diameter of 1m (~3ft)	1E-6 per tank
Release from a hole in inner tank with effective diameter of 0.3m (~1ft)	3E-6 per tank
Release from a hole in inner tank with effective diameter of 0.01m (0.4in)	1E-4 per tank
Process Vessels, Distillation Columns, Heat Exchangers, and Condensers	Failures per year of operation
Catastrophic Failure (Rupture)	5E-6 per vessel
Release from a hole with effective diameter of 0.01m (0.4in)	1E-4 per vessel
Truck Transfer	Failures per year of operation
Rupture of transfer arm	3E-4 per transfer arm
Release from a hole in transfer arm with effective diameter of 10% transfer arm diameter with maximum of 50mm (2-inches)	3E-3 per transfer arm
Rupture of transfer hose	4E-2 per transfer hose
Release from a hole in transfer hose with effective diameter of 10% transfer hose diameter with maximum of 50mm (2-inches)	4E-1 per transfer hose
Ship Transfer	Failures per year of operation
Rupture of transfer arm	2E-5 per transfer arm
Release from a hole in transfer arm with effective diameter of 10% diameter with maximum of 50mm (2-inches)	2E-4per transfer arm

Table 1: Nominal Failure Rates Specified in Current FRT

Type of Failure	FERC Nominal Failure Rate
Piping (General)	Failures per year of operation
Rupture at Valve	9E-6 per valve
Rupture at Expansion Joint	4E-3 per expansion joint
Failure of Gasket	3E-2 per gasket
Piping: d < 50mm (2-inch)	Failures per year of operation
Catastrophic rupture	1E-6 per meter of piping
Release from hole with effective diameter of 25mm (1-inch)	5E-6 per meter of piping
Piping: 50mm (2-inch) ≤ d < 149mm (6-inch)	Failures per year of operation
Catastrophic rupture	5E-7 per meter of piping
Release from hole with effective diameter of 25mm (1-inch)	2E-6 per meter of piping
Piping: 150mm (6-inch) ≤d < 299mm (12-inch)	Failures per year of operation
Catastrophic rupture	2E-7 per meter of piping
Release from hole with effective diameter of 1/3 diameter	4E-7 per meter of piping
Release from hole with effective diameter of 25mm (1-inch)	7E-7 per meter of piping
Piping: 300mm (12-inch) ≤d < 499mm (20-inch)	Failures per year of operation
Catastrophic rupture	7E-8 per meter of piping
Release from hole with effective diameter of 1/3 diameter	2E-7 per meter of piping
Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)	4E-7 per meter of piping
Release from hole with effective diameter of 25mm (1-inch)	5E-7 per meter of piping
Piping: 500mm (20-inch) ≤d < 1000mm (40-inch)	Failures per year of operation
Catastrophic rupture	2E-8 per meter of piping
Release from hole with effective diameter of 1/3 diameter	1E-7 per meter of piping
Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)	2E-7 per meter of piping
Release from hole with effective diameter of 25mm (1-inch)	4E-7 per meter of piping

Table 1: Nominal Failure Rates Specified in Current FRT (cont.)

2. Failure Rate Table Overview and Review of 3E-5 to 5E-5 FRT Criterion

2.1 Derivation of FRT

PHMSA's current FRT was derived in partnership with FERC, and its derivation is summarized in documents such as FERC Issuances 20111115-4001, 20120301-0016 and 20120507-4014. A more detailed description of its derivation was provided by Andrew Kohout of FERC in a 2012 paper[5] which noted that "The selection of the nominal failure rates were determined to provide conservative and consistent trends failure rates among the various types of failures with recognition that improved and updated failure rate data may be used pending review and acceptance of FERC and PHMSA." As noted both in this 2012 paper and in the title of the FRT, the equipment failure rates specified in the FRT are *nominal* failure rates and not *mean* or *median* failure rates. For more details the reader is referred to the 2012 paper which also summarizes that the derivation of the FRT included consideration of: the fact that outliers in the data can influence results versus only using mean or median values; that piping and equipment categorizations differ across failure rate data sets which can make it difficult to derive accurate mean or median values; and other factors.

2.2 Summary of FRT's Criterion Threshold Methodology

PHMSA and FERC apply the FRT by utilizing a criterion threshold methodology to determine the "Single accidental leakage source" (SALS) design spills for individual LNG plant components or piping segments. Details are specified in Appendix A which contains the "Design Spill Determination" information from PHMSA's current "LNG Plant Requirements: Frequently Asked Questions" webpage, and also in Volume II of FERC's *Guidance Manual for Environmental Report Preparation* issued December 2015. In brief, the FRT is to be applied to numerous individual piping segments and equipment components in order to determine if the 3×10^{-5} per year failure rate criterion is equaled or exceeded for that particular piping segment and equipment component; if so, then this design spill must be evaluated. PHMSA and FERC apply this methodology and the FRT to all hazardous materials in proposed LNG facilities including LNG, gaseous natural gas, propane, butane, ethylene, acid gases, etc.

The FRT criterion and methodology differs from some other risk assessment methodologies and appeared to the project team to be somewhat unique, although another example of using a risk threshold criterion methodology is a Maximum Credible Event scenario analyses[6,7]. For example, the FRT criterion and methodology defines potential accident scenarios, estimates potential accident frequencies, evaluates event consequences and impacts, and then requires the impacts to not extend beyond the legal control of the operator. This is similar to a Quantitative Risk Assessment (QRA) which also defines potential accident scenarios, estimates potential accident frequencies, evaluates event consequences and impacts, but then compares the cumulative risk to a Frequency-Number (F-N) curve or plot of allowable Societal Risk (SR). The former essentially does not allow individual events with a certain failure rate from impacting the public, but may allow certain cumulative risks from extending onto populated areas, while the latter does not allow certain cumulative risks from extending onto populated areas, but may allow for individual events with certain failure rates from impacting the public. One example of a regulatory approach that utilizes a QRA methodology is the "RIVM BEVI '09" document referenced in Section 3.1.

2.3 Review of 3E-5 to 5E-5 FRT Criterion

The primary federal regulation that pertains to LNG facilities is US 49 CFR Part 193 *Liquefied Natural Gas Facilities: Federal Safety Standards*; its "Subpart B – Siting Requirements" incorporates NFPA 59A Table 2.2.3.5 (2001 edition) by reference such as in Section 193.2059.

NFPA 59A Table 2.2.3.5 (2001 edition) specifies that the "Design Spill" for "Impounding areas serving only vaporization, process, or LNG transfer areas" must be "The flow from any single accidental leakage source". NFPA 59A Table 2.2.3.5 (2001 edition) also specifies Design Spill for containers in three configurations.

The basis of the threshold failure rate criterion of 3 x 10^{-5} to 5 x 10^{-5} failures per year in the FRT is summarized in the 2012 paper by Andrew Kohout of FERC[8]. The reader is referred to that paper for details, but a brief summary follows with quotations from that paper:

- Unfortunately neither NFPA 59A (2001 edition) or US 49 CFR Part 193 define a single accidental leakage source for "impounding areas serving only vaporization, process, or LNG transfer areas".
- FERC "received a wide variety of single accidental leakage sources, ranging from packing and flange leaks to full guillotine ruptures of ship loading lines" in proposed applications for LNG facilities.
- In order to achieve a consistent approach in LNG facility proposal applications submitted to FERC, "FERC staff researched the failure rates of the Design Spill specified for storage tanks" (in Table 2.2.3.5 of NFPA 59A 2001 edition). FERC staff determined that "the rupture of a storage tank outlet line is on the order of one failure every 20,000 to 30,000 years (6 x 10^{-5} to 3 x 10^{-5} failures per year)" (sic) based on the failure rates contained in five references (these references are referenced in Section 3.1 as "AGA FP LNG '84", "GRI LNG FRD '81", "AGA LNG EXP '79", "PNL PSRP '82", and "PNL RP '84").
- "Because this failure rate applies to a design spill for containment that is specified by NFPA 59A and adopted into 49 CFR Part 193, FERC staff used this rate to determine appropriate single accidental leakage sources for impounding areas serving process areas. PHMSA concurred with this approach."
- "In addition, FERC staff also researched and compiled past and present internationally used risk criteria … and determined the failure rate selected is also consistent with risk criteria and consistent with risk criteria when considering multiple single accidental leakage events (e.g., 1 – 100) may have overlapping consequences…"

This project team reviewed the five references and agreed with FERC's findings that there are estimates that the rupture of a storage tank outlet line will be "on the order of one failure every 20,000 to 30,000 years" (5 x 10^{-5} to 3 x 10^{-5} failures per year) within these references. For example:

- "PNL PSRP '82" evaluated release prevention systems for an LNG Peakshaving Facility that contained one single-containment tank (348,000 barrel capacity) with external pumps ("LNG is pumped from the storage tank to the vaporizers by three vertical submerged, pot-mounted pumps" as per p. 3.5) and through a 12" diameter outlet line with an internal valve and with one expansion joint. Section 4.2.6 “Outlet Line Rupture” on Page 4.11 of “PNL PSRP ‘82” states that:

> The outlet line from the storage tank is 12 in. in diameter and exits through the bottom of the inner tank. LNG is drawn from the tank for vaporization about 20 days per year. The outlet line will rupture about 5 x 10^{-5} times per year, resulting in a release of 28,000 gallons of LNG if stopped in one minute. If the release is isolated in ten minutes, 280,000 equivalent gallons of LNG will be released. The probability of the release occurring and not being stopped in one minute is 1 x 10^{-5} times per year. A fault tree analysis for rupture of the outlet line is shown in Figure B.8. Critical system components are expansion joints, 12 in. internal valve, and operators.

- “PNL ITRP ‘82” evaluated release prevention systems for an LNG import terminal that contained two single-containment tanks (each 550,000 barrel capacity) with internal pumps. “Each storage tank contains two submerged primary sendout pumps which boost the LNG” and “All piping connections to the inner tank enter through the roof of the storage tank and are supported by independent structures” as per pp. 3.3-3.4. Page 4.16 of “PNL ITRP ‘82” states that:

> …Rupture of an outlet LNG line will occur about 3 x 10^{-5} times per year. If the sendout system is shut down and the release isolated in 1 minute, 5,000 gallons would be spilled. If the system is not shut down for 10 minutes, 41,000 gallons would be released. This will occur 2 x 10^{-2} per demand, resulting in a probability of about 5 x 10^{-7} per year for this scenario. If an inlet or outlet line ruptures, gas detectors in the storage tank dike area will warn the operator that an emergency condition exists and the operator would then have to activate the ESD. Fault trees for rupture of storage tank inlet and outlet lines are shown in Figures B.10 and B.11. Supporting calculations are given in Table B.7 and B.8.

Other observations from the review of these and other references from the 1970s-80s included:

- The 3 x 10^{-5} failures per year criterion refers to an estimated failure rate for an equipment component failure, and not the resulting level of risk to society or to an individual as is analyzed in some other risk assessment methods.
- The criterion appears to be derived from the failure rate associated with the failure of one of the most critical plant components, i.e. the LNG container liquid withdrawal line. The failure rate criteria associated with the failure of line connection penetrations to the primary container may or may not set an equivalent risk level required for all other equipment component failure rates.
- The criterion is derived from the risk level primarily associated with pool boiling evaporation from a single accidental release from the primary LNG container, in comparison to the analysis of multiple jetting and flashing release scenarios from piping and other equipment as typically required to conform to the FRT.
- The Fault Tree Analysis (FTA) of “Large Release from Storage Tank Outlet Line” for peak shaving plants in “PNL PSRP ‘82” (shown in Table 7 and Table B.7 in Appendix A):
    - included an internal valve.

- included one (single ply) expansion joint, and the estimated failure rate of the expansion joint of 1 x 10^{-7} failure/hour drives the conclusion of this FTA (the Top Event failure rate reduces from 1 x 10^{-5} to 1.5 x 10^{-7} if the expansion joint is eliminated); the accuracy of the 1 x 10^{-7} failure/hour of expansion joint is of limited pedigree, as described in section 4.7.

(While modern single containment tanks typically utilize in-tank pumps without bottom penetrations and without expansion joints in LNG tank outlet lines upstream of the pump discharge block valve, there is no prohibition against using the design analyzed in this FTA.)

- NFPA 59A 2001 edition as enforced by US 49 CFR Part 193 permits LNG containers with penetrations below the liquid level and without internal shutoff valves. Table 2.2.3.5 defines the duration of the Design Spill (using the formula $q=(4/3)*d^2*\sqrt{h}$) to be:
    - "1 hour" for "Containers with penetrations below the liquid level with internal shutoff valves in accordance with 6.3.3.3"
    - "until the differential head acting on the opening is 0 (zero)" for "Containers with penetrations below the liquid level without internal shutoff valves"; that is, the duration of the Design Spill is the nearly complete emptying of the primary LNG container.

In other words, the FRT criterion could be associated with the consequences generated by a 1 hour spill (of the peak shaving tank in "PNL PSRP '82") while US 49 CFR Part 193 also permits evaluation of other consequences such as the nearly complete emptying of the primary LNG container.

- An alternate FTA of "Release from Storage Tank Outlet Line with Alternative Design of In-Tank Pumps" for peak shaving plants was also included in "PNL PSRP '82" (shown in Table 7 and Table B.16 in Appendix A), which is more representative of LNG plant design practices today but not of those when the SALS language of NFPA 59A was adopted by US 49 CFR Part 193. As comparison information, the largest failure rate estimate in this FTA is 1 x 10^{-6} failures/year of the three sub-scenarios considered in calculation nos. 18, 19 and 20 on pp. B56-B57.
- An alternate FTA for an import terminal with in-tank pumps in "PNL ITRP '82" in its base case scenario is shown in Table 4.1 and Table B.8 in Appendix B. It estimated the probability of "Rupture of Storage Tank Outlet Lines" as 5 x 10^{-7} failures per year, and not 3 x 10^{-5} failures per year, when it considered the Emergency Shutdown Device that is included in all LNG plant designs (including in 1982).
- The estimated failure rates for tank outlet lines were predictions derived by Fault Tree Analyses (based on a particular number of sendout/vaporization hours/year), and not from any failure rate data of observed actual failures.
- The estimated failure rates for tank outlet lines were based on estimates of subcomponent reliability that appear to be taken primarily from the nuclear power industry, including the failure of a single ply expansion joint for which the pedigree of its estimated failure rate is limited.

- The SALS language appears to be fully formed in the 1975 (4th) edition of NFPA 59A, but similar predecessor language appears in the 1971 (2nd) edition in paragraph 2135, and in the 1972 (3rd) edition in paragraph 2111.
- A 1975 risk assessment by Science Applications Inc. prepared for the Western LNG Terminal Company for a LNG terminal proposed for Oxnard, CA (referred to in Section 3.2 and this document as "SAI '75") also prepared a number of FTAs and estimated the probability that a "Leak Occurs in Storage Tank or Tank Outlet Lines" is 1×10^{-6} (for one tank) and the probability that a "Leak Occurs in Outlet of Tank" as 9.8×10^{-11} failures/year (when the isolation systems are considered). This terminal was proposed to use four 550,000 barrel capacity tanks with in-tank pumps. Appendix I contains excerpts from this alternate estimate of failure frequency of a LNG tank outlet line and LNG tank developed in the 1970s-80s.

2.4 Comparison to Other U.S. Risk Criteria

No direct analysis was made to compare the current FRT criterion of 3×10^{-5} to other regulated risk criteria in the U.S., since such an analysis of the risks to individuals and society of applying the FRT's methodology and criterion to vaporization, process, or LNG transfer components versus the risks associated with failure of a primary LNG container outlet line was beyond the scope of this analysis. Such an analysis may also include comparing the impacts of a 1-hour spill versus total loss of containment of a primary LNG container.

A direct comparative analysis may also involve a comparison to an F-N plot for allowable IR and SR. PHMSA recently funded a significant body of risk-related research that provides significant additional relevant information to aid PHMSA and FERC in their review of IR and SR levels; see for example PHMSA research reports produced in 2016 entitled "Approaches for Preventing Catastrophic Events" by GTI[9], and "Paper Study on Risk Tolerance" by Keifner and Associates Inc.[10] This PHMSA research provides important information to support PHMSA's future regulatory decision-making.

NFPA 59A 2013 and 2016 editions illustrate F-N plots of societal risk criteria used by different jurisdictions in Figure A.15.10.2 of those editions. Comparative F-N risk criteria information from select U.S. governmental agencies also follows.

<u>U.S. Federal Energy Regulatory Commission</u>

FERC has developed public risk criteria when assessing tolerable individual and societal risk guidelines for dams in its publication *Risk-Informed Decision Making Guideline* documents; Figure 1 illustrates Incremental Risk Guidelines excerpted from Version 4.1 (March 2016) of its Chapter 3: Risk Assessment.[11]

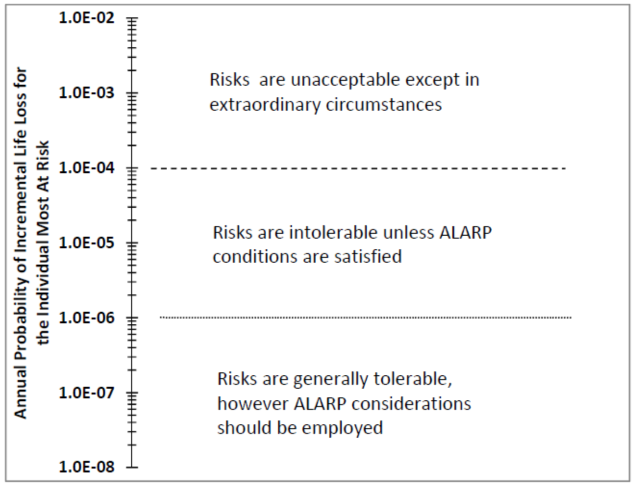


Figure 3-2. Individual Life Safety Risk Guideline for Incremental Risk

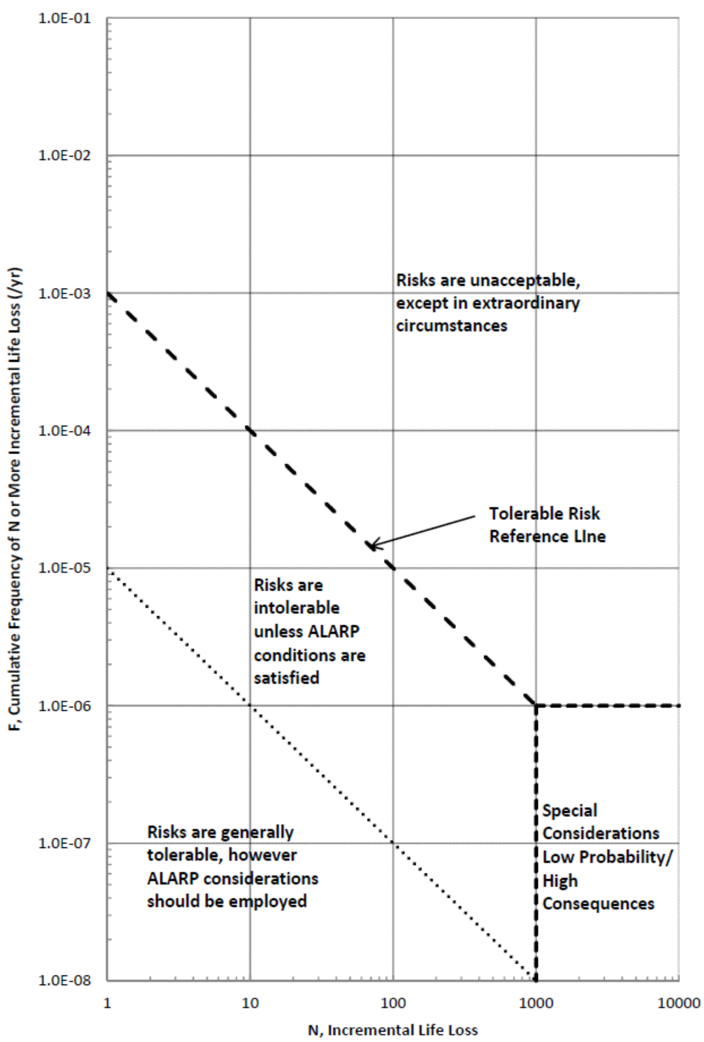


Figure 3-3. Societal Risk Guideline for Incremental Risk (F-N)

Figure 1: FERC Risk Criteria F-N Plot and Risk Criteria for Dam Construction

U.S. Department of Transportation Federal Aviation Administration

The U.S. DOT FAA has established public risk criteria for commercial space launches. The maximum risk to all members of the public is 1 x 10^{-4} casualties/launch, and the maximum risk to an individual member of the public should not exceed a casualty expectation of 1 x 10^{-6} per launch for each hazard. An excerpt from the current US 14 CFR Part 417.107 follows:

> (b) *Public risk criteria.* A launch operator may initiate the flight of a launch vehicle only if flight safety analysis performed under paragraph (f) of this section demonstrates that any risk to the public satisfies the following public risk criteria:
>
> (1) A launch operator may initiate the flight of a launch vehicle only if the total risk associated with the launch to all members of the public, excluding persons in water-borne vessels and aircraft, does not exceed an expected number of 1×10^{-4} casualties. The total risk consists of risk posed by impacting inert and explosive debris, toxic release, and far field blast overpressure. The FAA will determine whether to approve public risk due to any other hazard associated with the proposed flight of a launch vehicle on a case-by-case basis. The E_c criterion applies to each launch from lift-off through orbital insertion for an orbital launch, and through final impact for a suborbital launch.
>
> (2) A launch operator may initiate flight only if the risk to any individual member of the public does not exceed a casualty expectation of 1×10^{-6} per launch for each hazard.
>
> (3) A launch operator must establish any water borne vessel hazard areas necessary to ensure the probability of impact (P_i) with debris capable of causing a casualty for water borne vessels does not exceed 1×10^{-5}.
>
> (4) A launch operator must establish any aircraft hazard areas necessary to ensure the probability of impact (P_i) with debris capable of causing a casualty for aircraft does not exceed 1×10^{-6}.

U.S. Department of Defense

The U.S. Department of Defense has established risk criteria standards for national test ranges. Figure 2 shows an F-N plot and risk criteria established by DoD in its Standard #321-16 (most recently revised in August of 2016). [12]

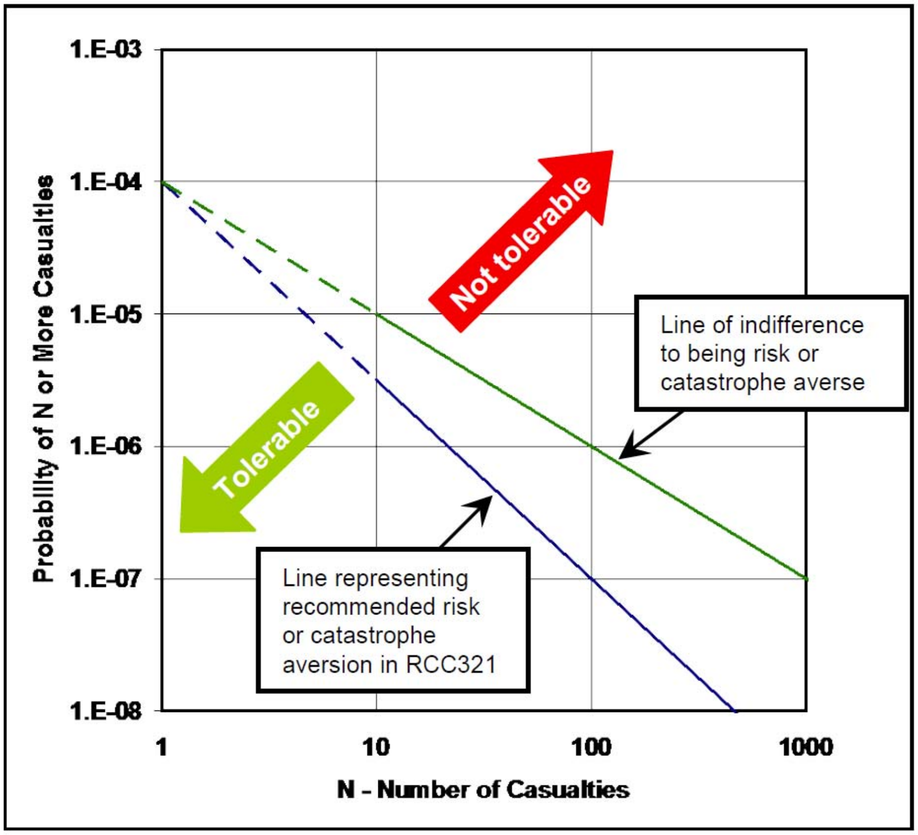


Figure 3-1. Tolerable Catastrophic Risks for the Public

Table 3-2. Summary of Commonality Criteria

	General Public		Mission-Essential and Critical Operations Personnel	
Per Mission	**Max. Acceptable**	**Undesired Event**	**Max. Acceptable**	**Undesired Event**
	1E−6[b]	Individual Probability of Casualty	10E−6	Individual Probability of Casualty
	100E−6[b]	Expected Casualties	300E−6	Expected Casualties
	0.1E−6[a]	Individual Probability of Fatality	1E−6[a]	Individual Probability of Fatality
	30E−6[a]	Expected Fatalities	300E−6[a]	Expected Fatalities
Annual	3000E−6	Expected Casualties	30000E−6	Expected Casualties
	1000E−6[a]	Expected Fatalities	10000E−6[a]	Expected Fatalities

[a] Advisory Requirements.

[b] If a flight operation creates a toxic risk, then the range must separately ensure the allowable level of risk enforced by them does not exceed other standards for toxic exposure limits for the GP when appropriate mitigations are in place. Chapter 8 of the supplement provides an approach for implementing this requirement.

Figure 2: DoD Risk Criteria F-N Plot and Risk Criteria for National Test Ranges

U.S. Department of the Interior and U.S. Army Corps of Engineers

The U.S. Department of the Interior Bureau of Reclamation and U.S. Army Corps of Engineers have established risk criteria standards for dam and levee safety, and Figure 3 shows the F-N plots effective as of July 2015.[13] The DOI uses annualized dam failure probability (similar to Individual Risk criteria) and loss of life (similar to Societal Risk criteria) guidelines to assess dam safety risk, and calls out the As Low as Reasonably Practicable (ALARP) region.

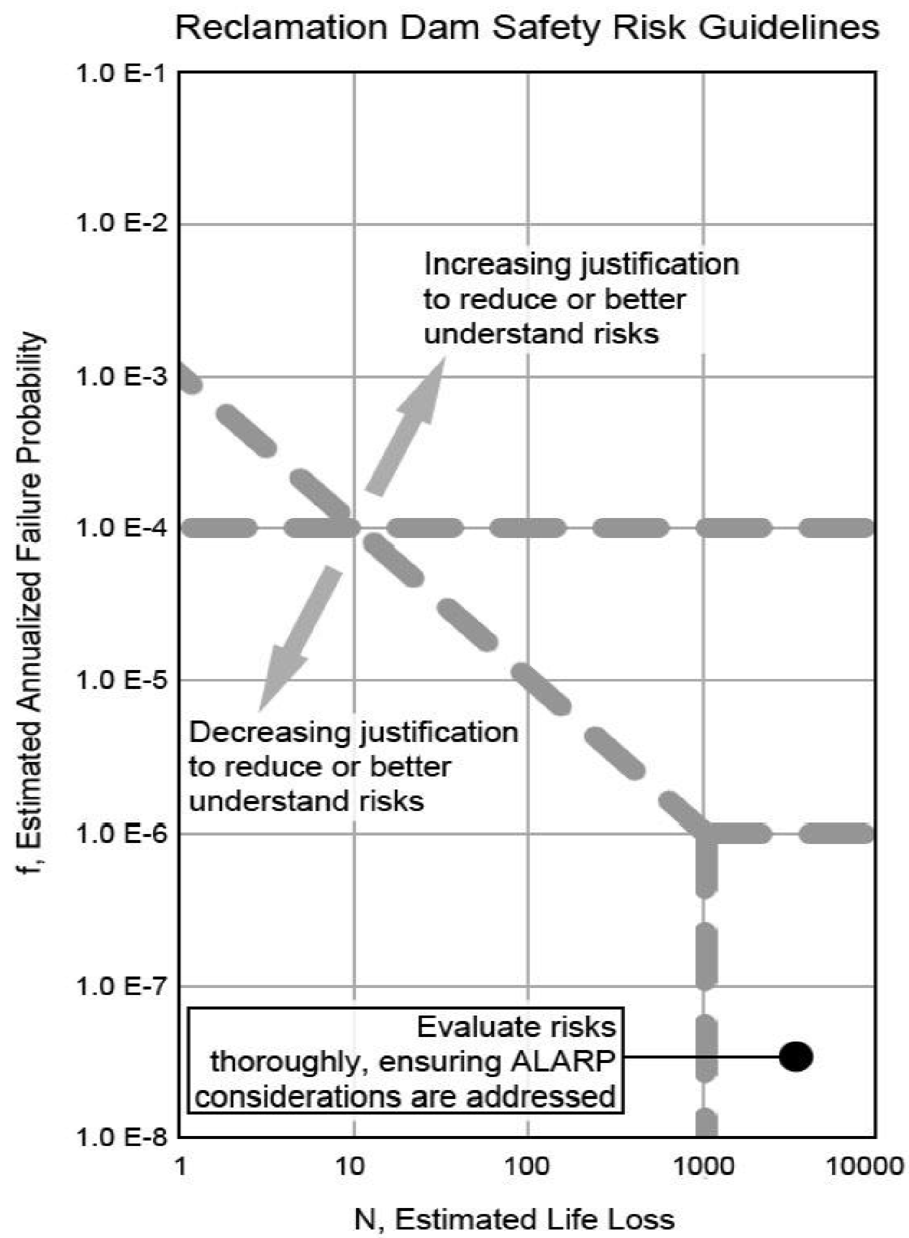


Figure 7. Reclamation's Dam Safety Public Protection Guidelines [9]

Figure 3. U.S. Dept. of Interior Bureau of Reclamation and U.S. Army Corp of Engineer F-N Plots

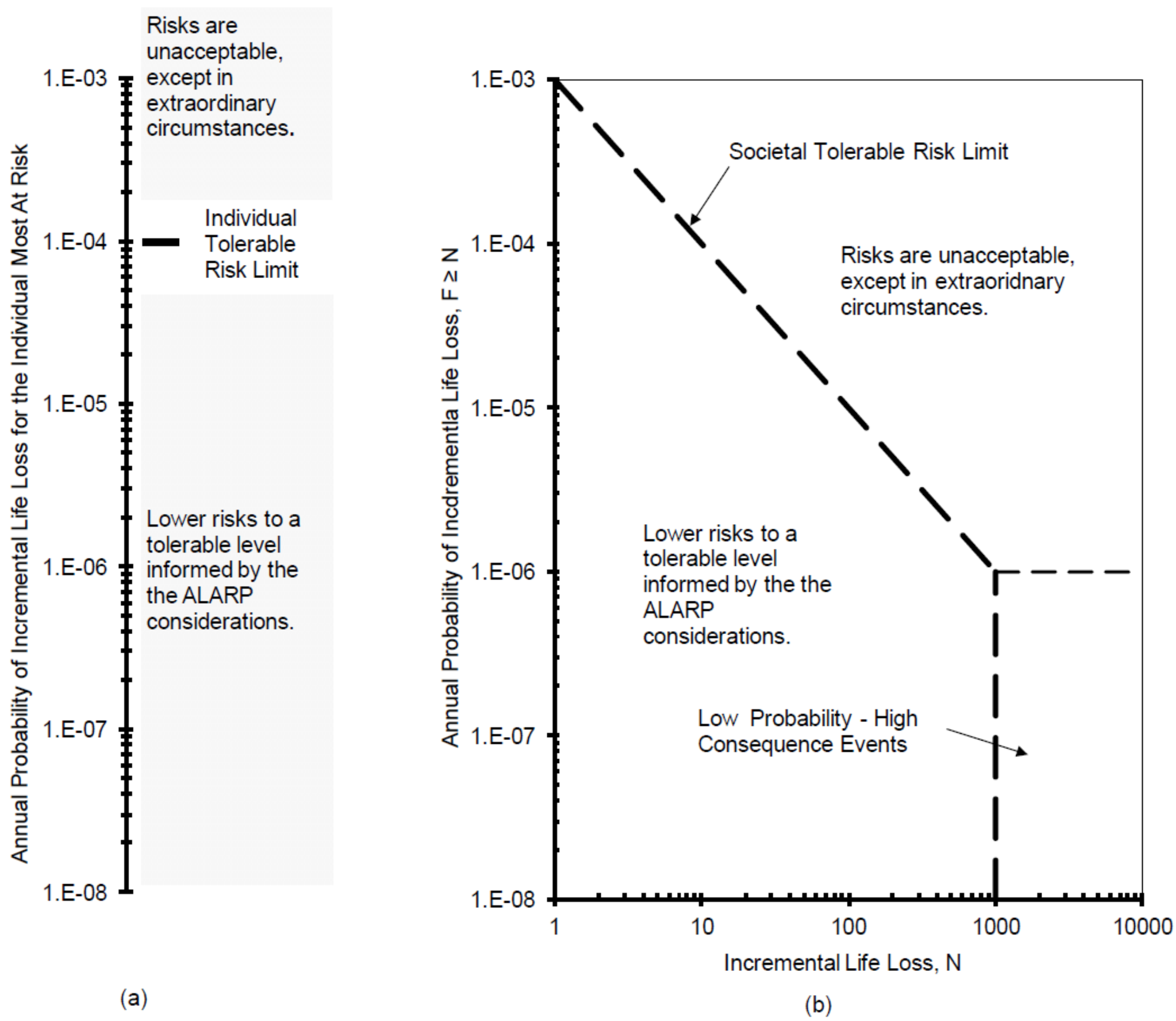


Figure 8. USACE Risk Guidelines for Existing Dams [10]
a – Individual Guideline for Incremental Risk
b – Societal Guideline for Incremental Risk

Figure 3 (cont.). U.S. Dept. of Interior Bureau of Reclamation and U.S. Army Corp of Engineer F-N Plots

PHMSA has also recently funded related research that evaluates the extent of vapor dispersion exclusion zones using the current FRT and different dispersion models, such as the research in 2016 entitled “Comparison of Exclusion Zone Calculations and Vapor Dispersion Modeling Tools” performed by CH-IV International Inc.[14]

3. Failure Rate Reference Sources: Identification

3.1 Reference Sources Cited in Current FRT

FERC cited the following twelve references in its 2012 issuance #20120301-0016 dated March 1, 2012. The abbreviated names for reference sources identified in [brackets] are used in this report, as listed below as well as in the References and Bibliography.

1. NFPA *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG),* NFPA 59A, 2012 DRAFT. ["59A '12 DRAFT"]
2. Mniszewski, K.R., IIT Research Institute, "Fire Protection Planning for LNG Facilities", *AGA Distribution Transmission Conference Proceedings*, San Francisco, California, May 7-9, 1984. ["AGA FP LNG '84"]
3. Johnson, D.W., and Welker, J.R., Applied Technology Corp. *Development of an Improved LNG Plant Failure Rate Database*, Final Report for Gas Research Institute, GRI-80/0093, 1981. ["GRI LNG FRD '81"]
4. Welker, J. R., and H. P. Schorr, *LNG Plant Experience Database*, American Gas Association, Operating Section Proceedings, United States, 1979. ["AGA LNG EXP '79"]
5. Pelto, P.J., Baker, E.G., Holter, G.M, and Powers, T.B., *Analysis of LNG Peakshaving Facility Release Prevention Systems,* Pacific Northwest Laboratory, PNL-4153, 1982. ["PNL PSRP '82"]
6. Pelto, P.J. and Baker, E.G., *Analysis of Liquefied Natural Gas (LNG) Release Prevention Systems,* Pacific Northwest Laboratory, PNL-SA-12278, AIChE Summer National Meeting, August 1984. ["PNL RP '84"]
7. Mannan, Sam, *Lees' Loss Prevention in the Process Industries – Hazard Identification, Assessment and Control*, Third Edition, Volume 3, Appendix 14, Elsevier, Inc. 2005. The project team reviewed the Third edition and also the Fourth Edition of this reference by Mannan, Sam, Elsevier, Inc., 2012. ["LEES '12"].
8. TNO *Guidelines for Quantitative Risk Assessment (TNO Purple Book*), Committee for the Prevention of Disasters (CPR), National institute of Public Health and the Environment (RIVM), The Netherlands Organization for Applied Scientific Research (TNO). First edition 1999/2005. ["TNO PURPLE '05"]
9. TNO *Methods for the Determination of Possible Damage (TNO Green Book),* Committee for the Prevention of Disasters (CPR), National Institute of Public Health and the Environment (RIVM), The Netherlands Organization for Applied Scientific Research (TNO). First edition 1992 ["TNO GREEN' 92"]
10. TNO *Methods for Determining and Processing Probabilities (TNO Red Book),* Committee for the Prevention of Disasters (CPR), National Institute of Public Health and the Environment (R1VM), The Netherlands Organization for Applied Scientific Research (TNO). Second edition. 1997/2005. ["TNO RED '05"]
11. HSE *Failure Rate and Event Data for use within Risk Assessments,* UK, June 28, 2012 ["HSE FRED JUN'12"]

12. RIVM *Reference Manual Bevi Risk Assessment*, Version 3.2, Module C, the Netherlands National Institute of Public Health and Environment (RIVM), July 1, 2009. ["RIVM BEVI '09"]

3.2 Additional Primary Reference Sources Identified

Available relevant equipment failure rate references were collected in the following manner:

- Literature Review
- Input from this project's Technical Advisory Panel (TAP)
- Input from more than 50 Subject Matter Experts beyond the TAP (see Appendix L)

The primary additional reference sources considered in this analysis that contain equipment failure rate data, estimates or specifications were:

1. Alber, T.G., Hunt, R.C., Fogarty, S.P., Wilson, J.R., *Idaho Chemical Processing Plant Failure Rate Database*, Idaho National Engineering Laboratory, NEL-95/0422, August 1995. ["INL CHEM '95"]
2. API, *Risked-Based Inspection Methodology*, *Recommended Practice 581*, Third Edition, American Petroleum Institute, 2016 ["API 581 '16"]
3. Baker, E.G, *Analysis of LNG Import Terminal Release Prevention Systems,* Pacific Northwest Laboratory, PNL-4152, 1982. ["PNL ITRP '82"]
4. Cadwallader, L., *Vacuum Bellows, Vacuum Piping, Cryogenic Break, and Copper Joint Failure Rate Estimates for ITER Design Use*, Idaho National Engineering Laboratory, INL/EXT-10-18973, June 2010. ["INL VJ '10"]
5. CCPS *Guidelines for Process Equipment Reliability Data with Data Tables*, American Institute of Chemical Engineers, Center for Chemical Process Safety, New York, NY, 1989. ["CCPS '89"]
6. CONCAWE *Performance of European Cross-Country Oil Pipelines: Statistical Summary of Reported Spillages in 2014 and Since 1971*, Report No. 7/16, June 2016. ["CONCAWE '16"]
7. DNV, *Failure Frequency Guidance – Process Equipment Leak Frequency Data for Use in QRA*, DNV GL AS03-2013, 2013. ["DNV FFG HCRD '13"]
8. DNV, LEAK Software v. 3.3, 2016. ["DNV LEAK 3.3"]
9. EGIG *Gas Pipeline Incidents, 9th Report of the European Gas Pipeline Incident Data Group (1970 – 2013)*, Doc. Number EGIG 14.R.0402 Feb. 2015 ["EGIG '15"].
10. HSE *Hydrocarbon Releases Database System* (HCRD), 2016 ["HSE HCRD '16"].
11. HSE *Failure frequencies for major failures of high pressure storage vessels at COMAH sites: A comparison of data used by HSE and the Netherlands*, Dec 2006. ["HSE COMAH '06"]
12. IOGP *Risk Assessment Data Directory, Process Release Frequencies,* International Association of Oil and Gas Producers Report No. 434 – 1, March 2010. ["IOGP 434-1"]

13. IOGP *Risk Assessment Data Directory, Storage Incident Frequencies*, International Association of Oil and Gas Producers Report No. 434 – 3, March 2010. ["IOGP 434-3"]

14. Kim, Hyo, Koh, Jae-Sun, Kim, Youngsoo, University of Seoul Department of Chemical Engineering, and Theofanous, Theofanius, University of California at Santa Barbara Center for Risk Studies and Safety, "Risk Assessment of Membrane Type LNG Storage Tanks in Korea – based on Fault Tree Analysis," *Korean Journal of Chemical Engineering*, Vo. 22., No. 1, 1-8, 2005. ["KJCE '05"]

15. Lam, Chio, *Statistical Analyses of Historical Pipeline Incident Data with Application to the Risk Assessment of Onshore Natural Gas Transmission Pipelines*, Master of Science Thesis, The University of Western Ontario, July 2015 ["PHMSA NGT LAM '15]

16. Lee, S. R. "Safety comparison of LNG tank designs with fault tree analysis", *International Gas Union 23rd World Gas Conference proceedings*, Amsterdam, Holland. 2006. ["KGSC '06"]

17. LNE *Handbook of Failure Frequencies*, and *Appendix*, Safety Report, Flemish Government LNE Department Environment, Nature and Energy Policy Unit Safety Reporting Division, 2009. ["LNE '09"]

18. Miyazaki, Sinichi, Tokyo Gas Co. Ltd. and Yamada, Yoshihisa, Tokyo Gas Engineering Co., Ltd., "Quantitative Risk Assessment of LNG Above Ground Tanks Based on Past Operating Records of LNG Regasification Terminals and Life Cycle Assessment", *International Gas Union 22nd World Gas Conference proceedings*, Tokyo, June 1-5, 2003. ["TGC '03"].

19. NFPA *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG),* NFPA 59A, 2013 Edition. ["NFPA 59A '13"]

20. NFPA *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG),* NFPA 59A, 2016 Edition. ["NFPA 59A '16"]

21. O'Donnell, IJ and Phillips, DW, Serco Assurance, and Winter, PW, AEA Technology, "A New Estimate of the Likelihood of Spontaneous Catastrophic Failure of Pressurized LPG Storage Vessels", Hazards XXVIII, *Symposium Series No. 150*, IChemE, 2004. ["SERCO AEA '04"]

22. OREDA *Offshore and Onshore Reliability Data, 6th Edition, Volume 1-3 – Topside Equipment*, Published by the OREDA Participants, Prepared by SINTEF and NTNU, and Distributed by DNV GL, 2015 ["OREDA '15"].

23. Plants, N. P. *Industry-average performance for components and initiating events at US commercial nuclear power plants*, Idaho National Engineering Laboratory, NUREG/CR-6928 (2007) ["INL NUC '07"]

24. PHMSA Natural Gas Transmission Pipeline Incident Data[15], applied in this analysis as described in Section 6 and as analyzed in Appendix J ["PHMSA NGT GTI '16"]

25. PHMSA Hazardous Liquid Pipeline Accident Data[16], applied in this analysis as described in Section 6 and as analyzed in Appendix K ["PHMSA HL GTI '16"]

26. SAI, *LNG Terminal Risk Assessment Study for Oxnard, California*, Science Applications, Inc. SAI-75-615-LJ, 1975 ["SAI '75"]

27. SIGGTO, *Accident Prevention – The Use of Hoses & Hard Arm at Marine Terminals Handling Liquefied Gas*, Information Paper No. 4, 1996 [“SIGGTO IP4 ‘96”]
28. Welker, J.R., Brown, L.E., Ice, J.N., Martinsen, W.E., and West, H.H., *Fire Safety Aboard LNG Vessels*, Final Report DOT-CG-42, 355A, Task #1 [“WELKER ‘76”]

More than 150 additional reference sources were considered in this analysis as summarized in the References and the Bibliography. Some of the historical references (e.g. “SAI ‘75” and “WELKER ‘76”) are incorporated by reference in subsequent references, but were included in order to capture additional original source content. “SERCO AEA ‘04” was included in part because its Table 2 provided confidence levels for pressurized storage vessels in its analysis.

Another potential source of data that could be used for input to assess future failure rates are FERC’s incident reports and semi-annual reports and DOT PHMSA’s incident reports and annual reports:

- LNG plants under FERC jurisdiction are required to report incidents within 24 hours for significant non-scheduled events, and safety- and security-related incidents, including, but not be limited to: leaks and releases of hazardous fluids that constitute an emergency or exist for 5 minutes or more; explosions; fires; estimated property damage of $50,000 or more; and death or personal injury necessitating in-patient hospitalization. LNG plants under FERC jurisdiction are also required to report on a semi-annual basis certain operational activities, changes to facility design and operation, as well as abnormal operating and maintenance including, but not be limited to: ship arrivals with quantity and composition of imported and exported LNG; liquefied and vaporized quantities; boil off/flash gas quantities; unloading/loading/shipping problems; potential hazardous conditions from offsite vessels; storage tank stratification or rollover; geysering; storage tank pressure excursions; cold spots on the storage tanks; storage tank vibrations and/or vibrations in associated cryogenic piping; storage tank settlement; significant equipment or instrumentation malfunctions or failures; non-scheduled maintenance or repair (and reasons therefore); relative movement of storage tank inner vessels; hazardous fluids releases; fires involving hazardous fluids and/or from other sources; negative pressure (vacuum) within a storage tank; higher than predicted boil off rates; and adverse weather conditions and the effect on the facility.
- LNG plants under US DOT PHMSA jurisdiction are required to report incidents as soon as practicable but not more than 30 days after detection, for incidents that meet the definition of US 49 CFR Section 191.3; information that must be reported regarding those incidents is contained in PHMSA form F 7100.3. LNG plants under US DOT PHMSA jurisdiction are also required to report operational activities on an annual basis in form PHMSA F7100.3-1; this includes leaks and other events that occurred during the reporting year.

Detailed equipment population data for the facilities that submit these reports would need to be created in order to generate failure rate frequencies (e.g. number or length, and diameter and type of valves or piping). Also, the calculated equipment failure rate frequencies would be based on the reporting threshold requirements listed above, i.e. include only those incidents that are large enough to be reportable. Refinements in the characterization of leak hole sizes and rupture definition in future reporting requirements may also be beneficial.

4. Failure Rate Reference Sources: Qualitative Analysis

Comments are provided below about individual references and data sources from which the results are derived, and are organized by the specific equipment categories currently used in the FRT. Additional details about the data included in this project's database is contained in the database file provided to PHMSA as a deliverable of this contract.

4.1 Review and Analysis Applicable to Multiple Equipment Categories

Comments re: UK "HSE FRED JUN'12"

The *Failure Rate and Event Data for use within Risk Assessments* (28/06/2012) "HSE FRED JUN'12" document produced by the UK Health and Safety Executive (HSE) was one of the documents cited in the derivation of the FRT. It provides a very good informational understanding of the basis of its failure rate estimates, although many of its citations are confidential documents.

As a point of comparison, Singapore requires the use of "HSE FRED JUN'12" for Fixed Installations in its *QRA Technical Guidance Manual* issued August 2016.[17]

Comments re: Dutch "RIVM BEVI '09"

The *Reference Manual Bevi Risk Assessments* ("RIVM BEVI '09") produced by the Dutch National Institute of Public Health and the Environment (RIVM) was one of the documents cited in the derivation of the FRT. It replaced the TNO Purple Book, and also stipulates that DNV's SAFETI-NL software must be used for QRA calculations in the Netherlands, as per p. 3 of its Introduction.

Comments re: Flemish "LNE '09"

The *Handbook Failure Frequencies* 2009 ("LNE '09") produced by the Flemish Flemish Environment, Nature and Energy Department (LNE) was not cited in the 2012 derivation of the FRT, but constitutes another failure rate reference for PHMSA's/FERC's consideration.

Comments re: "IOGP 434-1" and "IOGP 434-3"

The International Association of Oil & Gas Producers (now IOGP and formerly known as OGP) publishes a number of risk assessment documents. Of these, *Risk Assessment Data Directory, Process Release Frequencies* document 434-1 and *Risk Assessment Data Directory, Storage Incident Frequencies* document 434-3 contain data relevant to FRT; both documents issued in March 2010. Other IOGP documents reviewed during this project include those listed in the Bibliography. IOGP documents were not cited in the 2012 derivation of the FRT, but constitute another failure rate reference set for PHMSA's/FERC's consideration.

The basis of process piping and equipment release frequencies in IOGP 434-1 is the UK Hydrocarbon Release Database System (HCRD), as summarized in this excerpt from p. 27:

> The release frequencies for the main process equipment items presented in Section 2.0 are based on an analysis of the HSE hydrocarbon release database (HCRD) for 1992-2006 [9], according to a methodology described in [4].

where [9] refers to the publically available UK HCRD dataset (https://www.hse.gov.uk/hcr3/) and [4] refers to Confidential DNV Report 2004-0869 which appears to be consistent with subsequent DNV-authored papers such as "DNV FFG HCRD '13" based on the methodology described in Section 4.1.2 of "IOGP 434-1."

In summary, the "IOGP 434-1" process equipment and piping failure rate frequencies are drawn from the UK HCRD dataset. Where "IOGP 434-1" data was included in the database for this project, the release data used was "All Releases" (which included "Full Releases", "Limited Releases" and "Zero Pressure" releases such as may occur during equipment maintenance).

While the underlying source for the process release frequencies in IOGP 434-1 is not from LNG facilities, Page 19 of IOGP 434-1 states that:

> The data presented in Section 2.0 can be used for process equipment on the topsides of offshore installations and for onshore facilities handling hydrocarbons, and could also be used as appropriate for subsea completions.
>
> DNV [3] have compared failure rate data for LNG facilities with the data presented in Section 2.0. The comparison indicates that LNG failure frequencies may be around 40% to 65% of those given here. However, this has not been verified and the data for LNG installations is relatively sparse. We therefore recommend use of the same frequencies for LNG installations as given in Section 2.0. A 50% reduction could be considered as a sensitivity but decisions on this would need to be fully addressed.

As a point of comparison, a representative of Korea Gas Corp. (KOGAS) indicated that KOGAS primarily uses the IOGP data for its QRAs.[18]

<u>Comments re: "NFPA 59A '16"</u>

NFPA 59A includes "Chapter 15 Performance (Risk Assessment) Based LNG Plant Siting" in its 2013 and 2016 editions, which contain identical equipment failure rate data. This project's analysis include the identical "Example Component Failure Database" data contained in:

- Table 15.6.1 of NFPA 59A 2016 edition
- Table 15.6.1 of NFPA 59A 2013 edition, as revised by TIA 13-1

and for simplicity refers to this same data as "NFPA 59A '16".

<u>Comments re: "GRI LNG FRD '81" and "AGA LNG EXP '79"</u>

The "GRI LNG FRD '81" reference summarizes work performed by Johnson and Welker of Applied Technology Corp. in which they analyzed 27 separate LNG base load or satellite facilities (representing "approximately 1,626,000 hours of plant in-service time", as per p. 5), which built upon the prior "AGA LNG EXP '79" analysis of 25 LNG peak-shaving plants by Welker of Applied Technology Corp. and Schorr of Brooklyn Union Gas Co. (representing "more than 1.3 million manhours of operating time", as per p. T-263).

As per pp. 6-7 of "GRI LNG FRD '81", Johnson and Welker defined:

> Two distinct failure types are presented: major failures and minor failures. Minor failures are defined as those which cause (or would have caused) an unscheduled shutdown of

equipment for a period of less than 24 hours. A major failure is defined as any failure which results in an unscheduled shutdown for a period of greater than 24 hours. …

> The overall failure rate is simply the sum of major and minor failures divided into the total operating hours of the equipment in question. …
>
> Safety-related failures were defined as failures which resulted either in a fire, injury, loss of life, or a large leak of liquid or gas. To qualify as a safety-related failure, the liquid or gas release must have been large enough to: 1) have the potential to injure plant personnel; 2) actually have injured plant personnel; or 3) been severe enough to propagate to another area had it not been controlled in the area in which it originated.

Welker and Schorr use similar definitions in "AGA LNG EXP '79", and the following quotation from page T-263 provide some additional context:

> …Minor failures are defined as those that cause an unscheduled shutdown of operating equipment caused by equipment damage where the shutdown period for repairs is less than 24 hours. In almost all cases, a minor failure does not result in either a liquid spill or gas leak. In a few cases, liquid dripping may occur, or small gas losses may occur. Neither fires nor injury for either public or operating crews results from minor failures.
>
> Major failures are those that result in an unscheduled shutdown of operating equipment where the repair period is more than 24 hours. In these cases of major failure, injury occurred to plant operating personnel. In all the equipment failures that were surveyed and in all the data that were taken, neither public injury nor potential for public injury was found. As in the case for minor failures, a major failure may or may not have either gas leak or liquid spill; most do not. However, in any case where a substantial gas leak or liquid spill occurred, the failure was judged to be a major failure.
>
> The total failure rate is simply the sum of the major and minor failures lumped together over the period of operation of the facility in question.
>
> A safety related failure is one which resulted either in a fire or a large leak of liquid or gas. In this case, the liquid or gas release must have been large enough to provide a potential for injury, or the failure must be severe enough to propagate to another area had it not been controlled in the area in which it existed. There were no failures found in this survey that did in fact result in propagation of a failure from one area to another. Safety related failures generally were small, although some did result in fires or substantial liquid or gas leaks. Most of the failures reported in this survey could be described more accurately as malfunctions because they caused no danger and resulted in short term interruption of normal operations.

Most of the Mean Time Between Failure (MTBF) data reported in these two references refers to that for Major or Minor failures (i.e. primarily operational failures) and not Safety-related failures (i.e. primarily release failures); therefore, this MTBF data for Major or Minor failures was not included in the project database. Where Safety-related failure MTBF data is reported in "AGA LNG EXP '79" by component, it represents *minimum* failure rates calculated as of the time of the analysis *for all equipment other than for vaporizers*. This project's analysis included Safety-related MTBF data for vaporizers in the project database (Section 4.3 describes the calculation by the project team that yielded a vaporizer failure rate of 3.1×10^{-5} per hour combined from the 1979 and 1981 analyses) but excluded all other Safety-related MTBF data from "AGA LNG EXP '79" since it represents a *minimum* rate rather than an actual rate.

To elaborate on the above point:

- The 1979 analysis of 25 LNG peak-shaving plants identified *zero* Safety-related failures of: LNG (single containment) tanks; cryogenic valves; LNG pipelines and fire water mains; gas pretreatment and liquefaction systems; and other equipment not considered in the FRT.
- The 1981 analysis of 27 LNG base load or satellite facilities identified *zero* Safety-related failures of: LNG (single containment) tanks; cryogenic valves ("One safety failure was reported, but this failure was attributed to human error and is not included as a valve failure." as per p. 27); cryogenic piping; heat exchangers; vaporizers; gas pretreatment systems; and other equipment not considered in PHMSA's FRT. Section 4.1.13 entitled "Spills and Leaks" on p. 34 identifies that "The major causes of spills and leaks were electrical seal failures, overfilling of tanks, weld failures, and gasket leaks." Section 4.1.17 entitled "Safety Related Failures" on p. 45 states that:

> Safety related failures occurred infrequently. Only 2 safety-related failures were reported as such in the survey, although there were 3 other incidents which qualified as being safety-related. All three were crankcase explosions in reciprocating compressors and caused equipment shutdowns of several days in each incident. Twenty-nine leak situations were reported, but not enough information was given in 18 of them to determine if a leak actually occurred. The MTBF for safety-related failures ranged from 48,000 to 325,000 hours depending on whether all potential and actual or only actual occurences were counted. Since the reported leaks and spills all involved less than 200 gallons of LNG, a relatively small amount and probably not enough to be considered a substantial safety problem, the true MTBF for safety-related failures is more than likely in the area of one failure per 325,000 hours of plant operation. It is important to note that none of the safety related failures (either reported as such or inferred from the information on the questionnaires) affected or would have affected the general public.

<u>Comments re: "PNL PSRP '82" and "PNL ITRP '82"</u>

Pacific Northwest Laboratories assessed LNG plant equipment and system release prevention systems in several projects funded by the U.S. Department of Energy in the early 1980s. The analyses most relevant to this PHMSA project are PNL's release prevention analyses of Peak Shaving and Import Terminals in report nos. PNL-4153 and PNL-4152, respectively. These reports both published in 1982 and are referenced in the Bibliography as "PNL PSRP '82" and "PNL ITRP '82", respectively.

These two analyses assessed failure rate data for key LNG plant components, and share identical assessments of LNG equipment failure data in the following tables, except for "Vaporizer":

- "Table 3: Generic Failure Rates for Components of LNG Peakshaving Facilities" in "PNL PSRP '82"
- "Table 3.3: Generic Failure Rates for Components of LNG Import Terminals" in "PNL ITRP '82"

For simplicity this same data source in Table 3 or 3.3 is referred to as "PNL PSRP '82" in the database developed under this PHMSA project. Both reports indicate that:

> Over a dozen sources were used to obtain the failure rate information included in the FMEAs. Only one of the sources dealt specifically with land-based LNG facilities (Welker 1979). For most components, generic failure rate information was used. In most instances these failure rates came from studies in the nuclear industry (USNRC 1975) and the chemical processing industry (Anyakora 1971, Lees 1973, Kletz 1973, Kletz 1975). In addition, some information was obtained from a study of safety on LNG ships (Welker 1976). Most of the failure rate information in this last study is generic and was obtained from previously mentioned sources.

It was also noted that PNL appears to have used the MTBF rate for Major Failures (i.e. that which "results in an unscheduled shutdown for a period of 24 hours", and a failure to operate that could be due to a number of potential causes including a leak) from the Welker and Schorr 1979 source (i.e. "AGA LNG EXP '79") as equipment leak or rupture failure data in at least one of PNL's release prevention analyses (e.g. Table B.9 of "PNL PSRP '82"). For example, text on p. 4.12 of "PNL PSRP '82" analysis states:

> A recent study (Welker 1979) indicated that submerged combustion vaporizer tube failures occurred at a rate of approximately 1×10^{-4} per hour or 5×10^{-2} times/yr.

and Table 3 of "PNL PSRP '82" entitled "Generic Failure Rates for Components of LNG Peakshaving Facilities" identifies the failure mode as rupture:

Component	Failure Mode	Faults/Hr	Reference
Vaporizer	Tube or Panel Rupture	1×10^{-4}	(Welker 1979)

In comparison, Welker and Schorr ("AGA LNG EXP '79") state in the section entitled "Vaporizers" that "Figure 3 shows that major failures of vaporizers occurred at a mean time of about 8,000 hours". This equates to 1.25×10^{-4} per hour; or in other words, it appears that "PNL PSRP '82" apparently used "Major Failure" and not "Safety Failure" rate data as its vaporizer tube or panel rupture data.

And in further comparison, Welker and Schorr ("AGA LNG EXP '79") also state in the section entitled "Vaporizers" that "Safety-related failures occurred at a mean time of a little over 15,000 operating hours" and "The vaporizers considered in Figure 3 are primarily submerged combustion and direct fired vaporizers."

Thus vaporizer rupture data based solely on Walker and Shorr's 1979 analysis of Safety-related incidents at peakshaving plants appears to have occurred at a mean time of about 15,000 hours which equates to 6.7×10^{-5} per hour (not 1×10^{-4} per hour) and for at least two types of vaporizers (not just submerged combustion). In section 4.3 below, the project team calculated an estimated vaporizer leak or rupture data at a mean failure time of 3.1×10^{-5} per hour directly from the 1979 and 1981 original works by Welker and Schorr ("AGA LNG EXP '79") and Johnson and Welker ("GRI LNG FRD '81").

Additional comments about "PNL PSRP '82" are provided in the following sections, but in summary all data identified as a rupture in Table 3 of "PNL PSRP '82" (and thus the corresponding Table 3.3 in "PNL ITRP '82") was incorporated in this project's database, other than for those equipment components not in the analysis framework and with the clarification that vaporizer rupture data (see section 4.3) and "Pipe Section >3 inch Diameter" (see section 4.9) were excluded; more specifically, rupture data was included for: Storage Tank; Valve; Expansion Joints; Pipe Fittings (Flanges); and Loading Arm. In addition, rupture data from the body of the "PNL PSRP '82" report was included for Gross Failure of Storage Tank and failure rate of Flexible Metal Hose as summarized in Sections 4.2 and 4.4, respectively.

The two PNL analyses "PNL PSRP '82" and "PNL ITRP '82" then used Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) to predict the likelihood of failure events for various LNG plant subsystems. This project's analysis did not include any of these FMEA or FTA results since they represent integrated system or subsystem failures (and not individual equipment component failures).

Comment re: "LEE'S '12"

Lee's Loss Prevention in the Process Industries – Hazard Identification, Assessment and Control Fourth Edition contains a significant amount of background information and data, such as in Chapter section 12.30 and Appendices 7, 8 and 14 (including for example Table A14.7 that contains failure rate data from the Rasmussen Report AEC WASH-1400 Reactor Safety Study, 1975). The Third Edition (2005) was cited in the 2012 derivation of the FRT.

In some cases the equipment failure mode is not specifically identified; in some cases it is clear that all failure modes are included, but in a number of cases there is ambiguity. The database for this project's results included data from Chapter section 12.30 and Appendices 7, 8 and 14 that was clearly identified as rupture, catastrophic failure, guillotine break or (in two cases) "serious leak", except for that data where units were undefined (e.g. length of piping "section"). Data for "disruptive failures", failure to operate, and undefined other "failures" were excluded since the size of the crack, leak or other defect that prompted the incident or required repair or replacement was not specified.

Comments re: "WELKER '76"

The database for this project's results only included data that was clearly identified as "rupture", and excluded data marked as "External leak or rupture" or "leak" or "external leak" (since no hole sizes were defined, or the failure mode was not clearly defined).

Comment re: "INL CHEM '95"

The Idaho National Engineering Laboratory *Idaho Chemical Processing Plant Failure Rate Database* 1995 ("INL CHEM '95") was not cited in the 2012 derivation of the FRT, but constitutes another failure rate data set from the chemical process industry for PHMSA's/FERC's consideration. Appendix D contains "generic equipment failure database data" which was "taken from a Westinghouse Savannah River Report Savannah River Site Generic Database Development." The Savannah River Site Generic Data Base Development reference document was published in 1982; it considered data sources from multiple industries but its Category 1 ("sources with actual failure data obtained from a detailed review of failure events") utilized the NUCLARR (Nuclear Computerized Library for Assesing Reactor Reliability) database plus Savannah River Site Reactor data.[19] The database for this project reviewed equipment relevant to the Framework and

- included Chemical Process and Compressed Gas categories
- excluded Water, HVAC/Exhaust, Electric Power, and other categories.

Failure frequency rates were excerpted from the categories of "Heat Exchangers and Condensors", "Valves" and "Vessels" in Appendix D and included in the database for this project's results. Unfortunately failure rate data from the Idaho Chemical Process Plant itself (as contained in Table 1) could not be included in this project's database since leak sizes are not characterized nor are rupture rates provided.

Comments re: "INL NUC '07"

The Idaho National Laboratory's *Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants* 2007 summarizes industry-averaging performance for components at U.S. commercial nuclear power plants from 1998-2002. It also was not cited in the 2012 derivation of the FRT but was included in this analysis for comparative purposes and in support of a Bayesian analysis. The population of components was large, containing more than 13,000 valves, 700 Heat Exchangers and 700 Pressurized Tanks, but obviously in much different service than in LNG, CPI, oil and gas, or other hydrocarbon service. This project's database included "External Leak Large" from Table 5-1 as rupture data (i.e. consistent with a relevant historic definition of rupture[20] as cited on p. 15) but excluded "External Leak Small" since the leak size is not characterized.

Comments re: "OREDA '15"

The *Offshore and Onshore Reliability Data* (OREDA) data set was not cited in the 2012 derivation of the FRT, but constitutes an additional failure rate reference and data set analysis of process equipment in the oil and gas industry for PHMSA's/FERC's consideration. However its population of (non-subsea) equipment in categories in the FRT is small, e.g.: 43 Heat Exchangers; 55 Vessels; and 703 Valves.

Unfortunately the OREDA data set does not differentiate between leak vs. rupture failure modes, but instead lists one category of "External Leakage". With respect to other references, the project team only considered as "ruptures" that data that was clearly identified as "rupture" , "catastrophic failure" or "Large Leak" (or related terminology). But because OREDA provides some additional key useful data (e.g. specifically for valves) for comparison, this difference was made in order to provide additional comparative information - - OREDA's "Critical Failure" mode "External Leakage" reliability data was considered as "rupture" data, even though "External Leakage" may have been a leak rather than a rupture. For context, OREDA does define a "Critical Failure" as "a failure which causes immediate and complete loss of an equipment unit's capability of providing its output", so presumably an "External Leakage" would have been a significant leak in order to be assigned as a "Critical Failure".

Additional clarifications related to "OREDA '15" as used in this project's database include:

- "Degraded", "Incipient" or "Unknown" mode "External Leakage" reliability data was excluded. This data could theoretically be applied to a leak hole category, but no hole size data is provided or could be inferred. OREDA for example defines a "Degraded Failure" as a "failure which is not critical, but it prevents an equipment unit from providing its output within specifications. Such a unit would usually, but not necessarily, be gradual or partial, and may develop into a critical failure in time."
- Only "External Leakage" of "Process medium" was considered. "External Leakage" of "Utility medium" was excluded.
- Only OREDA's "Volume 1 – Topside Equipment" was considered. Reliability data in OREDA's "Volume 2 – Subsea Equipment" was excluded.

- All reliability data used was based on calendar time (and not operational time).
- "Vessels" were considered to be Process Vessels (and not Pressure Vessels, i.e. Pressure Storage Vessels) and were considered to be single-wall vessels.

Comments re: "API 581 '16"

API Recommended Practice 581 *Risk-Based Inspection Methodology* was not cited in the references identified in the 2012 derivation of the LNG Failure Rate Table, but it provides another failure rate data set for process equipment in the oil and gas industry for PHMSA's/FERC's consideration. All data in Table 3.1 "Suggested Component Generic Failure Frequencies" of "API 581 '16" was included in the database developed for this project except that for compressor and pipe. The pipe data was excluded because "API 581 '16" specifies the failure frequency of pipe as "failures/yr" but does not define a piping or section length, and no assumed average pipe length would necessarily be relevant to the FRT; lengths considered could range from individual piping elbows to much longer piping sections (e.g. mill-run pipe); others have also pointed out this issue in API 581.[21] Hole size are defined in Table 4.4 as Small (6.4 mm), Medium (25 mm), and Large (102 mm).

Comments re: UK HCRD Database

The UK Hydrocarbon Release Database System (HCRD) was not specifically cited in the 2012 derivation of the LNG Failure Rate Table, but this failure rate data set contains some of the most detailed hole leak size data available for process equipment and piping to the oil and gas industry. It was generated from off-shore oil & gas operations and is a primary data basis used by IOGP, DNV's LEAK software, and apparently by RIVM in DNV's SAFETI-NL, a customized version of DNV's software that is the sole software program used for performing QRAs in the Netherlands.[22] DNV also recommended using the UK HCRD data set for LNG risk assessments in its 2014 *Liquefied Natural Gas (LNG) Bunkering Study* commissioned by the US DOT Maritime Administration.[23]

Actual leak hole sizes are recorded by the dutyholders in the HCRD, but the largest leak hole size recorded is "> 100 mm" (~4").

Appendix L graphically illustrates some of the data in the HCRD in order to help PHMSA and FERC better understand this database, and Appendix M provides cumulative probability curves developed by GTI for PHMSA and FERC from this public database.

Comments re: DNV's assessments of UK HCRD Reliability Data, including "DNV FFG HCRD '13", and "DNV LEAK 3.3"

DNV has reviewed the HCRD data in detail and developed their commercial LEAK software product based on their analysis. "DNV FFG HCRD '13" summarizes their analysis methodology, and provides some representative predicted failure rate frequencies.

DNV notes on p. 9 of "DNV FFG HCRD '13" that the HCRD data does not directly support a separate frequency for ruptures:

> It is important to be aware that the leak frequency form is imposed on the data and that this is a mathematical representation of historical data. The data itself does not directly

support a separate frequency for ruptures. The historical data related to releases from large hole sizes is very limited and the uncertainty related to estimation of such leaks is therefore considerable. The additional rupture frequency F_{rup} and the slope parameter m are assumed to be constants, i.e. not to be dependent on equipment size, for any equipment type.

DNV does however state on page 9 "The frequency of full-bore ruptures, i.e. holes with diameter *D*, is: $F(D) = f(D)\ D^m + F_{rup}$" where "D = equipment diameter (mm)".

A review of Appendixes L and M is useful in this regard, while keeping in mind that the largest leak hole size recorded is 100 mm (~4"). GTI concurs with DNV that the HCRD data does not directly support a separate frequency for ruptures. For comparison purposes, however, estimates of full-bore rupture were developed from the HRCD data consistent with the statement quoted above from page 9 of "DNV FFG HCRD '13". For example, "DNV FFG HCRD '13" indicates on p. 20 that a total failure frequency rate for a > 150 mm (6") hole to occur in a 6" (150 mm) flange is 6.852×10^{-6} failures/year. GTI likewise used DNV's LEAK software to calculate the frequency for full-bore leaks of piping, valves, and other components to develop estimates of ruptures using the "DNV LEAK 3.3" software merely for comparison purposes.

The results provided by GTI to PHMSA in the project database and this report (including the Appendixes) that use DNV's LEAK 3.3 software are: 1) based on the leak hole size ranges defined in Table 2 below; and 2) conservatively use "Total" leak frequencies (i.e. all release types including "Full pressure leaks" and "Zero pressure leaks") from the HCRD. Some basic information is summarized below in order to provide some context regarding the conservatism of this basis; the reader is referred to those sources if additional information as desired.

- Pages of 9-11 of "DNV FFG HCRD '13" summarize the definition of these terms and Figure 4 calculates that:
  - 94% of all leaks in the HCRD are "Full pressure leaks", which consist of 49% "Full leak" and 51% "Limited leak" scenarios
  - 6% of leaks in the HCRD were "Zero pressure leaks". Page 10 summarizes in part regarding "Zero pressure leaks" that "This scenario includes all leaks where the pressure inside the leaking equipment is virtually zero (0.01 barg or less). This may be because the equipment has a normal operating pressure of zero (e.g. open drains), or because the equipment has been depressurized for maintenance, but not de-inventoried."
- A summary of IOGP's recommendation in Section 3.3 of "IOGP 434-1" on pp. 20-21 is:
  - "Full Releases" "should always be included in quantified risk assessements".
  - "Limited Releases" "should normally be included" in Coarse QRAs, and "could be considered" for Detailed QRAs.
  - Zero Pressure leaks are "typically excluded from QRA assessments"

For those equipment types for which leak rates are dependent on equipment size (i.e. process pipe, flanges, and manual and actuated valves) in the LEAK 3.3 software, GTI calculated the leak frequency results by using the arithmetic mean of the results calculated for diameters of 2" increments within the FRT's diameter ranges (e.g. the average of the results calculated for 12"D, 14"D, 16"D and 18"D piping to represent the 12" ≤ d < 20" piping category).

Comments re: Selection of Leak Hole Size Range

The calculation of frequency of leaks and ruptures from piping, valves, flanges and equipment requires the definition of hole size categories, which will impact the calculated results, and no industry-consensus definition of hole size categories was identified during this research. The following basis was used in this project analysis, and is shown in comparison to recommendations from the Singapore *QRA Technical Guidance* manual, three example Quantitative Risk Assessments[24,25,26] , and the definitions used by EGIG and in API RP 581.

	Representative Hole Size or Rupture	**Hole Size Range Defined**
Basis used in this Project for DNV LEAK software - - Release from hole with effective diameter of:		
2 mm	2 mm	1 - 3 mm
10 mm	10 mm	3 - 15 mm
25 mm	25 mm	15 - 35 mm
50 mm	50 mm	35 - 65 mm
100 mm	100 mm	65 - 135 mm
10% diam. of Piping 300 mm ≤ d < 499 mm, up to 50 mm	30 mm	20 - 40 mm
	35 mm	25 - 45 mm
	40 mm	25 - 55 mm
	45 mm	35 - 60 mm
10% diam. of Piping 500 mm ≤ d < 1000 mm, up to 50 mm	50 mm	35 - 65 mm
1/3 diam. of Average Pipe 150 mm ≤ d < 299 mm	50 mm	35 - 65 mm
	67 mm	50 - 85 mm
	75 mm	65 - 100 mm
	83 mm	70 - 110 mm
1/3 diam. of Average Pipe 300 mm ≤ d < 499 mm	100 mm	65 - 135 mm
	117 mm	90 - 150 mm
	133 mm	100 - 175 mm
	150 mm	120 - 200 mm
1/3 diam. of Average Pipe 500 mm ≤ d < 1000 mm	167 mm	135 - 205 mm
	183 mm	150 - 215 mm
	200 mm	155 - 230 mm
	217 mm	160 - 260 mm
	233 mm	170 - 290 mm
	250 mm	175 - 325 mm
	267 mm	185 - 345 mm
	283 mm	190 - 360 mm
	300 mm	195 - 375 mm
	317 mm	200 - 400 mm
	Catastrophic Rupture (for comparison only)	≥ Pipe Diameter

Comparative Examples:		
QRA Technical Guidance, Singapore Government	10 mm	0 - 15 mm
	25 mm	16 - 49 mm
	75 mm	50 mm onwards
	Catastrophic Failure/Guillotine	Full Bore Release
QRA Example A	5 mm	3 - 10 mm
	25 mm	10 - 50 mm
	Full Bore Rupture	50 mm and larger
QRA Example B	2 mm	1 - 2.8 mm
	12mm	2.8 - 16.7 mm
	25 mm	16.7 - 31.1 mm
	75 mm	31.1 - 100 mm
	> 100 mm	> 100 mm
QRA Example C	10 mm	3 - 25 mm
	50 mm	25 - 75 mm
	100 mm	75 - 125 mm
	Line Diameter (Full Bore Rupture)	125 mm - Line Diameter
"EGIG 15"	Pinhole/crack	Hole ≤ 20 mm
	Hole	20 mm < Hole ≤ Pipe Diam.
	Full Bore Rupture	Hole > Pipe Diam.
"API 581 '16"	6.4 mm	0 - 6.4 mm
	25 mm	6.4 - 51 mm
	102 mm	51 - 152 mm
	Rupture	Min (Line Diameter, 406 mm)

Table 2: Leak Hole Size Range Used for "DNV LEAK 3.3" Software in this Research Compared to Other Leak Hole Size Range Specifications

The specification of the hole size range is an important determinant in the calculated result and corresponding conclusion, since of course the probability of a release depends directly on it. Figure 3 illustrates this dependency, using as an example the HCRD data as modeled by "DNV LEAK 3.3" software for an average pipe diameter in two of the FRT's piping size categories.

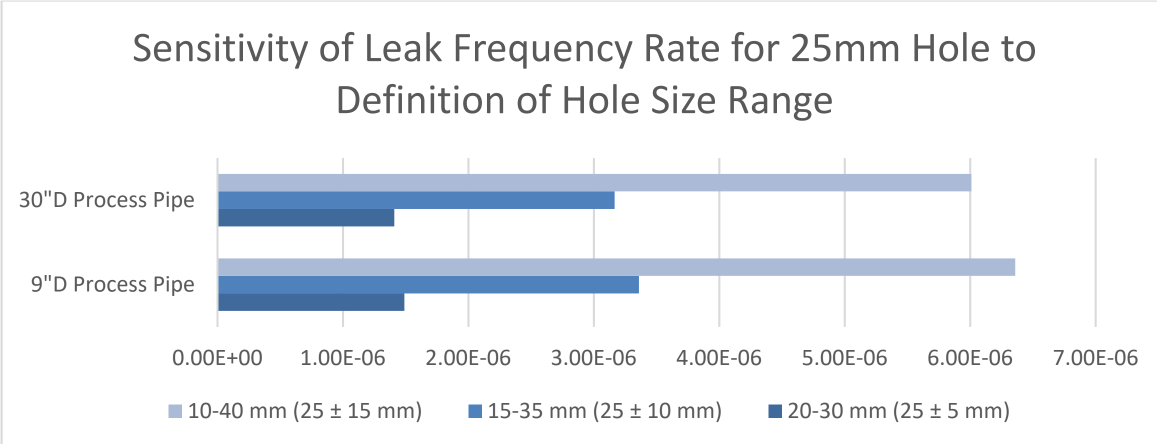


Figure 4: Comparison of Leak Frequency Rates as a Function of Hole Size Ranges. Results Generated Using DNV LEAK 3.3 software.

Differing definitions of "rupture" can also create significant differences in failure frequency results, e.g. in comparative estimates of rupture using LEAK 3.3 software. The basis defined above that is used in this project is consistent with this quotation from p. 21 of "IOGP 434-1":

> 3.4 Consquence modelling for the largest release size
>
> Where the data tables in Section 2.0 show ">50 mm" or ">150 mm" for the largest hole diameter range, the consequences of the release should be modelled using the size of the actual pipe/valve/flange or the largest connection to other equipment types.

4.2 Cryogenic Atmospheric Storage Tanks

US 49 CFR Part 193.2013 recognizes specific respective sections of the 2001 and 2006 editions of NFPA 59A. Table 2.2.3.5 of the NFPA 59A 2001 edition specifies Design Spills from LNG containers. The FRT currently also specifies leak and rupture rates for LNG Atmospheric Storage Tanks, which differs from the Design Spill for containers defined in NFPA 59A 2001 edition.

<u>Comments re: "PNL PSRP '82"</u>

Both Table 3 on p. 3.13 of the "PNL PSRP '82" analysis of LNG peak shaving plants and Table 3.3 of "PNL ITRP '82" analysis of LNG import terminals indicates Storage Tank rupture rates of 1×10^{-9} and 1×10^{-10} failures per hour; this equates to 8.8×10^{-6} and 8.8×10^{-7} failures per year and was included in this project's database for single containment atmospheric storage tanks.

In addition, Table 7 on p. 4.3 of the "PNL PSRP '82" analysis indicates a "Gross Failure of Storage Tank" at 1×10^{-5} per year. Whereas other release scenarios studied in this analysis utilized FTA calculations, this particular estimate appears to based solely on this text from p. 4.8:

> In their risk assessment of the proposed import terminal at Oxnard, California, SAI assumed that LNG tank ruptures occur approximately 1×10^{-6} times per tank-year (Science Applications, Inc. 1975). Based on data for petroleum refinery tanks and our analysis of some operating scenarios that could lead to failure of the storage tank (discussed below), it appears that more than 1×10^{-6} failures (maybe 1×10^{-5}) per tank-year can be expected.

In comparison, the first entry of Table 7 on p. 4.3 of PNL's report lists the "Gross Failure of Storage Tank" as only the upper limit of 1 x 10^{-5}.

The reference peakshaving system used by PNL for its analysis in "PNL PSRP '82" was based on:

- a single containment 350,000 bbl LNG tank (p. 3.3),
- with bottom penetrations -- "The outlet line from the storage tank is 12 inch in diameter and exits through the bottom of the inner tank" (p.4.11)
- with an expansion joint - - "The reference storage tank has a single ply expansion joint on the storage tank withdrawal line at the point where the line exits the outer tank shell." (p. 5.2)
- and with an internal shutoff valve - - "The reference storage tank has a flapper valve inside the tank to close off the bottom withdrawal line. There are no other block valves downstream until after the expansion joint." (p. 5.2)

While modern single containment tanks typically utilize in-tank pumps without bottom penetrations and without expansion joints in LNG tank outlet lines upstream of the pump discharge block valve, this project's analysis included PNL's prediction of "Gross Failure of Storage Tank" from "PNL PSRP '82" for consideration and applied this data in the following manner:

- applicable only to a single containment LNG tank.
- included both failure rate estimates i.e. 1 x 10^{-6} and 1 x 10^{-5}.

<u>Comments re: "LNE '09"</u>

The Flemish Government *Handbook Failure Frequencies* 2009 ("LNE '09") was not included in the 2012 derivation of the LNG Failure Rate Table, but constitutes another failure rate data set for PHMSA's/FERC's consideration. The tank rupture and d_{eq}=10mm leak failure rate frequency included from Table 3 (p. 14) of "LNE '09" was applied in this project's database in the following manner consistent with Figure 1 on its p. 15:

- "Tank type 4" data was applied to the FRT's existing "Full Containment Cryogenic Atmospheric Storage Tank" category. This was consistent with the "Full Containment" designation in Table 13 on p. 32 of the Appendix.
- "Tank type 3" data was applied to the FRT's existing "Double Containment Cryogenic Atmospheric Storage Tank" category. This was consistent with the "Double containment" designation in Table 13 on p. 32 of the Appendix.
- "Tank type 2" data was applied to the FRT's existing "Single Containment Cryogenic Atmospheric Storage Tank" category, since this is representative of LNG Single Containment Tanks. This was consistent with the "Single Containment With Protective Outer Shell" designation in Table 13 on p. 32 of the Appendix.
- "Tank type 1" data was applied to an ancillary category in the framework entitled "Single Containment Refrigerated Atmospheric Storage Tank", since this is not representative of LNG tanks but instead is representative of single-shell, externally-insulated tanks such as used to store refrigerated ammonia or LPG. This was consistent with the "Single

Containment Without Protective Outer Shell” designation in Table 13 on p. 32 of the Appendix. This category is provided merely for comparison and the project team is not proposing this as a potential revision to the FRT.

It was noted that the “LNE ’09” storage tank data applies to both cryogenic/refrigerated tanks as well as other service temperatures, due to this comment in Table 13 (p. 32) of Appendix of “LNE ’09” – “No separate frequencies are available for cryogenic tanks.”

Comments re: “HSE FRED JUN’12”

The failure rate data used in this project’s database and taken from Item #FR 1.1.2.1 “LNG Refrigerated Vessels” on p. 16 of UK “HSE FRED JUN’12” were those specified for Tank Volumes > 12,000 m^3.

As per Note #34 on p. 16 of UK “HSE FRED JUN’12”, the failure rate for single-walled LNG tanks are the same as those in the generic values in Item FR 1.1.2, where single wall tanks are defined as “Single wall tanks, where there is no outer containment designed to hold the cryogenic liquid or vapour.” (i.e. single containment, which would typically also have an outer tank wall containing the insulation system). The failure rate data for single containment tanks used in this project’s database was thus taken from Item #FR 1.1.2 “Refrigerated Ambient Pressure Vessels” on page 13 and were those specified for Tank Volumes > 12,000 m^3.

Note #34 on page 16 of UK “HSE FRED JUN’12” states that the failure rate for the release of vapour from a double walled tank “should be set to zero”. Zero was approximated as 1 x 10^{-12} in this project’s database.

The “HSE FRED JUN’12” data source was the only reference identified in this analysis that specified failure rate of LNG tank roofs (i.e. release of vapour only).

Comments re: “RIVM BEVI ‘09”

The failure rates frequencies excerpted from Netherlands RIVM *Reference Manual Bevi Risk Assessments* “RIVM BEVI ’09” and included in this project’s database were based on the inner tank having no floor (or bottom) penetrations (reference Note #5 on page 40 of 130), consistent with modern tank designs.

Comments re: “IOGP 434-3”

The Catastrophic Rupture Frequency for new single containment tanks included from IOGP’s “Storage Incident Frequencies” (“IOGP 434-3”) in the database for this project was based on “Primary Containment Only”, i.e. the rupture frequency for the “Secondary Containment” (“corresponds to bund overtopping” as clarified in footnote #2 of Table 2.3 on page 5) was excluded from this project’s database. The specified frequencies for both existing and new single containment tanks were included in the database for this project, since FERC and PHMSA receive applications pertaining to both existing and proposed new LNG facilities.

The Catastrophic Rupture Frequencies for “Double Containment Tanks”, “Full Containment Tanks” and “Membrane Tank” used the “Secondary Containment” data (and not “Primary Containment Only”) in Table 2.3 of the “IOGP 434-3” reference.

Comments re: Membrane Tank Failure Rate Estimates, including "TGC '03"

Three estimates of predicted membrane tank failure rates based on FTA analyses were identified and included in this project's database for PHMSA's and FERC's information, although membrane tanks are not permitted in the NFPA 59A editions specified by US 49 CFR Part 193. These reference were denoted as "TGC '03", "KJCE '05" and "KGSC '06" and Section 3.2 provides the complete citations.

The 2003 predictive analysis by Miyazaki and Yamada of Tokyo Gas ("TGC '03") estimates failure rates for LNG Membrane tanks and "Steel/PC Double Shell Tank". The latter data was applied to the FRT's "Double Containment Cryogenic Atmospheric Storage Tank" category, since the authors note that "There is a difference in the vapor control method between a full containment tank and a Steel/PC double shell tank." And, "In the Steel/PC double shell tank, … The PC outer wall operates as a secondary container, preventing liquid spread in an emergency."

Comments re: Comparative Information from the Industrial Gas Industry (relevant to both Section 4.1 Cryogenic Atmospheric Storage Tanks and Cryogenic Pressure Vessel-related content in Section 4.2)

The following comparison point was identified from the industrial gas industry for cryogenic atmosphere storage tanks and pressure vessels commonly used for storing liquid nitrogen, oxygen or argon at bulk production sites (i.e. air liquefaction plants) and also at end-user customer sites. The flat-bottomed bulk cryogenic atmospheric storage tanks at air separation production sites are akin to LNG single-containment storage tanks, but are of much smaller volumetric capacity and are built to different code requirements.

- British Compressed Gases Association (BCGA) Technical Information Sheet 23[27] entitled "BCGA Policy Regarding Internal Examination and Proof Pressure Testing of Static Cryogenic Liquid Storage Tanks" states that as of 2012 there had been zero failures of inner tanks in its survey database:

  > There are approximately 60,000 cryogenic tanks in service within Europe; some having been in service since the 1960's. They have accumulated a very large number of safe operating hours without failure of the inner vessel during this time.

  Appendix 1 of BCGA Technical Information Sheet 23 summarizes the results of 72 inspections of cryogenic tanks, many of which were performed with an independent authority present:

  - 17 inspections were of flat-bottomed bulk storage cryogenic tanks, which were typically 11 m – 21 m in diameter and ranged in age from 9 – 34 years in service; and
  - 3 inspections were of spherical bulk storage tanks; and
  - 52 inspections were of vacuum-insulated storage tanks, which were typically 1.0 m – 3.9 m in diameter

- European Industrial Gas Association (EIGA) document 119/04/E[28] entitled "Periodic Inspection of Static Cryogenic Vessels" in its section 8 "Incident Statistics" aligns with BCGA Technical Information Sheet 23. It notes zero internal defects identified in inspections of 60,000 vessels (apparently the same population as that in BCGA Technical

Information Sheet #23):

> EIGA member companies collate their own incident data and send it to EIGA for circulation. There are approximately 60,000 cryogenic vessels in service within Europe, some of which have been in service since the 1960's. They have amassed a large number of safe operating hours during this time. Individual member groups of EIGA e.g. the BCGA in the UK compile their own data at the request of the enforcing authority to ensure the continued safe operation of these vessels in service. This includes the demolition and internal examination of a number of vessels every year to ensure that there is no unsuspected failure mechanisms at work. None have ever been found.
>
> Inspections of cryogenic vessel shells that have been carried out by member companies over a large number of years are also available.
>
> The inspections were generally carried out during equipment modification or maintenance when the opportunity was taken to examine the vessel shells either fully, internal of external only, or locally (where the amount of shell able to be examined was limited by the access available).
>
> On a number of occasions thorough examinations have been made, in conjunction with Inspecting Authorities, on particular vessels to confirm the industry's view that vessels in cryogenic service do not deteriorate. These examinations have resulted in the Inspecting Authorities giving exemptions from periodic inspection or test.
>
> It is considered that the large amount of evidence produced, the safe operation of the vessels, and that no cases have been observed of cryogenic vessels exhibiting defects reducing the integrity and strength of the vessel shells, provides considerable support for not requiring their periodic inspection and test during service.

No minimum failure rates can be developed from these references since the 60,000 population includes undefined numbers and ages of large flat-bottomed atmospheric bulk storage tanks, spherical bulk storage tanks, and vacuum-insulated cryogenic (pressure) vessels (presumably the majority of which are the latter based on conventional use in the industrial gas industry), but this reference does highlight that zero failures of inner tanks were observed in this population of cryogenic liquid storage tanks (and vessels). But if, for example the average age of the 60,000 cryogenic tanks and vessels was 20 years, then the observed consolidated failure rate per tank or vessel would be $< 8.3 \times 10^{-7}$ failures/year ($< 1/(20 \times 60{,}000)$).

4.3 Process Vessels, Distillation Columns, Heat Exchangers and Condensers

The current FRT contains the category entitled "Process Vessels, Distillation Columns, Heat Exchangers and Condensers". This category can contain a wide range of equipment. Potential refinements to the FRT investigated during this project included evaluating potential subcategories.

Differentiating process vessels from pressure vessels may be a potential refinement of the FRT and was evaluated in this analysis. One example definition of a "Pressure Vessel" and "Process Vessel" is given below:

> A Pressure Vessel is a storage vessel in which the pressure is substantially more than 1 bar absolute. Vessels in which only the quantity of substance changes, must be considered as a Pressure Vessel. A buffer vessel in a process installation can be seen as an example of this.
>
> In a Process Vessel, a change in the physical properties of the substance occurs, e.g. temperature or phase. Examples of process vessels are distillation columns, filters and vessels in which substances are mixed or separated. Vessels where only the level of liquid changes are considered as Pressure Vessels.

The above definition is a variation of that used in "RIVM BEVI '09" Reference Manual Module C (ref. p. 45 of 130). The "RIVM BEVI '09" definition considers distillation columns in a separate category (with additional component details) from process vessels.

Overall Comments

Where data was presented in any reference as either Process or Pressure Vessels, the data was applied to that respective category in this project's database.

All failure rate data for Process and Pressure Vessels presented in all sources was assumed to be single-wall vessel data unless it was identified otherwise.

Comments re: Pressure Vessels in "IOGP 434-3"

The leak frequency for pressure vessels used in the database for this project included the data for "Storage Vessels" but not "Small Containers", as provided on Table 2.3 on page 6 of "IOGP 434-3" reference. As summarized on page 3 of "IOGP 434-3" reference, storage vessels refers to fixed tanks whereas "small containers" are "portable cylinders and drums less than approximately 2 m^3 capacity."

Comments re: Pressure Vessels in "SERCO AEA '04"

O'Donnell, Phillips and Winter in "SERCO AEA '04" analyzed failure rate data of pressurized LPG storage vessels for both small and large LPG vessels. This project's database only considered the results of their analysis of failure rates for large LPG vessels, which apparently applies to vessels >6,600 kg capacity (i.e. roughly >3,000 US gallons). Failure rate data for small vessels was not considered in this analysis.

Comments re: Pressure Vessels and Tank Containers in UK "HSE FRED JUN'12"

Failure rate data used in the database for this project's results for Pressure Vessels included data taken from Item #FR 1.1.3 "Pressure Vessels" on page 19 of "HSE FRED JUN'12". These "are derived in the Chlorine Siting Policy Colloquium and are applicable to chlorine pressure vessels in a typical water treatment plant. Although they are not applicable to all types of pressure vessels the values are a good starting point when trying to derive failure rates for vessels in other applications."

The “HSE FRED JUN’12” reference does not provide any overall estimates of cryogenic pressure vessels, but implies that cryogenic pressure vessels may have a *higher* failure rate than non-cryogenic pressure vessels; page 19 of “HSE FRED JUN’12” refers to “site-specific factors indicating that a higher rate is appropriate (e.g. semi refrigerated vessels [cryogenic pressure vessels]).” Several of the 40 advice notes and bibliography references cited by HSE in Item #FR 1.1.3 “Pressure Vessels” of “HSE FRED JUN’12” appear to arise from cryogenic applications, including a confidential reference that “Estimates the failure rate of pressure vessels for LOX storage to be in the order of 10^{-5} per yr.”

Tank Containers (i.e. ISO Containers) are used for various purposes in LNG plants. The only failure rate data available for ISO containers identified in this project analysis was in the “HSE FRED JUN’12” document. Although unlikely, it is possible that an applicant may propose to build a LNG facility that incorporates a stationary ISO container as plant infrastructure (subject to approval by FERC and PHMSA), so for the sake of completeness data was applied in this project’s database from Item #FR 3.2.1 on page 60 of “HSE FRED JUN’12” but in stationary service. The reader is referred to Item #FR 3.2.1 if they seek failure rate data that includes dynamic movement (e.g. accidental dropping) of ISO containers.

Comments re: Cryogenic-Specific Pressure Vessels

The following excerpt from the Dutch LNG Safety Program website highlights that RIVM (via a consultant) is currently reviewing failure rate frequencies for double wall LNG storage tanks, with an apparent focus on vacuum-insulated tanks (i.e. pressure vessels):

> The research on the failure frequencies double walled LNG storage tanks was performed by AVIV commissioned by RIVM.
>
> There are issues about the failure of double walled LNG storage tanks under significant heat load from external sources, resulting in relative high failure frequencies for this equipment. During 2015, RIVM has asked consultancy firm AVIV to execute a literature survey to obtain relevant data for answering the questions.
>
> During their survey, AVIV did not find statistically sufficient evidence to deviate from the existing failure frequency numbers that have earlier been issued by RIVM. During 2016, AVIV will extend their earlier survey to a more generic basis, allowing potentially more relevant data to be available for the statistical database.[29]

In addition, the following comparison points were identified from the industrial gas industry for cryogenic pressure vessels that are used to store liquid nitrogen, oxygen or argon in vacuum-insulated vessels at end-user customer sites:

- British Compressed Gases Association (BCGA) Technical Information Sheet 23, and European Industrial Gas Association (EIGA) document 119/04/E, as summarized in Section 4.2.
- The Vice President of Engineering for Chart Industries, Inc. estimated that since 1970 there have been about 1,800,000 vessel-years of worldwide experience using stationary shop-built cryogenic pressure (storage) vessels (utilizing either perlite or multi-layer insulation in vacuum annular space) containing all types of cryogenic liquids (LIN, LOX, LAR, LH2, LNG, etc.) and excluding portable containers/dewars; he was unaware of any ruptures of the inner tanks of this vessel population (before or after 1970) other than one accident in Japan that occurred due to blatant misoperation.[30] This estimate would imply

that the rate of instantaneous failure of the inner tank of stationary shop-built cryogenic vessels (i.e. not portable containers/dewars) is < 5.6 x 10^{-7} failures/vessel-year (unless the one gross operating failure in Japan is considered).

The rupture of the liquid nitrogen vessel in Japan occurred at a food factory in 1992 and resulted from the "shutoff valve for the safety valve had been closed manually" and the internal pressure in the tank gradually rose over 50-80 days until it exceeded the vessel's design pressure.[31]

Chart's representative also highlighted that a few fracture incidents of the outer shells of cryogenic vessel have occurred (e.g. due to contact with cryogenic liquid), but that these incidents have resulted in minor cracks or frosting of the outer shell that served as a indicator that the vessel needed repair or replacement.

<u>Comments re: Mounded/Underground Pressure Vessels</u>

"RIVM BEVI '09" in Table 15 (p. 34) of Module C specifies the same failure frequencies for "underground/mounded pressurized storage tanks" that are "mainly used for storage of LPG" as it does in Table 13 for "pressurized storage tank aboveground".

<u>Comments re: Vaporizers in "GRI LNG FRD '81", "AGA LNG EXP '79", "AGA FP LNG '84" and "PNL PSRP '82"</u>

The "GRI LNG FRD '81" analysis identified on p. 50 that "No safety-related failures were reported in this study for vaporizers, although 5 of the reported failures involved leaks or ruptures of heat exchanger tubes, a potential safety-related failure. Two safety-related failures were reported in the peakshaving study". The "peakshaving study" refers to "AGA LNG EXP '79".

Unfortunately the data cannot clearly be differentiated by vaporizer type, since detailed equipment counts were not reported by type in the 1979 or 1981 reports. However, p. 14 of the 1981 report identifies that "Over 70 percent of the reported operating hours were on submerged combustion vaporizers with the majority of the remaining operating hours on direct fired units." Other vaporizers reported in the 1981 report were running film and plate fin type.

On the above basis, the database for this project included vaporizer rupture and leak data combined from the 1979 and 1981 sources at a mean failure rate of (2+5 ruptures or leaks) / (35,000 + 188,000 vaporizer operating hours) which equates to 3.1 x 10^{-5} ruptures or leaks per vaporizer operating hour. To put this rate on an annualized rate, a conventional design basis for an LNG Peak Shaving Plant of 10 days/year of vaporizer sendout was applied (i.e. equivalent to 240 vaporizer operating hours/year of plant operation). This resulted in a mean failure rate of 7.5 x 10^{-3} vaporizer ruptures or leaks per plant operating year, and this failure rate was conservatively assigned as a rupture rate to both direct fired heat exchangers and submerged combustion heat exchangers (since the five reported leak or rupture failures were "potential safety related failures").

Mniszewski in "AGA FP LNG '84" provides a "mean time between failures" of 1.8 x 10^4 hours/failure (i.e. 5.6 x 10^{-5} failures/hour) for "Vaporizers" in its Table 6 "Safety Related Probability Data for LNG Facilities", which cites Reference 20 ("AGA LNG EXP '79") as its basis. The failure rate of 1.8 x 10^4 hours/failures is consistent with the "Safety"-related MTBF shown for vaporizers on Figure 3 of “AGA LNG EXP ‘79”. But the failure rate of 5.6×10^{-5} failures/hour was excluded from this project’s database because the rate of 3.1×10^{-5} failures/hour calculated above from the combined results of “AGA LNG EXP ‘79” and “GRI LNG FRD ‘81” includes the associated data.

As pointed out in Section 4.1, the 1982 analyses by PNL (as reported for example in “PNL PSRP ’82” and “PNL ITRP ’82”) apparently applied MTBF for “Major Failures” as data for leaks or ruptures of vaporizers; for this reason, the vaporizer failure rate data reported by ”PNL PSRP ’82” was excluded from this project’s database and this analysis. It was also noted that vaporizer “Tube or Panel Rupture” data differed in these two PNL-authored 1982 reports but were both attributed to “(Welker 1979)” (i.e. “AGA LNG EXP ‘79”), as shown in Appendixes G and H:

- cited as 1×10^{-5} faults/hour on Table 3.3 on p. 3.9 of “PNL ITRP ‘82” by Baker
- cited as 1×10^{-4} faults/hour on Table 3 on p. 3.13 of “PNL PSRP ‘82” by Pelto etal

<u>Comments re: Heat Exchangers in “GRI LNG FRD ’81”</u>

The “GRI LNG FRD ‘81” analysis reported *zero* Safety-related failures for heat exchangers (ref. section 4.1.2 on p. 14) and thus no MTBF leak or rupture data for heat exchangers (other than vaporizers) was derived from this reference. This same section and page does identify that “The primary cause of major failures in heat exchangers was tube failure (leaking or cracking).”, but the Major Failure MTBF data of 177,000 hours (i.e. 5.65×10^{-6} faults/hour) could not be assigned a hole size to calculate a leak frequency, even if one approximated the “primary cause” of tube failure as the only cause of this Major failure MTBF rate, and assumed that all failures were external releases (vs. say tube-to-tubesheet failures or other leaks between fluid streams).

<u>Comments re: Plate Heat Exchangers</u>

The framework in this project considered a subcategory for “plate heat exchangers” because a number of equipment failure rate references provided this data. However, it is recognized that plate heat exchangers are not commonly used in LNG facilities in hydrocarbon or hazardous fluid service. While plate heat exchangers may be used in LNG occasionally in glycol-to-cooling water service, a rupture there would pose an operational problem but not a safety event. The “plate heat exchanger” data was included merely for comparison to other heat exchanger failure rates.

4.4 Truck Transfer – Arms and Hoses

Most generic hose failure rate data has apparently been derived from chlorine, LPG, ammonia and other non-cryogenic service. For example, only one of the 27 references identified in “HSE FRED JUN’12” Item FR 1.2.3 was clearly identified to be from cryogenic service (in an air separation plant).

The FRT currently specifies failure rates for truck loading arms and hoses as “Failures per year of operation”. Some source references for the failure rates of truck loading hoses and arms differed in its basis, e.g.:

- “NFPA 59A ‘16” specifies failure rates as ruptures “per year”
- “HSE FRED JUN ‘12” specifies failure rate as “Failure rate per operation”

- “RIVM BEVI ‘09”, “LNE ‘09”, “PNL PSRP ’82”, “LEES ‘12”, “TNO PURPLE” and “INL CHEM ‘95” specifies failure rates as “per hour” (“LNE ‘09” draws its specified failure rates from RIVM BEVI, as per item 8.1 page 60 of its Appendix)
- “CCPS ‘89” specifies as “Aggregated time in service” in hours.
- “INL CHEM ‘95” reports failure rate as “failure rate/hour-foot”

To put the data on a “per year of operation” basis the following basis was used:

- 500 transfer operations/year
- 1 hour/transfer operation
- 20 foot hose length

The typical number of operations at an LNG facility can vary widely and the application of 500 operations/year represents a typical use rate considering the spectrum of LNG facilities. For example:

- 25 operations/year (i.e. equivalent to 25 LNG trailers) in order to completely re-fill a LNG satellite peak shaving facility that has three 90,000 gallon vacuum-insulated LNG tanks.
- 250 operations/year (i.e. equivalent to 250 LNG trailers, containing in total about 2,700,000 gallons of LNG or about 0.2 BCF natural gas equivalent), during a summertime season in order to “top-up” of a LNG peak shaving satellite facility that has one 1 BCF flat-bottomed tank. This would typify one of the largest satellite LNG peak shaving facilities.
- 500 – 1,000+ operations/year/rack at a very large merchant fuel production or import facility. ENGIE’s Distrigas subsidiary in Boston is the largest LNG truck-loading company in the U.S., and on average it loads 9,000 LNG trucks per year from four racks, i.e. 2,350 truck loadings/rack/year.[32]

If for example a LNG facility hose has a maximum useful life of 8 years, then a basis of 500 operations/year equates to 4,000 uses/lifetime (i.e. desirable failure rate < 2.5×10^{-4} failures/operation), or a basis of 2,500 operations/year of use equates to 20,000 uses/lifetime (i.e. desirable failure rate < 5×10^{-5} failures/operation). Hoses are also required to have yearly pressure tests.

<u>Comments re: “RIVM BEVI ‘09”</u>

“RIVM BEVI ‘09” specifies failure rates for loading activities that “take place from a storage tank to a transport unit (road tanker, tank wagon or ship) or from a transport unit to a storage tank” and prescribes items that are present at LNG facilities. An excerpt from Module C Section 3.15 of “RIVM BEVI ’09” is provided below.

The “additional scenarios” listed in Table 51 “RIVM BEVI ‘09” were not considered, since LNG is non-toxic.

Table 50 Scenarios for loading activities

	Frequency Loading/unloading arm (per hour)	Frequency Loading/unloading hose (per hour)
1. Rupture of loading/unloading arm or loading/unloading hose	3×10^{-8}	4×10^{-6}
2. Leak in loading/unloading arm or loading/unloading hose with an effective diameter of 10% of the nominal diameter, up to a maximum of 50 mm.	3×10^{-7}	4×10^{-5}

Table 3: Excerpt of "RIVM BEVI '09" Module C Section 3.15 "Loading Activities"

Comments re: UK "HSE FRED JUN'12"

Failure rate data used in the project database for hoses included data taken from Item #FR 1.2.3 on page 40 of "HSE FRED JUN'12", and on the basis that LNG facilities governed by PHMSA meet the "Average" facility definition below:

Average — Two pullaway prevention systems (one of which should be wheel chocks) as well as inspection and pressure/leak tests to prevent transfer system leaks and bursts but no effective pullaway mitigation.

The other categories of specified rates (i.e. not incorporated in this project's database) are defined in "HSE FRED JUN'12" as:

Basic — These have one pullaway prevention systems such as wheel chocks, carry out inspection and pressure/leak tests to prevent transfer system leaks and bursts, but have no effective pullaway mitigation.

Multi safety Systems — Two pullaway prevention systems, and also an effective pullaway mitigation system and inspection and pressure/leak tests to prevent transfer system leaks and bursts.

The operational basis that HSE used to determine its estimate of hose and coupling failure rates was not directly discernable. Note #92 on p. 40 of "HSE FRED JUN '12" identifies that the derivation of the failure rate frequency is from "The work was carried out for chlorine transfer facilities but should be applicable to similar transfer operations." "HSE FRED JUN '12" also references two internal (confidential) HSL reports as its basis (RAS/000/10 issued in 2000, and RAS/04/03/1 issued in 2004); thus no details are directly available.

However the failure rates for "Guillotine failure" in Item FR 1.2.3 of "HSE FRED JUN '12" match those for catastrophic failure on page 32 of the HSL's public document HSL/2000/09 analysis of hose and coupling failure rates published in 2000[33] ("HSE HOSE '00"), although the 15 mm diameter hole results differ. The "HSE HOSE '00" analysis identifies that:

- "The reference system is a chlorine unloading facility, i.e., a chlorine user site, dedicated to the unloading of chlorine. Transfers take place approximately every 6 to 8 weeks,…" as per p. 4. This equates to 7.4 operations/year (= 52 weeks/year x 1 operation/7 weeks).

- The overall failure rate derived by HSE appears to be based on a Fault Tree Analysis, as per this quotation from p. 28: "This report has described the development of a quantified fault tree analysis of a full bore loss of containment during the transfer of chlorine from a road tanker to storage for a hypothetical reference site. The generic rate for a catastrophic failure obtained in the analysis is 4.9×10^{-8} per operation which is lower than that of the 3×10^{-6} per operation currently used in RISKAT calculations. This reflects the fact that the RISKAT figure includes all significant releases for a typical facility, where the analysis here only considered catastrophic failure for a reference system incorporating numerous safety systems."
- The type of hoses are described on p. 16: "These hoses are constructed from convoluted monel tube and are protected by monel braiding, along with armoured outer braiding. The chlorine supply hose is 1.5 inch NB and the vent line 1 inch NB. Both are approximately 9 feet in length."

In summary:

- HSE's hose failure rate data appears to be based at least in part on hoses of 1.5" and 1.0" nominal diameter in chlorine service at ambient temperature.
- The generic rate for a catastrophic failure determined by HSE in its Fault Tree Analysis as reported in "HSE HOSE '00" is 4.9×10^{-8} per operation, which is substantially lower than those values currently specified in "HSE FRED JUN '12", i.e.:
    - 4×10^{-6} guillotine failure rate per operation for "Average facilities"
    - 2×10^{-7} guillotine failure rate per operation for "Multi safety system facilities"
- The direct basis of operations/year is unknown for Item FR 1.2.3 of "HSE FRED JUN '12", but HSE's "reference case" appears to be 7.4 operations/year.

<u>Comments re: "PNL PSRP '82" relevant to Truck Transfer arms and hoses</u>

The "PNL PSRP '82" analysis included a failure rate for flexible metal hoses in its narrative which does not appear in its Table 3. The following failure rate was included in this project's database directly from this text in Section 4.4.6 on p. 4.18:

> A 3-inch, flexible metal hose is used to connect the LNG trailer to the transport terminal. The historic failure rate for this type of hose is 1.7×10^{-6}/hour.

No reference for this failure rate of 1.7×10^{-6} faults/hour was identified in "PNL PSRP '82".

Both "Table 3: Generic Failure Rates for Components of LNG Peakshaving Facilities" of "PNL PSRP '82" and "Table 3.3: Generic Failure Rates for Components of LNG Import Terminals" in "PNL ITRP '82" indicate a rupture rate for loading arms of 3×10^{-7} faults/hour. This failure rate was not included in the project database for *truck* loading arms, because LNG trailer *truck* loading arms were infrequently used in 1982 and this failure rate was presumably intended for *ship* loading arms.

<u>Comments re: "NFPA 59A '13" and "NFPA 59A '16"</u>

The failure rate data of 3×10^{-8}/year provided as an example for "Transfer equipment – rupture of loading/unloading arm" was included for truck loading/unloading arms in the database for this project.

Comments re: "INL CHEM '95" Relevant to Truck Transfer hoses

The 20 foot hose length basis used to apply the failure rate data specified in "INL CHEM '95" to the FRT was selected as a representative length for hoses used on transport trailers, since as noted earlier the data sources used from "INL CHEM '95" data source were "Chemical Process System" and "Compressed Gas System".

4.5 Ship Transfer – Arms (and Hoses)

The FRT currently does not specify a rate for ship transfer loading hoses, which are being used or being considered for transfer of LNG as maritime vessel fuel during bunkering operations.

The FRT currently specifies failure rates for ship loading arms as "Failures per year of operation". Some source data for the failure rates of ship loading arms differed in its basis, e.g.:

- "NFPA 59A '16" specifies failure rates as ruptures "per year"
- "RIVM BEVI '09" and "LEES '12" specifies failure rates as "per hour"
- "PNL PSRP '82" (and "PNL ITRP '82") report loading arm rupture failure rate as "faults/hour"
- "LNE '09" draws its specified failure rates from RIVM BEVI (version 3.0, Jan. 1, 2008), as per item 8.1 page 60 in its Appendix
- "TNO PURPLE '05" reports failure rate as "Failure rate per transhipment"
- "HSE FRED JUN'12" reports failure rate as "Failure Frequencies per Transfer Operation"

To put the data on a "per year of operation" basis the following basis was used:

- 50 transhipments/year
- 50 transfer operations/year
- 12 hours/transfer operation

In comparison, in 2015 there were 4,057 LNG tanker voyages worldwide serving about 130 LNG export and import terminals [34,35], which equates to 62 LNG tanker transfer operations/terminal-year, on average.

The term "transshipment" is not specifically defined in "TNO PURPLE '05"; the project team understood the failure rate to be arising from cargo shipments (and not necessarily bunkering operations) since section 3.1 of "TNO PURPLE 2005" identifies that "Loading and unloading LOCs cover the transshipment of material from transport units to stationary installations and vice versa" and since LNG bunkering was not occurring in 2005.

The term "transfer operation" is not specifically defined in "HSE FRED JUN'12"; the project team understood it to be arising from cargo shipments (and not necessarily bunkering operations) since note #150.1 on p. 71 of "HSE FRED JUN'12" identifies that "a 12-hour transfer time has been assumed" and since LNG bunkering was not occurring in a significant manner when the document was issued in 2012.

Comments re: "RIVM BEVI '09" (and "LNE '09")

The "additional scenarios" listed in were not considered, since LNG is non-toxic.

Comments re: UK "HSE FRED JUN'12"

Failure rate data used in the database for this project for Ship Hardarms included data taken from Item #FR 3.3.1 on page 70 of "HSE FRED JUN'12" and on this basis: Transfer of liquefied gases (vs. liquid cargo); and only one hard arm used (vs. 2 or 3 hard arms used).

The "HSE FRED JUN '12" hose rupture data was not applied to *ship* transfer hoses since footnote #92 of Item FR 1.2.3 indicates that "The hose and coupling failure rates apply only to road tanker transfers."

Comments re: NFPA "59A '13" and "NFPA 59A '16"

The failure rate data of 3 x 10^{-8}/year provided as an example for "Transfer equipment – rupture of loading/unloading arm" was included for ship loading arms in this project's database.

Comments re: "WELKER '76"

The median frequency rate was included in this project database for Ship Transfer loading arms (but not Truck Transfer) since this analysis was for LNG Vessels where loading arms were commonly employed. This reference also includes failure frequencies for "External Leak" but specifies no hole size; these leak frequencies were not included in this project's database due to lack of hole size definition.

Comments re: "INL CHEM '95"

The "INL CHEM '95" hose rupture data was not applied to ship transfer hose.

Comments re: "SIGTTO IP4 '96"

The "SIGTTO IP4 '96" reference summarizes and analyzes accidents arising from failures or hard-arms, hoses, Emergency Release Couplings (ERC) or other causes that occurred during about 500,000 port calls over 13 years (1982-95) at marine terminals handling cargo shipments of liquefied gases such as LNG, LPG and ammonia; of these, the LNG port calls were approximately 3,000 per year (i.e. about 39,000 over 13 years). SIGTTO considered its analysis comprehensive and as per p. 35 of "SIGTTO IP4 '96" was "virtually certain that all major accidents for this trade have been recorded." For this project analysis:

- SIGTTO's accident data for ERCs was combined with its accident data for hard-arms, because SIGTTO recommended that an ERC be fitted to all hard-arms for LNG and refrigerated LPG (and terminals handling ships of over 30,000 m^3), and other failure rate references such as "HSE FRED JUN'12" (as per article 150.3) assume that all hardarms handling liquefied gases have ERCs. This is noteworthy because including ERCs with hard-arms tripled the reported failure rate frequency for hard-arms from 1 "Significant Accident" to 3 "Significant Accidents".
- *SIGTTO's "Significant Accidents" incident data from Table 9.3 was reviewed as rupture data for loading arms and hoses for a comparison data point in this analysis, even though all of the data arose from non-LNG service, and refrigerated LPG hoses can be of rubber construction*:

- 3 significant accidents arose from hard-arms and ERCs in LPG and ammonia service (and zero arose from hard-arms and ERCs in LNG service)
- 4 significant accidents arose from hoses in LPG and ammonia service (and zero arose from hoses in LNG service)

- "SIGTTO IP4 '96" does not identify the number of terminals using hard arms vs. hoses, but does identify on p. 36 that 18.1% of the annual port calls in its analysis were LPG ships >30,000 m^3 and LNG ships. Pages 3-5 of "SIGTTO IP4 '96" recommends that "there is a strong case for using hard-arms for ships" and that "terminals handling ships of over 30,000 m^3 should use hard-arms". If one assumed that 50% of the port calls in SIGTTO's analysis used hardarms vs. hoses, then:
    - When considering non-LNG service accident data, *these estimates being entered into the project database merely for comparison*:
        - Non-LNG hardarm failure frequency = 3 accidents/(0.5*500,000 port calls) = 1.2 x 10^{-5}/transfer
        - Non-LNG hose failure frequency = 4 accidents/(0.5*500,000 port calls) = 1.6 x 10^{-5}/transfer
    - Versus when considering only LNG service accident data:
        - LNG hardarm failure frequency = < 1 accident/(39,000 port calls) = < 2.6 x 10^{-5}/transfer
- SIGTTO's incident data for Quick Disconnects (QCDC) was excluded, since QCDCs are not always incorporated with a loading arm or hose. If the QCDC incident data from Table 9.3 were to be included and assigned proportionately to hardarms and hoses, then the frequencies would increase by roughly 50% since 3 significant accidents arose from QCDCs in LPG and ammonia service (and zero significant accidents arose from QCDCs in LNG service).

4.6 Piping – Rupture (and Leak) of Valve

No failure rate data was identified specifically for cryogenic valves beyond those that follow.

<u>Comments re: "GRI LNG FRD '81" and "AGA LNG EXP '79"</u>

The 1979 analysis by Welker and Schorr of 25 peak-shaving plants ("AGA LNG EXP '79") identified no Safety-related or Major Failures of cryogenic valves in 43,600,000 hours (i.e. 4,980 years) of operation (as per p. 57 of the associated document "GRI LNG FRD '81"). The "GRI LNG FRD '81" survey of 27 base load and satellite LNG plants identified on p. 27 that "One safety-related failure was reported, but this was attributed to human error and is not included as a valve failure" in 6,278,000 hours of operation (ref. Table 3). Thus these two key LNG-specific equipment rate failure analyses in 1979 and 1981 identifed *zero* cryogenic valve ruptures.

The "AGA LNG EXP '79" analysis did report two minor cryogenic valve leaks on p. T-265:

> There were no major failures reported for any cryogenic valve, and in more that 40 million operating hours, only two minor failures were reported. One of these was the failure of a bonnet gasket and one was the leaking of a valve which was repaired by

relapping the valve seat. Neither of these failures was considered to be a safety-related failure.

This equates to an actual observed LNG valve leak rate of 2 leaks / 4,980 years = 4 x 10^{-4} leaks/year. This data point was not included in the database for this analysis since the size of the bonnet gasket leak is unknown, but in Section 6.6 this data point is compared to the recommendations for valve leak rates specified in the FRT.

Comments re: "AGA FP LNG '84"

The 1984 work by Mniszewski ("AGA FP LNG '84") provides "Safety Related Probability Data for LNG Facilities" in its Table 6, and indicates that "Table 6 is presented for use in calculating risks. Probabilities are calculated from Reference 20." Mniszewski specifies a "mean time between failures" of 4 x 10^{7} hours/failure (i.e. 2.2 x 10^{-4} failures/year) for "LNG and cryogenic valves". But Reference 20 is "AGA LNG EXP '79" which defined:

- Major Failures as "any failure which results in an unscheduled shutdown for a period of 24 hours"
- Safety-related Failures as "failures which resulted either in a fire, injury, loss of life, or a large leak of liquid or gas. To qualify as a safety-related failure, the liquid or gas release must have been large enough to: 1) have the potential to injure plant personnel; 2) actually have injured plant personnel; or 3) been severe enough to propagate to another area had it not been controlled in the area which it originated."

Mniszewski in "AGA FP LNG '84" appears to have the specified MTBF failure data that is associated with a *minimum and not actual MTBF for a Major or Safety-related event* (i.e. calculated as of the time of the 1979 analysis) since 4 x 10^{7} hours/failure is consistent with Figure 6 of Welker and Schorr's paper which *denotes the minimum rate with an asterisk*. Thus this project's database did not include LNG and cryogenic valve MTBF data from AGA FP LNG '84, since it apparently represents a minimum rather than an actual number associated with either a Major or Safety-related Failure.

Comments re: "PNL PSRP '82" and "PNL ITRP '82"

Both of these 1982 analyses by PNL specify a "valve rupture" of 1 x 10^{-9} faults/hours and cite "(USNRC 1975 and Welker 1979)". This can be seen in Table 3 in Appendix G and Table 3.3 of Appendix H.

In contrast (as summarized above), the 1979 analysis by Welker and Schorr of 25 peak-shaving plants ("AGA LNG EXP '79") identified *zero* Safety-related or Major Failures of cryogenic valves in 43,600,000 hours of operation. It was unclear to the project team why PNL cited 1 x 10^{-9} faults/hours based on Welker's and Schorr's 1979 analysis.

Nevertheless, the valve rupture rate of 1 x 10^{-9} faults/hours from these two references was included in this project's database, since the USNRC 1975 source was also cited by PNL.

Comments re: "HSE FRED JUN'12"

Item FR 1.2.1 of the UK "HSE FRED JUN'12" specifies operational failure rates (e.g. failure to close or operate) for valves but does not specify any rupture rates for valves.

Item FR 1.2.1 Valves

ITEM FAILURE RATES

Type of event	Failure rate (per demand)	Notes
Failure to close	1×10^{-4}	Manual valve (Exc. Human Error)
Failure to close	3×10^{-2}	ROSOV (Inc. Human Error)
Failure to close	1×10^{-2}	ASOV
Failure to operate	1.3×10^{-2}	XSFV

SPRAY RELEASE FREQUENCY

	Frequency	Effective length of crack
Valve	2×10^{-4} per valve per year	Shaft circumference

Table 4: Excerpt of Item FR 1.2.1 Valves in "HSE FRED JUN'12"

Item FR 1.2.1 does specify a Spray Release Frequency for valves with the "Effective length of crack" being the "Shaft circumference". While the values in FR 1.2.1 are for chlorine duty they were derived from a review that "included LPG, petrochemical, steam/water, nuclear and other data" (but apparently no cryogenic data beyond "GRI LNG FRD '81"). The equivalent hydraulic diameter for an annulus leak is $d_{hydraulic} = D_{outside} – D_{inside}$. Valve stem leaks are typically addressed by tightening the valve packing sleeve nut.

For comparative analysis, the project team applied the Spray Release Frequency of 2×10^{-4} leaks per valve per year in Item FR 1.2.1 in this project's database to a "Release from a hole with an effective diameter of 2 mm", as an estimate of the maximum gap between a valve shaft and packing material arising from a loose packing assembly. This should be a very conservative application of the 2×10^{-4} leaks per valve per year rate, in light of the 0.05 mm definition of Spray Releases in items 78 and 79 on p. 32 of "HSE FRED JUN'12":

> A spray release is defined as a release where the spray from a hole is broken into droplets small enough to not rain out, i.e. it is atomised. It could occur in fixed pipework or in a flexible hose connection (say between a tanker and a storage vessel). Spray releases also arise from plant such as pumps and valves, particularly around shafts and drives. In order for a spray release to occur, two conditions are required:
>
> - A very narrow breach in the containment boundary (< 50µm)
> - A significant pressure (in excess of 1 barg)
>
> Only crack-like holes, (i.e. with considerable length) need be considered, because point defects of 50 µm size will have negligible flow rate. Clearly, these small breaches with specific geometry are a small subset of the range of failures that could occur. No data is available directly from industry on spray frequencies. Frequencies were estimated by considering sprays as a subset of all small holes. Data for small holes in the type of plant that might give rise to sprays were obtained from a variety of sources. The judgements used in deriving the spray release figures were agreed in an MSDU Panel Paper of 4 February 2004, entitled 'Spray Releases' by P J Buckley (Confidential, not in the public domain). The paper was presented at a panel meeting on 16 February 2004.

Item FR 1.2.1 does not specify any leak rates for valves larger than this Spray Release Frequency.

Comments re: "RIVM BEVI '09"

"RIVM BEVI '09" does not separately specify leak or rupture rates for valves, but instead includes valves with its pipeline failure rates (ref. pp. 42-43 of Module C). "RIVM BEVI '09" does specify failure to operate rates for excess flow and non-return valves (e.g. pp. 63-65 of Module C) and other failure to operate rates (e.g. pp. 113 of Module C). It was also noted that catastrophic rupture of a relief valve was "not deemed realistic", on p. 104 of Module C:

> The failure frequencies depend on the construction of the gas container, and are equal to $1 \times 10^{-5} - 2 \times 10^{-5}$ per annum for the failure of the seal and $1 \times 10^{-5} - 4 \times 10^{-5}$ per annum for opening the relief valves. Catastrophic rupture is not included in the safety report because it is not deemed realistic ($< 10^{-8}$ per annum). This is not substantiated.

Page 112 of this reference states that "For a manual operated valve (excluding human failure) the HSL reports give a failure frequency of 1×10^{-4} per operation" and references HSL FRED-related publications in 1999 and 2000. But this 1×10^{-4} per operation rate was excluded from this project's database since the failure mode is unclear and because HSE's updated document "HSE FRED JUN'12" does not contain this information.

Comments re: "LNE '09"

"LNE '09" does specify probable failure rates for non-return (check) valves, excess flow valves, and blocking valves on blocking systems, but all apparently refer to internal leakage or failure to close.

Comments re: "WELKER '76", "SAI '75" and "LEES '12"

Where valve rupture data was specified for chemical process or undefined service applications, the sources are in some cases 40+ years old and their pedigree is often from the nuclear power industry. For example:

- "SAI '75" used a "Valve Rupture Rate" of 1×10^{-8}/hour i.e. ~1×10^{-4}/year in its analysis of an LNG Import Terminal; "SAI '75" does not cite a specific source for its valve rupture data, but the 1975 WASH-1400 Reactor Safety Study (NUREG-75/104) is the one of few process-related references in its list of 21 References.
- "WELKER '76" indicates a median "External leak or rupture" of 1×10^{-8}/hour i.e. ~1×10^{-4}/year for manual and all automated valves, and cites a draft copy of the 1974 WASH-1400 Reactor Safety Study (NUREG-75/104) as its sole basis.
- The valve rupture data in Table A14.7 of "LEES '12" is data from the Rasmussen report i.e. the 1975 WASH-1400 Reactor Safety Study.

4.7 Piping – Rupture of Expansion Joint

Comments re: Current FRT Specification

The FRT's currently-specified expansion joint failure rate of 4×10^{-3} failures/year is greater than the FRT's 3×10^{-5} threshhold criteria and thus the failure of any piping segment that contains an expansion joint must be analyzed as a SALS. In addition, PHMSA and FERC have used "rupture" to mean a catastrophic full guillotine failure.

Operational history indicates that this failure rate appears conservative, at least for two-ply expansion joints. The Cove Point LNG facility received LNG through its marine transfer lines during its intermittent import operations over about 40 years, and has 100 two-ply expansion joints in its LNG liquid transfer lines[36,37]. The current FRT specifies that this facility (if proposed as new) must be designed for 0.4 full guillotine failures per year in its liquid transfer lines, i.e. equivalent to 8 full guillotine failures of expansion joints over 20 years, or 16 full guillotine failures of expansion joints over 40 years, if in continuous service. In comparison, no catastrophic failures of expansion joints are believed to have occurred to date at the Cove Point site during the intermittent operation of its marine transfer line.

<u>Comments re: "PNL PSRP '82" and "PNL ITRP '82"</u>

An expansion joint rupture frequency was shown as 1 x 10^{-7} faults/hour (~1 x 10^{-3}/year) on Table 3 on p. 3.13 of the "PNL PSRP '82" reference by Pelto etal (and the parallel Table 3.3 on p. 3.9 of "PNL ITRP '82" by Baker). Table 3 of PNL PSRP '82" cites two references ("Welker 1976, SAI 1975") for this data. Those two references are reviewed as follows.

<u>Comments re: "WELKER '76"</u>

This reference specifies a median "External leak or rupture" failure rate for an expansion joint of 2 x 10^{-6}/hour (~2 x 10^{-2}/year) with a Low rate of 1 x 10^{-8}/hour and High rate of 1 x 10^{-5}/hour, but specifies no hole size. This frequency rate was not included in this project database due to lack of failure mode or hole size definition (i.e. small or large leak vs. full bore rupture).

<u>Comments re: "SAI '75"</u>

This reference specifies a mean "Expansion Joint Ruptures" failure rate of 1 x 10^{-8}/hour (~1 x 10^{-4}/year), which was included in this project database. "SAI '75" does not cite a specific source for its expansion joint rupture data, but the 1975 WASH-1400 Reactor Safety Study (NUREG-75/104) is the one of few process-related references in its list of 21 References.

<u>Comments re: "LEES '12"</u>

Table A14.7 of this reference specifies a median "Leak (serious) in post-accident situation" failure rate of 3 x 10^{-7}/hour (~3 x 10^{-3}/year) for expansion joints based on the Rasmussen Report (i.e. 1975 WASH-1400 Reactor Safety Study), which was included in this project's database.

<u>Comments re: "PNL ITRP '82" and Possible Basis for Current FRT Specification</u>

The FRT's current specified failure rate of 4 x 10^{-3} per year may perhaps be based on the failure rate shown in Table 3 for "Rupture of Main Transfer Line or Components During Transfer" of the 1984 paper by Pelto and Baker entitled *Analysis of LNG Peakshaving Facility Release Prevention Systems* ("PNL RP '84") cited in FERC issuance 20120301-0016. This rate may be based on an an FTA analysis shown on Table B.3 on p. B.20 in "PNL ITRP '82" that a "large release occurs" of a "LNG Transfer Line" will occur at a rate of 2.5 x 10^{-6} faults/hour or 4 x 10^{-3} faults/year based on 13 different equipment or control system failure rates within the transfer line configuration. The database for this project's analysis did not include the failure rate of 4 x 10^{-3} per year since no other source for this failure rate was identified, and it appears to represent a

FTA fault estimate of the integrated LNG Transfer Line (and not an individual expansion joint failure).

The "PNL ITRP '82" reference analyzes the failure rate of a Double Ply Expansion Joint assembly (with pressure detection system) in a FTA in its Table B.12 (see Appendix B) which implies:

- The expansion joint rupture frequency of 1×10^{-7} faults/hour (9×10^{-4}/year) represents single ply construction
- The rupture of double ply construction expansion joint assembly (with leak detection system) was calculated as 2×10^{-9} ruptures/year.

4.8 Piping – Failure (Rupture or Leak) of Gasket

PHMSA's FRT currently specifies a failure rate for gaskets but does not identify a failure rate mechanism (e.g. rupture or effective hole size). "Gaskets" is often understood by users of the FRT to also mean "Flanges".

Comments re: "WELKER '76"

This reference specifies a median rate of 3×10^{-6}/hour (~3×10^{-2}/year) for gasket leak, but specifies no hole size. This frequency rate was not included in this project database due to lack of failure mode or hole size definition (i.e. small or large leak vs. full bore rupture).

Comments re: "GRI LNG FRD '81" and "AGA LNG EXP '79"

The 1979 analysis of 25 peak-shaving plants ("AGA LNG EXP '79) did identify (on p. T-266) that "One major leak was caused by a flange gasket failure", but no data is available on the total gasket count or the quantity of the "major leak" that would allow a frequency calculation and categorization of the associated failure rate. As also noted in Section 4.9, p. T-265 of AGA LNG EXP '79" states that:

> There have been no failures in any of the pipelines or in the piping insulation systems… There were no reported failures of LNG or cryogenic piping, although in one plant, gasketing was replaced on the cryogenic lines when the Teflon gaskets cold-flowed and leaks occurred at the flange joints. The piping failures reported do not include small leaks from gaskets, which occur more frequently when the system is being cooled down during startup.

The 1981 analysis of 27 base load or satellite facilites ("GRI LNG FRD '81") also did not provide any detailed analysis of incidents arising from gaskets or flanges. Section 4.1.13 entitled "Spills and Leaks" on p. 34 identifies that "The major causes of spills and leaks were electrical seal failures, overfilling of tanks, weld failures, and gasket leaks."

Comments re: "LEES '12"

Page 615 in Chapter 12 of this reference includes:

> Frequency of Gasket Failure:
>
> Gaskets 0.6 mm thick = 3×10^{-6} failures/year

Gaskets 3 mm thick = 5×10^{-6} failures/year

but specifies no hole size and the source of this data was unclear to the project team. This frequency rate was excluded from this project database due to lack of failure mode or hole size definition (i.e. small or large leak vs. full bore rupture), but is provided here as an additional comparison point.

Comments re: UK HCRD

Flange leak incidents in the UK HCRD database are "selected from Ring Type (RTJ), Compressed, Spiral Wound, Clamp (Grayloc or similar), or Hammer Union (Chicksan), Other or Not Known"[38]. Appendixes L provides additional background information about types of gaskets represented in this failure rate database and Appendix M provides cumulative probability distribution for flange leak derived by GTI from the raw data in the HCRD.

Comments re: UK "HSE FRED JUN'12"

Failure rate data provided in Item #FR 1.2.4 on p. 44 of "HSE FRED JUN'12" defines failure rates for flanges and gaskets, and the following excerpt includes the derivation.

Item FR 1.2.4 Flanges and Gaskets

ITEM FAILURE RATES

Type of event	Failure rate (per year per joint)	Notes
Failure of one segment of a gasket.	5×10^{-6}	The hole size is calculated as the distance between two bolts and the gasket thickness.
Failure of Spiral Wound Gasket	1×10^{-7}	Hole size calculated as gasket thickness multiplied by pipe circumference.

SPRAY RELEASE FREQUENCY

	Frequency	Effective length of crack
Fixed pipe flange	5×10^{-6} per flange per year	Pipe diameter (max 150mm crack length)

Derivation

92. All rates are taken from the MHAU handbook volume 3 (now archived). The 5×10^{-6} value is derived in the Components Failure Rates paper, which is a comparison of 9 sources of joint failure rates derived elsewhere. The values were derived for chlorine duty although the review included LPG, petrochemical, steam/water, nuclear and other data. Assuming a fibre or ring type gasket in a 25 mm pipe, four bolt flange and a 3.2 mm gasket the gasket failure will produce an equivalent hole of 13 mm diameter.

Table 5: Excerpt of Item FR 1.2.4 Flanges and Gaskets in "HSE FRED JUN'12"

To apply the equivalent hole size associated with failure of one segment of a gasket, the project team considered a 3 mm gasket thickness and:

- Considered two alternate methodologies to apply "Hole size calculated as gasket distance between two bolts and the gasket thickness":
    1. The equivalent hydraulic diameter of this area was calculated to be 6 mm (0.25") hole size, for all pipe sizes including the largest piping category in the current FRT, using the conventional definition of hydraulic equivalent diameter d = 4 x cross-sectional area of hole / wetted perimeter of hole (as also defined by UK HSE for the HCRD in its *Hydrocarbon Releases System Internet Help File* document).
    2. The equivalent hole diameter of a circle of this area was calculated to be about 16 - 24 mm (about 0.6" – 1.0") for piping of 25 – 1,000 mm (about 1" – 40") diameter, respectively (based on 600 lb Weld Neck flanges).
- Applied the failure rate frequency of 5 x 10^{-6} failure per year per joint as a 25 mm hole in the framework for this project; this being considered a reasonable basis, especially in comparison to the equivalent hydraulic diameter of 6 mm.
- Also observed that Note #73 on page 30 of "HSE FRED JUN'12" utilizes a slightly different (3 x 10^{-6} vs. 5 x 10^{-6}) failure rate for flanges; it identifies that for chemical reactors "each flange should be given a failure rate of 3 x 10^{-6} per year with a hole size equivalent to assuming a loss of a segment of gasket between two bolts."

To apply the hole size associated with "Failure of a Spiral Wound Gasket", the project team considered a 3 mm spiral wound gasket thickness and:

- Considered two alternate methodologies to apply "Hole size calculated as gasket thickness multiplied by pipe circumference":
    1. The equivalent hydraulic diameter of this area was calculated to be a 6 mm (0.25") hole size, for all pipe sizes including the largest piping category in PHMSA's FRT.
    2. The equivalent hole diameter of a circle of this area was calculated to be approximately: 51 mm (2") for a 8" diameter pipe gasket; 70 mm (2.75") for a 16" diameter pipe gasket; 85 mm (3.4") for a 24" diameter pipe gasket; or 105 mm (4.2") for a 36" diameter pipe gasket (based on outside diameter of piping).
- Reviewed the HCRD database and observed that the largest rupture of a spiral wound gasket in the HCRD was 4.82 mm; in total, ten ruptures of spiral wound gaskets were recorded from 1992 through 2015, and they ranged in size from 0.05 mm to 4.82 mm. Appendix L contains more details.
- Applied the 1 x 10^{-7} failure rate frequency as a 50 mm hole in the framework for this project; this being considered a reasonable basis, especially in comparison to the equivalent hydraulic diameter of 6 mm and the maximum HCRD data of 4.82 mm.

The project team did not directly apply the Spray Release Frequency of 5 x 10^{-6} failure per flange in this project's database, because "HSE FRED JUN'12" does not define crack width.

But for comparison, the Spray Release Frequency of 5 x 10^{-6} failure per flange matches the "Failure of one segment of a gasket" if for example a flange crack had the maximum length of 150 mm (6 in) and an approximate width of 3 mm (0.12"); thus yielding an equivalent hydraulic diameter of about 6 mm or equivalent hole diameter (of circle of this area) of about 24 mm.

The project team also noted that a recent analysis of circumferential cracks in nuclear power plant piping utilized equivalent hydraulic diameter.[39]

Comments re: "RIVM BEVI '09"

"RIVM BEVI '09" does not separately specify leak or rupture rates for flanges, but instead includes flanges its pipeline failure rates (ref. pp. 42-43 of Module C).

Comments re: "IOGP 434-1"

Table 3.1 on page 27 of "IOGP 434-1" provides release frequency modification factors for different flange types of ANSI Ring Joints, ANSI Raised Face, Compact and Grayloc. Section 3.5.5 of "IOGP 434-1" clarifies that "the release frequency for each flange type is based on the release frequency for flanges from HCRD data". The frequency modification rates in Table 3.1 provide some additional comparative points to PHMSA's FRT categories, but were not considered in this project's database because:

- "IOGP 434-1" cites only two studies that developed these modification factors.
- No explanation was identified in "IOGP 434-1" for the significant step-changes in modification factors in its Table 3.1, such as increasing from 0.064 to 1.02 when evaluating 10-50 mm vs. 50-150 mm Grayloc flanges (respectively), or why some modification factors exceed unity.

4.9 Piping – By Diameter

Comments re: Cryogenic Piping Failure Rate Data and "GRI LNG FRD '81"

The only directly-observed failure rate data set specifically for cryogenic piping identified in the literature was one data point derived from the combined results of the "GRI LNG FRD '81" analysis and its prior companion "AGA LNG EXP '79" reference. The "GRI LNG FRD '81" analysis of 27 LNG base load or satellite LNG facilities identified two failures of cryogenic piping, and on p. 27 states that "Both failures occurred at welded branch connections where a smaller pipe connected to a larger pipe. These failures were attributed to poor quality welds. One of the failures resulted in a leakage of about 1 cubic meter of LNG."

The "GRI LNG FRD '81" analysis built upon the 1979 ("AGA LNG EXP '79") results that analyzed 25 LNG peak shaving plants. "AGA LNG EXP '79" states on p. T-265 that:

> There have been no failures in any of the pipelines or in the piping insulation systems… There were no reported failures of LNG or cryogenic piping, although in one plant, gasketing was replaced on the cryogenic lines when the Teflon gaskets cold-flowed and leaks occurred at the flange joints. The piping failures reported do not include small leaks from gaskets, which occur more frequently when the system is being cooled down during startup.

The “GRI LNG FRD ’81” report combined the 1981 and 1979 (“AGA LNG EXP ‘79”) results. Page 59 of the “GRI LNG FRD ’81” summarizes that “Only 2 failures [of cryogenic piping] were reported from both the peak-shaving and this study in over two and a half billion foot-hours of operation.” This single data point was applied in this project’s database in the following manner:

- Failure rate - - 2 failures in over two and a half billion foot-hours of operation results in a MTBF of about 1,250,000,000 foot-hours (which is consistent with the Combined Studies results shown in Figure 24 of “GRI LNG FRD ’81”) and this MTBF (equivalent to 8 x 10^{-10} failures/foot-hour) is used in this project’s database.
- Classified as leak not rupture - - The “GRI LNG FRD ’81” reference does not indicate the pipe size or diameter, or provide any details about the amount of time that fluid leaked, during the two piping failures that it identified in its report. But given the relatively small amount of leakage identified (“1 cubic meter of LNG”), and given that both failures occurred at a welded branch connection, it appears unlikely that complete rupture of the larger pipe occurred in these failures. So this analysis included the 8 x 10^{-10} failures/foot-hour rate as representing “Release from a hole with effective diameter of 10% diameter, up to 50mm (2 inches)” for line sizes up to 12” diameter (and not larger based on consideration of the population of LNG facilities in this survey).

The MTBF data in the “GRI LNG FRD ’81” and “AGA LNG EXP ‘79” reports are based on operating hours and not calendar hours. However, the cryogenic piping failure data was converted to be equivalent to PHMSA’s current definition of “Failures per year of operation”, i.e. the piping failure rate data of “per foot-hour” was directly converted to an annualized rate equivalent to continuous service (disregarding maintenance and repair periods). In contrast, factors were applied to put vaporizer heat exchanger MTBF data from these two reports on an annualized basis, in the manner described in Section 4.3.

<u>Comments re: “NFPA 59A ‘16”</u>

Piping size diameter categories in Table 15.6.1 of NFPA 59A ‘13 and ‘16 editions differ from the FRT. In addition, the NFPA 59A data specifies its applicability to “aboveground piping”. To apply and compare the piping failure data in NFPA 59A to the FRT, the following approximate alignment of pipeline categories was utilized:

NFPA 59A Aboveground Piping Rupture Diameter Category	**Est. FRT Equivalent Category**
Nominal diameter < 3 in. (75mm)	Piping: d < 50mm (2-inch)
Nominal diameter from 3 in. (75mm) up to and including 6 in. (150mm)	Piping: 50mm (2-inch) ≤ d < 149mm (6-inch)
Nominal diameter > 6 in. (150mm)	Piping: 150mm (6-inch) ≤ d < 299mm (12-inch)
Nominal diameter > 6 in. (150mm)	Piping: 300mm (12-inch) ≤ d < 499mm (20-inch)
Nominal diameter > 6 in. (150mm)	Piping: 300mm (12-inch) ≤ d < 499mm (20-inch)
Nominal diameter > 6 in. (150mm)	Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch)

Table 6: Approximation used to align NFPA 59A data and FRT

Comments re: UK "HSE FRED JUN'12"

The categories and failure rates for piping in the FRT appear to be primarily based on the specifications in Item #FR 1.3 "Pipework" of "HSE FRED JUN'12" as shown below. The project team utilized the same approximations of nominal diameter as currently used in the FRT, i.e. 50 mm = 2", 150 mm = 6", 300 mm = 12", 500 mm = 20", and 1,000 mm = 40".

- All of the pipework diameter categories in the FRT exactly match the categories for "Pipework" in Item #FR 1.3 on p. 47 of "HSE FRED JUN'12"; and
- All of the data in the FRT exactly matches the failure rates in Item #FR 1.3 of "HSE FRED JUN'12" with only two small differences:
  - 2×10^{-6} failures/meter-year instead of 1×10^{-6} failures/meter-year for "Release from a hole with effective diameter of 25mm (1-inch)" for Piping size "50 mm (2-inch) ≤ d < 149mm (6-inch)".
  - 2×10^{-8} failures/meter-year instead of 4×10^{-8} failures/meter-year for "Catastrophic Rupture" for Piping size "500 mm (20-inch) ≤ d < 1000mm (40-inch).

Failure rates (per m per y) for pipework diameter (mm)					
Hole size	**0 - 49**	**50 - 149**	**150 - 299**	**300 - 499**	**500 - 1000**
3 mm diameter	1×10^{-5}	2×10^{-6}			
4 mm diameter			1×10^{-6}	8×10^{-7}	7×10^{-7}
25 mm diameter	5×10^{-6}	1×10^{-6}	7×10^{-7}	5×10^{-7}	4×10^{-7}
1/3 pipework diameter			4×10^{-7}	2×10^{-7}	1×10^{-7}
Guillotine	1×10^{-6}	5×10^{-7}	2×10^{-7}	7×10^{-8}	4×10^{-8}

Table 7: Excerpt from FR 1.3 "Pipework" of "HSE FRED JUN'12"

"HSE FRED JUN'12" also specifies failure rates for "Above Ground Pipelines" in Item #FR 3.1.2 (ref. p. 56) that are "applicable to general natural gas aboveground installations where no site specific information is available" and "The above ground section of pipeline under assessment to be entirely within a secure compound." It defines "Rupture (>110 mm)" and specifies rupture failure rate of 6.5×10^{-9} per meter-year for all pipe sizes. The data in Item FR 3.1.2 was excluded from this project's database since they are only to be used where no site specific information is available and cannot be used without contacting HSE's Topic Specialist.

Comments re: "IOGP 434-1"

The process piping failure rate data in "IOGP 434-1" is derived from DNV's analysis of the UK HCRD database (ref. p. 19 of "IOGP 434-1").

Comments re: "LNE '09"

The "LNE '09" reference specifies failure frequencies for both above ground pipelines and underground pipelines. The aboveground pipeline frequencies are specified in terms of L/D, and were excluded from this project's database because no representative length would necessarily be correct for the FRT. The underground pipeline rupture frequency of 2.8×10^{-8} per meter-year was included in this analysis.

Comments re: PHMSA DOT Natural Gas Transmission Pipeline Incident Data

DOT PHMSA maintains a database of recorded incidents on natural gas transmission and gathering pipelines, and this data was not cited in the 2012 derivation of the FRT. LNG facilities and their associated exclusion zones are governed by US 49 CFR Part 193, wheras the transmission of natural gas and other gas by pipeline is governed by US 49 CFR Part 192. Nevertheless, PHMSA's database of recorded incidents on natural gas transmission pipelines provides for comparison a failure rate data set for high pressure, carbon steel piping in natural gas transmission service at ambient temperature.

A 2015 review by Lam[40] ("PHMSA NGT LAM '15") analyzed onshore gas transmission pipeline rupture incident data in PHMSA's database from 2002 to 2013, and presented rupture frequency data by categories of pipe diameter in PHMSA's database, which are different than those in the FRT (see Table 8). As summarized by Lam, PHMSA's data represents approximately 475,000 km of pipelines, of which "steel pipelines consistently account for over 99% of the total pipeline length" and about 97-98% of the steel pipelines are cathodically protected coated pipelines.

PHMSA Natural Gas Transmission and Gathering Failure Rate Data Diameter Categories	**PHMSA LNG FRT Category**
diameter < 4"	Piping: 50mm (2-inch) ≤ d < 149mm (6-inch)
4" ≤ diameter < 10"	Piping: 150mm (6-inch) ≤ d < 299mm (12-inch)
10" ≤ diameter < 20"	Piping: 300mm (12-inch) ≤ d < 499mm (20-inch)
20" ≤ diameter < 28"	Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch)
diameter ≥ 28"	Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch)

Table 8: Comparison of Piping Size Categories in FRT to those in PHMSA's Natural Gas Transmission and Gathering Incident Database (and Lam's analysis)

GTI separately analyzed this PHMSA incident data set in order to more accurately match this incident data to the piping size categories in the FRT. Additional details are provided in Appendix J and the results are shown in Table 9. In summary:

- GTI only used the pipeline rupture data from 2010 - 2015 to calculate the rupture rates for the diameters given in Table 9, because PHMSA's data from 2002 – 2009 does not contain actual pipeline diameters (it only provides a range of diameters such as 0<d≤4, 4<d≤10, 10<d≤20, 20<d≤28 and 28<d).
- GTI compared the rupture rates from 2002 – 2015 and found them to be very similar to those rupture rates from 2010 – 2015, so the 2010 – 2015 results are also quite representative of the 2002 – 2015 time period.
- GTI's calculation of pipeline rupture rates from PHMSA's database was in close agreement with Lam's results, and also considered additional incident data as detailed in Appendix J.

Diameter Category (inch)	Piping Rupture Rate Specified in LNG FRT	Pipeline Rupture Rates from PHMSA's Natural Gas Transmission Pipeline Incident Database 2010-2015 "PHMSA NGT GTI '16" (per m-year)	Pipeline Rupture Rates from PHMSA's Hazardous Liquid Pipeline Incident Database 2010-2015 "PHMSA HL GTI '16" (per m-year)
0≤d<2	1.00E-06	na	na
2≤d<6	5.00E-07	2.78E-08	3.95E-08
6≤d<12	2.00E-07	3.23E-08	2.45E-08
12≤d<20	7.00E-08	4.20E-08	2.01E-08
20≤d<40	2.00E-08	2.96E-08	3.90E-08

Table 9: Comparison of Piping Rupture Rates in FRT vs. those in PHMSA's NG Transmission and Hazardous Pipeline Incident Databases (2010-2015) as calculated in Appendix J and K

Comments re: DOT PHMSA Hazardous Liquid Pipeline Incident Data

DOT PHMSA also maintains a database of incidents that occur in the distribution of hazardous liquids such as crude oil, fuel oil, gasoline, diesel, propane, jet fuel, LPG, carbon dioxide, and ammonia and this data was not cited in the 2012 derivation of the FRT. GTI analyzed this database and developed overall rupture rates by the piping size categories in the FRT, to provide additional data and as a direct comparison to the analysis of PHMSA's natural gas transmission incident data. Details are provided in Appendix K and the results are also shown in Table 9.

Comments re: "EGIG'15"

The European Gas Pipeline Incident Data Group (EGIG) maintains a database of recorded incidents on natural gas transmission lines in Europe. EGIG's data was not included in the 2012 derivation of the LNG Failure Rate Table, but it provides another failure rate data set for high pressure, carbon steel piping in natural gas transmission service at ambient temperature for comparison purposes. Criteria for inclusion in EGIG's database are that:

- The incident must lead to an unintentional gas release
- The pipeline must fulfill the following conditions:
    - To be made of steel
    - To be onshore
    - To have a Maximum Operating Pressure higher than 15 bar
    - To be located outside the fences of the gas installations

EGIG contains some useful hole size data and defines:

- Pinhole/crack: the effective diameter of the hole is smaller than or equal to 2 cm
- Hole: the effective diameter of the hole is larger than 2 cm and smaller than or equal to the diameter of the pipe
- Rupture: the effective diameter of the hole is larger than the pipeline diameter

The database for this project:

- used EGIG's Rupture data as "Catastrophic Rupture" data.
- approximated EGIG's Pinhole/Crack data for holes ≤ 20 mm as comparable to the FRT's "Release from a Hole with Effective Diameter of 25mm"
- disregarded EGIG's Hole data since it represents a very broad hole size category (i.e. 20 mm < d ≤ pipeline diameter).

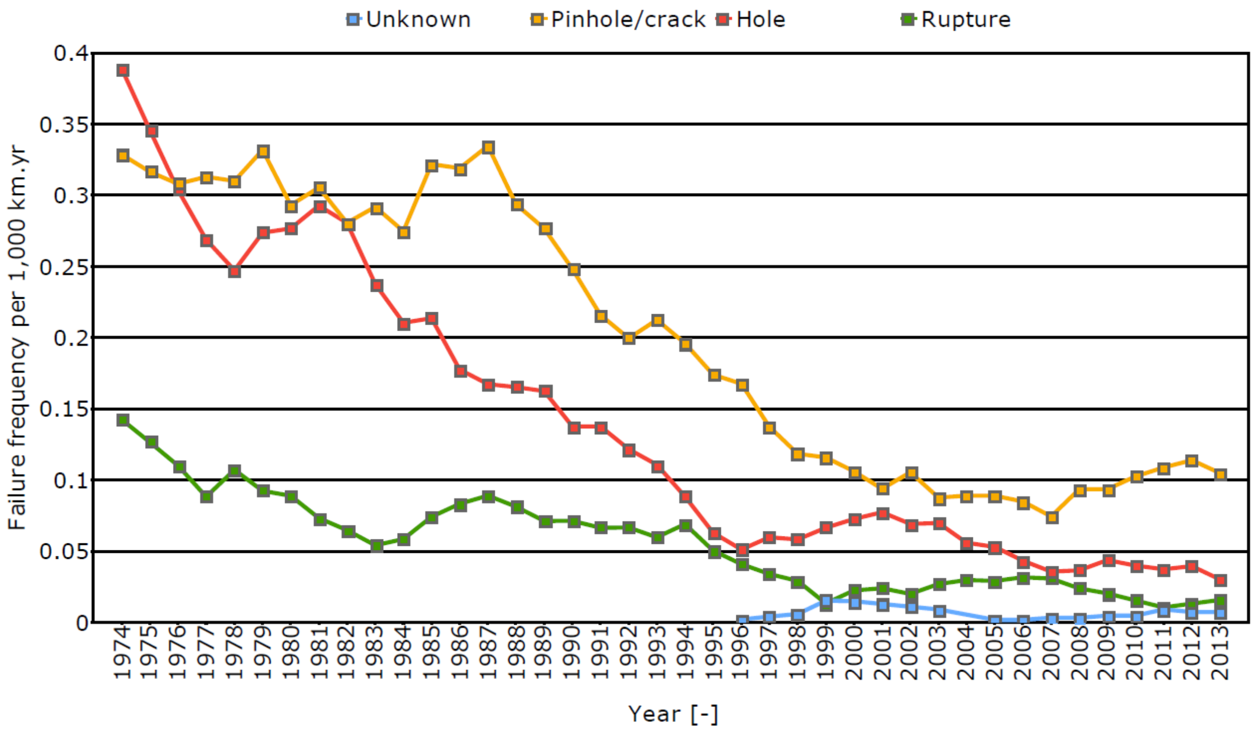
EGIG data primarily represents underground and unprotected natural gas transmission service data "located outside the fences of the gas installations", and a significant number of incidents arise from external influence or ground movement. For example, 48% of incidents during 2004-2013 occurred due to external influence or ground movement (e.g. arising from landslides, flooding, or swelling rivers) as shown in Figure 5 below.

The project team aligned EGIG's data to the FRT categories using the following approximation, and applied data from EGIG's entire reporting period of 1970-2013:

Pipeline Rupture Rate (/m-yr) "EGIG '15" actual data (1970-2013)	**EGIG Nominal Diameter Category**	**Est. FRT Equivalent Category**	**Piping Rupture Rate (/m-yr) specified in current FRT**
1.33E-07	diameter < 5"	50mm (2") ≤ d < 149mm (6")	5.00E-07
6.40E-08	5" ≤ diameter < 11"	150mm (6") ≤ d < 299mm (12")	2.00E-07
4.10E-08	11" ≤ diameter < 17"	300mm (12") ≤ d < 499mm (20")	7.00E-08
3.40E-08	17" ≤ diameter < 23"	300mm (12") ≤ d < 499mm (20")	7.00E-08
1.20E-08	23" ≤ diameter < 29"	500mm (20") ≤ d < 1000 mm (40")	7.00E-08
1.40E-08	29" ≤ diameter < 35"	500mm (20") ≤ d < 1000 mm (40")	7.00E-08
3.00E-09	35" ≤ diameter < 41"	500mm (20") ≤ d < 1000 mm (40")	7.00E-08
0.00E+00	41" ≤ diameter < 47"	NA	NA
6.00E-09	diameter ≥ 47"	NA	NA

Table 10: Approximation used to align EGIG data with FRT Piping Categories

The time span of EGIG's failure rate data (when analyzed by leak size details) is a potential consideration and potential weighting factor. Table 8 on Page 59 of "EGIG '15" highlights that the frequency of primary failure incidents reported during 2004-2013 (i.e. primary failure frequency of 0.157 per 1,000 km-yr) is about 48% of that reported during 1970-2013 (i.e. primary failure frequency of 0.329 per 1,000 km-yr). The figure below (i.e. Figure 13 from "EGIG '15" reproduced below in Figure 5) illustrates this overall reduction in incident rates. Unfortunately "EGIG '15" does not provide data for primary failure frequencies by pipeline diameter and size of leak for any time period other than 1970-2013, so the data available from 1970-2013 (i.e. Table 3 from "EGIG '15" reproduced below in Figure 5) was used in this analysis so that EGIG's Pinhole/crack and Rupture rates could be compared to those in the FRT.



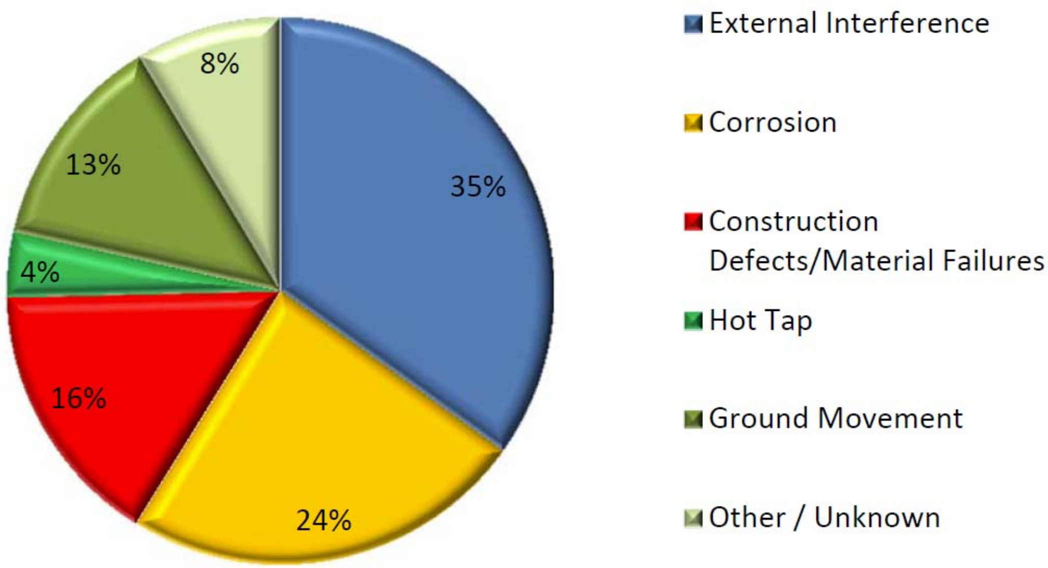
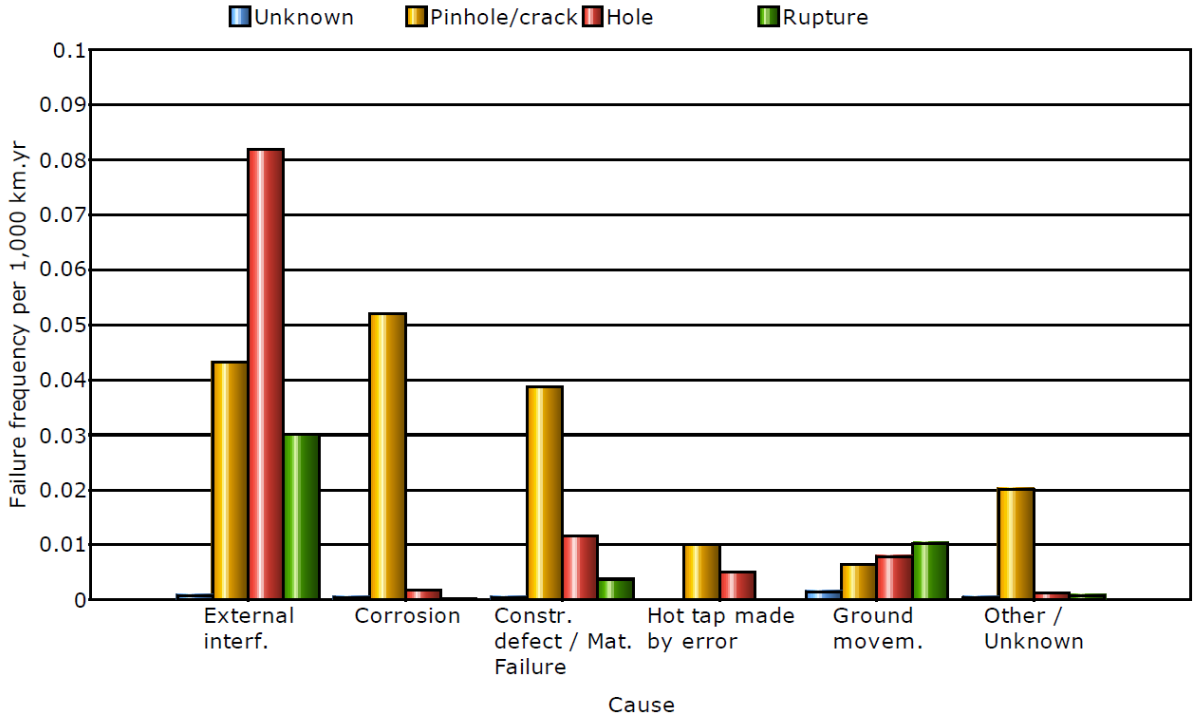


Figure 5: "EGIG '15" Figures 13, 16 and 19 and Table 3 reprinted by permission of EGIG:
"Figure 13: Primary (5-year moving average) failure frequency as a function of leak hole size" **(top)**
"Figure 16: Distribution of incidents (2004-2013)" **(upper middle)**
"Figure 19: Relation primary failure frequency, cause and size of leak (1970-2013)" **(lower middle)**
"Table 3: Primary failure frequency, pipeline diameter and size of leak (1970-2013)" **(bottom)**



Nominal diameter	System exposure $\cdot 10^6$ km·yr	Primary failure frequency per 1,000 km·yr			
		Unknown	Pinhole/crack	Hole	Rupture
diameter < 5''	0.436	0.005	0.445	0.268	0.133
5" ≤ diameter < 11"	1.066	0.008	0.280	0.197	0.064
11" ≤ diameter < 17"	0.714	0.004	0.127	0.098	0.041
17" ≤ diameter < 23"	0.442	0.005	0.102	0.050	0.034
23" ≤ diameter < 29"	0.401	0.000	0.085	0.027	0.012
29" ≤ diameter < 35"	0.214	0.000	0.023	0.005	0.014
35" ≤ diameter < 41"	0.389	0.000	0.023	0.008	0.003
41" ≤ diameter < 47"	0.146	0.000	0.007	0.000	0.000
diameter ≥ 47"	0.170	0.000	0.006	0.006	0.006

Figure 5 (cont.): "EGIG '15" Figures 13, 16 and 19 and Table 3 reprinted by permission of EGIG:
"Figure 13: Primary (5-year moving average) failure frequency as a function of leak hole size" **(top)**
"Figure 16: Distribution of incidents (2004-2013)" **(upper middle)**
"Figure 19: Relation primary failure frequency, cause and size of leak (1970-2013)" **(lower middle)**
"Table 3: Primary failure frequency, pipeline diameter and size of leak (1970-2013)" **(bottom)**

Comment re: Potential Use of Discount or other Adjustment Factors to Raw Data

Various weighting, relevancy or discount factors could be applied to EGIG's and PHMSA's pipeline incident rate raw data when considering its applicability to LNG plants, given the above differences. But this project incorporated EGIG's and PHMSA's pipeline incident rate data in a unadjusted, "as is" manner in this project's database, except for the influence of the overall weighting factors considered in sensitivity analysis as described in Section 5.

Comments re: DOT PHMSA Natural Gas Distribution Incident Data

DOT PHMSA also maintains a database of recorded incidents on natural gas distribution. This data was excluded from this analysis, since it contains a significant amount of polyethylene or other non-metallic pipe used for the lower-pressure distribution of natural gas.

Comments re: CONCAWE European Cross-Country Oil Pipeline Incident Data ("CONCAWE '16")

Concawe is a division of the European Petroleum Refiners Association, whose members are 41 companies that operate petroleum refineries in Europe. Concawe has collected and provides data on spillages from European cross-country oil pipeline from 1971-2014. Concawe data was not included in this project's database, since: hole size definitions include pipe diameter dependency; hole size data (including rupture) is available for only 55% of the recorded spillages; spill frequencies by hole size include losses due to theft or attempted theft, which was significant duing the latest reporting period; and spill frequencies include both hot and cold pipelines and for example "Whereas 81% of hot oil pipeline spillages are related to corrosion, the figure is only 19% for cold pipelines, for which third party-related incidents and mechanical failure are the most prevalent."[41]

Comments re: "IOGP 434-1"

No data was included in this project's database from the IOGP Risk Assessment Data Directory Report No. 434-4 entitled "Riser & Pipeline Release Frequencies", since the release frequencies are based on the EGIG data and CONCAWE data, and this project's database already included the most recent data from EGIG.

Comments re: Canadian National Energy Board (NEB) Pipeline Incident Data

Canada's National Energy Board (NEB) compiles statistics of pipeline incidents, but no NEB data was included in this project's analysis. Available incident data from the NEB[42] does not include leak or hole size, or classify ruptures versus leaks. NEB does summarize pipeline ruptures on NEB-regulated pipelines[43], but is "presented for historical perspective only" and "should be used with caution."

Comments re: Aboveground vs Underground Pipeline Failure Rate Data

A number of references that provide failure rate data for piping and pipelines do not differentiate between above ground or below ground.

Pages 42-43 of 130 of Module C of "RIVM BEVI '09" does provides some comparative data for rupture rates, but implies that the most significant difference in failure rates applies to underground piping housed in a pipe bay. The database for this project included "RIVM BEVI '09" data for above ground pipelines. Specified pipeline rupture frequencies per meter-year are:

- Above ground pipelines: 1×10^{-7}, 3×10^{-7} or 1×10^{-6} (depending on diameter)
- Underground transport pipeline all other pipelines: 5×10^{-7} (any diameter)
- Underground transport pipeline complying with NEN 3650: 1.525×10^{-7} (any diameter)
- Underground transport pipeline in pipe bay: 1×10^{-9} (any diameter)

Failure rates for above ground pipelines are specified in Item #FR 3.1.2 on page 56 of "HSE FRED JUN'12" but could not be directly compared to failure rate data specified for buried pipelines in Item #FR 3.1.1, since "HSE FRED JUN'12" directs that buried pipeline failure rate frequencies be taken from HID C15's (now HSE CEHMD5) MCPIPIN software.

Comments re: Stainless Piping Failure Rate Data

No failure rate data was identified for stainless steel piping specifically in cryogenic service. For comparison, the "rupture failure mode" rate of stainless piping used in fission nuclear reactor power plant as calculated in 2006 EPRI Report EPRI-TR-1013141 revision 1 by K. N. Fleming and B. Lydell entitled *Pipe Rupture Frequencies for Internal Flooding PRAs*, and as reported in Table 4-2 of "INL VJ '10", were included in this project's database. The 2013 revision of this analysis was not reviewed because its purchase price[44] was not within this project's budget. As noted in "INL VJ '10", nuclear fission power plant feedwater piping can operate at up to ~280°C (~536°F) and 4.8 to 6.8 MPa (700 to 990 psi) of pressure. The mean failure rupture rate for fission reactor feedwater stainless steel pipe from 2006 EPRI Report EPRI-TR-1013141 revision 1 as reported in Table 4-2 of "INL VJ '10" is 3.07 x 10^{-8} failures/foot length-reactor year (i.e. 1.01 x 10^{-7} failures/meter length-reactor year).

Comments re: Consideration of Piping Rupture Rate Data when Specified as "Per Section"

Piping rupture failure rate data was exluded from this project's database when the failure was stated on a "per section" or undefined length basis, since no appropriate length could be inferred or assigned. This included: "Pipe Section >3 in dia" in "PNL PSRP '82"; "Section Rupture" for "Pipe < 3" and " Pipe > 3" " in "WELKER '76"; "Pipe ≤ 3 in. (per section)" and "Pipe > 3 in. (per section)" in Table A14.7 of "LEES '12"; Item #13 "Pipings" on p. 6.57 of "TNO RED '05"; "Above ground pipeline" in "LNE '09"; and "Pipe" in Table 3.1 of "API 581 '16".

The following references cite an identical median or nominal piping rupture rate of 1 x 10^{-10} faults/hour or failures/hour: "Pipe Section >3 in dia. - Rupture" in "PNL PSRP '82" (and also in "PNL ITRP '82"); "Section Rupture" for " Pipe > 3" " in "WELKER '76"; and "Pipe > 3 in. (per section) – Rupture/plug" in Table A14.7 of "LEES '12". For comparison purposes, this equates to 4.4 x 10^{-6} faults/year if one assumes a pipe section length of 5 meters or to 8.8 x 10^{-6} faults/year if one assumes a pipe section length of 10 meters.

4.10 Summary of Qualitative Review and Analysis

In summary, references contained in this project's results that expand upon FERC's 2012 citations are indicated in Table 11 and include "NFPA 59A '16" data, "IOGP 434-1" and "IOGP 434-3" data, "LNE '09" data, "OREDA '15" data, PHMSA natural gas transmission and hazardous liquid pipeline data, EGIG natural gas transmission data, API 581, various reliability data sets from INL, a SIGTTO reference document, membrane tank reliability estimates in the "KGSC'06", "KJCE '05" and "TGC "03" references, and two earlier source documents.

Reference Abbreviation	In FERC's 2012 References (Issuance #20120301-0016)	Data Specifically Included in Analysis	Add / Exclude	Comment
AGA FP LNG '84	Yes	No	-	See reasons in Section 4
AGA LNG EXP '79	Yes	No	-	See reasons in Section 4
API 581	No	Yes	+	
CCPS '89	No	Yes	+	
DNV FFG HCRD '13	No	Yes	*	Used more current LEAK 3.3
DNV LEAK 3.3	No	Yes	+	
EGIG '15	No	Yes	+	
GRI LNG FRD '81	Yes	Yes	*	
HSE FRED JUN'12	Yes	Yes	*	
INL CHEM '95	No	Yes	+	
INL NUC '07	No	Yes	+	
INL VJ '10	No	Yes	+	
IOGP 434-1	No	Yes	+	
IOGP 434-3	No	Yes	+	
KGSC '06	No	Yes	+	
KJCE '05	No	Yes	+	
LEES '12	Yes	Yes	*	Reviewed 4th Edition
LNE '09	No	Yes	+	
NFPA 59A 2001	No	No	-	No data found
NFPA 59A 2012 DRAFT	Yes	No	-	No data found
NFPA 59A 2016	No	Yes	+	(Data is same as 2013 edition)
OREDA '15	No	Yes	+	
PHMSA NGT GTI '15	No	Yes	+	
PHMSA HL GTI '15	No	Yes	+	
PNL PSRP '82	Yes	Yes	*	
PNL RP '84	Yes	No	-	See reasons in Section 4
RIVM BEVI '09	Yes	Yes	*	
SERCO AEA '04	No	Yes	+	
TGC '03	No	Yes	+	
TNO PURPLE ‘05	Yes	Yes	*	
TNO GREEN ‘92	Yes	No	-	No data found
TNO RED ‘05	Yes	Yes	*	

Notes: "+" = not a FERC 2012 reference; "-" = was a FERC 2012 reference but no data was applied in database for reason listed; "*" = was a FERC 2012 reference and data was applied in database.

Table 11: Comparison of Data Sources Cited by FERC and Used in This Analysis

5. Failure Rate Reference Sources: Quantitative Analysis Methodology

5.1 Overall Methodology

The project team developed and explored a framework of equipment component categories that expanded upon the current FRT, built a database of the relevant failure rate data contained in the references, and used a Bayesian statistical methodology combined with three different sensitivity techniques to analyze the results.

5.1.1 Framework Layout and Component Protocols

Appendix C presents the framework layout and component protocols that were developed in this project as a hierarchical list of the components and their potential sub-components. The framework maintained the protocol categories currently used in the FRT, and explored potential changes such as by:

- allowing for the subdivision of the broad category "Process Vessels, Distillation Columns, Heat Exchangers, Condensers" into more specific components as listed below.
- exploring to see if failure rate data could be applied to both cryogenic and non-cryogenic categories of Process Vessels, Distillation Columns, Heat Exchangers, Condensers, Expansion Joints, Gasket Flange, Valves, Truck and Ship transfer arms, and Piping.
- gathering membrane cryogenic atmospheric storage tank data for PHMSA's information, as well as attempting to consider available data for cryogenic liquid nitrogen, oxygen and argon storage.

Column C of Appendix C also identifies the data sources that were input into different equipment categories (some of which were excluded under different sensitivity and analysis scenarios described below).

Each equipment protocol in the Framework was assigned a row number. Data obtained from references was assigned to each row number in the following manner, which was intended to both help tease out any meaningful differences in the results and to help identify all cryogenic-derived data for components such as valves or hoses:

- Data was included in non-cryogenic protocol subcategory where it appeared that the data source was derived entirely from non-cryogenic sources (e.g. "EGIG '15", "INL NUC '07", and "PHMSA NGT LAM '15")
- Data was included in the cryogenic protocol subcategory where it appeared that the data source was derived entirely from LNG or cryogenic references (e.g. "GRI LNG FRD '81")
- Other data was included in the "top level" (i.e. neither cryogenic or non-cryogenic) protocol subcategory.

One benefit of a Bayesian analysis is that subject matter expertise can be applied. The judgements made by the project team can be reviewed in the Index (left hand) column of Appendix C. Assigning the data in this manner does not affect the "roll up" results in the Bayesian Network analysis, but it provides some additional insights into the reference data.

Some "Super Categories" were also included in the Framework Layout. These "Super Categories" were included merely to provide some higher-level "roll-up" results or other failure rate data for comparative information or interest, and are *not* suggested changes to the FRT:

- Ambient Atmospheric Storage Tanks
- Refrigerated Atmospheric Storage Tanks (typically single shell)
- Cryogenic Atmospheric Storage Tanks (all types)
- Piping: All diameters

The FRT as established by FERC and PHMSA analyzes static and stationary equipment. Rotating equipment categories (e.g. pumps and compressors) and mobile equipment (e.g. trailers and mobile ISO containers) were considered during this analysis, but were excluded from the framework and the FRT for this reason.

5.1.2 Database Development

Data files were developed in Microsoft Excel® software for each individual data source listed in Table 11 and Appendix C. The relevant equipment protocol row number was then assigned to each specific data item.

5.1.3 Bayesian Network Statistical Analysis

A Bayesian statistical analysis approach was utilized and leveraged AgenaRisk software[45], a well-proven and recognized commercial software.

Bayesian analysis is a method of statistical inference in which Bayes theorem is used to update the probability of a hypothesis as more evidence or information becomes available. Mathematically, Bayes theorem is represented with the equation below.

$$P(A \mid B) = \frac{P(B \mid A)P(A)}{P(B)}$$

where, P (A) is the prior distribution which refers to the information known about A before B is observed.

P (B|A) is the likelihood and refers to the observed fact B, for all values of A

P (A|B) is the posterior distribution which refers to the information known about A after B is observed. Bayes equation can be further reduced to

$$P(A|B) \propto P(A)P(B|A)$$

$$posterior \propto prior * likelihood$$

To combine multiple data sources into a single database, the information known from one data source was set as the prior and the information from the second data source was set as the likelihood. The posterior calculated was then assigned as a prior to the next data source and that next data source was set as the likelihood. With this repeated process, the probability distributions of the combined dataset was derived. The final probability distribution fed into the Bayesian network.

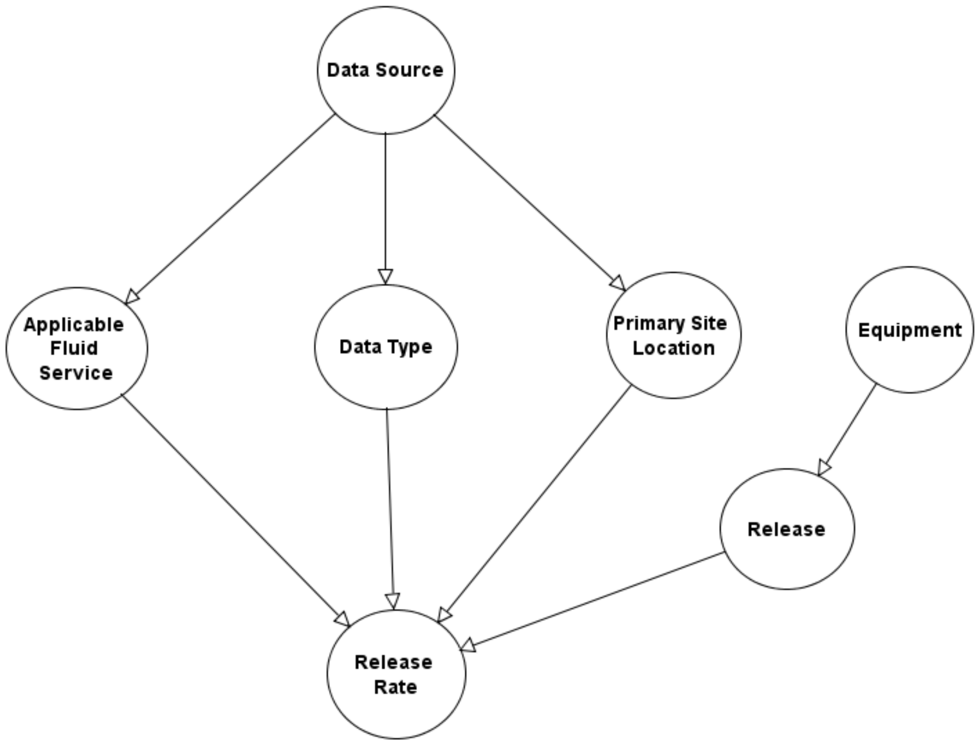


Figure 6: Bayesian network for failure rate calculation

Figure 6 illustrates the Bayesian network of factors used to derive failure rate using the "Perceived Relevancy" analysis methodology. Failure rates were calculated by applying the category weightings discussed in Section 5.2.1or 5.2.2 to the combined database (data sources). These categories were Applicable Fluid Service, Data Type, and Primary Site Location. The failure rate also depends on the equipment selected and nature of failure (e.g. rupture or diameter of leak hole).

5.1.4 Custom Input/Output Script

A custom input/output script was developed in order to read data from the database files, apply the chosen weighting factors and filters, run the AgenaRisk software, and present the data in the form of graphs as well as tabular summaries.

5.2 Sensitivity Analysis

Three methods of sensitivity analysis were considered in this analysis.

5.2.1 Analysis Using Perceived Relevancy Factors

The data obtained from the references was evaluated using weightings of perceived relevancy shown in Table 12. Three example illustrations were developed. Example A weighting provided one "baseline" analysis, and Examples B and C compared results when increased emphasis was put on generic chemical process industry references vs. from oil and gas industry references, and vice versa.

DESIGNATION	SYMBOL	EXAMPLE A WEIGHTING	EXAMPLE B WEIGHTING	EXAMPLE C WEIGHTING
Source Fluid Service ("SFS")				
LNG Facilities	LNG	1.0	1.0	1.0
Non-LNG Hydrocarbon (O&G, NGLs, LPG, etc.)	N_LNG_HC	0.8	0.5	0.8
Chemical Process Industry	CPI	0.8	0.8	0.5
Combined/Unspecified	UNSP	0.8	0.8	0.3
Pipeline - Natural Gas	NG_PL	0.8	0.5	0.8
Pipeline - Non-Nat. Gas Hydrocarbon	N_NG_PL	0.7	0.4	0.7
LIN/LOX/LAR/LH2	LAIR	0.7	0.8	0.3
Chlorine	CHL	0.3	0.5	0.1
Ammonia	NH3	0.5	0.7	0.3
Nuclear Industry	NUC	0.3	0.2	0.1
Water	WAT	0.1	0.0	0.0
Vacuum	VAC	0.1	0.1	0.1
Primary Site Location ("PSL")				
Off-Shore, Port or Coast	OFFSH	1.0	1.0	1.0
On-Shore	ONSH	1.0	1.0	1.0
Combined/Unspecified	UNSP	1.0	1.0	1.0
Data Type ("DT")				
Observed - Primary Source	OPS	1.0	1.0	1.0
Observed - Consolidated/Derived	OCD	0.9	0.9	0.9
Regulation/Specified	REG	0.8	0.8	0.8
Predicted	PRED	0.6	0.6	0.6
Applicable Fluid Service ("AFS")				
LNG	LNG	1.0	1.0	1.0
Non-LNG	N_LNG	0 or 1.0	0 or 1.0	0 or 1.0

Table 12: Weighting Factors Applied to Data for "Perceived Relevancy" Analysis

The terminology utilized in this project and in the above table is defined as follows:

- "Source Fluid Service" (or "SFS") refers to the primary fluid service from which specific equipment failure rate source data/reference was derived (if identified), in the judgement of the Project Team. Thus, "Source Fluid Service" does not necessarily refer the fluid service for which the data is specified as applicable to. For example, hose failure rate data provided in the "HSE FRED JUN'12" is derived from the chlorine industry, but HSE FRED failure rate data is applied broadly including to LNG.

- “Applicable Fluid Service” (or “AFS”) refers to whether or not the failure rate source data is predicted, specified or regulated for LNG, in the judgement of the Project Team. For example, the “HSE FRED JUN’12” hose failure data is derived from the chlorine industry, but the FRED failure rate data is applied broadly including to LNG. In contrast, the EGIG ’15 data of natural gas transmission pipeline failure rate data is not by itself intended to be directly specified for LNG. This AFS “filter” just provides another way to easily perform some sensitivity analysis of the data.

Table 13 summarizes the categorization of SFS and AFS to the data sets applied in the “Perceived Relevancy” analysis:

Reference Abbreviation	Source Fluid Service ("SFS")	Applicable Fluid Service ("AFS")	Primary Site Location ("PSL")	Data Type ("DT")
API 581 '16	UNSP	N_LNG	UNSP	OCD
CCPS '89	CPI	LNG	UNSP	OCD
DNV LEAK 3.3	N_LNG_HC	LNG	OFFSH	OPS
EGIG '15	NG_PL	N_LNG	ONSH	OPS
GRI LNG FRD '81	LNG	LNG	UNSP	OPS
HSE FRED JUN'12	*M	LNG	UNSP	REG
INL CHEM '95	NUC	N_LNG	UNSP	OCD
INL NUC '07	NUC	N_LNG	UNSP	OCD
INL VJ '10	*M	N_LNG	UNSP	OCD
IOGP 434-1	N_LNG_HC	LNG	UNSP	OPS
IOGP 434-3	UNSP	LNG	UNSP	OCD
KGSC '06	LNG	LNG	UNSP	PRED
KJCE '05	LNG	LNG	UNSP	PRED
LEES '12	*M	LNG	UNSP	OCD
LNE '09	*M	LNG	UNSP	REG
NFPA 59A '16	UNSP	LNG	UNSP	REG
OREDA '15	N_LNG_HC	N_LNG	UNSP	OPS
PHMSA HL GTI '16	N_NG_PL	N_LNG	ONSH	OPS
PHMSA NGT GTI '16	NG_PL	N_LNG	ONSH	OPS
PNL PSRP '82	UNSP	LNG	UNSP	OCD
RIVM BEVI '09	*M	LNG	UNSP	REG
SAI '75	UNSP	LNG	UNSP	OCD
SERCO AEA '04	N_LNG_HC	N_LNG	UNSP	OCD
SIGTTO IP4 '96	UNSP	N_LNG	OFFSH	OPS
TGC '03	LNG	LNG	UNSP	PRED
TNO PURPLE '05	UNSP	LNG	UNSP	REG
TNO RED '05	UNSP	LNG	UNSP	REG
WELKER '76	UNSP	LNG	UNSP	OCD

Notes: *M = Multiple SFS classifications with this reference

Table 13: Categorization of Referenced Data for “Perceived Relevancy” Sensitivity Analysis

5.2.2 Analysis Using Example Wisdom of the Crowd

A "Wisdom of the Crowd" methodology was also analyzed, by assigning weighting factors to individual data sets. Eight example illustrations were developed, with the intent to illustrate potential results as one tries to reduce duplication of underlying source data and increase the weighted importance of some of the more well-known or more commonly-used international references/regulatory guidance documents. The examples are shown in Table 14, by moving from Example 1 to Examples 3 and 4.

Examples 5 through 8 were included to allow PHMSA and FERC to more easily compare the data in some of the more well-known or more commonly-used international references/regulatory guidance documents. Example 5 is the "HSE FRED JUN '12" reference; the piping failure rates currently specified in the FRT closely match those in "HSE FRED JUN '12".

Reference Abbreviation	**Example 1 Wgtg: Uniform**	**Example 2 Wgtg:**	**Example 3 Wgtg:**	**Example 4 Wgtg:**	**Example 5 Wgtg: 100% "HSE FRED JUN '12"**	**Example 6 Wgtg: 100% "RIVM BEVI '09"**	**Example 7 Wgtg: 100% "LNE '09"**	**Example 8 Wgtg: 100% "IOGP 434-1 & 434-3"**
API 581 '16	1.0	0.7	0.4	0.1	0.0	0.0	0.0	0.0
59A '16	1.0	0.5	0.3	0.1	0.0	0.0	0.0	0.0
CCPS '89	1.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
DNV LEAK 3.3	1.0	0.7	0.4	0.0	0.0	0.0	0.0	0.0
EGIG '15	1.0	0.5	0.1	0.0	0.0	0.0	0.0	0.0
GRI LNG FRD '81	1.0	1.0	0.7	0.5	0.0	0.0	0.0	0.0
HSE FRED JUN'12	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0
INL CHEM '95	1.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0
INL NUC '07	1.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0
INL VJ '10	1.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0
IOGP 434-1	1.0	0.5	0.3	0.1	0.0	0.0	0.0	1.0
IOGP 434-3	1.0	0.5	0.3	0.1	0.0	0.0	0.0	1.0
KGSC '06	1.0	0.5	0.3	0.1	0.0	0.0	0.0	0.0
KJCE '05	1.0	0.5	0.3	0.1	0.0	0.0	0.0	0.0
LEES '12	1.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0
LNE '09	1.0	1.0	0.7	0.5	0.0	0.0	1.0	0.0
OREDA '15	1.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0
PHMSA HL GTI '16	1.0	0.7	0.5	0.3	0.0	0.0	0.0	0.0
PHMSA NGT GTI '16	1.0	0.7	0.5	0.3	0.0	0.0	0.0	0.0
PNL PSRP '82	1.0	0.5	0.3	0.1	0.0	0.0	0.0	0.0
RIVM BEVI '09	1.0	1.0	0.7	0.5	0.0	1.0	0.0	0.0
SAI '75	1.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0
SERCO AEA '04	1.0	0.5	0.3	0.1	0.0	0.0	0.0	0.0

SIGTTO IP4 '96	1.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0
TGC '03	1.0	0.5	0.3	0.1	0.0	0.0	0.0	0.0
TNO PURPLE '05	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TNO RED '05	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WELKER '76	1.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0

Table 14: Categorization of References for Example "Wisdom of the Crowd" Analyses

5.2.3 Analysis Using Alternate Bayesian Priors

This project used Beta distribution as Bayesian priors in its analysis. The Beta distribution is a continuous probability distribution having two parameters α and β that control the shape of the distribution. The Beta prior describes initial knowledge about probability of equipment failures before new evidence of failure has been incorporated and models uncertainty related to the probability of failures of equipment. Alternate Bayesian priors such as binomial distribution and Bernoulli distributions were considered in the analysis, but no substantive difference in results in was observed.

6. Failure Rate Reference Sources: Quantitative Analysis Results and Recommendations

6.1 Overall Summary of Framework, Sources and Results

The project team built a framework and database, and applied data from the sources identified in FERC's 2012 Issuance #20120301-0016 as well as other data sources identified during this project. The project team then used a Bayesian Network statistical analysis approach and two different methodologies as described in Section 5 to develop this project's results.

Appendix C illustrates the framework and component protocols used. Column C of Appendix C shows the data sources that were applied to each of the individual equipment protocol categories. One observation from Appendix C is that cryogenic-specific or LNG-specific data is even more limited than may have been previously thought, based on the findings summarized in Section 4 in which the key LNG-specific equipment references from 1979 – 1984 (i.e. "AGA LNG EXP '79", "GRI LNG FRD '81", "PNL PSRP '82", and "AGA FP LNG '84") provide only a few actual leak or rupture failure rate data points generated from actual LNG or cryogenic service.

The Bayesian Network computational results were generated by applying the weighting factors in the Perceived Relevancy and Wisdom of the Crowd example scenarios and running a large number of iterative cycles to converge on a calculated result. Some slight differences between the calculated results and a single dataset can sometimes occur (e.g. as in Wisdom of the Crowd Examples 5, 6, 7 and 8) since an uninformed prior was used.

Graphical summaries of the raw data and the probably distribution were developed for each equipment entry in the Framework. Two examples are provided below in Figures 7 and 8 for framework category #237 – Catastrophic rupture of a piping 6" ≤ d < 12". Credible intervals were also developed for each framework category.

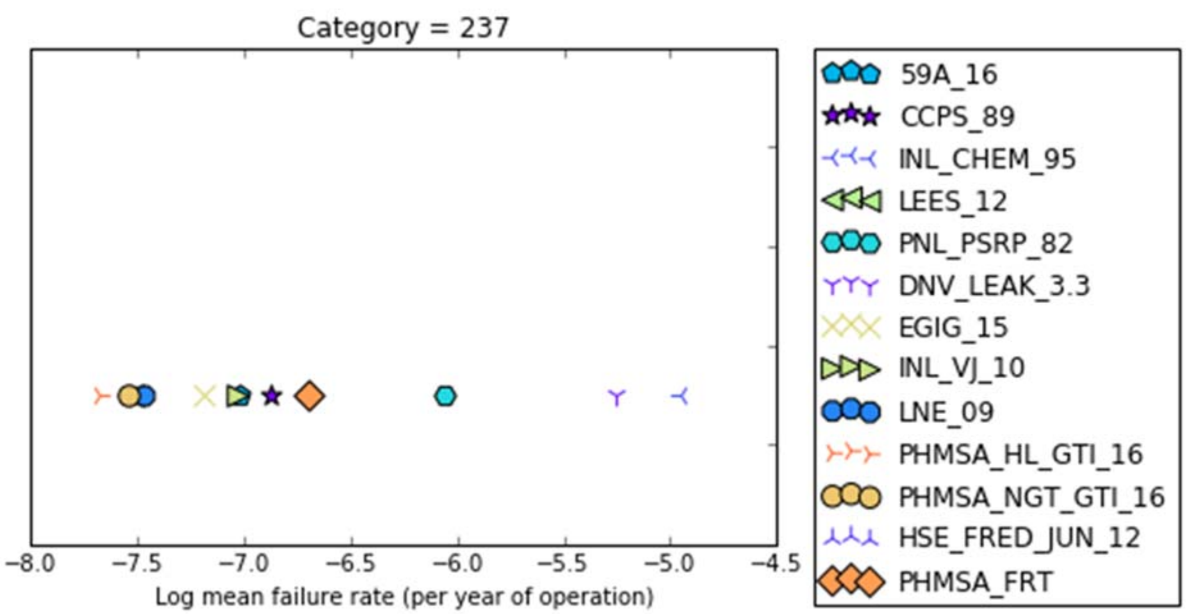


Figure 7: Summary of data in project database for Category #237 - Catastrophic rupture of piping 6" ≤ d < 12".

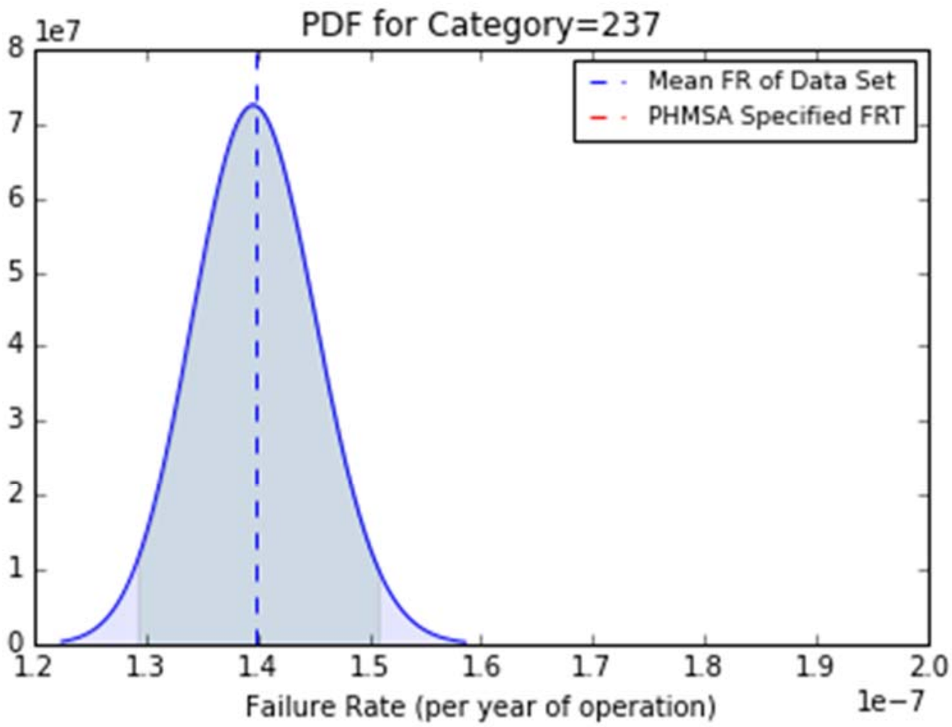


Figure 8: Calculated probability distribution function for Category #237 - Catastrophic rupture of piping 6" ≤ d < 12" for the "Wisdom of the Crowd" Example #4 (the FRT's current specification of 2 x 10^{-7} is overlaid on right axis).

6.1.1 Results Using Perceived Relevancy Analysis

Appendixes D and E summarize in tabular form the results for estimated mean failure rates using the "Perceived Relevancy" analysis approach for all of the data sets with the weighting factors from Table 12 applied to the data in the references in the following manner:

Data Set Classification	Comparison 1	Comparison 2	Comparison 3	Comparison 4
Source Fluid Service (SFS)	ALL	ALL	LNG	LNG
Primary Site Location (PSL)	ALL	ALL	ALL	ALL
Applicable Fluid Service ("AFS")	ALL	LNG	ALL	LNG
Data Type (DT)	ALL	ALL	ALL	ALL

Table 15: Comparisons of Results Provided in Appendix D and E

and also when considering all references or the exclusion of three specific references:

	Appendix D	Appendix E
Included "OREDA '15", "CCPS '09", and "INL CHEM '95"	Yes	No
Applied Percieved Relevancy Weighting Factors	Yes	Yes

Table 16: Comparisons of Scenarios in Appendix D and E

A comparative review of Appendix D and E indicates that the effect of the perceived analysis weighting factors was relatively small, and very little LNG-sourced failure rate data was identified in this analysis. The "Perceived Relevancy" sensitivity analysis effort provided context for the project and helped identify some data sources that were substantially different than the bulk of the data for some equipment protocols, but its effectiveness was limited in part because of the very small amount of available data that had high degree of relevance to LNG or cryogenics and that could inform the generic prior data.

Additional Percieved Relevancy scenarios can also be considered and evaluated (including refinement of the database and focusing on specific data sets) as guided by PHMSA and FERC, if futher refinement of this analysis approach is desired in a follow-up step.

6.1.1 Results Using Example Wisdom of the Crowd Analysis

Appendix F presents the results of a "Wisdom of the Crowd" approach, where individuals can assign their own opinions about which failure rate references should be heavily emphasized, or not, when reviewing available references.

The examples shown are mere illustrations of what different hypothetical individuals might consider as they reduce duplication of underlying source data, but with the intent that they put a greater weighted importance on the more well-known or commonly used international references or failure rate regulatory guidance documents moving from Example 1 to Examples 4-8.

Reviewing the Wisdom of the Crowd results in Appendix F (e.g. looking at Examples 3, 4 and 5) provides another useful way to quantitatively compare the overall data sets and draw the results and develop the recommendations that follow, in conjunction with the qualitative analysis and conclusions summarized in Section 4.

Additional Wisdom of the Crowd scenarios can also be considered and evaluated, as guided by PHMSA and FERC, if futher refinement of this analysis approach is desired in a follow-up step.

6.2 Cryogenic Atmospheric Storage Tanks

The results for cryogenic atmosphere tanks are summarized by tank type in each of the analysis scenario examples. This comparison is provided only for information and potential future use, since the failure rates of atmospheric LNG storage tanks (i.e. containers in NFPA 59A) is already specified in Table 2.2.3.5 of NFPA 59A 2001 edition specified by 49 CFR 193. Also, NFPA 59A 2001 edition does not permit membrane storage tanks (i.e. containers in NFPA 59A). This information may be relevant for PHMSA and FERC, if for example future regulations by those agencies allow design spills to be determined using methodologies different from the NFPA 59A 2001 edition.

Recommendations:

- PHMSA and FERC should consider eliminating cryogenic atmospheric storage tanks from the FRT since NFPA 59A 2001 edition enforced by 49 CFR Part 193 already specifies Design Spills for LNG tanks.
- If PHMSA and FERC retain the category of cryogenic atmospheric storage tanks in the FRT, then PHMSA and FERC should consider clarifying the use of this information for single accidental leakage sources for cryogenic atmospheric tanks in impounding areas serving only vaporization, process or LNG transfer areas.

6.3 Process Vessels, Distillation Columns, Heat Exchangers and Condensers

Some of the results presented in Appendixes D, E and F show a significant difference in rupture and leak failure rates for Pressure Vessels vs. Process Vessels. This difference appears in some of the scenario results in part because "RIVM BEVI '09" and "LNE '09" specify a 10x difference. However "HSE FRED JUN'12" does not make this distinction. The differences are summarized graphically below to aid PHMSA's and FERC's understanding. References to Tables in "RIVM BEVI '09" refer to those tables in Module C of "RIVM BEVI '09".

Specified Rates of Failures/Vessel-Year: "Catastrophic Failure" or "Rupture" or "Instantaneous Release"	**Pressure Vessel**	**Process Vessel**
"LNE '09" Table 1 "Pressure tanks" - "Process installations and other"		3.20E-06
"LNE '09" Table 1 "Pressure tanks" - "Storage tanks" "Underground or mounded"	1.00E-07	
"LNE '09" Table 1 "Pressure tanks" - "Storage Tanks" "Above ground (incl. road tankers and tankwagons)"	3.20E-07	
"RIVM BEVI '09" Table 31 "Reactor vessels and process vessels"		5.00E-06
"RIVM BEVI '09" Table 15 "Underground/mounded pressurized storage tanks"	5.00E-07	
"RIVM BEVI '09" Table 13 "Pressurized storage tank, aboveground"	5.00E-07	
"HSE FRED JUN'12" Item FR 1.1.4 "Chemical Reactors"		1.00E-05
"HSE FRED JUN'12" Item FR 3.2.1 "Tank Containers (ISO Tankers)" †	3.00E-06	
"HSE FRED JUN'12" Item FR 1.1.3.2 "LPG Pressure Vessels"	2.00E-06	
"HSE FRED JUN'12" Item FR 1.1.3 "Pressure Vessels" *	4.00E-06	
"NFPA 59A '16" "Pressurized storage (Containers)"	5.00E-07	
FRT "Process Vessels, Distillation Columns, Heat Exchangers and Condensers"	5.00E-06	5.00E-06
* Median catastrophic rate for Item FR 1.1.3 (Lower = 2.0E-06; Upper = 6.0E-06) † with a pressure relief system, and zero lifts (i.e. stationary service)		

Table 17: Comparison of Pressure Vessel and Process Vessel Failure Catastrophic Failure, Rupture or Instantaneous Release Rate Specifications

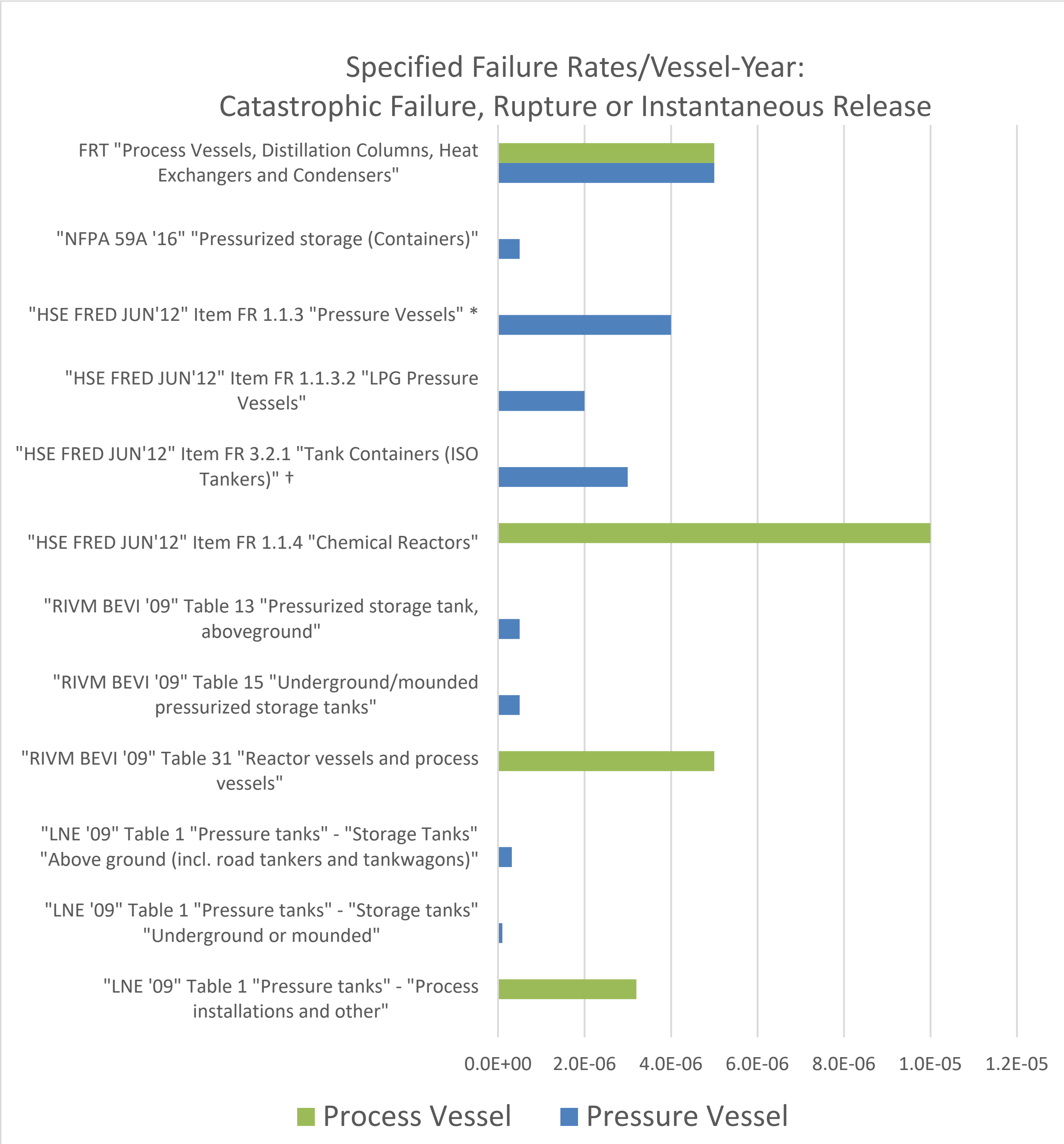


Figure 9:
Comparison of Pressure Vessel and Process Vessel Failure Catastrophic Failure, Rupture or Instantaneous Release Rate Specifications

Specified Rates of Failures/Vessel-Year: **Release from a Hole with Effective Diameter of 10 mm**	**Pressure Vessel**	**Process Vessel**
"LNE '09" Table 1 "Pressure tanks" - "Process installations and other"		1.20E-04
"LNE '09" Table 1 "Pressure tanks" - "Storage tanks" "Underground or mounded"	1.20E-05	
"LNE '09" Table 1 "Pressure tanks" - "Storage Tanks" "Above ground (incl. road tankers and tankwagons)"	1.20E-05	
"RIVM BEVI '09" Table 31 "Reactor vessels and process vessels"		1.00E-04
"RIVM BEVI '09" Table 15 "Underground/mounded pressurized storage tanks"	1.00E-05	
"RIVM BEVI '09" Table 13 "Pressurized storage tank, aboveground"	1.00E-05	
"HSE FRED JUN'12" Item FR 1.1.4 "Chemical Reactors" *		1.00E-05
"HSE FRED JUN'12" Item FR 3.2.1 "Tank Containers (ISO Tankers)" *†	6.00E-05	
"HSE FRED JUN'12" Item FR 1.1.3.2 "LPG Pressure Vessels" *	1.00E-05	
"HSE FRED JUN'12" Item FR 1.1.3 "Pressure Vessels" *	1.00E-05	
FRT "Process Vessels, Distillation Columns, Heat Exchangers and Condensers"	1.00E-04	1.00E-04
* approximating 13 mm specification as 10 mm † with a pressure relief system, and zero lifts (i.e. stationary service)		

Table 18:
Comparison of Pressure Vessel and Process Vessel Release from 10 mm Hole Rate Specifications

The above tables include data from Item FR 1.1.4 Chemical Reactors from "HSE FRED JUN'12". This data is provided only for comparative purposes and was considered by the project team to be of limited applicability to LNG; two the three advice notes for Item FR 1.1.4 describe glass lined agitator vessels, reactors, filters and centrifuges.

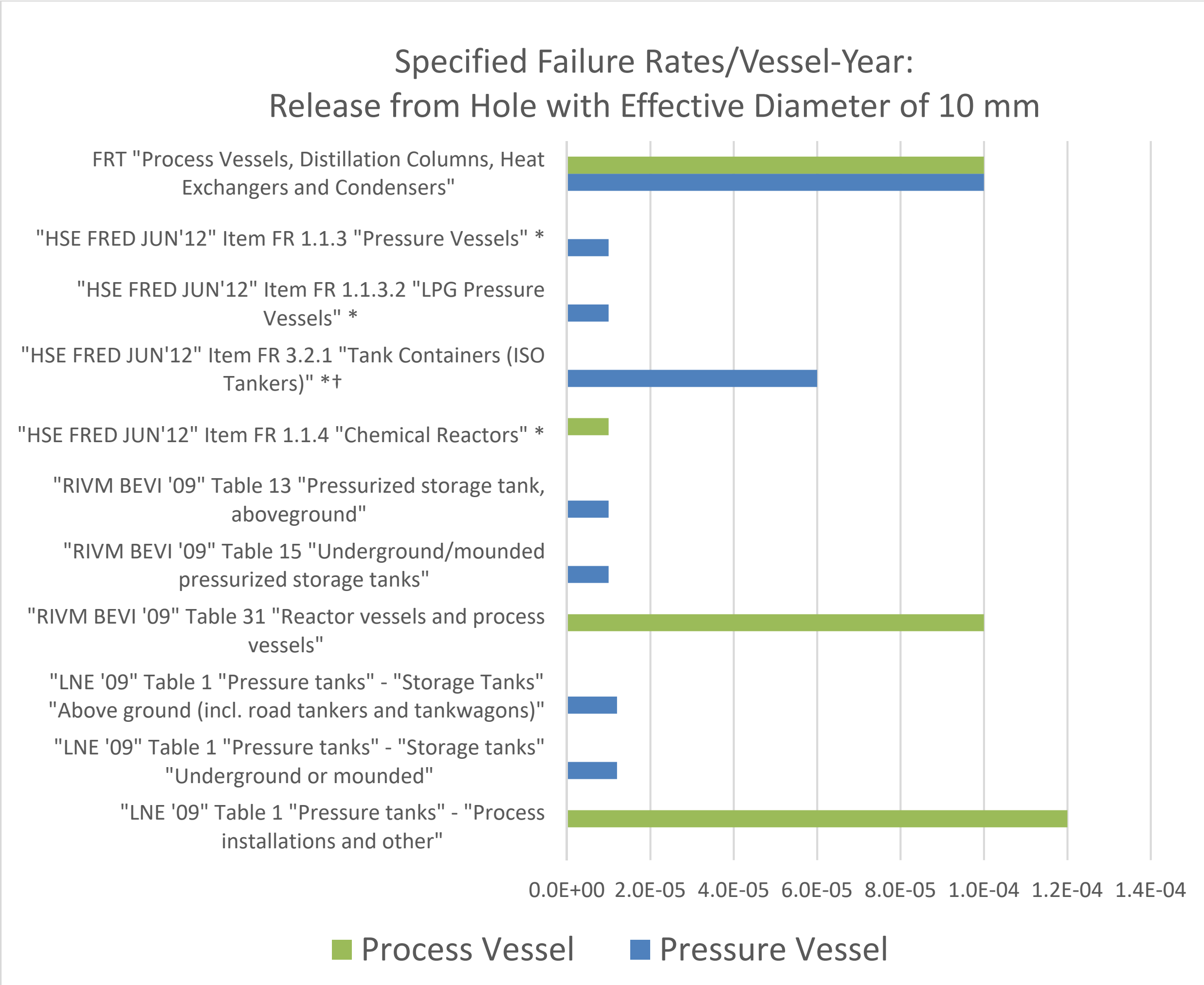


Fig 10:
Comparison of Pressure Vessel and Process Vessel Release from 10 mm Hole Rate Specifications

<u>Comments re: Rupture of Pressure Vessels and Process Vessels</u>

An HSE analysis led by Clive Nussey in 2006[46] compared the estimated failure frequencies of pressure vessels since “HSE has been criticized for using failure frequencies that are too pessimistic when compared to values used in the Netherlands”. Nussey’s analysis cited 25 references (including the 2004 detailed analysis “SERCO AEA ‘04”) and his conclusions (ref. p. 13) include that “no convincing evidence or arguments were found to support the claim that the HSE failure frequencies are too pessimistic”.

As noted in section 4.3, the “HSE FRED JUN’12” in its Item FR 1.1.3 included advice notes and bibliography references that appear to arise from cryogenic applications, whereas it was unclear to the project team if the “LNE ‘09” specification includes this type of analysis in its basis.

Pittiglio, Bragatto and Delle Site have also reviewed pressure vessel failure rates and noted the approximate 10x difference in pressure vessel failure rates when comparing various analyses worldwide, and concluded that “At the end API an HSE values, as quite conservative, are basically confirmed by experimental Italian data, whilst other data are too 'optimistic" and inadequate for an application by Italian Authorities"[47] (sic).

For the above reasons, the project team recommends that PHMSA and FERC consider retaining its current failure frequency of 5 x 10^{-6} failures/year for rupture for "Process Vessels, Distillation Columns Heat Exchangers, and Condensers" since this is more conservative and is more consistent with the above findings than the alternative of specifying a separate, lower failure rate frequency for rupture of pressure (storage) vessels as currently specified in "RIVM BEVI '09" or "LNE '09". In addition, the issue of specifying potentially lower rupture rates for Pressure Vessels vs. Process Vessels is also moot since the current rupture frequency of 5 x 10^{-6} failures/year is less than the 3 x 10^{-5} FRT criterion threshold.

However it should be noted that a significant portion of past analysis of pressure vessel failure rates appears to have been focused on single wall pressure vessels, such as to properly consider and safeguard for a Boiling Liquid Expanding Vapor Explosion (BLEVE) event of an LPG storage vessel. The anecdotal information provided by the Vice President of Engineering for Chart Industries summarized in Section 4.3 implies that the frequency of instantaneous rupture of shop-built double-wall cryogenic pressure vessels such as can be used to store LNG appears to be < 5 x 10^{-7} failures/vessel-year. The research going on in 2016 being supported by the Dutch LNG Safety Program and RIVM (see Section 4.3) will hopefully provide additional information on this topic to PHMSA and FERC, including perhaps both rupture and hole leak frequencies for double-walled cryogenic pressure vessels.

<u>Comments re: Heat Exchangers (all types)</u>

"HSE FRED JUN'12" does not specify failure rates for Heat Exchangers.

"LNE '09" specifies failure rates for pipe (shell and tube) heat exchangers shown in Table 19, and these compare well with the FRT. For example, the 1.3 x 10^{-5} failures/year rupture rate is approximately one-half decade different than the FRT's specification of 5 x 10^{-6} failures/year, and both values are below the FRT's 3 x 10^{-5} failures/year Criterion. The 10 mm leak failure rates differ by less than a half decade, i.e. 6 x 10^{-3} failures/year versus the FRT's specification of 1 x 10^{-4} failures/year for "Process Vessels, Distillation Columns Heat Exchangers, and Condensers"; both values are greater than the FRT's 3 x 10^{-5} failures/year Criterion.

Table 5: Failure frequencies (shell) [/heat exchanger.year] for pipe heat exchangers

Type of failure - shell	Failure frequency [/heat exchanger.year]
Small leak 0 < d ≤ 25 mm d_{eq} = 10 mm	6.0 10^{-3}
Medium leak 25 < d ≤ 50 mm d_{eq} = 35 mm	3.9 10^{-3}
Large leak 50 < d ≤ 150 d_{eq} = 100 mm	1.6 10^{-5}
Rupture	1.3 10^{-5}

Table 19: Excerpt from Section 5.1 "Pipe Heat Exchangers" of "LNE '09"

Comments re: Air-Cooled (Fin Fan) Heat Exchangers

Failure rate data for fin-fan heat exchangers was identified for PHMSA and FERC in this analysis since these are common in many LNG facilities (e.g. export terminal liquefaction trains). The data sources identified are shown in Appendix C.

"HSE FRED JUN'12", "RIVM BEVI '09", and "LNE '09" do not specify leak rates for fin-fan heat exchangers. One data source that contains hole size information for fin-fan heat exchangers is the HCRD database. Our review of the HCRD data set identified that there were six leak events in fin-fan heat exchangers in the HCRD data set, with hole sizes ranging from 0.1 to 2.6 inches. The FRT's current specification of 1×10^{-4} per year releases from a 0.01m (0.4") hole "Process Vessels, Distillation Columns Heat Exchangers, and Condensers" aligns well with a prediction by DNV from the HCRD data of 3.802×10^{-4} failures per year for a 3 – 10 mm hole (ref. p. 22 of "DNV FFG HCRD '13"). Appendixes L and M provide additional details.

Comments re: Leak of "Process Vessels, Distillation Columns Heat Exchangers, and Condensers"

The FRT currently specifies 1×10^{-4} failures/year for a "Release from a hole with effective diameter of 0.01m (0.4 in)" for "Process Vessels, Distillation Columns Heat Exchangers, and Condensers". This rate is consistent with other leading regulatory documents for process vessels such as "RIVM BEVI '09" and "LNE '09" as shown in Figure 10.

The FRT currently does not specify any leak hole sizes larger than 0.01m (and smaller than rupture). In this manner the FRT is consistent with "RIVM BEVI '09". The "LNE '09" does specify 1.1×10^{-5} failures/year for a "Medium Leak $10<d<50$ mm $d_{eq} = 25$ mm" and could be considered in the FRT but the point may be moot since this failure frequency is less than the 3×10^{-5} FRT criterion threshold.

For PHMSA's and FERC's information and at their request, the project team also provided estimates of leak rates for hole sizes of 2, 10, 25, 50 and 100 mm calculated using DNV's LEAK 3.3 software in Appendixes D, E and F for the categories considered in this framework related to the general category of Process Vessels, Distillation Columns, Heat Exchangers and Condensers.

Recommendation:

- PHMSA and FERC should consider retaining the existing category name and its currently-specified failure rate. The FRT's currently-specified rate for Pressure Vessels aligns well with those rate specified in "HSE FRED JUN'12", which also includes process vessels such as distillation columns; "HSE FRED JUN'12" is silent on Heat Exchangers. A corollary recommendation is:
    - PHMSA and FERC should continue to review and consider future refinements and potential other categories within this general category for any risk assessment methodologies other than the current FRT methodology; this may include new failure rate for cryogenic double-wall pressure vessels.

6.4 Truck Transfer – Arms and Hoses

The failure rate results for truck transfer hose and arm failure rate in the example Wisdom of the Crowd results for Examples 3 and 4 indicate that the FRT's specified failure rates for truck transfer arms and hoses is about 10x – 100x larger than other references analyzed. However, these results will vary greatly depending on the reference case selected, since:

- the FRT specifies a fixed rate in "failures per year of operation"; whereas
- most other references specify failure rates on a "per hour of operation" or "per operation" frequency basis.

Disadvantages of specifying a rate in "failures per year of operation" include determining a reasonable usage basis for setting the criteria, without creating unnecessary safety-, operational- or feasibility-related implications for those facilities that have fewer transfer operations.

A summary of some recent developments related to LNG hose failure rates is provided below, to provide additional context to the conclusions and recommendations.

<u>Relevant Recent Comparison Analysis by RIVM</u>

The following excerpt from the Dutch LNG Safety Program website highlights that in 2015 RIVM and its consultant reviewed but did not identify any statistically-sound existing data to update LNG delivery hose failure rate frequencies in "RIVM BEVI '09":

> Failure of the hoses during the offloading of an LNG tanker truck to the LNG storage vessel is perceived as one of the main contributors to the risk profile of an LNG refuelling station. In 2015, RIVM has asked consultancy firm AVIV to execute a literature survey to obtain relevant data for a possible decision to lower the failure frequency of typical hoses used for this operation.
>
> During their survey, AVIV did not find statistically sound data to update the existing failure frequencies for LNG delivery hoses.
>
> Starting in 2016, RIVM will research the availability of incident data for all fuel transfer systems, to derive update failure frequencies.[48]

<u>Recent Physical Testing of Cryogenic Truck Transfer Hoses</u>

The Dutch LNG Safety Program[49] and its Program Partners recently sponsored the development of new data for cryogenic transfer hoses conducted by TNO, the Netherlands Organisation for Applied Scientific Research. TNO with project partners recently concluded physical crush and fatigue tests in two Phases[50,51] on 2" and 4" diameter multi-composite hoses and metal corrugated hoses. The following excerpt from page 3 of TNO report 2016 R10126 summarizes that the purpose of this research included:

> This project aims to prove that, for small scale LNG transfer systems, the full bore rupture scenario is much too conservative for existing technology and that much less LNG or NG outflow can be substantiated. The approach is to prove that there are credible failure scenarios that may result in leakage but not to full bore rupture. It is hoped that authorities, based on the project results, can update their QRA calculation procedures with certain leak scenarios.

TNO provides detailed results in its reports 2015 R10689 (Phase 1 tests) and 2016 R10126 (Phase 2 tests). In summary, crush testing under truck wheels (either 4 or 8 passes) on both edges and flat surfaces was performed at cryogenic temperatures on:

- Four 2" diameter corrugated metal hoses made by three different manufacturers (two double-braided and one single-braded).

- 2" and 4" diameter multi-composite hoses made by one manufacturer

Fatigue testing was performed on 2" and 4" diameter multi-composite hoses from one manufacturer, and in summary:

- The first observed leak of any type for 2" diameter hose under cryogenic and atmospheric axial fatigue testing occurred at 0.3 – 4.0 million cycles.
- The first observed leak at a level judged to be detectable in service for 2" diameter hose under cryogenic and atmospheric axial fatigue testing occurred at 0.9 – 3.0 million cycles.
- The first observed leak of any type for 4" diameter hose under cryogenic and atmospheric axial fatigue testing occurred at 0.13 - 0.6 million cycles.
- The first observed leak in service for 2" diameter hose under cryogenic bending fatigue testing occurred at 900 cycles. The bending fatigue test included a bend restriction device and flexible length of the hose was only 16 cm (6.3").
- No full bore ruptures occurred before leakage judged to be detectable by an operator occurred and testing stopped (such as would occur by a hose being taken out of service).

Conclusions from Phases 1 and 2 of this project include the following excerpt from pages 34 and 36 of TNO report 2016 R10126:

> **7.2 Project conclusions on "leak before burst"**
>
> For one of the credible scenarios – a loaded trailer wheel running over a pressurized hose - it is demonstrated that none of the five hoses tested (significantly) leaked. The lightest metal corrugated hose without outer protective wire only showed minor leakage in the order of 1 l/min after multiple wheels passing. This is very much less than a "full bore rupture" release. For the composite hoses it is even demonstrated that the crush damage does not affect the pressure resistance of the hose (>100 barg). It is concluded that "leak before burst" is proven for the incident "crush by trailer wheel" for five different types of hoses that could be used in small scale LNG transfer operations. Based on the discussion in chapter 8, it is expected (that is: it is not proven) that the observed performance will likely hold for a wider range of crash and impact scenarios, other diameters, and other brands using similar materials and technologies. This is in particular the case for multi composite based hoses. Metal hose suppliers can design their product such that it resists crush loads specified.
>
> Gradual degradation over service due to cyclic loads cannot be avoided and is a potential cause of inducing burst failure. It is demonstrated that 2" and 4" multi composite hoses of a particular brand, subjected to cyclic loads, developed leak paths that grow relatively slowly over time while the residual burst pressure remain (significantly) higher than the maximum operating pressure (21 barg). Thus, full bore rupture of a fatigue degraded 2" or 4" composite hose of Gutteling during a LNG transfer operation is not a credible scenario. The confidence in extrapolation to fatigue test results shifts from "there is evidence" to "it is not possible" for respectively other loading conditions, other diameters of the same brand, and different brands. No conclusions can be drawn on the performance of metal hose with fatigue damage.

For the scenario crush and fatigue it is clearly demonstrated that for the composite hoses tested: 1) the damage is (likely) detectable, 2) full bore rupture is not expected and 3) that the resulting release of product (LNG/NG) will be insignificant compared to full bore rupture. With respect to metal hoses tested it is demonstrated that a high crush load 1) will not (always) result in damage, 2) significant damage that may cause leakage is detectable, 3) the resulting release of product (LNG/NG) will be insignificant compared to full bore rupture.

It is concluded that there are scenarios, which so far were intuitively labeled as potentially resulting in full bore rupture, will result in a relatively very small leakage of NG or LNG that is insignificant in view of the currently assumed full bore rupture.

And also provided below are a few of the question and answers in section 8 of TNO report 2016 R10126:

8 Review of project aims

1 Is it feasible to prove leak before burst for a particular multi composite hose for at least two potential critical failure scenarios?

Yes, for a multi composite hose it has been demonstrated that crushing and fatigue likely result in leakage that will be detected by an operator under normal operating conditions while the residual pressure resistance is higher than the normal operating pressures (10 to 18 barg).

3 What will be the likely failure modes based on technical judgement (not necessarily supported by evidence with tests or literature)?

The likely failure mode for multi composite hoses featuring materials, design and manufacturing technologies similar to that of Gutteling, under incidents referenced under point 1, is leakage of NG and or limited LNG. Full bore rupture will likely not occur. Further it has been demonstrated that fatigue damage will grow relatively slowly which improve the chance on detection.

Metal corrugated hoses have only been tested under crush loads only. From this test program no further conclusions can be drawn. Based on the hose design and material behavior it is assumed that, if fatigue cracks or large plastic deformations are present, leakage can develop faster than in composites.

7 What tests shall be executed to (partially) provide input to RIVM with respect to reduction of safety distances.

During execution of the project the input RIVM, being a member of the hose working group, was taken into account in selecting scenarios and tests. The RIVM representative stated at the final stage of phase 2, that for composite hoses no other tests are high on their priority list with respect to proving “leak before failure”. Obviously it is recognized by the working group that for metal corrugated hoses such evidence is not provided in this test program and is not found in open literature.

If one concluded for example from these recent tests that an experimentally-observed failure rate for 4” diameter LNG hoses is 0.1 million cycles (1×10^{-5}) until any type of leak was observed (i.e. a very small hole category, and comparable to or no greater than “release from hole with effective diameter of 10% transfer hose diameter”, or 0.4”), then this would equate to:

- 5 x 10^{-3} leak failures/year if there are 500 operations/year (= 1 leak failure/((100,000 cycles/500 operations/yr)

which would compare to the FRT's current specification of 4 x 10^{-1} leak failures/year for "release from hole with effective diameter of 10% diameter with maximum of 50 mm (2 in)" in the current FRT, i.e. a ~100x difference.

In summary, these recent test results:

- Provide data that five different types of hoses (both multi composite and corrugated metal) that could be used in small scale LNG transfer operation survived truck tire crushing without rupturing.
- Provide data that a full bore rupture of a fatigue-degraded 2" or 4" diameter multi composite Multi-LNG White hose made by Gutteling B.V. is not a credible scenario in both the fatigue and crush tests performed in these tests. In every scenario tested no full bore ruptures occurred before leakage at a level judged to be detectable by an operator occurred and testing was stopped.
- Support the possible reduction of up to 100x in the truck transfer hose leak frequency failure rate specified in the FRT. However, the recent fatigue testing was only done on composite hoses (and none on any corrugated metal or other hoses) and thus in its consideration of the potential for fatigue-induced burst failure TNO concluded:

> Thus, full bore rupture of a fatigue degraded 2" or 4" composite hose of Gutteling during a LNG transfer operation is not a credible scenario. The confidence in extrapolation to fatigue test results shifts from "there is evidence" to "it is not possible" for respectively other loading conditions, other diameters of the same brand, and different brands. No conclusions can be drawn on the performance of metal hose with fatigue damage.

<u>Summary Comments</u>

There are a number of active developments currently underway to develop new types of LNG truck transfer hoses and loading arms. This equipment category is an important "technology watch" area, and additional statistical failure frequency estimates or rates will likely be generated.

- At this time, no direct basis was identified to propose revising the specification in the FRT for truck hose leak "release from a hole in transfer hose with effective diameter of 10% transfer hose diameter with a maximum of 50 mm (2-inches)", including any that would raise the specified leak frequency above the FRT 3 x 10^{-5} failures/year threshold criterion.
- However, it appears that credible evidence has been developed for PHMSA and FERC to consider eliminating the truck hose rupture rate in the FRT specifically for multi composite hoses such as Multi-LNG White made by Gutteling B.V. PHMSA and FERC may want to pursue additional discussions with RIVM regulators to assess RIVM's conclusions regarding the recent cryogenic hose testing performed by TNO for the Dutch LNG Safety Program.

Also, PHMSA and FERC could consider revising the FRT so that hoses and arms failure rates are specified on a "per operation" or "per hour of operation" basis. FERC currently guides applicants to describe the number of LNG truck loadings and unloadings per year in their applications[52].

Recommendations

- If FERC and PHMSA want to retain a "failures per year of operation" basis of specification, then they may consider making no change to the truck transfer hose leak or rupture frequencies because even a 100x decrease in the leak rate frequency, e.g. from 4 x 10^{-1} to 5 x 10^{-3} failures per year, is still greater than the FRT criterion and triggers analysis of a SALS design spill. Corollary recommendations are:
  - PHMSA and FERC should consider if the current rupture rates for truck transfer hoses are still appropriate based on the results on the recent tests by TNO, and perhaps after consultation with RIVM and others. For example, PHMSA and FERC could consider eliminating the truck transfer hose rupture failure rate frequency if an applicant's proposed hose is a multi-composite hose such as either Gutteling B.V.'s Multi-LNG White hose or a multi-composite hose of similar materials, design and manufacture.
  - PHMSA and FERC should continue to review and consider new technical data generated related to LNG truck transfer hose and loading arm leak and rupture rates as it considers future revisions to the FRT.
  - PHMSA and FERC should consider reviewing this specification again in more detail if it specifies hose rupture rate for any risk assessment methodologies other than the current FRT Criterion methodology.
- If FERC and PHMSA want to consider a "time of use" or "frequency per hour of operation" on an annual basis in the FRT specification, then FERC and PHMSA could consider applying the "RIVM BEVI '09" specifications since these are on a per hour basis and thus take into account duration of use, and also because they are applicable to ship transfer (bunkering) operations. Consideration of potentially eliminating the truck hose rupture failure rate for multi-composite hoses could be included in this manner also.

6.5 Ship Transfer – Arms (and Hoses)

The failure rate results for ship transfer arm failure rate in the example Wisdom of the Crowd results indicate that the FRT's specified failure rates for ship transfer arms is approximately equivalent to the "RIVM BEVI '09" in the reference case analyzed, and lesser than "HSE FRED JUN'12". However, these results will vary greatly depending on the reference case selected, since:

- the FRT specifies a fixed rate in "failures per year of operation"; whereas
- most other references (except NFPA 59A 2013 and 2016 editions) specify failure rates on a "per hour of operation" or "per operation" frequency basis.

Disadvantages of specifying a rate in "failures per year of operation" include determining a reasonable usage basis for setting the criteria, without creating unnecessary safety-, operational- or feasibility-related implications for those facilities that have fewer transfer operations.

A summary of some recent events related to LNG ship hose failure rates is provided below, to provide additional context to the conclusions and recommendations.

Comments re: GIIGNL (The International Group of Liquefied Natural Gas Importers)

A representative of GIIGNL's Technical Study Group (TSG) indicated that the TSG currently has an initiative underway to analyze GIIGNL's database of incidents that occured at GIIGNL member's facilities; it is possible that some data may be publicly released in 2017.[53] This representative also highlighted a GIIGNL-authored technical paper[54] delivered at the LNG17 conference in 2013; this paper provides failure/leak rate statistics by plant subsystem (e.g. 1.49 incidents/million hours for "LNG Tanks, In-Tank Pumps & BOG Facilities", but unfortunately provides no break-out data specifically for specific components such as transfer arms).

Ship Transfer Hoses in addition to Arms

PHMSA with FERC may want to consider adding a category in the FRT for ship transfer hoses, since hoses are currently being used for some LNG bunkering operations as well as ship-to-ship transfer, and this application is expected to grow. Commercial products such as Trelleborg Industrial Solutions' LNG Cryoline floating LNG hose are being considered at small-scale LNG terminals.[55] Results from this project's database for ship transfer hose failure rates are provided.

Physical Testing of Ship Transfer Hoses in 2011

TNO, the Dutch contract research organization, performed physical testing in 2011 of 8" diameter multi-composite hoses manufactured by Gutteling B.V. for ship-to-ship transfer of LNG, and reported that it "successfully passed all EN 1474-part 2 requirements."[56] These requirements include that a minimum of 400,000 bending cycles not result in leakage or damage under operating conditions (cryogenic and pressure). This implies that a LNG hose leak (or rupture) failure frequency that meets EN 1474-part 2 requirements should be $< 2.5 \times 10^{-6}$ failures/cycle (i.e. <1 failure/400,000 bending cycles). This equates to a failure rate of:

- $< 1.25 \times 10^{-4}$ leaks/year if 50 cycles/year
- $< 1.25 \times 10^{-3}$ leaks/year if 500 cycles/year

Comments re: relevant analysis by DNV

As an additional point of comparison, DNV applied an estimated failure frequency of 7.6×10^{-5} total failures/visit for LNG bunkering hardarms in a QRA conducted in 2013 for Skangass AS' LNG Bunkering Terminal at Risavika Harbour in Norway.[57]

Summary Comments

There are a number of active developments currently underway to develop new types of LNG ship transfer hoses and loading arms, for applications ranging from bunkering facilities to import/export terminals. This equipment category is an important "technology watch" area, and additional statistical failure frequency estimates or rates will likely be generated. However at this time, no direct basis was identified to propose revising the specification in the FRT for this category.

Recommendations

- If FERC and PHMSA want to retain a "failures per year of operation" basis of specification, then they may consider that no change is needed to the ship transfer arm rupture or leak rates currently specified in the FRT. A corollary recommendation is:

- PHMSA and FERC should continue to review and consider new technical data generated related to LNG ship transfer loading arm and hose leak and rupture rates as it considers future revisions to the FRT.

- If FERC and PHMSA want to consider a "frequency per hour of operation" for loading arms on an annual basis in the FRT specification, then FERC and PHMSA could consider applying the "RIVM BEVI '09" specifications since these are on a per hour basis and thus take into account duration of use.
- PHMSA should consider establishing a category for ship transfer hoses, and if so then FERC and PHMSA could consider applying the "RIVM BEVI '09" specifications since these are applicable to ship transfer operations.

6.6 Piping – Rupture (and Leak) of Valve

Analysis of Valve Rupture

The source references that contained valve rupture data are shown in Appendix C, and calculations shown for valve rupture rates in scenario evaluations are shown in Framework Index #143. A summary of the findings in Section 4.6 and this analysisis:

- The equipment failure rate regulatory references that appear to be frequently cited and used globally such as "HSE FRED JUN'12", "RIVM BEVI '09" and "LNE '09" do not specify a valve rupture rate. "RIVM BEVI '09" includes the failure of valves with its failure rate for piping, and does not separately define valve failure rate frequencies (ref. Module C p. 42).
- The data arising from "GRI LNG FRD '81", the most relevant analysis found for LNG and cryogenic valves, identified *zero* cryogenic valve ruptures and two leaks in more than 43 million hours of operation. As noted in Section 4.6 of "GRI LNG FRD '81", "One safety-related failure was reported, but this was attributed to human error and is not included as a valve failure". This equates to an observed LNG valve rupture failure rate $< 2 \times 10^{-4}$ ruptures/year (=1/4,909 years), but does not inform the rate specified in the FRT since this is merely a minimum rate based on the very short time period examined in "GRI LNG FRD '81".
- The source of other generic data for valve rupture rates in some of the references are based in part on nuclear reactor plant valves, where the definition of rupture can be leakage from piping "greater than 50 gpm"[58].

For additional comparison:

- A more recent comparative analysis of nuclear plant valve rupture failure rates is 3.12×10^{-9} failures/year, i.e. 2.2×10^{-5} failures/year as per the mean failure rate for "Manual Valve External Large Leak" in Table 5-1 of "INL NUC '07" (considered a rupture as noted in Section 4.1); this failure rate database presumably comprises significant carbon steel as well as some stainless material in valve construction, and the value of 2.2×10^{-5} failures/year is less than the current FRT criterion of 3×10^{-5}.
- "DNV FFG HCRD '13" indicates 4.859×10^{-5} failures/year and 1.347×10^{-5} failures/year total failure frequency rates for a >150 mm (>6") hole to occur in a 6" (150 mm) manual or actuated valve, respectively (ref. pp. 32 and 34) - - i.e. which some could consider as a

full-bore rupture as defined on p. 9 of this reference. However as noted in section 4.1, GTI concurs with DNV's comment in "DNV FFG HCRD '13" that there is considerable uncertainty related to using the HRCD data to estimate equipment ruptures.

- The mean failure rate for Catastrophic "Valves-Manual" on p. 199 of "CCPS '89" is more than 100 times greater than that specified in the current FRT. No explanation for this large difference was identified. "CCPS '89" p. 128 cites SAIC's proprietary data set, and four of the five sub-references cited appear to pertain prinicipally to nuclear power plants.
- The valve rupture failure rate data in Appendix D of "INL CHEM '95" is also approximately 100 times greater than that specified in the current FRT. As summarized in Section 4.1, the analysis underlying Appendix D of "INL CHEM '95" considered data sources from multiple industries but its Category 1 data ("sources with actual failure data obtained from a detailed review of failure events") was generated from the nuclear industry.
- "OREDA '15" provides a valve failure data for "External leakage – Process medium" but as noted in section 4.1 judgement is required to characterize the severity of this leak and its relevance to valve "rupture".

In summary, there is a wide range of data associated with valve rupture of differing pedigrees and industry sources, and some of the higher failure rate frequencies appear to be associated with data originating principally from the nuclear power industry. The rupture rate of valve of 9×10^{-6} failures/year currently specified in the FRT appears to be conservative in comparison to an effective rate of zero in HSE FRED JUN'12", "RIVM BEVI '09", "LNE '09" and zero valve ruptures identified in "GRI LNG FRD '81"; the current rate also exactly matches the value contained in "PNL PSRP '82". It is recommended that the current valve rupture rate in the FRT be retained.

Of course one notable valve rupture incident that did occur in the LNG industry was in 1977 at an LNG plant in Arzew, Algeria. However that valve body that ruptured was constructed of cast aluminum, whereas the current practice is that valves in LNG service are constructed of stainless steel.[59]

Analysis of Valve Leak

Limited quantitative data of valve leak rates by hole size was found.

"RIVM BEVI '09" and "LNE '09" do not specify valve external leak rates.

"HSE FRED JUN'12" in its Item FR 1.2.1 "Valves" does not specify a valve rupture rate, but it does specify a 2×10^{-4} Spray Release Frequency failures/year for valve leaks.

- HSE cites its confidential Components Failure Rates publication in its derivation of the rates in Item FR 1.2.1 "Valves", which included "a comparison of 12 sources of failure rates derived elsewhere" and that the "values are for chlorine duty although the review included LPG, petrochemical, steam/water, nuclear and other data." It also lists 34 additional references.
- As summarized in Section 4.6, the project team associated 2×10^{-4} Spray Release Frequency failures/year rate with "Release from a hole with effective diameter of 2 mm", which the project team considered a conservative assignment.

- HSE's specified rate of 2 x 10^{-4} Spray Release failures/year frequency matches surprising well with the 4 x 10^{-4} leaks/year leak rate (of unidentified size) for LNG cryogenic valves identified in "AGA LNG EXP '79 and "GRI LNG FRD '81", as computed by this project's team (see Section 4.6).

The HCRD database provides one resource to evaluate valve leak frequencies for various hole sizes. As an illustration, Figures 11 and 12 provide some publicly-available estimates of valve total leak frequencies arising from the HCRD database as presented in "DNV FFG HCRD '13" and "IOGP 434-1"; if considered to represent 25 mm and 100 mm holes, respectively, then these estimated failure frequencies will tend to be higher than those in Appendixes D, E and F because of their larger hole size ranges. But these figures illustrate the sensitivity of estimated leak frequency results to hole size, valve size and valve type when considering information in the HCRD database.

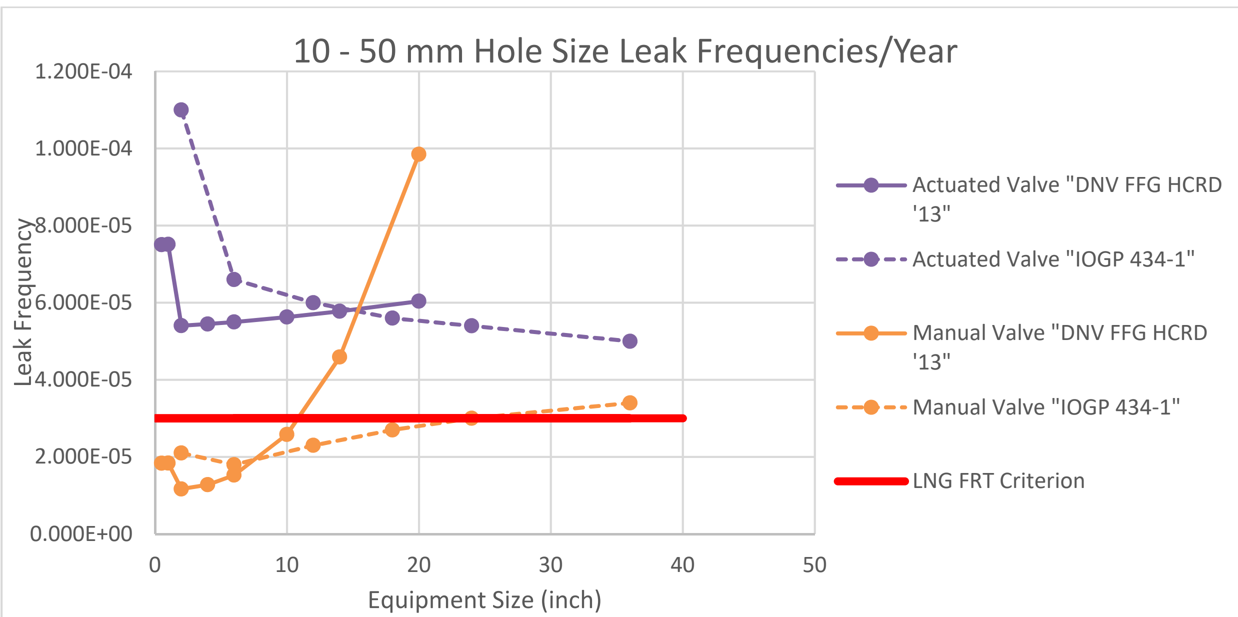


Figure 11: 10 – 50 mm Hole Size Valve Leak Rate Frequencies/Year in "DNV FFG HCRD '13" (Total Frequency) and "IOGP 434-1" (All Releases)

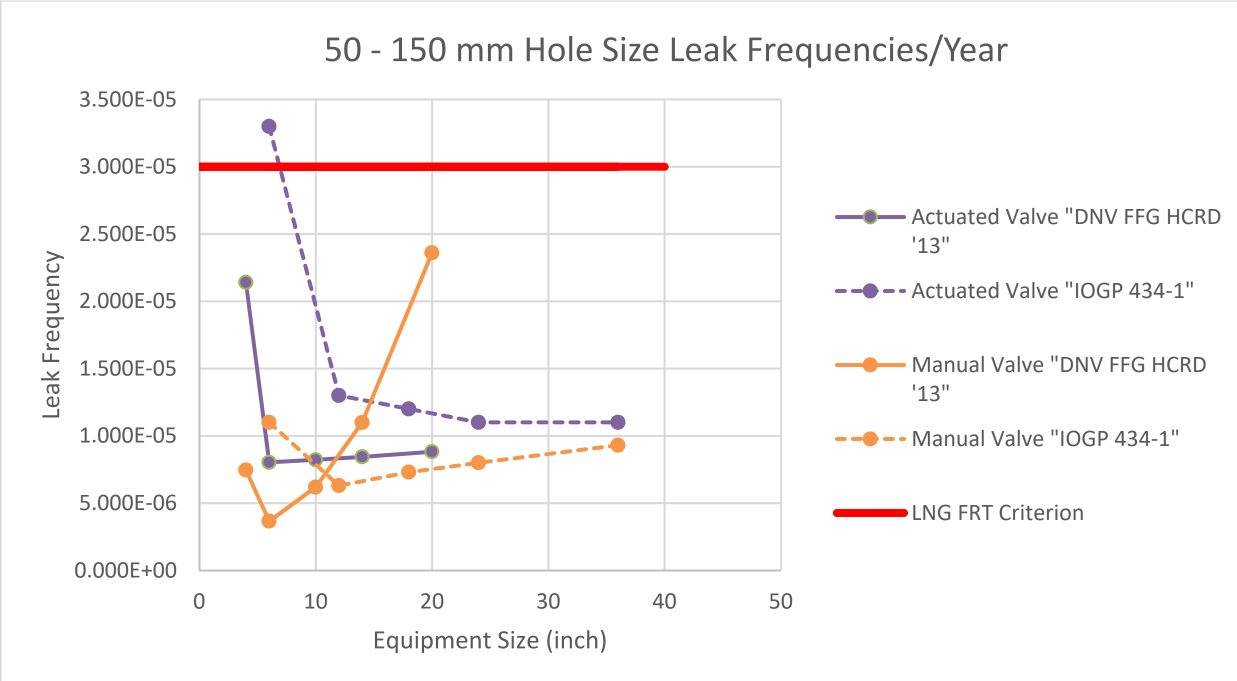


Figure 12: 50 – 150 mm Hole Size Valve Leak Rate Frequencies/Year in "DNV FFG HCRD '13" (Total Frequency) and "IOGP 434-1" (All Releases)

For PHMSA's and FERC's information and at their request, the project team provided estimates of valve leak rates for hole sizes of 2, 10, 25, 50 and 100 mm calculated using DNV's LEAK 3.3 software in Appendixes D, E and F. Observations from a review of these LEAK 3.3 software results in these Appendixes include:

- Estimated failure rates vary based on valve diameter and valve type (manual or automatic). This is consistent with the public information summarized in the above graphs.
- The failure frequency associated with a 2 mm hole in actuated valves is very close to the 2×10^{-4} Spray Release Frequency failures/year that the project team proposes to associate with a 2 mm hole size. The failure frequency associated with a 2 mm hole in manual valves is considerably less than 2×10^{-4}. Thus the LEAK 3.3 results for 2 mm hole results appear consistent with associating the 2×10^{-4} Spray Release Frequency failures/year rate with "Release from a hole with effective diameter of 2 mm" for the "worst case" valve type (i.e. actuated valves) in the HCRD.
- All failure frequencies calculated for either a 50 mm or 100 mm hole for any of the FRT's pipe diameter ranges, and for either manual or actuated valves, are less that the FRT criterion of 3×10^{-5} and therefore fall below the FRT's analysis threshold.
- Failure frequencies calculated for a 25 mm hole vary across the FRT's pipe diameter ranges, and for either manual or actuated valves, but for the "worst case" actuated valves the average is 3×10^{-5} failures/year. If PHMSA and FERC want to associate a failure rate to a 25 mm valve hole leak, then PHMSA and FERC might consider a 3×10^{-5} failure/year frequency rate if they want to use a rate based solely on the HCRD database and using the hole size range used in this analysis.

- Failure frequencies calculated for a 10 mm hole vary across the FRT's pipe diameter ranges, and for either manual or actuated valves, but for the "worst case" actuated valves the average is 2×10^{-4} failures/year. If PHMSA and FERC want to associate a failure rate to a 10 mm valve hole leak, then PHMSA and FERC might consider a 2×10^{-4} failure/year frequency rate if they want to use a rate based solely on the HCRD database and using the hole size range used in this analysis.

While the HCRD is very valuable, it does represents one data set. In comparison, HSE includes more than 35 citations in its References, Advice Note and Bibliography in its determination of its specifications in Item FR 1.2.2 "Valves".

The piping failure rate categories used in the FRT are consistent with those in Item FR 1.3 "Pipework" of "HSE FRED JUN'12" (with two small exceptions). For consistency, the project team recommends that PHMSA and FERC similarly apply for valves the specifications in Item FR 1.2.1 "Valves" of "HSE FRED JUN'12" and associate the Spray Release Frequency with a 2 mm hole size.

As an additional point of comparison, Table 1 (ref. p. 18) of "INL CHEM '95" cites average "leak" rates ranging from 3.22×10^{-6} failures/year to 3.48×10^{-6} failures/year for gate, ball and globe valves in the Idaho Chemical Processing Plant Failure Rate Database; the size of the leak is not characterized, and rupture rates are not provided in this database. But the rupture rate recommended below (i.e. retaining the FRT's current specification of 9×10^{-6} failures/year) also appears conservative in comparison to this reference.

<u>Recommendation:</u>

- PHMSA and FERC should consider retaining its current valve rupture rate of 9×10^{-6} failures/year, which exactly matches the value contained in "PNL PSRP '82". Some other leading failure rate references effectively assign valve rupture rate to zero, so a corollary recommendation is:
    - PHMSA and FERC should continue to re-assess the specified valve rupture rate of 9×10^{-6} failures/year if it considers applying this rate to any risk assessment methodologies other than the current FRT Criterion methodology.
- PHMSA and FERC should consider adding a valve leak rate of 2×10^{-4} failures/year as "Release from valve with a hole with effective diameter of 2mm (0.08 inch)".

6.7 Piping – Rupture of Expansion Joint

Section 4.7 summarizes that the FRT's current specification of 4×10^{-3} failures/year may perhaps be associated with the failure of an complete transfer line rather than an individual expansion joint component.

The only reference sources identified for expansion joint failure rates were more than 40 years old. For example, the failure rate of "Leak (serious) in post-accident situation, λ_o" for "Elbows, flanges, expansion joints (containment quality)" listed in Table A14.7 of "LEES'12" is from "the Rasmussen Report (AEC, 1975)" i.e. the WASH-1400 reactor safety study.

While "PNL PSRP '82" specifies 1 x 10^{-7} faults/hour (~1 x 10^{-3}/year) as "Expansion Joint Rupture", it refers to two sources:

- "SAI '75" specifies a mean "External Joint Ruptures" failure rate of 1 x 10^{-8}/hour (~1 x 10^{-4}/year).
- "WELKER '76" specifies a median "External leak or rupture" failure rate for an expansion joint of 2 x 10^{-6}/hour (~2 x 10^{-2}/year) with a Low rate of 1 x 10^{-8}/hour (~1 x 10^{-4}/year) and High rate of 1 x 10^{-5}/hour (~1 x 10^{-1}/year)."

Based on the above one could reasonably consider that PHMSA and FERC should specify the "SAI '75" rate of 1 x 10^{-4} faults/year rather than the "PNL PSRP '82" rate of 1 x 10^{-3}/year, since the underlying reference indicates that the rate used by PNL is for *rupture or leak*.

The "PNL ITRP '82" reference analyzes the failure rate of a Double Ply Expansion Joint assembly (with pressure detection system) in a FTA in its Table B.12 (see Appendix B), and calculated a failure rate of 2 x 10^{-9} faults/year, based on a single ply failure rate of 1 x 10^{-7} faults/hour and 1,500 hours/yr operation. If a pressure detection system is not present, then the failure rate based on the methodology in Table B.12 would be (1.5 x 10^{-4} faults/yr)^2 = ~2 x 10^{-8} faults/year.

If the failure rate for a single ply expansion joint is revised to 1 x 10^{-4}faults/year, then the failure rate of a double ply expansion joint is estimated as (1 x 10^{-4} faults/year)^2 = 1 x 10^{-8} faults/year, or comparable to the failure rates described in the prior paragraph when considering the "PNL ITRP '82". While the pedigree of even the base single ply failure rate of 1 x 10^{-4}faults/year for a single ply expansion joint is unclear, these calculations support an estimated failure rate of a double ply expansion joint well below the FRT's 3 x 10^{-5} criterion.

<u>Recommendation:</u>

- PHMSA and FERC should consider revising its rupture failure rate specification from 4 x 10^{-3}/year to 1 x 10^{-4}/year and clarify that it applies to Single Ply Expansion Joint. A corollary recommendation is:
    - PHMSA and FERC should consider reviewing this specification again in more detail if it specifies a Single Ply Expansion Joint rupture rate for any risk assessment methodologies other than the current FRT Criterion methodology.
- PHMSA and FERC should consider specifying a rupture failure rate specification of 1 x 10^{-8}/year for "Double Ply Expansion Joint" based on the above analysis

6.8 Piping – Failure (Rupture or Leak) of Gasket

The failure rate results identified in this analysis are substantially different than the "failure of gasket" failure rate that is specified in the current FRT.

The source references applied in this analysis for failure rates associated with flanges and gaskets are shown in Appendix C. Calculations for rupture rates in different scenario evaluations are shown for example in Framework Index #173 for all diameters.

<u>Analysis of Gasket Leak</u>

Limited quantitative data of gasket leak rates by hole size was found.

"RIVM BEVI '09" and "LNE '09" do not specify gasket or flange leak rates.

As summarized in Section 4.8, "HSE FRED JUN'12" in its Item FR 1.2.4 "Flanges and Gaskets" does specify a gasket failure rate, and hole sizes of 25 mm and 50 mm were associated in this analysis with those specifications.

In addition, the HCRD database provides one resource to evaluate flange leak frequencies for various hole sizes. Appendix L illustrates that the majority of the flanges in the HCRD database are compressed flanges, and many are also of Ring Type (RTJ) or Clamp (e.g. Grayloc) type. Figures 13 and 14 illustrate some publicly-available estimates of flange total leak frequencies based on the HCRD database as presented in "DNV FFG HCRD '13" and "IOGP 434-1"; if considered to represent 25 mm and 100 mm holes, respectively, then these failure estimated failure frequencies will tend to be higher than those in since the Appendixes D, E and F because of their larger hole size ranges. But these figures provide one indication of the sensitivity of the results to flange and hole size on leak frequency from information in the HCRD database.

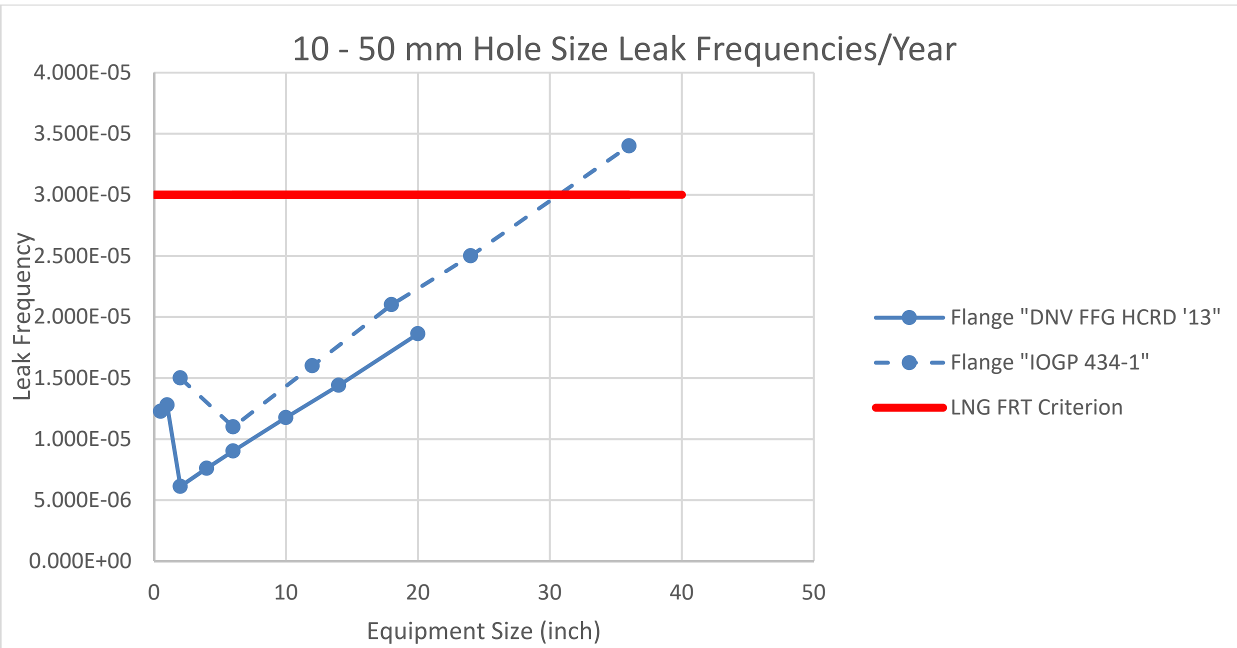


Figure 13: 10-50 mm Flange Leak Rate Frequencies/Year in "DNV FFG HCRD '13" (Total Frequency) and "IOGP 434-1" (All Releases)

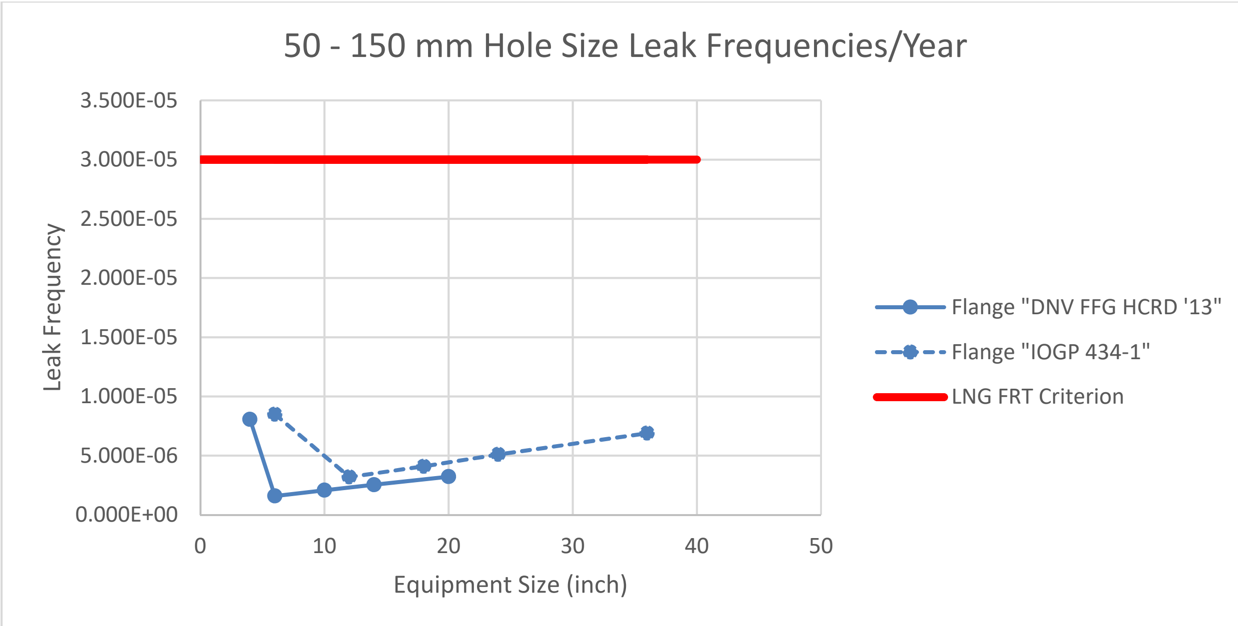


Fig. 14: 50-150 mm Flange Leak Rate Frequencies/Year in "DNV FFG HCRD '13" (Total Frequency) and "IOGP 434-1" (All Releases)

For PHMSA's and FERC's information and at their request, the project team provided estimates of flange leak rates for hole sizes of 2, 10, 25, 50 and 100 mm calculated using DNV's LEAK 3.3 software in Appendixes D, E and F. Calculated estimates of flange leak rates for the various analysis scenarios when all reference sources were considered are also provided in Appendixes D, E and F. See for example the results of index #368 for a 25mm hole and #369 for a 50 mm hole.

As described in Section 4.8 this analysis also considered the gasket leak rates specified in Item FR 1.2.4 "Flanges and Gaskets" of "HSE FRED JUN'12" , which lists 25 citations in its reference, advice note and bibliography. The failure rates specified in "HSE FRED JUN'12" and associated in this analysis with 25mm and 50mm leak hole sizes align well with the results shown in Appendixes D, E and F in index #368 (for 25mm hole) and #369 (for 50 mm hole). Therefore it is recommended that PHMSA and FERC consider incorporating the "HSE FRED JUN'12" leak rate data and assign the leak rate frequencies to the hole diameters identified in Section 4.8.

<u>Analysis of Gasket Rupture</u>

The leading failure rate references "HSE FRED JUN'12", "RIVM BEVI '09" and "LNE '09" do not specify a large-scale (i.e. full-bore or complete failure) rupture rate for gaskets or flanges:

- "RIVM BEVI '09" includes failure of connections with failure of the pipes, and does not separately define flange failure rate frequencies (e.g. ref. Module C pp. 30, 42-44).
- "HSE FRED JUN'12" specifically addresses flanges and gaskets in its Item FR 1.2.4 but does not specify a rupture rate.

Where gasket or flange rupture data was specified, the sources identified were 40+ years old and their pedigree appears to be from the nuclear power industry. For example, "SAI '75" cites a "Connection Flange Ruptures" rate of 1 x 10^{-8}/hour or 1 x 10^{-4}/year; "SAI '75" does not cite a specific source for its connection flange rupture data, but the 1975 WASH-1400 Reactor Safety Study is one of few process-related references in its list of twenty References.

For comparison, "DNV FFG HCRD '13" indicates on page 20 that the total failure frequency rate for a >150 mm (>6") hole to occur in a 6" (150 mm) flange is 6.852 x 10^{-6} - - i.e. which some could consider a full-bore rupture of a gasket/flange as defined on p. 9 of this reference. As noted in section 4.1, GTI concurs with DNV's comment in "DNV FFG HCRD '13" that there is considerable uncertainty related to using the HRCD data to estimate ruptures. Appendixes L and M illustrates the raw data in the HCRD database, and the limited basis for predicting flange (or other equipment) ruptures from HCRD data.

The "HSE FRED JUN'12" leak rate specification provides useful comparative information. This project team did not identify any engineering reasoning why a full-bore gasket rupture frequency (if specified) should exceed leak frequency (i.e. > 1 x 10^{-7} failures/year) specified in "HSE FRED JUN'12" that this analysis associated with a 50 mm hole. Therefore it is recommended that the FRT be clarified that "Failure of Gasket" does not refer to a full-bore or complete guillotine flange rupture.

Recommendation:

- PHMSA and FERC should consider revising the gasket failure rate specification as follows:
  - Add "Release of one segment of gasket as a hole with effective diameter of 25 mm (1-inch)" failure rate as 5 x 10^{-6} failures/year
  - Add "Release of a Spiral Wound Gasket as a hole with effective diameter of 50 mm (2-inch)" failure rate to 1 x 10^{-7} failures/year
  - Eliminate "Failure of Gasket" terminology.

6.9 Piping – By Diameter

The only LNG-specific (and cryogenic-specific) directly-observed piping failure rate data identified in this project analysis was that obtained from the combined results of "GRI LNG FRD '81" and "AGA LNG EXP '79" analysis of peak shaving plants, as summarized in Section 4.9. The project team's analysis of that data resulted in a rate of:

- 2 x 10^{-6} failures/meter-year (= 8 x 10^{-10} failures/foot-hour)

which compares favorably to PHMSA's current FRT specifications of:

- 2 x 10^{-6}, 5 x 10^{-6} or 7 x 10^{-7} specified failures/meter-year frequency rate if the hole represents "Release from a hole with effective diameter of 25mm (1 inch)" in piping size categories <2"d, 2"≤d<6" or 6"≤ d<12", respectively

Calculated failure rate results based on the various weighting scenarios considered in this analysis are presented in Appendixes D, E and F. Results can vary significantly depending on the weightings given to individual data sets or perceived relevancies. This is to be expected given the relatively large span of estimated failure rate data.

Table 20 and Figure 15 compare specified or actual rupture or guillotine failure frequencies from some key references.

	FRT Piping Diameter Category			
Reference	**2"≤d<6"**	**6"≤d<12"**	**12"≤d<20"**	**20"≤d<40"**
FRT Nominal Failure Rates "Piping" "Catastrophic Rupture"	5.00E-07	2.00E-07	7.00E-08	2.00E-08
"NFPA 59A '16" "Piping - aboveground" "Rupture"	3.00E-07	1.00E-07	1.00E-07	1.00E-07
"HSE FRED JUN'12" Item FR 1.3 "Pipework" "Guillotine"	5.00E-07	2.00E-07	7.00E-08	4.00E-08
"HSE FRED JUN'12" Item FR 3.1.2 "Above Ground Pipelines" "Rupture (>110mm diameter)" ("...applicable to natural gas above ground installations..." but see Item FR 3.1.2 for limitations)	6.50E-09	6.50E-09	6.50E-09	6.50E-09
"RIVM BEVI '09" "pipelines aboveground" "Rupture"	3.00E-07	1.00E-07	1.00E-07	1.00E-07
"RIVM BEVI '09" "underground transport pipelines" "Other pipelines" "Rupture"	5.00E-07	5.00E-07	5.00E-07	5.00E-07
"RIVM BEVI '09" "underground transport pipelines" "Pipeline complies with NEN 3650" "Rupture"	1.53E-07	1.53E-07	1.53E-07	1.53E-07
"RIVM BEVI '09" "underground transport pipelines" "Pipeline in pipe bay" "Rupture"	7.00E-09	7.00E-09	7.00E-09	7.00E-09
"LNE '09" "Underground pipeline" "Rupture"	2.80E-08	2.80E-08	2.80E-08	2.80E-08
"EGIG '15" Nat. Gas Trans. Onshore Pipelines "Rupture" (actual '70-'13)	1.33E-07	6.40E-08	3.75E-08	9.67E-09
"PHMSA NGT GTI '16" Nat. Gas Trans. Onshore Pipelines "Rupture" (actual '10-'15) as calculated in App. J	2.78E-08	3.23E-08	4.20E-08	2.96E-08
"PHMSA HL GTI '16" Haz. Liquid Trans. Onshore Pipelines "Rupture" (actual '10-'15) as calculated in App. K	3.95E-08	2.45E-08	2.01E-08	3.90E-08

Table 20: Comparison of Piping Rupture or Guillotine Failure Rates/m-yr, by FRT Piping Diameter Category (see text for approximations used to apply data to FRT's piping diameter categories, when necessary)

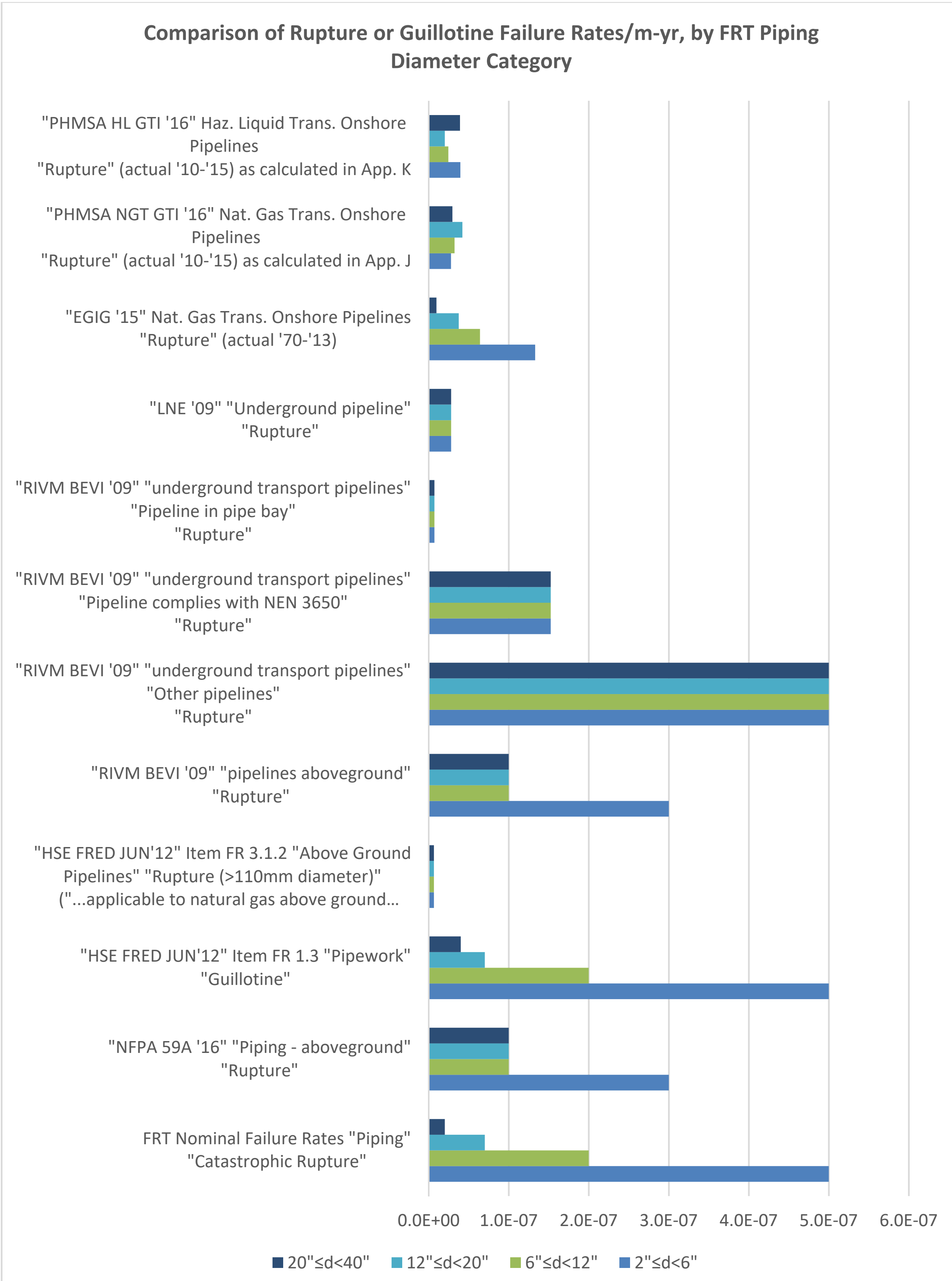


Figure 15: Comparison of Piping Rupture or Guillotine Failure Rates/m-yr, by FRT Piping Diameter Category (see text for approximations used to apply data to FRT's piping diameter categories, when necessary)

A review of Table 20 and Figure 15 indicates that the nominal piping rupture rate frequencies specified by the FRT are greater than the actual mean ruptures rates calculated in Appendix J and K for onshore natural gas transmission pipeline and hazardous liquid pipeline from PHMSA's pipeline incident database for 2010-2015 for all categories except 20"≤d<40". When considering this it may be beneficial to recall that external interference and corrosion are the leading cause of the pipeline ruptures; for example, Figure 5 illustrates that about 70% of EGIG's pipeline ruptures are due to external interference, and 59% of all EGIG's pipeline incidents are due to either external interference or corrosion (of carbon steel piping). In contrast LNG facilities are fenced-off and secured areas with minimal construction typically underway, and all cryogenic piping is typically made of stainless steel. Nevertheless, PHMSA and FERC could consider revising the failure rate for the 20"≤d<40" category from 2×10^{-8} failures/m-year to 4×10^{-8} failures/m-year and match the rate specified in "HSE FRED JUN'12".

Table 21 and Figure 16 compare specified or actual leak rates for holes of effective diameter of 20 or 25 mm (or some may so associate) from some public references, actual rates from PHMSA's natural gas and hazardous pipeline incidents database (2010-2015) as calculated in Appendix L and M, DNV's LEAK 3.3 software, and information publicly available in "DNV FFG HCRD '13". The following approximation was made solely in Table 21 and Figure 16 in order to illustrate this "DNV FFG HCRD '13" information (this approximation was not made in the database for this project) - - Total leak frequencies drawn from "DNV FFG HCRD '13" used these pipe sizes from the available data: 4"D for 2"≤d<6"; 10"D for 6"≤d<12"; and 14"D for 12"≤d<20". The "DNV FFG HCRD '15" data shown is based on the period October 1992 to March 2010, whereas the DNV LEAK 3.3 software includes HCRD data more recent than 2010.

	FRT Piping Diameter Category			
Reference	2"≤d<6"	6"≤d<12"	12"≤d<20"	20"≤d<40"
FRT Nominal Failure Rates "Piping" "Release from hole with effective diameter of 25 mm"	2.00E-06	7.00E-07	5.00E-07	4.00E-07
"HSE FRED JUN'12" Item FR 1.3 "Pipework" "25 mm diameter"	1.00E-06	7.00E-07	5.00E-07	4.00E-07
"HSE FRED JUN'12" Item FR 3.1.2 "Above Ground Pipelines" ("...applicable to natural gas above ground installations..." but see Item FR 3.1.2 for limitations) "Pin Hole (≤ 25 mm diameter)"	1.60E-07	1.60E-07	1.60E-07	1.60E-07
"RIVM BEVI '09" "underground transport pipelines" "Other pipelines" "Leak with an effective diameter of 20 mm"	1.50E-06	1.50E-06	1.50E-06	1.50E-06
"RIVM BEVI '09" "underground transport pipelines" "Pipeline complies with NEN 3650" "Leak with an effective diameter of 20 mm"	4.58E-07	4.58E-07	4.58E-07	4.58E-07
"RIVM BEVI '09" "underground transport pipelines" "Pipeline in pipe bay" "Leak with an effective diameter of 20 mm"	6.30E-08	6.30E-08	6.30E-08	6.30E-08
"DNV LEAK 3.3" "Process Pipe" "Total" Frequency (based on HCRD database) (15 - 35 mm) as calculated in this project	7.40E-06	3.37E-06	3.00E-06	2.93E-06
"DNV FFG HCRD '13" "Process Pipe" "Total" Frequency (based on HCRD database) (10 - 50 mm) (using 4"D, 10"D and 14"D available data)	7.46E-06	5.52E-06	5.40E-06	
"EGIG '15" Nat. Gas Trans. Onshore Pipelines (actual '70-'13) "Pinhole/crack" (Eff. Diam. ≤ 20 mm)	4.45E-07	2.80E-07	1.15E-07	4.37E-08

Table 21: Comparison of Failure Rates/m-yr for a Release from a Hole of Effective Diameter of 20 or 25 mm (or some may so associate), by FRT Piping Diameter Category (see text for approximations used to apply data to FRT's piping diameter categories, when necessary)

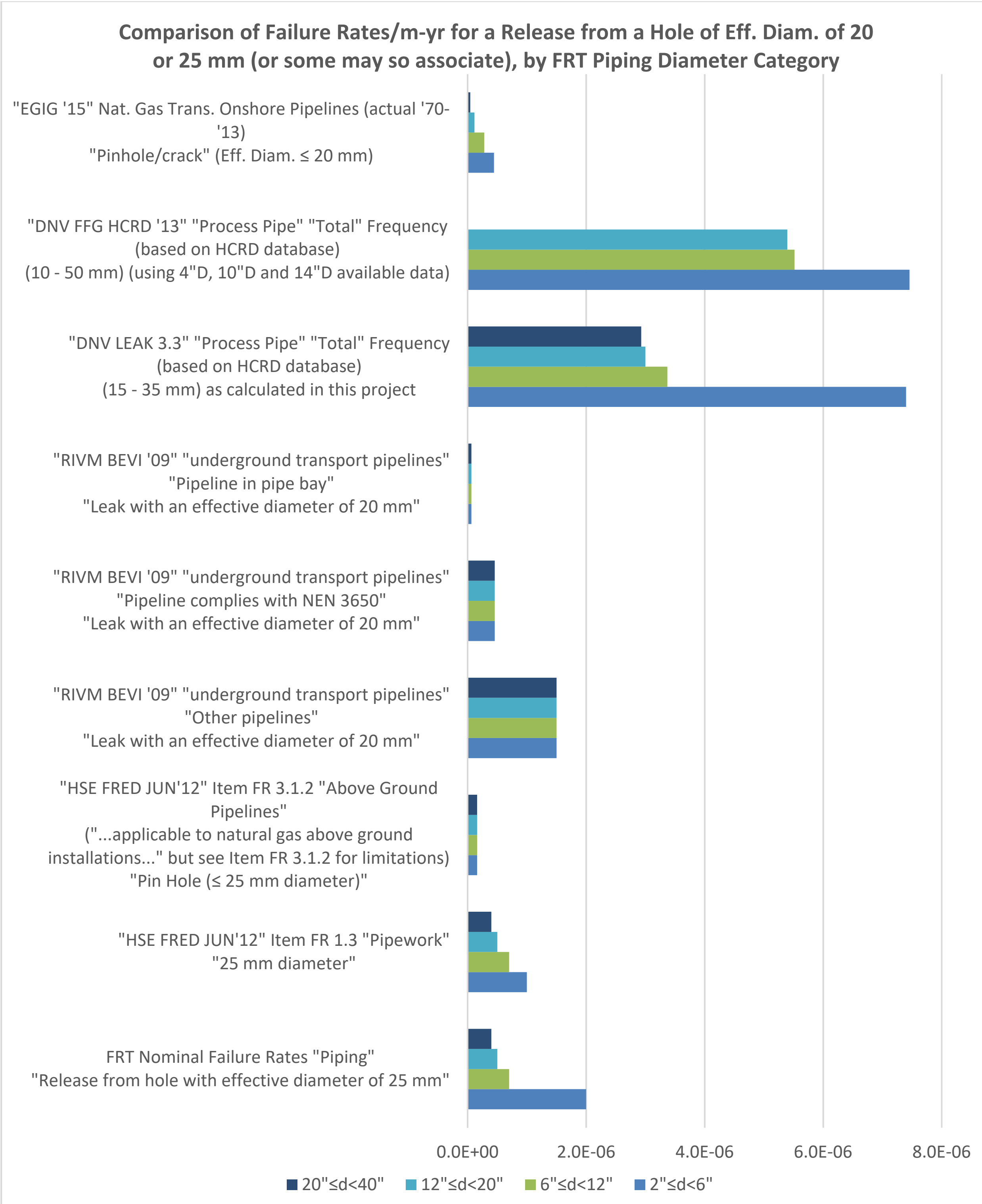


Figure 16: Comparison of Failure Rates/m-yr for a Release from a Hole of Effective Diameter of 20 or 25 mm (or some may so associate), by FRT Piping Diameter Category (see text for approximations used to apply data to FRT's piping diameter categories, when necessary)

Potential Reduction Factors for Transfer Piping and Inter-Unit Piping

PHMSA and FERC could consider specifying reduction factors for piping failure rate frequencies for transfer piping or for inter-unit piping that spans multiple individual units (examples would be rundown lines or rundown headers which span from liquefaction units to other liquefaction units).

Previous correspondence between FERC and PHMSA appears to support an assertion by some that the FRT may over-predict single accidental leakage sources for long lengths of large diameter solid welded piping.

On April 19, 2005 FERC sent a formal letter to DOT PHMSA Office of Pipeline Safety (OPS) requesting concurrence on their approach for determining single accidental leakage sources. The letter states that "the design construction, operation and historical integrity of all-welded large diameter marine transfer piping does not support a full pipe rupture without ignition as a credible accident scenario. Marine transfer systems are constructed of a relatively thick-walled seamless pipe, fully x-ray inspected during construction, and operated at moderate pressures (50 to 80 psi). Maximum flow rates are limited to the 10 to 12 hour cargo unloading period, a time when extra staff is on hand to monitor operations and detect abnormal events and quickly activate emergency shutdown systems. As a result, our determination of a single accidental leakage source for a marine transfer system is based on facility-specific review of piping and instrumentation diagrams to identify all small diameter attachments to the transfer piping for instrumentation, pressure relief, recirculation, etc. and any flanges that may be used at valves or other equipment, in order to determine the largest spill rate."[60]

On May 6, 2005, the OPS responded to FERC staff concurring with FERC's approach. In addition, OPS noted that "the OPS agrees that the design and construction of marine cargo transfer systems is very robust and that failure is unlikely under operational constraints. Moreover, the extensive security and safety oversights provided by the USGC before, during, and after transfer operations further reduces the risk that a spill could threaten life and property. There is no documented evidence of a catastrophic failure ever having occurred in either LNG operational experience or research. ..."[61]

In 2005, the majority of projects proposed were import terminals as the energy conditions in the US supported import rather than export of LNG. While the previous correspondence for marine transfer lines for import terminals is directly related to marine transfer lines for export terminals, that correspondence also can be applied to other large bore fully welded stainless steel piping with minimal connections and all of the other safeguards explicitly referenced.

"IOGP 434-1" specifies on p. 25 these reductions for inter-unit and transfer piping:

> The frequencies given in datasheet 1 for steel piping are, for onshore installations, intended to be applied within process units. For piping linking process units (inter-unit pipe) and piping to/from storage or loading facilities (transfer pipe), the following release frequency modification factors can be applied:
>
> - Inter-unit pipe: 0.9
> - Transfer pipe: 0.8
>
> These have been derived from detailed analysis of the causes of piping failure [5] and application to this analysis of judgemental modifications to account for the differences in inter-unit and transfer pipes [6].

where datasheet 1 refers to "Equipment Type: (1) Steel process pipes", and references [5] and [6] refer to confidential reports prepared by Technica or DNV Technica. The project team considers the rates specified by IOGP to be conservative reductions based on PHMSA's and FERC's correspondence in 2005 summarized above.

As an additional comparison, DNV comments on page 7 of "DNV FFG HCRD '13" that:

> A common aspect of uncertainty in QRA is associated with the frequency of inter-unit pipework / pipeline releases. It is widely accepted that the application of process pipework failure data will tend to give overly conservative values with respect to longer inter-unit pipe segments. This can be of particular relevance to LNG facilities, where the loading lines are often several kilometers long. In the course of conducting a large number of QRA studies, DNV has had the opportunity to draw on the experience of a range of operators. On the basis of these discussions, it is considered appropriate to apply a factor of 10 reductions in the pipe-work failure frequency for inter-unit piping. It should be recognised that this is an engineering judgement assumption, based on acknowledging operational experience that inter-unit pipework fails very rarely (in comparison to the process pipework within the main process areas). This revised basis can be of particular relevance to loading lines, although should not substitute for consideration of all potential loads (and hence potential frequency modification factors) that may apply to a particular facility, or particular loading line.

<u>Applicability of Generic Piping Failure Rate Data to LNG or Other Cryogenic Service</u>

The UK "HSE FRED JUN '12" does not specify any reductions in its Item #FR1.3 piping failure rates for LNG facilities.

Likewise, "IOGP 434-1":

- also bases its failure frequency rates for process piping (and other process equipment items) on the UK HRCD database (ref. p. 27); and
- states that its process release frequencies "can be used for process equipment on the topsides of offshore installations and for onshore facilities handling hydrocarbons…" and also states that "We therefore recommend use of the same frequencies for LNG installations as given in Section 2.0. A 50% reduction could be considered as a sensitivity but decisions based on this would need to be fully justified." (ref. p. 19).

<u>Comments re: Pipe-in-Pipe Piping (all types)</u>

The "HSE FRED JUN '12", "RIVM BEVI '09", "LNE '09", and "IOGP 434-1" references do not address Pipe-in-Pipe piping or other types of double-containment piping (including vacuum-jacketed piping).

A 2012 analysis by Cadwallader and Pinna of INL[62] reviewed the available operating experiences of double walled piping used in hazardous chemicals in different industries (including consideration of pressurized, vacuum and purge configurations) as part of the design considerations for the International Thermonuclear Experimental Reactor facility in France. They also identified very little available failure rate information for double containment piping, and recommended a Beta factor of 0.1 for a conceptual design level review:

> Literature searches were performed to identify operating experiences that would indicate failure rates of double containment piping. Despite the fact that double containment systems have been widely used in the chemical industry since the 1990s, very little

information was found in the literature. There is some qualitative information that industrial systems overall have performed very well. Two additional cases are described below. No data sets were found that could serve as a basis for a failure rate calculation. Therefore, either modeling or analyst judgment is needed to determine the reliability. Analyst judgment approaches vary in the risk literature from assuming independent piping to a conservative common-cause type approach of a 0.5 multiplier on the failure rate of single walled piping to account for the secondary containment pipe. …

A good approach to quantify the reliability of double containment piping where there can be temperature, vibration, or other effects, is to apply a Beta factor to account for the outer, non-independent pipe. The carrier pipe is given a multiplier of 0.01 to its leakage failure rate to account for the second, proximate-location pipe of the same material. Therefore, the external leak failure rate of the double containment pipe would be the carrier pipe leak failure rate multiplied by 0.01. If the outer pipe is a different, less strong material, then a Beta factor of 0.1 is recommended. This Beta approach was put forward early in the ITER international project and remains a valid approach today. Certainly some can argue that this approach is also conservative, that the outer pipe could function better than the Beta factor suggests, especially in view of the opportunity for constant monitoring of the pipe annulus. For early reliability studies on conceptual designs, this Beta factor approach is recommended for its simplicity and speed to address the double-walled piping issue.

For designs advanced past the conceptual design level, there will be enough design information to support a detailed analysis. The two pipes can either be modeled as a primary and standby component, as mentioned above, or an engineering assessment can be performed. A rigorous finite element analysis can be performed to determine if any common modes (pipe walls touching and transferring forces, vibration through spacers or centering rings) are affecting both pipes. A corrosion assessment can be performed for both pipes to determine if there is a high likelihood of corrosion pitting or breaches in either pipe. The reliability analyst can use these analysis results to estimate the "leak tightness" of the double containment system.

If the outer pipe is of a different material but provides as a passive independent layer of protection (IPL) from the external environment, then the minimum applicable Probability of Failure on Demand (PFD) could be considered as 1×10^{-2}, based on Table 6.3 of *Layer of Protection Analysis: Simplified Process Risk Assessment* (Edition 1) published by Center for Chemical Process Safety (CCPS) and Wiley in 2001; if this IPL configuration is considered an "inherently safe" design, then Table 6.3 of this reference identifies example PFDs from 1×10^{-2} to 1×10^{-6}.

Comments re: Pipe-in-Pipe LNG Piping in "PNL ITRP '82" (non Vacuum-Jacketed)

PNL in its "PNL ITRP '82" analysis of LNG Import Terminals used a FTA to assess the benefit of double pipe transfer line that "consists of two concentric stainless steel pipes with the inner line containing the LNG and the annular space being purged with nitrogen" (ref. p. 5.4). PNL estimated that "it would reduce the number of expected large releases from the transfer line from 1×10^{-3} per year to 2×10^{-7} per year. Failure of the expansion joints in the inner and outer lines would be the primary cause of failure" (ref. pp. 5.4-5.5). Details are shown in Table B.13 and Figure B.16 of "PNL ITRP '82" in Appendix I. This analysis was based on the outer pipe having the same integrity as the inner pipe (i.e. 2.5×10^{-6} faults/hour probability).

In summary, PNL predicted a 5,000 reduction in failure rate (i.e. a 0.0002 multiplier) for double containment piping, if the outer pipe has the same integrity as the inner pipe and there is a pressure monitoring system.

Comments re: Vacuum-Jacketed or Vacuum-Insulated Pipe-in-Pipe Piping

No failure rate data was found for vacuum-jacketed (also known as vacuum-insulated, e.g. VJ or VI) piping that is sometimes used in LNG facilties. The “HSE FRED JUN ‘12”, “RIVM BEVI ‘09”, “LNE ‘09”, and “IOGP 434-1” references do not address vacuum-jacketed piping.

For comparison, a predicted VJ pipe leak rate data of 1.8 x 10^{-12} failures/meter-hour (i.e. 1.6 x 10^{-8} failures/meter-year on continuous basis) was identified on p. 33 of the “INL VJ ‘10” reference, but it was for 250 DN (10”) and 300 DN (12”) diameter Schedule 20 (6.3 mm wall thickness) vacuum piping service (i.e. thinner than typical ANSI B31.3 process piping schedule and thickness used at LNG facilities). In addition, this rate was for a leak (not rupture) associated with small air leaks (to be overcome by the vacuum system) with no hole size characterization, and so this leak rate prediction was not included in any results calculated from the project database.

Comments re: Piping <2” and >40” in Diameter

Piping that is less than 2” does not need to be tracked by applicants, as per PHMSA’s answer to question #DS2 (see Appendix A). In addition, PHMSA requires “a minimum 2-inch hole should be considered at any location along any piping of 2 inches or larger diameter” as per the answer to question #DS3. Removing the category for piping <2” from the FRT would help simplify the FRT and clarify PHMSA’s communication about the FRT’s requirements with end-users.

The FRT currently does not specify failure rates for piping that is greater than 40”, although some facility designers want to consider piping > 40” in diameter. While the piping size categories in current FRT matches those in “HSE FRED JUN’12”, the average incident rates for natural gas transmission piping >41” diameter (to consider one data set available for large diameter piping in natural gas service) do not exceed and in general are significantly lower the average incident rates of piping 23” ≤ d < 41”, based on EGIG’s 1970-2013 data (see Fig. 5 in Section 4.9). Removing the 40” upper limit from the piping category from the FRT would help clarify PHMSA’s communication about the consideration of large-diameter piping to end-users.

Summary:

- The single LNG-specific and cryogenic-specific piping leak rate data point that is available (i.e. from “GRI LNG FRD ‘81”) aligns favorably with the piping failure rate frequencies in the current FRT.
- The piping failure rate frequencies in the current FRT are identical to the failure rates in Item #FR 1.3 “Pipework” on p. 47 of “HSE FRED JUN’12” (with only two small exceptions), and the “HSE FRED “JUN’12” specification document is a recognized international standard for failure rate frequencies. The basis of “HSE FRED JUN’12” specifications includes consideration of more than 40 references in its underlying analysis (a significant portion of which are confidential). PHMSA and FERC could consider revising the two exceptions so that all of the piping failure frequencies in the FRT directly match the failure rates in Item #FR 1.3 “Pipework” on p. 47 of “HSE FRED JUN’12”.

- The FRT currently provides a failure rate frequencies for piping < 2” in diameter and there may be an opportunity to simplify the FRT and enhance its consistency with PHMSA’s LNG Plant Requirements: Frequently Asked Questions webpage.
- The FRT currently provides no failure rate frequencies for piping > 40” in diameter, and there may be an opportunity to simplify the FRT and enhance communication with end-users.
- The FRT currently provides no specification for long transfer or inter-unit piping runs. It appears reasonable to consider some reductions on an application-specific basis, but no generalized reduction factors were identified for consideration for the FRT.
- The FRT currently provides no specification for pipe-in-pipe piping.
    - INL’s 2012 analysis of all types of double containment systems summarized that:
        - “The carrier pipe is given a multiplier of 0.01 to its leakage rate to account for the second, proximate-location pipe of the same material.”
        - “If the outer pipe is a different, less strong material, then a Beta factor of 0.1 is recommended.”
    - “PNL ITRP ‘82” calculated a 0.0002 multiplier in its analysis in Table B.13 to account for the second, proximate-location pipe of the same material using nitrogen (not vacuum) in the annular space in LNG service and with a pressure monitoring system.
    - The CCPS reference *Layer of Protection Analysis: Simplified Process Risk Assessment* in its Table 6.3 indicates a minimum 0.1 multiplier as an example for any IPL, including “inherently safe” designs.

<u>Recommendations:</u>

PHMSA and FERC should consider retaining their current failure rate frequencies for piping, with these modifications:

- PHMSA and FERC should consider evaluating if the requirement that “a minimum 2-inch hole should be considered at any location along any piping of 2 inches or larger diameter” should be maintained.
- PHMSA and FERC should consider eliminating the current category of d < 2” in the FRT, if they intend to maintain the requirement that “a minimum 2-inch hole should be considered at any location along any piping of 2 inches or larger diameter” and that piping less than 2” in diameter “does not need to be tracked by applicants”.
- PHMSA and FERC should consider revising the current category of (20” ≤ d < 40”) to be (20” ≤ d).
- PHMSA and FERC should consider applying modification factors to its failure frequency rates for pipe-in-pipe piping as follows:
    - Multiplier of 0.01 if outer and inner pipes are of the same material and schedule.
    - Multiplier of 0.10 if outer and inner pipes are not of the same material and schedule, and outer pipe is made of carbon steel.

In addition:

- PHMSA and FERC may want to consider revising the two small exceptions to the failure rates in Item #FR 1.3 “Pipework” in “HSE FRED JUN’12” so that all of the piping failure rate frequencies in the FRT directly match those in HSE FRED JUN’12”.
- PHMSA and FERC may want to consider applying modification factors to inter-unit piping between process units and to piping to/from storage or loading facilities (transfer pipe).

7. Gap Analysis of FRT and Failure Rate Data

7.1 Age of Available Relevant Failure Rate Data

Unfortunately much equipment failure rate data is dated, but by necessity continues to be used. For example, a review by Beerens, Post, and Uijt de Haag of RIVM in 2006 noted that:

> "The accuracy of the calculations is determined by the quality of the data used. To use QRA methods for land-use planning, it is of great importance that the results are standardized using reliable data. However, the set of available failure frequencies is nowadays not up-to-date anymore, not only in the Netherlands but all over Europe and in fact worldwide. Thus, there is a necessity for reviewing and updating the failure rate frequencies defined in the guidebooks, like the Purple Book, for a number of standard scenarios and installations."

and illustrated this dependency in Figure 17[63] below (modified below in this report in blue font to reflect that the "RIVM BEVI '09" superceded the most recent edition of the TNO Purple Book "TNO PURPLE '05").

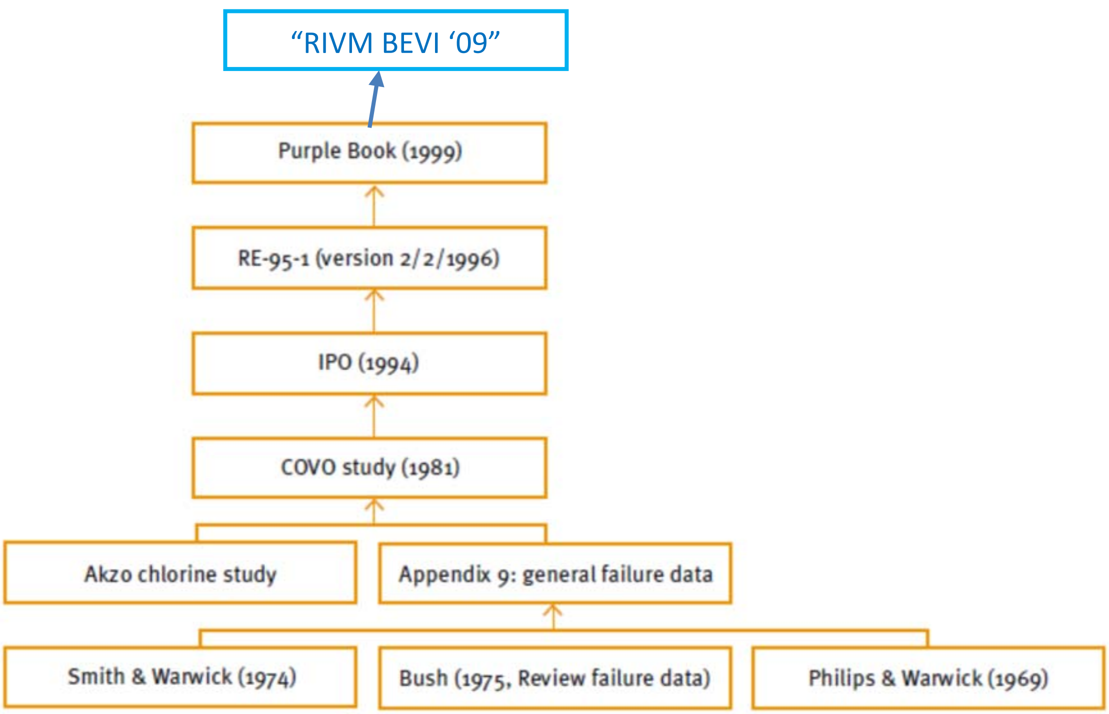


Figure 17: History of the Failure Frequencies used in The Netherlands for Pressure Vessels

7.2 Inability to See Some Underlying Data

The "HSE FRED JUN'12" is one primary failure rate reference document in use globally, but many of the reference sources cited are confidential or internal reports. For example, 60-70% of the citations identified in items 1.2.3, 1.2.4 and 1.3 ("Hoses and Couplings", "Flanges and Gaskets", and "Pipework") are marked as confidential or internal reports.

7.3 Non-Uniform Nomenclature

There can be significant variations in the definitions, regimes and uncertainty of failure rate data, as is well summarized by Dr. Sam Mannan in Appendix 14 of "LEES '12". But as one illustration of some of the variations in piping failure rate data, there is:

- Lack of uniformity in piping diameter size categories
- Lack of uniformity regarding hole size category definitions (including definition of rupture), both in how the data is captured and how the data is sometimes applied (e.g. see Table 2)
- Lack of uniformity in scope of components included with the pipe failure data, e.g.:
    - "HSE FRED JUN'12" excludes valves and flanges, and differentiates process Pipework from Above Ground Pipeline
    - "RIVM BEVI 09" (ref. p. 42 of "Module C) "apply to the pipeline with connections, such as flanges, welds and valves." and makes "no distinction is made between process pipes or transport pipes, the materials from which a pipeline is made, the presence of cladding, the design pressure of a pipeline or its location on a pipe bridge."

7.4 Use of Predicted Rather than Observed Failure Rates

Many past and some recent estimates of LNG equipment failures are predictions based on FTA or other techniques (e.g. for comparing types of atmospheric storage tanks or new types of LNG equipment), because relatively few catastrophic failures or major leak incidents of LNG facilities have occurred, and very limited cryogenic or LNG-specific failure rate data is available or has been derived. The favorable safety record is of course a very good thing.

7.5 Very Limited Cryogenic or LNG Equipment Failure Rate Data

This review identified very little statistical leak or rupture failure rate data specifically for LNG and cryogenic equipment. Certainly more publicly-available equipment leak or rupture failure rate data that directly originates from the LNG and cryogenic industry is needed in order to help inform regulatory agencies. Sufficient operating hours must obviously also be available to support the derivation of failure rates, which in some cases are quite low.

The last major survey of equipment failure rate data specific to U.S. LNG plants was completed in 1981 and a number of LNG plant design practices have changed since (e.g. use of in-tank vs. external pumps, and limited applications of expansion joints). It was "the opinion of GRI that the failure rate data base should be periodically updated, at about 5-year intervals" as stated in "GRI FRD '81", but unfortunately no additional industry or federal funding was made available for this purpose since the 1981 analysis was completed.

7.6 Relevancy of Available Failure Rate Data to LNG

This analysis confirmed that much of the generic failure rate data in the FRT is derived from non-cryogenic and non-LNG facilities. Factors sometimes cited by those who favor specifying failure rate frequencies for LNG equipment and piping different from generic failure rate data can include that LNG facilities:

- are highly-protected and typically less likely to experience external interference, since all LNG plant piping is essentially "inside the fence" with well-documented pipe routing drawings, trained contractors and typically few major construction projects underway.
- are typically located on well-positioned-and-graded sites with above-ground piping, with design consideration for 100-year and other extreme weather events, so that ground movement issues are less likely to occur at LNG facilities.
- are serviced by well-trained personnel with established operating procedures who are unlikely to make hot tap errors or other incidents in comparison to exposed natural gas pipelines.
- typically contain a significant amount of stainless steel piping and vacuum-jacketed piping, and thus less susceptible to the general galvanic corrosion that can dominate the cause of pinhole/crack data in carbon steel piping.
- are sometimes located inland, in comparison to failure rate data derived from off-shore oil and gas operations in marine salt spray environment (all LNG terminals are of course located in a marine salt spray environment).
- can contain inert fluids in their piping and equipment, in comparison to more severe service conditions at some oil and gas or chemical process industry sites.
- may have fewer flanges per unit length of piping than offshore platforms (that can average 7 m (23 ft) of pipe for each flange[64]), and thus less susceptibility to failures arising from from weldment issues, insulation joint corrosion initiation points, etc.

and opposing factors can include:

- may have greater condensation potential than ambient temperature piping, which could increase galvanic corrosion or Stress Corrosion Cracking.
- may have Stress Corrosion Cracking of stainless steel piping if exposed to sea water.
- may have shorter piping run lengths and more welds/spool length than natural gas or hazardous liquid transmission pipelines, which could yield higher failure rates/meter-year in comparison.
- may have less onerous regulatory requirements for UK onshore vs. offshore loactions, as noted by DNV on p. 6 of "DNV FFG HCRD '13".

Nevertheless FERC's and PHMSA's consideration of the failure rate sources referenced in their derivation of the FRT, along with those considered in this report, appears to be consistent with other leading global authorities, since these sources appear to comprise the best available data:

- The UK HSE's "HSE FRED JUN'12" specification document does not make any special exceptions for LNG or other cryogenic facilities.
    - Item FR 1.1.2.1 specifically defines failure rates for "LNG Refrigerated Vessels".

- Item FR 1.3 defines failure rates for "Pipework" and cites 44 references, which include one confidential analysis of pipework associated with bulk storage of liquid oxygen and two gas terminal studies.
- Item FR 1.1.3 defines failure rates for "Pressure Vessels" and in describing their derivation note 44 implies that cryogenic pressure vessels should have a *higher* failure rate:

> The cold catastrophic and hole failure rates are taken from the MHAU handbook (now archived). These are derived in the Chlorine Siting Policy Colloquium and are applicable to chlorine pressure vessels in a typical water treatment plant. Although they are not applicable to all types of pressure vessels the values are a good starting point when trying to derive failure rates for vessels in other applications. The value chosen for catastrophic failure should normally be 2 chances per million (cpm), assuming that the vessel conforms to BS5500 or an equivalent standard and that there is good compliance with the HSW etc. act (1974), unless there are site-specific factors indicating that a higher rate is appropriate (e.g. semi refrigerated vessels [cryogenic pressure vessels]).

- IOGP's comments regarding the applicability of its recommendations include this excerpt from p. 19 of "IOGP 434-1": "We therefore recommend use of the same frequencies for LNG installations as given in Section 2.0" [i.e. for other oil & gas facilities]. "A 50% reduction could be considered as a sensitivity but decisions based on this would need to be fully justified".
- ISO Technical Specification ISO/TS16901[65] *Guidance on performing risk assessment in the design of onshore LNG installations including the ship/shore interface* in its section A.3 lists the many of the same references considered in this analysis and concludes "It should be noted that there are no publicly available incident databases for LNG plants that can be available to derive leak frequencies and therefore should rely on the above more general data."
- The Dutch government in "RIVM BEVI '09" document stipulates on page 3 of its Introduction that the "SAFETI-NL" calculation package by DNV London is "stipulated for carrying out the QRA calculations for establishments that fall under the Bevi". "SAFETI-NL" contains equipment failure rate data based apparently in large part on an analysis of the UK HCRD.
- EIGA in its guidance document 60/15[66] to apply SEVESO Directives to cryogenic industrial gas facilities in Europe highlights on p. 21 that a standardized version of DNV's PHAST/Risk software, named "SAFETI-NL" must be used in the Netherlands.
- Singapore requires the use of "HSE FRED JUN'12" for Fixed Installations in its *QRA Technical Guidance Manual* issued August 2016.

7.7 Gaps in Current FRT Categories

Potential gaps in the FRT were identified as part of this project. The project team considered a large number of new potential component categories (as summarized in Appendix C), and developed the recommendations in Section 6. Gaps that are proposed to be filled by the recommendations from this research are:

- Definition of valve leak rate hole sizes
- Definition of gasket leak rate hole sizes
- Inclusion of double ply expansion joint and clarification of single ply expansion joint
- Inclusion of pipe-in-pipe piping

Significant gaps in available failure rate data exist in almost every category of the current FRT. Those categories with some of the largest apparant gaps include:

- Cryogenic/LNG piping
- Cryogenic/LNG valves, expansion joints and gaskets
- Cryogenic/LNG transfer arms and hoses
- Cryogenic/LNG atmospheric storage containers
- Cryogenic/LNG pressure vessels

8. Summary and Recommendations

8.1 Summary and Recommendations Regarding FRT Criterion

A summary of the review in Section 2 of the FRT Criterion of 3 x 10^{-5} failures per year is:

- The project team confirmed that failure frequency estimates of 3 x 10^{-5} to 5 x 10^{-5} associated with the tank liquid outlet line are contained in the historical references, and its observations in Section 2.3 also included that:
  - The 3 x 10^{-5} failures per year criterion refers to an estimated failure rate for an equipment component failure, and not the resulting level of risk to society or an individual as is analyzed in some other risk assessment methodologies.
  - The criterion appears to be derived from the failure rate associated with the failure of one of the most critical plant components, i.e. the LNG container liquid withdrawal line. The failure rate criteria associated with the failure of line connection penetrations to the primary container may or may not set an equivalent risk level required for all other equipment component failure rates.
  - The 3 x 10^{-5} failures per year criterion appears to be associated with the failure rate of an LNG container liquid withdrawal line isolated with an internal shutoff valve, while US 49 CFR Part 193 also permits evaluation of events with other consequences such as the nearly complete emptying of the LNG container.
  - While for example the failure rates in the FRT for process piping exactly match HSE's FRED document (with two small exceptions), the FRT's threshold criteria methodology appears to be a somewhat unique risk assessment methodology.
  - A risk assessment prepared in 1975 by Science Applications Inc. for the Western LNG Terminal Company for a LNG terminal proposed for Oxnard, CA also prepared a number of FTAs and estimated the probability of a "Leak Occurs in Storage Tank or Tank Outlet" as 1 x 10^{-6} failures/year and a "Leak Occurs in Outlet of Tank" as 9.8 x 10^{-11} failures/year (when the isolation systems were considered).
- No direct analysis was made to compare the current FRT criterion of 3 x 10^{-5} to other regulated risk criteria in the U.S., since such an analysis of the risks to individuals and society of applying the FRT's methodology and criterion to vaporization, process, or LNG transfer components versus the risks associated with failure of a primary LNG container outlet line was beyond the scope of this analysis. This analysis may include a comparison of a 1-hour spill versus a complete loss of containment.

Recommendations arising from this review pertaining to the FRT Criterion are:

- No direct basis was identified to propose revising current the FRT Criterion of 3 x 10^{-5}, for the reason identified in the prior bullet above. Therefore it is recommended to retain the FRT Criterion of 3 x 10^{-5}.
- FERC and PHMSA should further consider whether methodologies other than the current FRT criterion methodology would be suitable for defining a SALS for impoundment areas serving only vaporization, process, or LNG transfer areas. Others have also recommended reviews of risk methodology assessment practices for LNG facilities in the

U.S., including at the federal level.[67,68]

8.2 Summary and Recommendations Regarding FRT Failure Rates and Categories

Appendix B concisely summarizes the specific recommendations for the FRT developed in this research for FERC's and PHMSA's consideration. Detailed recommendations are provided at the ends of Sections 6.2 – 6.9. A summary of key findings and recommendations related to the FRT's failure rates and its categories is:

- The leak and guillotine rupture failure rates specified for piping in the FRT directly match those in HSE's FRED guidance document (with only two small exceptions). The guillotine rupture failure rates specified for piping in the FRT are slightly less than, or greater than, the guillotine rupture failure rates specified in "RIVM BEVI '09" (depending on pipe diameter), and also appear reasonable with compared to the actual rupture rates observed in PHMSA's onshore natural gas and hazardous liquid pipeline database (2010-2015). The single actual data point for LNG piping leak rates identified in this analysis (from the 1981 survey of LNG peak shaving plants) also matches up favorably with the FRT's current specifications for piping. It is recommended to consider retaining the current piping failure rate specifications in the FRT, but to also consider eliminating the smallest piping size category (d < 2") and the current 40"D maximum limit of the largest piping size category (in order to enhance clarity to end-users of the FRT).
- The FRT currently does not address pipe-in-pipe piping such as the vacuum-jacketed piping that is sometimes used in LNG facilities. It is recommended to consider specifying failure rate reduction factors of 0.01 and 0.1 to modify piping failure rates when one of either two different types of pipe-in-piping is used. These reduction factors are based on a review of a 1982 analyses by Pacific Northwest Laboratory (PNL), a 2012 analysis of double containment piping by Idaho National Laboratory, and a relevant Center for Chemical Process Safety reference.
- The FRT currently does not address potential reductions in piping failure rates for long transfer lines or inter-unit piping as commonly exist in LNG terminals. Some relevant information was identified for PHMSA's and FERC's review and future consideration on a generalized basis, beyond those engineering analyses submitted for FERC's and PHMSA's consideration on a case-by-case project application basis.
- The leak and guillotine rupture failure rates for LNG transfer hoses and arms specified in the FRT were compared to other references in this study, and also to results of recent tests in Europe and other developments. There are significant technology developments underway on LNG transfer hoses and arms for both ships and trucks (trailers and trailer-mounted ISO containers). This equipment category was identified as an important watch area for PHMSA and FERC to seek new failure rate data in the future, because for example results of crush and fatigue tests on cryogenic hoses in Europe in 2016 indicates that the truck hose leak rate specified in the FRT may be about 100 times too conservative, and also that a guillotine rupture of a truck transfer hose may not be a credible event. However, at the present time it is recommended that: 1) if FERC and PHMSA want to retain the current basis of "Failures per year of operation", then they

may consider making no changes to the FRT's specification; and 2) that PHMSA and FERC review this new cryogenic test data and consider removing the rupture frequency specifically for multi-composite hoses. If they want to consider changing the FRT's basis of specification from "Failures per year of operation" to "Failures per hour of operation", then they could consider applying the failure frequency rates specified by Dutch and Flemish regulators. Sections 6.4 and 6.5 provide more details.

- The failure rate for valves specified in the FRT was compared to other references in this study. It is recommended to retain the FRT's currently-specified rupture rate for valves, but to also add a leak rate consistent with that specified in HSE's FRED guidance Item FR 1.2.1 for valves, using the 2 mm hole size considered in Section 4.6 of this report.
- The failure rate for gaskets (i.e. flanges) specified in the FRT was compared to other references in this study. It is recommended to consider eliminating the "Failure of Gasket" terminology and specify failure rates consistent with those specified in HSE's FRED guidance item FR 1.2.4 for gaskets (and flanges), using the 25 mm and 50 mm hole sizes considered in Sections 4.8 of this report.
- The failure rate for expansion joints specified in the FRT was compared to other references in this study and to underlying references. It is recommended to consider revising the specified failure rate from 4×10^{-3} to 1×10^{-4} failures/year in order to better align it with the 1975 risk analysis performed by Science Applications Inc. (excerpts shown in Appendix I) and to also clarify that it applies to single ply expansion joint; both the existing and recommended rates are greater than the 3×10^{-5} FRT threshold criterion. In addition, it is recommended to specify a rupture failure rate for double ply expansion joints.
- The guillotine rupture failure rate specified for "Process Vessels, Distillation Columns, Heat Exchangers and Condensers" in the FRT aligns well with the rate specified for Pressure Vessels in HSE's FRED guidance document and also with the rates specified by Dutch and Flemish regulators for Process Vessels. The 10 mm hole leak failure rate specified in the FRT also aligns well with the 10 mm hole leak failure rates specified by Dutch and Flemish regulators for process vessels, and is more conservative than than the 10 mm hole leak failure rates specified for Pressure Vessels in HSE's FRED guidance document. This research also reviewed and summarized the lower failure rates assigned to Pressure (Storage) Vessels (vs. Process Vessels) by Dutch and Flemish regulators than the rates specified by the UK HSE's FRED guidance for document Pressure (Storage) Vessels, but it was recommended that FRT retain its more conservative basis and not specify lower failure rates specifically for Pressure (Storage) Vessels as different than those rates for Process Vessels. This research also explored, accumulated and analyzed for PHMSA and FERC a number of potential equipment subcategories within this overall category. In summary it was recommended that the FRT retain this existing category name and its currently-specified rupture and leak failure rates.
- The FRT currently specifies leak and rupture rates for cryogenic atmospheric storage tanks. For determination of single accidental leakage sources for process facilities this information does not appear to be relevant because the Design Spill for LNG tanks (i.e. containers in NFPA 59A) is already specified in Table 2.2.3.5 of the NFPA 59A (2001 edition) specified by US 49 CFR Part 193. However, if DOT allows for design spills to be selected using a failure rate or risk based approach (e.g., NFPA 59A 2016 edition)

then this information may be relevant. Therefore, it is recommended that PHMSA consider eliminating this category or clarify the use of this information for single accidental leakage sources in impounding areas serving only vaporization, process or LNG transfer areas.

8.3 Recommendations Regarding Subsequent Research and Related Efforts

Recommendations regarding subsequent research and related efforts are:

- PHMSA and FERC should consider funding research to conduct a new survey of LNG facilites in the US, in order to update and expand upon the most recent survey study completed in 1981 ("GRI FRD '81"). The U.S. is in a unique position since many LNG facilities are older facilities built in the 1960s and 1970s. A new survey can potentially leverage this historical basis that represents a significant number of operational hours. In addition, many of the U.S. LNG facilities are in peak shaving service and utilize smaller piping and components than the many international LNG facilities in export/import service; the leak and failure rate data that can be generated or estimated from these facilities would be especially relevant to peak shaving plants (both new or upgrades), bunkering facilties that may fall under FERC's and PHMSA's jurisdictions, in addition to the many export terminal applications that FERC is currently reviewing.
- PHMSA and FERC should consider supporting the coordination of any new industry-government consortium efforts to create a national database of information related to the in-service performance of LNG piping and components. This effort can build upon the experience of the Plastic Pipe Database Consortium (PPDC), but should incorporate appropriately-defined nomenclature and should report both incidents and total populations as well as age, type and other relevant details defined by the consortium.

9. Summary of Project Final Financial Contributions

The financial contributions to the project were consistent with contract #DTPH56-15-T-00008, and no discrepancies or variances in contributions occurred.

Appendix A: PHMSA LNG Plant Requirements FAQ - Design Spill Determination

The information that PHMSA provides related to (DS) Design Spill Determination on its Frequently Asked Questions webpage (http://primis.phmsa.dot.gov/lng/faqs.htm) is copied below (valid as of the date of this report and last revised on 12/7/15). That webpage also provides other FAQs available in the categories of: (G) General; (D) Design; and (H) Hazards and Hazards Modeling.

DS1. PHMSA reviews the design criteria for design spills on a case-by-case basis to determine compliance with Part 193. What information is required to assist PHMSA in its determination of the design spill criteria acceptable for use?

Applicants must provide a piping and equipment inventory table of LNG plant components in hazardous or flammable fluid service. The piping and equipment inventory table should be submitted in Excel (*.XL*) format. Separate tabs or lists should be used for each type of hazardous fluid, as well as a separate tab or list to present all of the final design spill selections.

The table should include the following information:

a. Line segment or component number to identify potential design spill;
b. Hazardous fluid service (LNG, natural gas, refrigerants (such as ammonia, propane, ethane, mixed refrigerant), natural gas liquids or gas condensate, hydrogen sulfide, benzene, etc.) for each component;
c. General plant area or service (e.g. liquefaction train, refrigerant storage, marine area, etc.), unless the entire project is confined to one area;
d. Unit plot plan drawing number reference(s) for each component;
e. Beginning point location (e.g., exchanger outlet flange) for each line;
f. Ending point location (e.g., pump suction nozzle) for each line;
g. P&IDs and drawing number reference(s) for each component;
h. Piping line designation or equipment tag number on P&ID;
i. Pipe diameter or pipe size, volume of container, or size of equipment;
j. Length of piping (feet and meters); or number of components (each);
k. Maximum connection diameter in the piping segment;
l. Failure type or mode selected from the failure rate table;
m. Corresponding nominal failure rates per meter or unit;
n. Calculated failure rate based on pipe length or number of units and failure rates per meter or unit listed in the failure rate table;
o. Comparison of calculated failure rate to a failure rate criterion of 3x10-5 failures per year;
p. Process or storage conditions (e.g., fluid phase (liquid or vapor); density (lb/ft3); pressure (psig); temperature (°F); flow rate, (lb/hr); composition of mixed refrigerants, NGL/Condensates, acid gas);
q. Process flow diagram and corresponding heat and material balance stream number;
r. Heat and material design case (e.g., rich, lean, average, etc.);
s. Calculated equivalent hole size based on failure modes listed in the failure rate table; and
t. Calculated design spill flow rates.
u. Design spills selected with release duration, de-inventory duration, height, direction, orientation, rainout percentage, flashing and jetting vapor mass flow rate, pool vaporization mass flow rate, and total vapor mass flow rate

DS2. What sorts of pipe, equipment, and containers should be included on the piping and equipment inventory table?

Components that should be considered to fail in the analysis for determination of the single accidental leakage source are those containing hazardous or flammable fluids and are listed on the Failure Rate Table. The table must include pipe of 2 inch diameter and larger size, valves, gaskets, expansion joints, truck transfer hoses, truck transfer arms, ship transfer arms, pumps, compressors, process vessels, columns, heat exchangers, condensers, and storage tanks.

DS3. 49 CFR 193 requires that design spills for an LNG plant be selected according to NFPA 59A-2001 Paragraph 2.2.3.5. NFPA 59A requires the evaluation of accidental flow from "any single accidental leakage source" (SALS) but does not define this term. How should I select SALS events in an LNG plant?

For piping and equipment that handle LNG, flammable refrigerants, toxic components, or any other hazardous fluid, release sources may be chosen using the following guidelines. The SALS selection methodology is applied to determine the maximum hole sizes of interest for the most significant releases of each hazardous fluid in each portion of the LNG plant. (The SALS selections are one component of design spill definition. Please refer to other FAQs for additional design spill definition topics.)

A. For all piping and equipment (including transfer hoses and arms), the failure rate table should be applied to determine if the 3 x 10-5 per year failure rate criterion is equaled or exceeded; and,
B. For all piping, the failure rate table is applied to a piping segment (i.e., length of pipe) and the hole size is chosen based on equaling or exceeding the 3 x 10-5 per year failure rate criterion. The following rules should be applied to piping segments:
    1. Piping segments should be selected to begin and end at pieces of equipment and include all tees, loops, and branches; and
    2. A principle to be applied for piping segment begin/end locations is at points where the process conditions change significantly (typically temperature, pressure, or composition); and
    3. Piping segments should not be initiated or terminated at valves (e.g. pressure regulating valves, flow control valves, etc.), piping spec changes, flange connections, flow meters, reducers, piping fittings, or other piping appurtenances; and
    4. Piping segment length should be based on piping isometrics but may be based on engineering estimates of the piping path, accounting for vertical distances as well as horizontal distances.
C. For piping connections less than 6 inches in diameter, a full-bore rupture (guillotine failure) is assumed at the point of connection to the equipment item or piping. Small diameter piping is typically used for connections to equipment (e.g., storage tanks, vessels, heat exchangers, pumps, etc.) or to piping as drain lines, vent lines, nitrogen purge lines, PSV connections, valve bypass connections, instrument connections, etc.
D. Regardless of the results obtained by the failure rate table or connections approach above, a minimum 2-inch hole should be considered at any location along any piping of 2 inches or larger diameter.

DS4. Can a fractional time of use be applied when determining SALS events with a probabilistic spill selection methodology?

When determining the design spill through the use of a probabilistic spill selection method, a time-of-use factor may be applied to some piping or equipment groups based on their expected use. For groups that have a fractional time of use other than 1.0 (100% use), the applicant must be able to demonstrate that the group can be isolated, purged, instrumented, maintained, and continually documented in such a way that the fractional time of use is traceable. In groups that operate continually but in more than one mode, each mode must be considered as a potential design spill source and the sum of the fractional times of use in each mode must equal 1.0 (100% use). An example of this would be a loading/unloading line that moves a high mass rate when loading or unloading LNG, but moves a much smaller mass rate when recirculating to keep the line cooled down.

DS5. Is the largest size hole always used as the hole size in release modeling?

Not necessarily. For any defined maximum hole size, the applicant must demonstrate that that the hole size selected produces the greatest vapor dispersion distance when accounting for the mechanisms of jetting, flashing, aerosol formation, and rain-out. If a smaller hole size creates a larger vapor dispersion hazard distance, that smaller hole size should be used to define the design spill event. This applies to all single accidental leakage sources, including failures at piping, piping connections, and all other equipment (e.g., transfer hoses, vessels, heat exchangers, pumps, valves, flanges, etc.).

DS6. What are the proper release height and orientation to use for a design spill?

For each design spill identified, release height and orientation should be selected to define the largest vapor dispersion hazard distance while properly characterizing the release scenario. If an applicant can show that only certain release orientations are possible based on the piping connections and direction of the piping (e.g., vertically upward for connections to relief valve inlet piping, vertically downward for gravity drain connections, and downward for shrouded piping) then a specific orientation may be used in the modeling. All other piping and equipment failures must consider all horizontal and vertical directional orientations.

DS7. How are release locations defined?

For connection failures, the release location can be identified at the specific point of connection in the LNG plant. For piping segments to which the failure rate table has been applied, the selected hole can occur at any location along the piping segment. If vapor barriers, shrouds, or pipe-in-pipe designs are used to reduce the vapor dispersion distance, locations potentially not impacted by the vapor barrier, shroud, or pipe-in-pipe should also be selected.

DS8. How do I determine the process conditions to evaluate for hazard modeling?

Process conditions should be based on heat and material balance modes of operation and design cases (e.g., rich, lean, average, etc.) that produce the worst case dispersion results from flashing and jetting and liquid releases. The leakage sources from branch connections should be considered using the potential operational conditions along the pipe as well as the potential operational conditions that could be experienced at or near the branch pipe connection to a main process line. In cases that would reduce the back pressure on pump(s) or compressor(s), the flow rates should consider the potential increased pump or compressor flow determined by the pump and compressor curve(s) as detailed in D10 and also consider the decrease in temperature from depressurization.

DS9. Is it permissible to use spill duration of less than 10 minutes for design spill calculations?

For design spills other than those from LNG containers, the event is defined in NFPA 59A to last "for 10 minutes or a shorter time based on demonstrable surveillance and shutdown provisions acceptable to the authority having jurisdiction." Demonstrable surveillance and shutdown should include the time required to detect that the spill is occurring, the time to alert operators to this condition, the time required for operators to take action, and the time for the system to fully respond to the shutdown action that is initiated, including any valve closure times. In this case, the applicant should provide a detailed justification or demonstrate that a maximum or steady state dispersion distance has already been reached by the shorter time.

In cases where a system may deplete its inventory in less than 10 minutes, a release duration of less than 10 minutes may be used. In this case, the applicant should provide a detailed justification or demonstrate that a maximum or steady state dispersion distance has already been reached by the shorter time.

DS10. What considerations should be given to system inventory in the design spill definition?

The release modeling should account for the available system inventory (including pipework, process vessels, and other process equipment), the normal flow of fluid into the system, and the demonstrable surveillance and shutdown provisions that may apply. The release modeling should also continue (even beyond 10 minutes) until the available system inventory is depleted; available system inventory may be modified during the event by valve closures. For systems that rely on isolation by emergency shutdown valves, the valves must be protected from failure, including fire and external impacts.

If the event the duration would potentially be greater than 10 minutes, release and dispersion modeling should continue after 10 minutes unless a release is demonstrated to reach its furthest vapor dispersion extent within 10 minutes.

DS11. Do I need to consider pump run-out in release scenario calculations?

Yes. Applicants should use pump run-out (greater flow than in normal pump flow operations) in failure calculations if the pump design allows increases in flow as the discharge pressure is reduced. Pump run-out parameters are presented by the pump manufacturer as a pump curve that shows flow increasing as the discharge pressure decreases. If pump run-out flows are not known at the time of submittal, engineering estimates may be employed provisionally.

DS12. Should multiple pumps be considered when calculating the greatest flow from a spill to size impoundments?

Where the greatest flow is potentially fed from multiple pumps, calculate the flow assuming that all pumps are running at possible pump run-out conditions, unless a mechanical interlock or passive preventive measure is installed that prevents all pumps from running concurrently.

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Appendix B: Potential Revisions to the FRT Considered in this Research

		CURRENT	RECOMMENDATIONS
	Type of Failure	**Nominal Failure Rate**	**Nominal Failure Rate**
Retain	Cryogenic Storage Tanks (General)	Failures per year of operation	Failures per year of operation
Retain	Rupture of Storage Tank Outlet/Withdrawal Line	3E-5 (Failure Rate Criterion)	3E-5 (Failure Rate Criterion)
Delete	~~Single Containment Atmospheric Storage Tanks~~	~~Failures per year of operation~~	
Delete	~~Catastrophic Failure, Release to Atmosphere~~	~~5.0E-06~~	
Delete	~~Catastrophic Failure of Tank Roof~~	~~1.0E-04~~	
Delete	~~Release from a hole in inner tank with eff. diam. of 1 m (~3ft)~~	~~8.0E-05~~	
Delete	~~Release from a hole in inner tank with eff. diam. of .3 m (~1ft)~~	~~2.0E-04~~	
Delete	~~Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)~~	~~1.0E-04~~	
Delete	~~Double Containment Atmospheric Storage Tanks~~	~~Failures per year of operation~~	
Delete	~~Catastrophic Failure, Release to Atmosphere~~	~~5.0E-07~~	
Delete	~~Catastrophic Failure of Tank Roof~~	~~1.0E-04~~	
Delete	~~Release from a hole in inner tank with eff. diam. of 1 m (~3ft)~~	~~1.0E-05~~	
Delete	~~Release from a hole in inner tank with eff. diam. of .3 m (~1ft)~~	~~3.0E-05~~	
Delete	~~Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)~~	~~1.0E-04~~	
Delete	~~Full Containment Atmospheric Storage Tanks~~	~~Failures per year of operation~~	
Delete	~~Catastrophic Failure, Release to Atmosphere~~	~~1.0E-08~~	
Delete	~~Catastrophic Failure of Tank Roof~~	~~4.0E-05~~	
Delete	~~Release from a hole in inner tank with eff. diam. of 1 m (~3ft)~~	~~1.0E-06~~	
Delete	~~Release from a hole in inner tank with eff. diam. of .3 m (~1ft)~~	~~3.0E-06~~	
Delete	~~Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)~~	~~1.0E-04~~	
Retain	Condensers	Failures per year of operation	Failures per year of operation
Retain	Catastrophic Failure (Rupture)	5.0E-06	5.0E-06
Retain	Release from a hole with eff. diam. of 0.01m (0.4 in)	1.0E-04	1.0E-04
Retain	Truck Transfer	Failures per year of operation	Failures per year of operation
Retain	Rupture of transfer arm	3.0E-04	3.0E-04
Retain	Release from hole in transfer arm with effective diameter of 10% transfer arm diameter with maximum of 50mm (2-inches)	3.0E-03	3.0E-03
Retain	Rupture of transfer hose	4.0E-02	4.0E-02 *
Retain	Release from hole in transfer hose with effective diameter of 10% transfer hose diameter with maximum of 50mm (2-inches)	4.0E-01	4.0E-01
Retain	Ship Transfer	Failures per year of operation	Failures per year of operation
Retain	Rupture of transfer arm	2.0E-05	2.0E-05
Retain	Release from hole in transfer arm with effective diameter of 10% transfer arm diameter with maximum of 50mm (2-inches)	2.0E-04	2.0E-04

** Note: It is recommended that PHMSA and FERC consider if the current rupture rate for truck transfer hoses is still appropriate based on the results on the recent cryogenic hose tests by TNO, and perhaps after consultation with RIVM and others. For example, PHMSA and FERC could consider "Rupture of transfer hose unless an applicant's proposed hose is a multi-composite hose such as either Gutteling B.V.'s Multi-LNG White hose or another multi-composite hose of similar materials, design and manufacture."*

Appendix B: Potential Revisions to the FRT Considered in this Research

		CURRENT	RECOMMENDATIONS
	Type of Failure	**Nominal Failure Rate**	**Nominal Failure Rate**
Retain	Piping (General)	Failures per year of operation	Failures per year of operation
Delete	~~Rupture at Valve~~	~~9.0E-06~~	
Revise	*Rupture of Valve*		9.0E-06
New	*Release from valve with a hole with effective diameter of 2mm (0.08 inch)*		*2.0E-04*
Delete	~~Rupture of Expansion Joint~~	~~4.0E-03~~	
Revise	*Rupture of Single Ply Expansion Joint*		*1.0E-04*
Revise	*Rupture of Double Ply Expansion Joint*		*1.0E-08*
Delete	~~Failure of Gasket~~	~~3.0E-02~~	
New	*Release from hole in a Spiral Wound Gasket with effective diameter of 50mm (2-inches)*		*1.0E-07*
New	*Release from hole in One Segment of Gasket with effective diameter of 25mm (1-inch)*		*5.0E-06*
Delete	~~*Piping: d < 50mm (2-inch)*~~	~~*Failures per year of operation*~~	
Delete	~~*Catastrophic Rupture*~~	~~*1.0E-06*~~	
Delete	~~*Release from hole with effective diameter of 25mm (1 inch)*~~	~~*5.0E-06*~~	
Retain	Piping: 50mm (2-inch) ≤ d < 149mm (6-inch)	Failures per year of operation	Failures per year of operation
Retain	Catastrophic Rupture	5.0E-07	5.0E-07
Retain	Release from hole with effective diameter of 25mm (1 inch)	2.0E-06	2.0E-06
Retain	Piping: 150mm (6-inch) ≤ d < 299mm (12-inch)	Failures per year of operation	Failures per year of operation
Retain	Catastrophic Rupture	2.0E-07	2.0E-07
Retain	Release from hole with effective diameter of 1/3 diameter	4.0E-07	4.0E-07
Retain	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)	Failures per year of operation	Failures per year of operation
Retain	Release from hole with effective diameter of 25mm (1 inch)	7.0E-07	7.0E-07
Retain	Piping: 300mm (12-inch) <≤ d < 499mm (20-inch)	Failures per year of operation	Failures per year of operation
Retain	Catastrophic Rupture	7.0E-08	7.0E-08
Retain	Release from hole with effective diameter of 1/3 diameter	2.0E-07	2.0E-07
Retain	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)	4.0E-07	4.0E-07
Retain	Release from hole with effective diameter of 25mm (1 inch)	5.0E-07	5.0E-07
Revise	~~Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch)~~	~~Failures per year of operation~~	
New	*Piping: 500mm (20-inch) ≤ d*		Failures per year of operation
Retain	Catastrophic Rupture	2.0E-08	2.0E-08
Retain	Release from hole with effective diameter of 1/3 diameter	1.0E-07	1.0E-07
Retain	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)	2.0E-07	2.0E-07
Retain	Release from hole with effective diameter of 25mm (1 inch)	4.0E-07	4.0E-07
New	*Pipe-in-Pipe Failure Frequency Modification Multipliers*		*Failure Frequency Multiplier*
New	*Piping failure rate frequency multiplier for Pipe-in-Pipe systems if outer and inner pipes are of the same material and schedule*		*1.0E-02*
New	*Piping failure rate frequency multiplier for Pipe-in-Pipe systems if outer and inner pipes are not of the same material and schedule, and outer pipe is made of carbon steel*		*1.0E-01*

Note: *Italicized* and ~~struck-through~~ text highlights for the reader those changes to the FRT that were considered in this research.

Appendix C: Equipment Protocol Framework and Applied References

Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
1			Ambient Atm. Storage Tanks					
2		API_581_16, CCPS_89, INL_CHEM_95, INL_NUC_07, HSE_FRED_JUN_12	Catastrophic Failure, Release to Atmosphere					
3		HSE_FRED_JUN_12	Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
4		HSE_FRED_JUN_12	Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
5			Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
6			Refrigerated Atm. Storage Tanks (Typ. Single Shell)					
7		CCPS_89, LNE_09, TNO_PURPLE_05	Catastrophic Failure, Release to Atmosphere					
8			Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
9			Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
10		LNE_09, TNO_PURPLE_05	Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
11			Cryogenic Atm. Storage Tanks					
12		CCPS_89	Catastrophic Failure, Release to Atmosphere					
311			Catastrophic Failure of Tank Roof					
13			Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
14			Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
15			Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
16				Single Cont. Cryo. Atm. Storage Tanks				
17	Yes	59A_16, CCPS_89, IOGP_434_3, LNE_09, PNL_PSRP_82, RIVM_BEVI_09, TGC_03, TNO_PURPLE_05, HSE_FRED_JUN_12		Catastrophic Failure, Release to Atmosphere				
312	Yes	HSE_FRED_JUN_12		Catastrophic Failure of Tank Roof				
18	Yes	HSE_FRED_JUN_12		Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
19	Yes	HSE_FRED_JUN_12		Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
20	Yes	LNE_09, RIVM_BEVI_09		Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
21					Single Cont. Cryo. Atm. Storage Tanks - HC Only (LNG, Ethane, Ethylene) - Self-Supp. Inner Tar			
22		CCPS_89			Catastrophic Failure, Release to Atmosphere			
313					Catastrophic Failure of Tank Roof			
23					Release from a hole in inner tank with eff. diam. of 1 m (~3ft)			
24					Release from a hole in inner tank with eff. diam. of .3 m (~1ft)			
25					Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)			
26					Single Cont. Cryo. Atm. Storage Tanks - LIN/LOX/LAR - Self-Supp. Inner Tank			
27		HSE_FRED_JUN_12			Catastrophic Failure, Release to Atmosphere			
314					Catastrophic Failure of Tank Roof			
28					Release from a hole in inner tank with eff. diam. of 1 m (~3ft)			
29					Release from a hole in inner tank with eff. diam. of .3 m (~1ft)			
30					Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)			
31				Double Cont. Cryo. Atm. Storage Tanks				
32	Yes	59A_16, IOGP_434_3, LNE_09, RIVM_BEVI_09, TGC_03, TNO_PURPLE_05, HSE_FRED_JUN_12		Catastrophic Failure, Release to Atmosphere				
315	Yes	HSE_FRED_JUN_12		Catastrophic Failure of Tank Roof				
33	Yes	HSE_FRED_JUN_12		Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
34	Yes	HSE_FRED_JUN_12		Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
35	Yes	LNE_09, RIVM_BEVI_09		Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
36				Full Cont. Cryo. Atm. Storage Tanks				
37	Yes	59A_16, IOGP_434_3, KGSC_06, LNE_09, RIVM_BEVI_09, TNO_PURPLE_05, HSE_FRED_JUN_12		Catastrophic Failure, Release to Atmosphere				
316	Yes	HSE_FRED_JUN_12		Catastrophic Failure of Tank Roof				
38	Yes	HSE_FRED_JUN_12		Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
39	Yes	HSE_FRED_JUN_12		Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
40	Yes	LNE_09		Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
41				Membrane. Cryo. Atm. Storage Tanks				
42		59A_16, IOGP_434_3, KGSC_06, KJCE_05, RIVM_BEVI_09, TGC_03		Catastrophic Failure, Release to Atmosphere				
317				Catastrophic Failure of Tank Roof				
43				Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
44				Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
45				Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
46				Process Vessels, Distillation Columns, Heat Exchangers, and Condensers				
47	Yes			Catastrophic Failure (Rupture)				
48	Yes			Release from a hole with eff. diam. of 0.01m (0.4 in)				
802				Release from a hole with eff. diam. of 0.025m (1 in)				
803				Release from a hole with eff. diam. of 0.05m (2 in)				
804				Release from a hole with eff. diam. of 0.10m (4 in)				
49					Process Vessels incl Distillation Columns			
50		LEES_12, LEES_12, TNO_RED_05			Catastrophic Failure (Rupture)			
51		TNO_RED_05			Release from a hole with eff. diam. of 0.01m (0.4 in)			
805					Release from a hole with eff. diam. of 0.025m (1 in)			
806					Release from a hole with eff. diam. of 0.05m (2 in)			
807					Release from a hole with eff. diam. of 0.10m (4 in)			
52						PVs incl Dist. Columns - Single Wall		
53		OREDA_15				Catastrophic Failure (Rupture)		
54						Release from a hole with eff. diam. of 0.01m (0.4 in)		
808						Release from a hole with eff. diam. of 0.025m (1 in)		
809						Release from a hole with eff. diam. of 0.05m (2 in)		
810						Release from a hole with eff. diam. of 0.10m (4 in)		
318							Pressure Storage Vessels/Tanks (Single Wall)	
319		59A_16, CCPS_89, INL_CHEM_95, INL_NUC_07, IOGP_434_3, LNE_09, RIVM_BEVI_09, SERCO_AEA_05, TNO_PURPLE_05, HSE_FRED_JUN_12, HSE_FRED_JUN_12					Catastrophic Failure (Rupture)	
320		IOGP_434_3, LNE_09, RIVM_BEVI_09, HSE_FRED_JUN_12, HSE_FRED_JUN_12					Release from a hole with eff. diam. of 0.01m (0.4 in)	
380		IOGP_434_3, LNE_09, HSE_FRED_JUN_12, HSE_FRED_JUN_12					Release from a hole with eff. diam. of 0.025m (1 in)	
381		HSE_FRED_JUN_12, HSE_FRED_JUN_12					Release from a hole with eff. diam. of 0.05m (2 in)	
382		IOGP_434_3					Release from a hole with eff. diam. of 0.10m (4 in)	
321							Process Vessels (Single Wall)	
322		DNV_LEAK_3.3, LNE_09, RIVM_BEVI_09, TNO_PURPLE_05					Catastrophic Failure (Rupture)	
323		DNV_LEAK_3.3, IOGP_434_1, LNE_09, RIVM_BEVI_09					Release from a hole with eff. diam. of 0.01m (0.4 in)	
383		DNV_LEAK_3.3, IOGP_434_1, LNE_09					Release from a hole with eff. diam. of 0.025m (1 in)	

Appendix C: Equipment Protocol Framework and Applied References

Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
384		DNV_LEAK_3.3					Release from a hole with eff. diam. of 0.05m (2 in)	
386		DNV_LEAK_3.3, IOGP_434_1					Release from a hole with eff. diam. of 0.10m (4 in)	
55							Mole Sieve Vessel (Single Wall)	
56		OREDA_15					Catastrophic Failure (Rupture)	
57							Release from a hole with eff. diam. of 0.01m (0.4 in)	
387							Release from a hole with eff. diam. of 0.025m (1 in)	
388							Release from a hole with eff. diam. of 0.05m (2 in)	
389							Release from a hole with eff. diam. of 0.10m (4 in)	
58							Distillation Columns (Single Wall)	
59		API_581_16, RIVM_BEVI_09					Catastrophic Failure (Rupture)	
60		RIVM_BEVI_09					Release from a hole with eff. diam. of 0.01m (0.4 in)	
390		API_581_16					Release from a hole with eff. diam. of 0.025m (1 in)	
391							Release from a hole with eff. diam. of 0.05m (2 in)	
392		API_581_16					Release from a hole with eff. diam. of 0.10m (4 in)	
61							Separator (Single Wall)	
62							Catastrophic Failure (Rupture)	
63							Release from a hole with eff. diam. of 0.01m (0.4 in)	
393							Release from a hole with eff. diam. of 0.025m (1 in)	
394							Release from a hole with eff. diam. of 0.05m (2 in)	
395							Release from a hole with eff. diam. of 0.10m (4 in)	
64						PVs incl Dist. Columns - Double Wall (cryogenic)		
65						Catastrophic Failure (Rupture)		
66						Release from a hole with eff. diam. of 0.01m (0.4 in)		
396						Release from a hole with eff. diam. of 0.025m (1 in)		
397						Release from a hole with eff. diam. of 0.05m (2 in)		
398						Release from a hole with eff. diam. of 0.10m (4 in)		
70						ISO Containers		
71		HSE_FRED_JUN_12				Catastrophic Failure (Rupture)		
72		HSE_FRED_JUN_12				Release from a hole with eff. diam. of 0.01m (0.4 in)		
399						Release from a hole with eff. diam. of 0.025m (1 in)		
400						Release from a hole with eff. diam. of 0.05m (2 in)		
401						Release from a hole with eff. diam. of 0.10m (4 in)		
73					Heat Exchangers incl. Condensers			
74		OREDA_15, TNO_RED_05			Catastrophic Failure (Rupture)			
75		TNO_RED_05			Release from a hole with eff. diam. of 0.01m (0.4 in)			
402					Release from a hole with eff. diam. of 0.025m (1 in)			
403					Release from a hole with eff. diam. of 0.05m (2 in)			
404					Release from a hole with eff. diam. of 0.10m (4 in)			
76						Fired Heat Exchangers		
77		GRI_LNG_FRD_81				Catastrophic Failure (Rupture)		
78						Release from a hole with eff. diam. of 0.01m (0.4 in)		
405						Release from a hole with eff. diam. of 0.025m (1 in)		
406						Release from a hole with eff. diam. of 0.05m (2 in)		
407						Release from a hole with eff. diam. of 0.10m (4 in)		
324							Submerged Combustion Vaporizers	
325		GRI_LNG_FRD_81					Catastrophic Failure (Rupture)	
326							Release from a hole with eff. diam. of 0.01m (0.4 in)	
408							Release from a hole with eff. diam. of 0.025m (1 in)	
409							Release from a hole with eff. diam. of 0.05m (2 in)	
410							Release from a hole with eff. diam. of 0.10m (4 in)	
79						Non-Fired Heat Exchangers incl. Condensers		
80						Catastrophic Failure (Rupture)		
81						Release from a hole with eff. diam. of 0.01m (0.4 in)		
411						Release from a hole with eff. diam. of 0.025m (1 in)		
412						Release from a hole with eff. diam. of 0.05m (2 in)		
413						Release from a hole with eff. diam. of 0.10m (4 in)		
82							Shell & Tube Heat Exchangers	
83		LNE_09, OREDA_15					Catastrophic Failure (Rupture)	
84		LNE_09					Release from a hole with eff. diam. of 0.01m (0.4 in)	
414							Release from a hole with eff. diam. of 0.025m (1 in)	
415							Release from a hole with eff. diam. of 0.05m (2 in)	
416		LNE_09					Release from a hole with eff. diam. of 0.10m (4 in)	
85								Tube-side Heat Exchangers (HC in tube)
86		DNV_LEAK_3.3, INL_CHEM_95, INL_NUC_07, TNO_PURPLE_05						Catastrophic Failure (Rupture)
87		DNV_LEAK_3.3, IOGP_434_1, TNO_PURPLE_05						Release from a hole with eff. diam. of 0.01m (0.4 in)
417		DNV_LEAK_3.3, IOGP_434_1						Release from a hole with eff. diam. of 0.025m (1 in)
418		DNV_LEAK_3.3						Release from a hole with eff. diam. of 0.05m (2 in)
419		DNV_LEAK_3.3, IOGP_434_1						Release from a hole with eff. diam. of 0.10m (4 in)
88								Shell-side Heat Exchangers (HC in shell)
89		API_581_16, DNV_LEAK_3.3, INL_CHEM_95, INL_NUC_07, RIVM_BEVI_09						Catastrophic Failure (Rupture)
90		DNV_LEAK_3.3, IOGP_434_1, RIVM_BEVI_09						Release from a hole with eff. diam. of 0.01m (0.4 in)
420		API_581_16, DNV_LEAK_3.3, IOGP_434_1						Release from a hole with eff. diam. of 0.025m (1 in)
421		DNV_LEAK_3.3						Release from a hole with eff. diam. of 0.05m (2 in)
422		API_581_16, DNV_LEAK_3.3, IOGP_434_1						Release from a hole with eff. diam. of 0.10m (4 in)
91							Plate Heat Exchangers	
92		59A_16, DNV_LEAK_3.3, LNE_09, OREDA_15, RIVM_BEVI_09					Catastrophic Failure (Rupture)	
93		DNV_LEAK_3.3, IOGP_434_1, LNE_09, RIVM_BEVI_09					Release from a hole with eff. diam. of 0.01m (0.4 in)	
423		DNV_LEAK_3.3, IOGP_434_1					Release from a hole with eff. diam. of 0.025m (1 in)	
424		DNV_LEAK_3.3					Release from a hole with eff. diam. of 0.05m (2 in)	
425		DNV_LEAK_3.3, IOGP_434_1					Release from a hole with eff. diam. of 0.10m (4 in)	
94							Air Cooled (Fin Fan) Heat Exchangers	
95		API_581_16, DNV_LEAK_3.3					Catastrophic Failure (Rupture)	

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Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
96		DNV_LEAK_3.3, IOGP_434_1					Release from a hole with eff. diam. of 0.01m (0.4 in)	
426		API_581_16, DNV_LEAK_3.3, IOGP_434_1					Release from a hole with eff. diam. of 0.025m (1 in)	
427		DNV_LEAK_3.3					Release from a hole with eff. diam. of 0.05m (2 in)	
428		API_581_16, DNV_LEAK_3.3, IOGP_434_1					Release from a hole with eff. diam. of 0.10m (4 in)	
97							Printed Heat Exchangers	
98							Catastrophic Failure (Rupture)	
99							Release from a hole with eff. diam. of 0.01m (0.4 in)	
429							Release from a hole with eff. diam. of 0.025m (1 in)	
430							Release from a hole with eff. diam. of 0.05m (2 in)	
431							Release from a hole with eff. diam. of 0.10m (4 in)	
100							Plate-Fin Heat Exchangers	
101							Catastrophic Failure (Rupture)	
102							Release from a hole with eff. diam. of 0.01m (0.4 in)	
432							Release from a hole with eff. diam. of 0.025m (1 in)	
433							Release from a hole with eff. diam. of 0.05m (2 in)	
434							Release from a hole with eff. diam. of 0.10m (4 in)	
103							Ambient Vaporizer Heat Exchangers	
104							Catastrophic Failure (Rupture)	
105							Release from a hole with eff. diam. of 0.01m (0.4 in)	
435							Release from a hole with eff. diam. of 0.025m (1 in)	
436							Release from a hole with eff. diam. of 0.05m (2 in)	
437							Release from a hole with eff. diam. of 0.10m (4 in)	
106				Truck Transfer Arm				
107	Yes	59A_16, LEES_12, LNE_09, RIVM_BEVI_09, TNO_PURPLE_05		Rupture of transfer arm				
108	Yes	LNE_09, RIVM_BEVI_09, TNO_PURPLE_05		Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
109					Truck Transfer Arm - Cryogenic			
110					Rupture of transfer arm			
111					Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
112					Truck Transfer Arm - Non-cryogenic			
113					Rupture of transfer arm			
114					Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
115				Ship Transfer Arm				
116	Yes	59A_16, LEES_12, LNE_09, PNL_PSRP_82, RIVM_BEVI_09, SIGTTO_IP4_96, TNO_PURPLE_05		Rupture of transfer arm				
117	Yes	LNE_09, RIVM_BEVI_09, TNO_PURPLE_05		Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
118					Ship Transfer Arm - Cryogenic			
119					Rupture of transfer arm			
120					Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
121					Ship Transfer Arm - Non-cryogenic			
122					Rupture of transfer arm			
123					Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
124				Truck Transfer Hose				
125	Yes	CCPS_89, INL_CHEM_95, LNE_09, PNL_PSRP_82, RIVM_BEVI_09, TNO_PURPLE_05		Rupture of transfer hose				
126	Yes	LNE_09, RIVM_BEVI_09, TNO_PURPLE_05		Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
127					Truck Transfer Hose - Cryogenic			
128					Rupture of transfer hose			
129					Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
130					Truck Transfer Hose - Non-cryogenic			
131		HSE_FRED_JUN_12			Rupture of transfer hose			
132					Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
133				Ship Transfer Hose				
134		LNE_09, RIVM_BEVI_09, SIGTTO_IP4_96		Rupture of transfer hose				
135		LNE_09, RIVM_BEVI_09		Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
136					Ship Transfer Hose - Cryogenic			
137					Rupture of transfer hose			
138					Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
139					Ship Transfer Hose - Non-cryogenic			
140					Rupture of transfer hose			
141					Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
142				Valve: All diameters				
143	Yes	OREDA_15, PNL_PSRP_82		Catastrophic Rupture				
327		HSE_FRED_JUN_12		Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
144				Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
328				Release from hole with eff. diam. of 25 mm (1 in) diam.				
329				Release from hole with eff. diam. of 50 mm (2 in) diam.				
330				Release from hole with eff. diam. of 100 mm (4 in) diam.				
145					Manual Valves: All diameters			
146		CCPS_89, INL_CHEM_95, LEES_12			Catastrophic Rupture			
331					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
147					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
332					Release from hole with eff. diam. of 25 mm (1 in) diam.			
333					Release from hole with eff. diam. of 50 mm (2 in) diam.			
334					Release from hole with eff. diam. of 100 mm (4 in) diam.			
148						Manual Valves - Cryogenic: All diameters		
149						Catastrophic Rupture		
335						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
150						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
336						Release from hole with eff. diam. of 25 mm (1 in) diam.		
337						Release from hole with eff. diam. of 50 mm (2 in) diam.		
338						Release from hole with eff. diam. of 100 mm (4 in) diam.		
151						Manual Valves - Non-cryogenic: All diameters		
152		INL_CHEM_95, INL_NUC_07				Catastrophic Rupture		
339						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		

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Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
153						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
340						Release from hole with eff. diam. of 25 mm (1 in) diam.		
341						Release from hole with eff. diam. of 50 mm (2 in) diam.		
342						Release from hole with eff. diam. of 100 mm (4 in) diam.		
154					Actuated Valves: All diameters			
155					Catastrophic Rupture			
343					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
156					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
344					Release from hole with eff. diam. of 25 mm (1 in) diam.			
345					Release from hole with eff. diam. of 50 mm (2 in) diam.			
346					Release from hole with eff. diam. of 100 mm (4 in) diam.			
157						Actuated Valves - Cryogenic: All diameters		
158						Catastrophic Rupture		
347						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
159						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
348						Release from hole with eff. diam. of 25 mm (1 in) diam.		
349						Release from hole with eff. diam. of 50 mm (2 in) diam.		
350						Release from hole with eff. diam. of 100 mm (4 in) diam.		
160						Actuated Valves - Non-cryogenic: All diameters		
161		INL_CHEM_95, INL_NUC_07, LEES_12				Catastrophic Rupture		
351						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
162						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
352						Release from hole with eff. diam. of 25 mm (1 in) diam.		
353						Release from hole with eff. diam. of 50 mm (2 in) diam.		
354						Release from hole with eff. diam. of 100 mm (4 in) diam.		
438					Valve: 2"≤D<6"			
439					Catastrophic Rupture			
440					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
441					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
442					Release from hole with eff. diam. of 25 mm (1 in) diam.			
443					Release from hole with eff. diam. of 50 mm (2 in) diam.			
444					Release from hole with eff. diam. of 100 mm (4 in) diam.			
445						Manual Valves: 2"≤D<6"		
446						Catastrophic Rupture		
447						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
448						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
449						Release from hole with eff. diam. of 25 mm (1 in) diam.		
450						Release from hole with eff. diam. of 50 mm (2 in) diam.		
451						Release from hole with eff. diam. of 100 mm (4 in) diam.		
452							Manual Valves - Cryogenic: 2"≤D<6"	
453							Catastrophic Rupture	
454							Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
455							Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
456							Release from hole with eff. diam. of 25 mm (1 in) diam.	
457							Release from hole with eff. diam. of 50 mm (2 in) diam.	
458							Release from hole with eff. diam. of 100 mm (4 in) diam.	
459							Manual Valves - Non-cryogenic: 2"≤D<6"	
460		DNV_LEAK_3.3					Catastrophic Rupture	
461		DNV_LEAK_3.3					Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
462		DNV_LEAK_3.3					Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
463		DNV_LEAK_3.3					Release from hole with eff. diam. of 25 mm (1 in) diam.	
464		DNV_LEAK_3.3					Release from hole with eff. diam. of 50 mm (2 in) diam.	
465		DNV_LEAK_3.3					Release from hole with eff. diam. of 100 mm (4 in) diam.	
466						Actuated Valves: 2"≤D<6"		
467						Catastrophic Rupture		
468						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
469						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
470						Release from hole with eff. diam. of 25 mm (1 in) diam.		
471						Release from hole with eff. diam. of 50 mm (2 in) diam.		
472						Release from hole with eff. diam. of 100 mm (4 in) diam.		
473							Actuated Valves - Cryogenic: 2"≤D<6"	
474							Catastrophic Rupture	
475							Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
476							Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
477							Release from hole with eff. diam. of 25 mm (1 in) diam.	
478							Release from hole with eff. diam. of 50 mm (2 in) diam.	
479							Release from hole with eff. diam. of 100 mm (4 in) diam.	
480							Actuated Valves - Non-cryogenic: 2"≤D<6"	
481		DNV_LEAK_3.3					Catastrophic Rupture	
482		DNV_LEAK_3.3					Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
483		DNV_LEAK_3.3					Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
484		DNV_LEAK_3.3					Release from hole with eff. diam. of 25 mm (1 in) diam.	
485		DNV_LEAK_3.3					Release from hole with eff. diam. of 50 mm (2 in) diam.	
486		DNV_LEAK_3.3					Release from hole with eff. diam. of 100 mm (4 in) diam.	
487					Valve: 6"≤D<12"			
488					Catastrophic Rupture			
489					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
490					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
491					Release from hole with eff. diam. of 25 mm (1 in) diam.			
492					Release from hole with eff. diam. of 50 mm (2 in) diam.			
493					Release from hole with eff. diam. of 100 mm (4 in) diam.			
494						Manual Valves: 6"≤D<12"		

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Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
495						Catastrophic Rupture		
496						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
497						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
498						Release from hole with eff. diam. of 25 mm (1 in) diam.		
499						Release from hole with eff. diam. of 50 mm (2 in) diam.		
500						Release from hole with eff. diam. of 100 mm (4 in) diam.		
501							Manual Valves - Cryogenic: 6"≤D<12"	
502							Catastrophic Rupture	
503							Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
504							Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
505							Release from hole with eff. diam. of 25 mm (1 in) diam.	
506							Release from hole with eff. diam. of 50 mm (2 in) diam.	
507							Release from hole with eff. diam. of 100 mm (4 in) diam.	
508							Manual Valves - Non-cryogenic: 6"≤D<12"	
509		DNV_LEAK_3.3					Catastrophic Rupture	
510		DNV_LEAK_3.3					Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
511		DNV_LEAK_3.3					Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
512		DNV_LEAK_3.3					Release from hole with eff. diam. of 25 mm (1 in) diam.	
513		DNV_LEAK_3.3					Release from hole with eff. diam. of 50 mm (2 in) diam.	
514		DNV_LEAK_3.3					Release from hole with eff. diam. of 100 mm (4 in) diam.	
515						Actuated Valves: 6"≤D<12"		
516						Catastrophic Rupture		
517						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
518						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
519						Release from hole with eff. diam. of 25 mm (1 in) diam.		
520						Release from hole with eff. diam. of 50 mm (2 in) diam.		
521						Release from hole with eff. diam. of 100 mm (4 in) diam.		
522							Actuated Valves - Cryogenic: 6"≤D<12"	
523							Catastrophic Rupture	
524							Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
525							Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
526							Release from hole with eff. diam. of 25 mm (1 in) diam.	
527							Release from hole with eff. diam. of 50 mm (2 in) diam.	
528							Release from hole with eff. diam. of 100 mm (4 in) diam.	
529							Actuated Valves - Non-cryogenic: 6"≤D<12"	
530		DNV_LEAK_3.3					Catastrophic Rupture	
531		DNV_LEAK_3.3					Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
532		DNV_LEAK_3.3					Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
533		DNV_LEAK_3.3					Release from hole with eff. diam. of 25 mm (1 in) diam.	
534		DNV_LEAK_3.3					Release from hole with eff. diam. of 50 mm (2 in) diam.	
535		DNV_LEAK_3.3					Release from hole with eff. diam. of 100 mm (4 in) diam.	
536					Valve: 12"≤D<20"			
537					Catastrophic Rupture			
538					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
539					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
540					Release from hole with eff. diam. of 25 mm (1 in) diam.			
541					Release from hole with eff. diam. of 50 mm (2 in) diam.			
542					Release from hole with eff. diam. of 100 mm (4 in) diam.			
543						Manual Valves: 12"≤D<20"		
544						Catastrophic Rupture		
545						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
546						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
547						Release from hole with eff. diam. of 25 mm (1 in) diam.		
548						Release from hole with eff. diam. of 50 mm (2 in) diam.		
549						Release from hole with eff. diam. of 100 mm (4 in) diam.		
550							Manual Valves - Cryogenic: 12"≤D<20"	
551							Catastrophic Rupture	
552							Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
553							Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
554							Release from hole with eff. diam. of 25 mm (1 in) diam.	
555							Release from hole with eff. diam. of 50 mm (2 in) diam.	
556							Release from hole with eff. diam. of 100 mm (4 in) diam.	
557							Manual Valves - Non-cryogenic: 12"≤D<20"	
558		DNV_LEAK_3.3					Catastrophic Rupture	
559		DNV_LEAK_3.3					Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
560		DNV_LEAK_3.3					Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
561		DNV_LEAK_3.3					Release from hole with eff. diam. of 25 mm (1 in) diam.	
562		DNV_LEAK_3.3					Release from hole with eff. diam. of 50 mm (2 in) diam.	
563		DNV_LEAK_3.3					Release from hole with eff. diam. of 100 mm (4 in) diam.	
564						Actuated Valves: 12"≤D<20"		
565						Catastrophic Rupture		
566						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
567						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
568						Release from hole with eff. diam. of 25 mm (1 in) diam.		
569						Release from hole with eff. diam. of 50 mm (2 in) diam.		
570						Release from hole with eff. diam. of 100 mm (4 in) diam.		
571							Actuated Valves - Cryogenic: 12"≤D<20"	
572							Catastrophic Rupture	
573							Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
574							Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
575							Release from hole with eff. diam. of 25 mm (1 in) diam.	
576							Release from hole with eff. diam. of 50 mm (2 in) diam.	

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Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
577							Release from hole with eff. diam. of 100 mm (4 in) diam.	
578							Actuated Valves - Non-cryogenic: 12"≤D<20"	
579		DNV_LEAK_3.3					Catastrophic Rupture	
580		DNV_LEAK_3.3					Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
581		DNV_LEAK_3.3					Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
582		DNV_LEAK_3.3					Release from hole with eff. diam. of 25 mm (1 in) diam.	
583		DNV_LEAK_3.3					Release from hole with eff. diam. of 50 mm (2 in) diam.	
584		DNV_LEAK_3.3					Release from hole with eff. diam. of 100 mm (4 in) diam.	
585					Valve: 20"≤D<40"			
586					Catastrophic Rupture			
587					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
588					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
589					Release from hole with eff. diam. of 25 mm (1 in) diam.			
590					Release from hole with eff. diam. of 50 mm (2 in) diam.			
591					Release from hole with eff. diam. of 100 mm (4 in) diam.			
592						Manual Valves: 20"≤D<40"		
593						Catastrophic Rupture		
594						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
595						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
596						Release from hole with eff. diam. of 25 mm (1 in) diam.		
597						Release from hole with eff. diam. of 50 mm (2 in) diam.		
598						Release from hole with eff. diam. of 100 mm (4 in) diam.		
599							Manual Valves - Cryogenic: 20"≤D<40"	
600							Catastrophic Rupture	
601							Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
602							Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
603							Release from hole with eff. diam. of 25 mm (1 in) diam.	
604							Release from hole with eff. diam. of 50 mm (2 in) diam.	
605							Release from hole with eff. diam. of 100 mm (4 in) diam.	
606							Manual Valves - Non-cryogenic: 20"≤D<40"	
607		DNV_LEAK_3.3					Catastrophic Rupture	
608		DNV_LEAK_3.3					Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
609		DNV_LEAK_3.3					Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
610		DNV_LEAK_3.3					Release from hole with eff. diam. of 25 mm (1 in) diam.	
611		DNV_LEAK_3.3					Release from hole with eff. diam. of 50 mm (2 in) diam.	
612		DNV_LEAK_3.3					Release from hole with eff. diam. of 100 mm (4 in) diam.	
613						Actuated Valves: 20"≤D<40"		
614						Catastrophic Rupture		
615						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
616						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
617						Release from hole with eff. diam. of 25 mm (1 in) diam.		
618						Release from hole with eff. diam. of 50 mm (2 in) diam.		
619						Release from hole with eff. diam. of 100 mm (4 in) diam.		
620							Actuated Valves - Cryogenic: 20"≤D<40"	
621							Catastrophic Rupture	
622							Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
623							Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
624							Release from hole with eff. diam. of 25 mm (1 in) diam.	
625							Release from hole with eff. diam. of 50 mm (2 in) diam.	
626							Release from hole with eff. diam. of 100 mm (4 in) diam.	
627							Actuated Valves - Non-cryogenic: 20"≤D<40"	
628		DNV_LEAK_3.3					Catastrophic Rupture	
629		DNV_LEAK_3.3					Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
630		DNV_LEAK_3.3					Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
631		DNV_LEAK_3.3					Release from hole with eff. diam. of 25 mm (1 in) diam.	
632		DNV_LEAK_3.3					Release from hole with eff. diam. of 50 mm (2 in) diam.	
633		DNV_LEAK_3.3					Release from hole with eff. diam. of 100 mm (4 in) diam.	
163				Expansion Joint- All diameters				
164	Yes	PNL_PSRP_82		Catastrophic Rupture				
355				Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
165				Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
356				Release from hole with eff. diam. of 25 mm (1 in) diam.				
357				Release from hole with eff. diam. of 50 mm (2 in) diam.				
358				Release from hole with eff. diam. of 100 mm (4 in) diam.				
166					Expansion Joint- Cryogenic: All diameters			
167					Catastrophic Rupture			
359					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
168					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
360					Release from hole with eff. diam. of 25 mm (1 in) diam.			
361					Release from hole with eff. diam. of 50 mm (2 in) diam.			
362					Release from hole with eff. diam. of 100 mm (4 in) diam.			
169					Expansion Joint- Non Cryogenic: All diameters			
170		LEES_12			Catastrophic Rupture			
363					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
171					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
364					Release from hole with eff. diam. of 25 mm (1 in) diam.			
365					Release from hole with eff. diam. of 50 mm (2 in) diam.			
366					Release from hole with eff. diam. of 100 mm (4 in) diam.			
634					Expansion Joint: 2"≤D<6"			
635					Catastrophic Rupture			
636					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
637					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			

Appendix C: Equipment Protocol Framework and Applied References

Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
638					Release from hole with eff. diam. of 25 mm (1 in) diam.			
639					Release from hole with eff. diam. of 50 mm (2 in) diam.			
640					Release from hole with eff. diam. of 100 mm (4 in) diam.			
641						Expansion Joint- Cryogenic: 2"≤D<6"		
642						Catastrophic Rupture		
643						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
644						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
645						Release from hole with eff. diam. of 25 mm (1 in) diam.		
646						Release from hole with eff. diam. of 50 mm (2 in) diam.		
647						Release from hole with eff. diam. of 100 mm (4 in) diam.		
648						Expansion Joint- Non Cryogenic: 2"≤D<6"		
649						Catastrophic Rupture		
650						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
651						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
652						Release from hole with eff. diam. of 25 mm (1 in) diam.		
653						Release from hole with eff. diam. of 50 mm (2 in) diam.		
654						Release from hole with eff. diam. of 100 mm (4 in) diam.		
655					Expansion Joint: 6"≤D<12"			
656					Catastrophic Rupture			
657					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
658					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
659					Release from hole with eff. diam. of 25 mm (1 in) diam.			
660					Release from hole with eff. diam. of 50 mm (2 in) diam.			
661					Release from hole with eff. diam. of 100 mm (4 in) diam.			
662						Expansion Joint- Cryogenic: 6"≤D<12"		
663						Catastrophic Rupture		
664						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
665						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
666						Release from hole with eff. diam. of 25 mm (1 in) diam.		
667						Release from hole with eff. diam. of 50 mm (2 in) diam.		
668						Release from hole with eff. diam. of 100 mm (4 in) diam.		
669						Expansion Joint- Non Cryogenic: 6"≤D<12"		
670						Catastrophic Rupture		
671						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
672						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
673						Release from hole with eff. diam. of 25 mm (1 in) diam.		
674						Release from hole with eff. diam. of 50 mm (2 in) diam.		
675						Release from hole with eff. diam. of 100 mm (4 in) diam.		
676					Expansion Joint: 12"≤D<20"			
677					Catastrophic Rupture			
678					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
679					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
680					Release from hole with eff. diam. of 25 mm (1 in) diam.			
681					Release from hole with eff. diam. of 50 mm (2 in) diam.			
682					Release from hole with eff. diam. of 100 mm (4 in) diam.			
683						Expansion Joint- Cryogenic: 12"≤D<20"		
684						Catastrophic Rupture		
685						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
686						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
687						Release from hole with eff. diam. of 25 mm (1 in) diam.		
688						Release from hole with eff. diam. of 50 mm (2 in) diam.		
689						Release from hole with eff. diam. of 100 mm (4 in) diam.		
690						Expansion Joint- Non Cryogenic: 12"≤D<20"		
691						Catastrophic Rupture		
692						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
693						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
694						Release from hole with eff. diam. of 25 mm (1 in) diam.		
695						Release from hole with eff. diam. of 50 mm (2 in) diam.		
696						Release from hole with eff. diam. of 100 mm (4 in) diam.		
697					Expansion Joint: 20"≤D<40"			
698					Catastrophic Rupture			
699					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
700					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
701					Release from hole with eff. diam. of 25 mm (1 in) diam.			
702					Release from hole with eff. diam. of 50 mm (2 in) diam.			
703					Release from hole with eff. diam. of 100 mm (4 in) diam.			
704						Expansion Joint- Cryogenic: 20"≤D<40"		
705						Catastrophic Rupture		
706						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
707						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
708						Release from hole with eff. diam. of 25 mm (1 in) diam.		
709						Release from hole with eff. diam. of 50 mm (2 in) diam.		
710						Release from hole with eff. diam. of 100 mm (4 in) diam.		
711						Expansion Joint- Non Cryogenic: 20"≤D<40"		
712						Catastrophic Rupture		
713						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
714						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
715						Release from hole with eff. diam. of 25 mm (1 in) diam.		
716						Release from hole with eff. diam. of 50 mm (2 in) diam.		
717						Release from hole with eff. diam. of 100 mm (4 in) diam.		
172				Gasket Flange- All diameters				
173	Yes	LEES_12, PNL_PSRP_82		Catastrophic Rupture				

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Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
367		IOGP_434_1		Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
174				Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
368		HSE_FRED_JUN_12		Release from hole with eff. diam. of 25 mm (1 in) diam.				
369		HSE_FRED_JUN_12		Release from hole with eff. diam. of 50 mm (2 in) diam.				
370				Release from hole with eff. diam. of 100 mm (4 in) diam.				
175					Gasket Flange- Cryogenic: All Diameters			
176					Catastrophic Rupture			
371					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
177					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
372					Release from hole with eff. diam. of 25 mm (1 in) diam.			
373					Release from hole with eff. diam. of 50 mm (2 in) diam.			
374					Release from hole with eff. diam. of 100 mm (4 in) diam.			
178					Gasket Flange- Non Cryogenic: All Diameters			
179		DNV_LEAK_3.3, INL_CHEM_95			Catastrophic Rupture			
375		DNV_LEAK_3.3			Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
180		DNV_LEAK_3.3			Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
376		DNV_LEAK_3.3			Release from hole with eff. diam. of 25 mm (1 in) diam.			
377		DNV_LEAK_3.3			Release from hole with eff. diam. of 50 mm (2 in) diam.			
378		DNV_LEAK_3.3			Release from hole with eff. diam. of 100 mm (4 in) diam.			
718					Gasket Flange: 2"≤D<6"			
719					Catastrophic Rupture			
720					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
721					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
722					Release from hole with eff. diam. of 25 mm (1 in) diam.			
723					Release from hole with eff. diam. of 50 mm (2 in) diam.			
724					Release from hole with eff. diam. of 100 mm (4 in) diam.			
725						Gasket Flange- Cryogenic: 2"≤D<6"		
726						Catastrophic Rupture		
727						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
728						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
729						Release from hole with eff. diam. of 25 mm (1 in) diam.		
730						Release from hole with eff. diam. of 50 mm (2 in) diam.		
731						Release from hole with eff. diam. of 100 mm (4 in) diam.		
732						Gasket Flange- Non Cryogenic: 2"≤D<6"		
733		DNV_LEAK_3.3				Catastrophic Rupture		
734		DNV_LEAK_3.3				Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
735		DNV_LEAK_3.3				Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
736		DNV_LEAK_3.3				Release from hole with eff. diam. of 25 mm (1 in) diam.		
737		DNV_LEAK_3.3				Release from hole with eff. diam. of 50 mm (2 in) diam.		
738		DNV_LEAK_3.3				Release from hole with eff. diam. of 100 mm (4 in) diam.		
739					Gasket Flange: 6"≤D<12"			
740					Catastrophic Rupture			
741					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
742					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
743					Release from hole with eff. diam. of 25 mm (1 in) diam.			
744					Release from hole with eff. diam. of 50 mm (2 in) diam.			
745					Release from hole with eff. diam. of 100 mm (4 in) diam.			
746						Gasket Flange- Cryogenic: 6"≤D<12"		
747						Catastrophic Rupture		
748						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
749						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
750						Release from hole with eff. diam. of 25 mm (1 in) diam.		
751						Release from hole with eff. diam. of 50 mm (2 in) diam.		
752						Release from hole with eff. diam. of 100 mm (4 in) diam.		
753						Gasket Flange- Non Cryogenic: 6"≤D<12"		
754		DNV_LEAK_3.3				Catastrophic Rupture		
755		DNV_LEAK_3.3				Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
756		DNV_LEAK_3.3				Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
757		DNV_LEAK_3.3				Release from hole with eff. diam. of 25 mm (1 in) diam.		
758		DNV_LEAK_3.3				Release from hole with eff. diam. of 50 mm (2 in) diam.		
759		DNV_LEAK_3.3				Release from hole with eff. diam. of 100 mm (4 in) diam.		
760					Gasket Flange: 12"≤D<20"			
761					Catastrophic Rupture			
762					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
763					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
764					Release from hole with eff. diam. of 25 mm (1 in) diam.			
765					Release from hole with eff. diam. of 50 mm (2 in) diam.			
766					Release from hole with eff. diam. of 100 mm (4 in) diam.			
767						Gasket Flange- Cryogenic: 12"≤D<20"		
768						Catastrophic Rupture		
769						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
770						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
771						Release from hole with eff. diam. of 25 mm (1 in) diam.		
772						Release from hole with eff. diam. of 50 mm (2 in) diam.		
773						Release from hole with eff. diam. of 100 mm (4 in) diam.		
774						Gasket Flange- Non Cryogenic: 12"≤D<20"		
775		DNV_LEAK_3.3				Catastrophic Rupture		
776		DNV_LEAK_3.3				Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
777		DNV_LEAK_3.3				Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
778		DNV_LEAK_3.3				Release from hole with eff. diam. of 25 mm (1 in) diam.		
779		DNV_LEAK_3.3				Release from hole with eff. diam. of 50 mm (2 in) diam.		
780		DNV_LEAK_3.3				Release from hole with eff. diam. of 100 mm (4 in) diam.		

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Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
781					Gasket Flange: 20"≤D<40"			
782					Catastrophic Rupture			
783					Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
784					Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
785					Release from hole with eff. diam. of 25 mm (1 in) diam.			
786					Release from hole with eff. diam. of 50 mm (2 in) diam.			
787					Release from hole with eff. diam. of 100 mm (4 in) diam.			
788						Gasket Flange- Cryogenic: 20"≤D<40"		
789						Catastrophic Rupture		
790						Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
791						Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
792						Release from hole with eff. diam. of 25 mm (1 in) diam.		
793						Release from hole with eff. diam. of 50 mm (2 in) diam.		
794						Release from hole with eff. diam. of 100 mm (4 in) diam.		
795						Gasket Flange- Non Cryogenic: 20"≤D<40"		
796		DNV_LEAK_3.3				Catastrophic Rupture		
797		DNV_LEAK_3.3				Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
798		DNV_LEAK_3.3				Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
799		DNV_LEAK_3.3				Release from hole with eff. diam. of 25 mm (1 in) diam.		
800		DNV_LEAK_3.3				Release from hole with eff. diam. of 50 mm (2 in) diam.		
801		DNV_LEAK_3.3				Release from hole with eff. diam. of 100 mm (4 in) diam.		
181			Piping: All diameters					
182			Catastrophic Rupture					
183			Release from hole with eff. diam. of 1/3 diam.					
184			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)					
185			Release from hole with eff. diam. of 25mm (1 in)					
186				Piping: d < 50mm (2-inch)				
187	Yes	59A_16, CCPS_89, INL_CHEM_95, IOGP_434_1, HSE_FRED_JUN_12		Catastrophic Rupture				
188				Release from hole with eff. diam. of 1/3 diam.				
189				Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
190	Yes	HSE_FRED_JUN_12		Release from hole with eff. diam. of 25mm (1 in)				
191					Piping: d < 50mm (2-inch) - Non-Cryogenic			
192		DNV_LEAK_3.3, LNE_09, RIVM_BEVI_09			Catastrophic Rupture			
193		DNV_LEAK_3.3			Release from hole with eff. diam. of 1/3 diam.			
194		DNV_LEAK_3.3, RIVM_BEVI_09			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
195		DNV_LEAK_3.3			Release from hole with eff. diam. of 25mm (1 in)			
196					Piping: d < 50mm (2-inch) - Cryogenic			
197					Catastrophic Rupture			
198					Release from hole with eff. diam. of 1/3 diam.			
199					Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
200		GRI_LNG_FRD_81			Release from hole with eff. diam. of 25mm (1 in)			
201						Piping: d < 50mm (2-inch) - Cryogenic - VJ PIPING		
202						Catastrophic Rupture		
203						Release from hole with eff. diam. of 1/3 diam.		
204						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
205						Release from hole with eff. diam. of 25mm (1 in)		
206						Piping: d < 50mm (2-inch) - Cryogenic - NON-VJ PIPING		
207						Catastrophic Rupture		
208						Release from hole with eff. diam. of 1/3 diam.		
209						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
210						Release from hole with eff. diam. of 25mm (1 in)		
211				Piping: 50mm (2-inch) ≤ d < 149mm (6-inch)				
212	Yes	59A_16, CCPS_89, INL_CHEM_95, IOGP_434_1, LEES_12, PNL_PSRP_82, RIVM_BEVI_09, TNO_PURPLE_05, HSE_FRED_JUN_12		Catastrophic Rupture				
213		IOGP_434_1		Release from hole with eff. diam. of 1/3 diam.				
214		RIVM_BEVI_09		Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
215	Yes	HSE_FRED_JUN_12		Release from hole with eff. diam. of 25mm (1 in)				
216					Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Non-Cryogenic			
217		DNV_LEAK_3.3, EGIG_15, LNE_09, PHMSA_HL_GTI_16, PHMSA_NGT_GTI_16			Catastrophic Rupture			
218		DNV_LEAK_3.3			Release from hole with eff. diam. of 1/3 diam.			
219		DNV_LEAK_3.3			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
220		DNV_LEAK_3.3, EGIG_15			Release from hole with eff. diam. of 25mm (1 in)			
221					Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic			
222					Catastrophic Rupture			
223					Release from hole with eff. diam. of 1/3 diam.			
224					Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
225		GRI_LNG_FRD_81			Release from hole with eff. diam. of 25mm (1 in)			
226						Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic - VJ PIPING		
227						Catastrophic Rupture		
228						Release from hole with eff. diam. of 1/3 diam.		
229						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
230						Release from hole with eff. diam. of 25mm (1 in)		
231						Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic - NON-VJ PIPING		
232						Catastrophic Rupture		
233						Release from hole with eff. diam. of 1/3 diam.		
234						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
235						Release from hole with eff. diam. of 25mm (1 in)		
236				Piping: 150mm (6-inch) ≤ d < 299mm (12-inch)				
237	Yes	59A_16, CCPS_89, INL_CHEM_95, LEES_12, PNL_PSRP_82, HSE_FRED_JUN_12		Catastrophic Rupture				
238	Yes	PNL_PSRP_82, HSE_FRED_JUN_12		Release from hole with eff. diam. of 1/3 diam.				
239				Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
240	Yes	HSE_FRED_JUN_12		Release from hole with eff. diam. of 25mm (1 in)				

Appendix C: Equipment Protocol Framework and Applied References

Index	Current PHMSA FRT Spec	Reference Source Applied	Super Category Comparison	Current FRT Category	Potential FRT SubCategory1	Potential FRT SubCategory2	Potential FRT Subcategory3	Potential FRT SubCategory4
241					Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Non-Cryogenic			
242		DNV_LEAK_3.3, EGIG_15, INL_VJ_10, LNE_09, PHMSA_HL_GTI_16, PHMSA_NGT_GTI_16			Catastrophic Rupture			
243		DNV_LEAK_3.3			Release from hole with eff. diam. of 1/3 diam.			
244		DNV_LEAK_3.3			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
245		DNV_LEAK_3.3, EGIG_15			Release from hole with eff. diam. of 25mm (1 in)			
246					Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic			
247					Catastrophic Rupture			
248					Release from hole with eff. diam. of 1/3 diam.			
249					Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
250		GRI_LNG_FRD_81			Release from hole with eff. diam. of 25mm (1 in)			
251						Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic - VJ PIPING		
252						Catastrophic Rupture		
253						Release from hole with eff. diam. of 1/3 diam.		
254						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
255						Release from hole with eff. diam. of 25mm (1 in)		
256						Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic - NON-VJ PIPING		
257						Catastrophic Rupture		
258						Release from hole with eff. diam. of 1/3 diam.		
259						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
260						Release from hole with eff. diam. of 25mm (1 in)		
261				Piping: 300mm (12-inch) ≤ d < 499mm (20-inch)				
262	Yes	59A_16, CCPS_89, INL_CHEM_95, PNL_PSRP_82, HSE_FRED_JUN_12		Catastrophic Rupture				
263	Yes	HSE_FRED_JUN_12		Release from hole with eff. diam. of 1/3 diam.				
264	Yes			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
265	Yes	HSE_FRED_JUN_12		Release from hole with eff. diam. of 25mm (1 in)				
266					Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Non-Cryogenic			
267		DNV_LEAK_3.3, EGIG_15, INL_VJ_10, LNE_09, PHMSA_HL_GTI_16, PHMSA_NGT_GTI_16			Catastrophic Rupture			
268		DNV_LEAK_3.3			Release from hole with eff. diam. of 1/3 diam.			
269		DNV_LEAK_3.3, EGIG_15			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
270		DNV_LEAK_3.3			Release from hole with eff. diam. of 25mm (1 in)			
271					Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic			
272					Catastrophic Rupture			
273					Release from hole with eff. diam. of 1/3 diam.			
274					Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
275					Release from hole with eff. diam. of 25mm (1 in)			
276						Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic - VJ PIPING		
277						Catastrophic Rupture		
278						Release from hole with eff. diam. of 1/3 diam.		
279						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
280						Release from hole with eff. diam. of 25mm (1 in)		
281						Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic - NON-VJ PIPING		
282						Catastrophic Rupture		
283						Release from hole with eff. diam. of 1/3 diam.		
284						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
285						Release from hole with eff. diam. of 25mm (1 in)		
286				Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch)				
287	Yes	59A_16, CCPS_89, INL_CHEM_95, RIVM_BEVI_09, HSE_FRED_JUN_12		Catastrophic Rupture				
288	Yes	HSE_FRED_JUN_12		Release from hole with eff. diam. of 1/3 diam.				
289	Yes	RIVM_BEVI_09		Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
290	Yes	HSE_FRED_JUN_12		Release from hole with eff. diam. of 25mm (1 in)				
291					Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Non-Cryogenic			
292		DNV_LEAK_3.3, EGIG_15, LNE_09, PHMSA_HL_GTI_16, PHMSA_NGT_GTI_16			Catastrophic Rupture			
293		DNV_LEAK_3.3			Release from hole with eff. diam. of 1/3 diam.			
294		DNV_LEAK_3.3			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
295		DNV_LEAK_3.3, EGIG_15			Release from hole with eff. diam. of 25mm (1 in)			
296					Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic			
297					Catastrophic Rupture			
298					Release from hole with eff. diam. of 1/3 diam.			
299					Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
300					Release from hole with eff. diam. of 25mm (1 in)			
301						Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic - VJ PIPING		
302						Catastrophic Rupture		
303						Release from hole with eff. diam. of 1/3 diam.		
304						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
305						Release from hole with eff. diam. of 25mm (1 in)		
306						Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic - NON-VJ PIPING		
307						Catastrophic Rupture		
308						Release from hole with eff. diam. of 1/3 diam.		
309						Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
310						Release from hole with eff. diam. of 25mm (1 in)		

Appendix D: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
1														Ambient Atm. Storage Tanks					
2		2.47E-03	4.95E-03			2.48E-03	4.99E-03			3.16E-03	5.97E-03			Catastrophic Failure, Release to Atmosphere					
3		9.98E-05	9.98E-05			9.98E-05	9.98E-05			9.98E-05	9.98E-05			Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
4		2.50E-03	2.50E-03			2.50E-03	2.50E-03			2.50E-03	2.50E-03			Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
5														Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
6														Refrigerated Atm. Storage Tanks (Typ. Single Shell)					
7		2.30E-03	2.30E-03			2.32E-03	2.32E-03			3.25E-03	3.25E-03			Catastrophic Failure, Release to Atmosphere					
8														Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
9														Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
10		1.26E-03	1.26E-03			1.26E-03	1.26E-03			1.26E-03	1.26E-03			Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
11														Cryogenic Atm. Storage Tanks					
12		7.22E-04	7.22E-04	5.25E-06	5.25E-06	7.40E-04	7.40E-04	5.17E-06	5.17E-06	7.82E-04	7.82E-04	5.25E-06	5.25E-06	Catastrophic Failure, Release to Atmosphere					
311		6.86E-05	6.86E-05	1.89E-05	1.89E-05	5.36E-05	5.36E-05	1.89E-05	1.89E-05	6.86E-05	6.86E-05	1.89E-05	1.89E-05	Catastrophic Failure of Tank Roof					
13		2.90E-05	2.90E-05	1.01E-06	1.01E-06	2.06E-05	2.06E-05	1.01E-06	1.01E-06	2.90E-05	2.90E-05	1.01E-06	1.01E-06	Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
14		2.39E-05	2.39E-05	3.06E-06	3.06E-06	1.75E-05	1.75E-05	3.06E-06	3.06E-06	2.39E-05	2.39E-05	3.06E-06	3.06E-06	Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
15		1.44E-03	1.44E-03			1.44E-03	1.44E-03			1.44E-03	1.44E-03			Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
16															Single Cont. Cryo. Atm. Storage Tanks				
17	5.00E-06	1.14E-03	1.14E-03	2.99E-05	2.99E-05	1.17E-03	1.17E-03	2.99E-05	2.99E-05	1.29E-03	1.29E-03	2.99E-05	2.99E-05		Catastrophic Failure, Release to Atmosphere				
312	1.00E-04	2.00E-04	2.00E-04			2.00E-04	2.00E-04			2.00E-04	2.00E-04				Catastrophic Failure of Tank Roof				
18	8.00E-05	1.00E-04	1.00E-04			1.00E-04	1.00E-04			1.00E-04	1.00E-04				Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
19	2.00E-04	8.00E-05	8.00E-05			8.00E-05	8.00E-05			8.00E-05	8.00E-05				Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
20	1.00E-04	1.19E-03	1.19E-03			1.19E-03	1.19E-03			1.19E-03	1.19E-03				Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
21																Single Cont. Cryo. Atm. Storage Tanks - HC Only (LNG, Ethane, Ethylene) - Self-Supp. Inner Tank			
22																Catastrophic Failure, Release to Atmosphere			
313																Catastrophic Failure of Tank Roof			
23																Release from a hole in inner tank with eff. diam. of 1 m (~3ft)			
24																Release from a hole in inner tank with eff. diam. of .3 m (~1ft)			
25																Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)			
26																Single Cont. Cryo. Atm. Storage Tanks - LIN/LOX/LAR - Self-Supp. Inner Tank			
27		2.20E-05	2.20E-05			2.20E-05	2.20E-05			2.20E-05	2.20E-05					Catastrophic Failure, Release to Atmosphere			
314																Catastrophic Failure of Tank Roof			
28																Release from a hole in inner tank with eff. diam. of 1 m (~3ft)			
29																Release from a hole in inner tank with eff. diam. of .3 m (~1ft)			
30																Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)			
31															Double Cont. Cryo. Atm. Storage Tanks				
32	5.00E-07	3.23E-08	3.23E-08	7.44E-08	7.44E-08	3.19E-08	3.19E-08	7.39E-08	7.38E-08	4.64E-08	4.64E-08	7.45E-08	7.44E-08		Catastrophic Failure, Release to Atmosphere				
315	1.00E-04	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05		Catastrophic Failure of Tank Roof				
33	1.00E-05	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06		Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
34	3.00E-05	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06		Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
35	1.00E-04	1.32E-03	1.32E-03			1.32E-03	1.32E-03			1.32E-03	1.32E-03				Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
36															Full Cont. Cryo. Atm. Storage Tanks				
37	1.00E-08	2.31E-07	2.31E-07	7.47E-07	7.47E-07	2.22E-07	2.22E-07	7.27E-07	7.27E-07	4.02E-07	4.02E-07	7.47E-07	7.47E-07		Catastrophic Failure, Release to Atmosphere				
316	4.00E-05	2.42E-10	2.46E-10	2.43E-10	2.43E-10	2.41E-10	2.46E-10	2.47E-10	2.47E-10	2.43E-10	2.44E-10	2.41E-10	2.43E-10		Catastrophic Failure of Tank Roof				
38	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06		Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
39	3.00E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06		Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
40	1.00E-04	2.40E-03	2.40E-03			2.40E-03	2.40E-03			2.40E-03	2.40E-03				Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
41															Membrane. Cryo. Atm. Storage Tanks				
42		2.11E-06	2.11E-06	4.46E-06	4.46E-06	2.05E-06	2.05E-06	4.46E-06	4.46E-06	3.14E-06	3.14E-06	4.46E-06	4.46E-06		Catastrophic Failure, Release to Atmosphere				
317															Catastrophic Failure of Tank Roof				
43															Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
44															Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
45															Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
46															Process Vessels, Distillation Columns, Heat Exchangers, and Condensers				
47	5.00E-06	2.05E-02	1.89E-02	2.72E-01	2.72E-01	2.32E-02	2.34E-02	2.72E-01	2.72E-01	3.06E-02	3.04E-02	2.72E-01	2.72E-01		Catastrophic Failure (Rupture)				
48	1.00E-04	1.22E-03	1.22E-03			1.26E-03	1.26E-03			1.13E-03	1.13E-03				Release from a hole with eff. diam. of 0.01m (0.4 in)				
802		3.26E-04	3.77E-04			2.94E-04	3.56E-04			4.00E-04	4.27E-04				Release from a hole with eff. diam. of 0.025m (1 in)				
803		1.16E-04	1.16E-04			1.17E-04	1.17E-04			1.22E-04	1.22E-04				Release from a hole with eff. diam. of 0.05m (2 in)				
804		9.97E-05	1.23E-04			8.89E-05	1.16E-04			1.22E-04	1.34E-04				Release from a hole with eff. diam. of 0.10m (4 in)				
49																Process Vessels incl Distillation Columns			
50		4.16E-03	3.65E-05			3.28E-03	3.36E-05			7.14E-03	5.28E-05					Catastrophic Failure (Rupture)			
51		1.94E-04	1.94E-04			1.66E-04	1.66E-04			2.99E-04	2.99E-04					Release from a hole with eff. diam. of 0.01m (0.4 in)			
805		9.47E-05	1.06E-04			8.11E-05	9.24E-05			1.41E-04	1.51E-04					Release from a hole with eff. diam. of 0.025m (1 in)			
806		3.73E-05	3.73E-05			3.87E-05	3.87E-05			4.29E-05	4.29E-05					Release from a hole with eff. diam. of 0.05m (2 in)			
807		4.59E-05	6.06E-05			3.85E-05	5.37E-05			6.53E-05	7.53E-05					Release from a hole with eff. diam. of 0.10m (4 in)			
52																	PVs incl Dist. Columns - Single Wall		
53		5.18E-03	3.89E-05			4.20E-03	3.51E-05			8.30E-03	5.86E-05						Catastrophic Failure (Rupture)		
54		2.22E-04	2.22E-04			1.93E-04	1.93E-04			3.28E-04	3.28E-04						Release from a hole with eff. diam. of 0.01m (0.4 in)		
808		9.47E-05	1.06E-04			8.11E-05	9.24E-05			1.41E-04	1.51E-04						Release from a hole with eff. diam. of 0.025m (1 in)		
809		3.73E-05	3.73E-05			3.87E-05	3.87E-05			4.29E-05	4.29E-05						Release from a hole with eff. diam. of 0.05m (2 in)		
810		4.59E-05	6.06E-05			3.85E-05	5.37E-05			6.53E-05	7.53E-05						Release from a hole with eff. diam. of 0.10m (4 in)		
318																		Pressure Storage Vessels/Tanks (Single Wall)	
319		1.28E-05	1.44E-05			1.44E-05	1.54E-05			1.39E-05	1.80E-05							Catastrophic Failure (Rupture)	
320		1.10E-05	1.10E-05			1.11E-05	1.11E-05			1.07E-05	1.07E-05							Release from a hole with eff. diam. of 0.01m (0.4 in)	
380		4.57E-06	4.57E-06			4.52E-06	4.52E-06			4.69E-06	4.69E-06							Release from a hole with eff. diam. of 0.025m (1 in)	
381		4.99E-06	4.99E-06			4.99E-06	4.99E-06			4.99E-06	4.99E-06							Release from a hole with eff. diam. of 0.05m (2 in)	
382		4.17E-06	4.17E-06			4.17E-06	4.17E-06			4.17E-06	4.17E-06							Release from a hole with eff. diam. of 0.10m (4 in)	
321																		Process Vessels (Single Wall)	
322		8.46E-05	8.46E-05			7.47E-05	7.47E-05			1.17E-04	1.17E-04							Catastrophic Failure (Rupture)	
323		4.28E-04	4.28E-04			3.86E-04	3.86E-04			5.29E-04	5.29E-04							Release from a hole with eff. diam. of 0.01m (0.4 in)	
383		Some cells shaded to protect copyrights or licensed software																Release from a hole with eff. diam. of 0.025m (1 in)	
384																		Release from a hole with eff. diam. of 0.05m (2 in)	
386																		Release from a hole with eff. diam. of 0.10m (4 in)	
55																		Mole Sieve Vessel (Single Wall)	
56																		Catastrophic Failure (Rupture)	
57																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
387																		Release from a hole with eff. diam. of 0.025m (1 in)	
388																		Release from a hole with eff. diam. of 0.05m (2 in)	
389																		Release from a hole with eff. diam. of 0.10m (4 in)	
58																		Distillation Columns (Single Wall)	
59																		Catastrophic Failure (Rupture)	
60		1.00E-04	1.00E-04			1.00E-04	1.00E-04			1.00E-04	1.00E-04							Release from a hole with eff. diam. of 0.01m (0.4 in)	
390																		Release from a hole with eff. diam. of 0.025m (1 in)	
391																		Release from a hole with eff. diam. of 0.05m (2 in)	
392																		Release from a hole with eff. diam. of 0.10m (4 in)	
61																		Separator (Single Wall)	
62																		Catastrophic Failure (Rupture)	
63																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
393																		Release from a hole with eff. diam. of 0.025m (1 in)	
394																		Release from a hole with eff. diam. of 0.05m (2 in)	
395																		Release from a hole with eff. diam. of 0.10m (4 in)	
64																	PVs incl Dist. Columns - Double Wall (cryogenic)		
65																	Catastrophic Failure (Rupture)		
66																	Release from a hole with eff. diam. of 0.01m (0.4 in)		
396																	Release from a hole with eff. diam. of 0.025m (1 in)		
397																	Release from a hole with eff. diam. of 0.05m (2 in)		

Appendix D: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
398																	Release from a hole with eff. diam. of 0.10m (4 in)		
70																	ISO Containers		
71		2.95E-06	2.95E-06			2.95E-06	2.95E-06			2.95E-06	2.95E-06						Catastrophic Failure (Rupture)		
72		6.01E-05	6.01E-05			6.01E-05	6.01E-05			6.01E-05	6.01E-05						Release from a hole with eff. diam. of 0.01m (0.4 in)		
399																	Release from a hole with eff. diam. of 0.025m (1 in)		
400																	Release from a hole with eff. diam. of 0.05m (2 in)		
401																	Release from a hole with eff. diam. of 0.10m (4 in)		
73																Heat Exchangers incl. Condensers			
74		3.70E-02	3.84E-02	2.72E-01	2.72E-01	4.39E-02	4.94E-02	2.72E-01	2.72E-01	4.86E-02	5.07E-02	2.72E-01	2.72E-01			Catastrophic Failure (Rupture)			
75		1.91E-03	1.91E-03			2.09E-03	2.09E-03			1.52E-03	1.52E-03					Release from a hole with eff. diam. of 0.01m (0.4 in)			
402		4.64E-04	5.44E-04			4.37E-04	5.44E-04			5.11E-04	5.44E-04					Release from a hole with eff. diam. of 0.025m (1 in)			
403		1.56E-04	1.56E-04			1.56E-04	1.56E-04			1.56E-04	1.56E-04					Release from a hole with eff. diam. of 0.05m (2 in)			
404		1.17E-04	1.41E-04			1.07E-04	1.36E-04			1.38E-04	1.49E-04					Release from a hole with eff. diam. of 0.10m (4 in)			
76																	Fired Heat Exchangers		
77		2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01				Catastrophic Failure (Rupture)		
78																	Release from a hole with eff. diam. of 0.01m (0.4 in)		
405																	Release from a hole with eff. diam. of 0.025m (1 in)		
406																	Release from a hole with eff. diam. of 0.05m (2 in)		
407																	Release from a hole with eff. diam. of 0.10m (4 in)		
324																		Submerged Combustion Vaporizers	
325		2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01					Catastrophic Failure (Rupture)	
326																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
408																		Release from a hole with eff. diam. of 0.025m (1 in)	
409																		Release from a hole with eff. diam. of 0.05m (2 in)	
410																		Release from a hole with eff. diam. of 0.10m (4 in)	
79																	Non-Fired Heat Exchangers incl. Condensers		
80		1.02E-02	1.34E-04			8.60E-03	1.20E-04			1.39E-02	1.67E-04						Catastrophic Failure (Rupture)		
81		2.02E-03	2.02E-03			2.25E-03	2.25E-03			1.56E-03	1.56E-03						Release from a hole with eff. diam. of 0.01m (0.4 in)		
411		4.64E-04	5.44E-04			4.37E-04	5.44E-04			5.11E-04	5.44E-04						Release from a hole with eff. diam. of 0.025m (1 in)		
412		1.56E-04	1.56E-04			1.56E-04	1.56E-04			1.56E-04	1.56E-04						Release from a hole with eff. diam. of 0.05m (2 in)		
413		1.17E-04	1.41E-04			1.07E-04	1.36E-04			1.38E-04	1.49E-04						Release from a hole with eff. diam. of 0.10m (4 in)		
82																		Shell & Tube Heat Exchangers	
83		1.41E-03	8.30E-05			1.20E-03	7.66E-05			1.89E-03	9.87E-05							Catastrophic Failure (Rupture)	
84		1.16E-03	1.16E-03			1.24E-03	1.24E-03			9.97E-04	9.97E-04							Release from a hole with eff. diam. of 0.01m (0.4 in)	
414		3.42E-04	3.94E-04			3.25E-04	3.94E-04			3.73E-04	3.94E-04							Release from a hole with eff. diam. of 0.025m (1 in)	
415		1.01E-04	1.01E-04			1.01E-04	1.01E-04			1.01E-04	1.01E-04							Release from a hole with eff. diam. of 0.05m (2 in)	
416		6.91E-05	8.13E-05			6.25E-05	7.72E-05			8.29E-05	8.90E-05							Release from a hole with eff. diam. of 0.10m (4 in)	
85																			Tube-side Heat Exchangers (HC in tube)
86		1.67E-04	8.85E-05			1.81E-04	8.41E-05			1.92E-04	9.79E-05								Catastrophic Failure (Rupture)
87																			Release from a hole with eff. diam. of 0.01m (0.4 in)
417																			Release from a hole with eff. diam. of 0.025m (1 in)
418																			Release from a hole with eff. diam. of 0.05m (2 in)
419																			Release from a hole with eff. diam. of 0.10m (4 in)
88																			Shell-side Heat Exchangers (HC in shell)
89		7.81E-05	1.03E-04			7.08E-05	9.75E-05			9.99E-05	1.14E-04								Catastrophic Failure (Rupture)
90																			Release from a hole with eff. diam. of 0.01m (0.4 in)
420																			Release from a hole with eff. diam. of 0.025m (1 in)
421																			Release from a hole with eff. diam. of 0.05m (2 in)
422																			Release from a hole with eff. diam. of 0.10m (4 in)
91																		Plate Heat Exchangers	
92		2.89E-02	2.36E-04			2.43E-02	1.99E-04			4.11E-02	3.48E-04							Catastrophic Failure (Rupture)	
93																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
423																		Release from a hole with eff. diam. of 0.025m (1 in)	
424																		Release from a hole with eff. diam. of 0.05m (2 in)	
425																		Release from a hole with eff. diam. of 0.10m (4 in)	
94																		Air Cooled (Fin Fan) Heat Exchangers	
95		3.00E-05	4.87E-05			2.59E-05	4.87E-05			3.95E-05	4.87E-05							Catastrophic Failure (Rupture)	
96																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
426																		Release from a hole with eff. diam. of 0.025m (1 in)	
427																		Release from a hole with eff. diam. of 0.05m (2 in)	
428																		Release from a hole with eff. diam. of 0.10m (4 in)	
97																		Printed Heat Exchangers	
98																		Catastrophic Failure (Rupture)	
99																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
429																		Release from a hole with eff. diam. of 0.025m (1 in)	
430																		Release from a hole with eff. diam. of 0.05m (2 in)	
431																		Release from a hole with eff. diam. of 0.10m (4 in)	
100																		Plate-Fin Heat Exchangers	
101																		Catastrophic Failure (Rupture)	
102																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
432																		Release from a hole with eff. diam. of 0.025m (1 in)	
433																		Release from a hole with eff. diam. of 0.05m (2 in)	
434																		Release from a hole with eff. diam. of 0.10m (4 in)	
103																		Ambient Vaporizer Heat Exchangers	
104																		Catastrophic Failure (Rupture)	
105																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
435																		Release from a hole with eff. diam. of 0.025m (1 in)	
436																		Release from a hole with eff. diam. of 0.05m (2 in)	
437																		Release from a hole with eff. diam. of 0.10m (4 in)	
106															Truck Transfer Arm				
107	3.00E-04	1.51E-05	1.51E-05			1.51E-05	1.51E-05			1.51E-05	1.51E-05				Rupture of transfer arm				
108	3.00E-03	2.09E-04	2.09E-04			2.09E-04	2.09E-04			2.09E-04	2.09E-04				Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
109																Truck Transfer Arm - Cryogenic			
110																Rupture of transfer arm			
111																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
112																Truck Transfer Arm - Non-cryogenic			
113																Rupture of transfer arm			
114																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
115															Ship Transfer Arm				
116	2.00E-05	1.03E-03	1.11E-03			1.02E-03	1.11E-03			1.03E-03	1.11E-03				Rupture of transfer arm				
117	2.00E-04	1.89E-02	1.89E-02			1.89E-02	1.89E-02			1.89E-02	1.89E-02				Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
118																Ship Transfer Arm - Cryogenic			
119																Rupture of transfer arm			
120																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
121																Ship Transfer Arm - Non-cryogenic			
122																Rupture of transfer arm			
123																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
124															Truck Transfer Hose				
125	4.00E-02	7.25E-03	4.92E-03			7.47E-03	5.06E-03			1.05E-02	5.07E-03				Rupture of transfer hose				
126	4.00E-01	2.82E-02	2.82E-02			2.82E-02	2.82E-02			2.82E-02	2.82E-02				Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
127																Truck Transfer Hose - Cryogenic			
128																Rupture of transfer hose			
129																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
130																Truck Transfer Hose - Non-cryogenic			
131		4.00E-04	4.00E-04			4.00E-04	4.00E-04			4.00E-04	4.00E-04					Rupture of transfer hose			

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132																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
133															Ship Transfer Hose				
134		2.71E-03	4.00E-03			2.61E-03	4.00E-03			2.71E-03	4.00E-03				Rupture of transfer hose				
135		4.00E-02	4.00E-02			4.00E-02	4.00E-02			4.00E-02	4.00E-02				Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
136																Ship Transfer Hose - Cryogenic			
137																Rupture of transfer hose			
138																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
139																Ship Transfer Hose - Non-cryogenic			
140																Rupture of transfer hose			
141																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
142															Valve: All diameters				
143	9.00E-06	1.98E-03	1.14E-04			1.83E-03	1.46E-04			2.10E-03	8.27E-05				Catastrophic Rupture				
327		2.01E-04	2.01E-04			2.01E-04	2.01E-04			2.01E-04	2.01E-04				Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
144															Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
328															Release from hole with eff. diam. of 25 mm (1 in) diam.				
329															Release from hole with eff. diam. of 50 mm (2 in) diam.				
330															Release from hole with eff. diam. of 100 mm (4 in) diam.				
145																Manual Valves: All diameters			
146		2.12E-04	2.13E-04			2.73E-04	2.80E-04			1.48E-04	1.44E-04					Catastrophic Rupture			
331																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
147																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
332																Release from hole with eff. diam. of 25 mm (1 in) diam.			
333																Release from hole with eff. diam. of 50 mm (2 in) diam.			
334																Release from hole with eff. diam. of 100 mm (4 in) diam.			
148																	Manual Valves - Cryogenic: All diameters		
149																	Catastrophic Rupture		
335																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
150																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
336																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
337																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
338																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
151																	Manual Valves - Non-cryogenic: All diameters		
152		1.41E-05	5.82E-06			1.73E-05	5.82E-06			1.41E-05	5.83E-06						Catastrophic Rupture		
339																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
153																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
340																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
341																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
342																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
154																Actuated Valves: All diameters			
155		2.70E-05	2.18E-05			3.01E-05	2.33E-05			2.70E-05	2.18E-05					Catastrophic Rupture			
343																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
156																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
344																Release from hole with eff. diam. of 25 mm (1 in) diam.			
345																Release from hole with eff. diam. of 50 mm (2 in) diam.			
346																Release from hole with eff. diam. of 100 mm (4 in) diam.			
157																	Actuated Valves - Cryogenic: All diameters		
158																	Catastrophic Rupture		
347																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
159																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
348																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
349																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
350																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
160																	Actuated Valves - Non-cryogenic: All diameters		
161		2.70E-05	2.18E-05			3.01E-05	2.33E-05			2.70E-05	2.18E-05						Catastrophic Rupture		
351																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
162																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
352																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
353																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
354																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
438																Valve: 2"≤D<6"			
439																Catastrophic Rupture			
440																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
441																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
442																Release from hole with eff. diam. of 25 mm (1 in) diam.			
443																Release from hole with eff. diam. of 50 mm (2 in) diam.			
444																Release from hole with eff. diam. of 100 mm (4 in) diam.			
445																	Manual Valves: 2"≤D<6"		
446																	Catastrophic Rupture		
447																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
448																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
449																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
450																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
451																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
452																		Manual Valves - Cryogenic: 2"≤D<6"	
453																		Catastrophic Rupture	
454																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
455																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
456																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
457																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
458																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
459																		Manual Valves - Non-cryogenic: 2"≤D<6"	
460																		Catastrophic Rupture	
461																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
462																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
463																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
464																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
465																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
466																	Actuated Valves: 2"≤D<6"		
467																	Catastrophic Rupture		
468																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
469																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
470																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
471																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
472																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
473																		Actuated Valves - Cryogenic: 2"≤D<6"	
474																		Catastrophic Rupture	
475																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
476																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
477																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
478																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
479																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
480																		Actuated Valves - Non-cryogenic: 2"≤D<6"	
481																		Catastrophic Rupture	
482																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
483																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	

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484																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
485																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
486																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
487																Valve: 6"≤D<12"			
488																Catastrophic Rupture			
489																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
490																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
491																Release from hole with eff. diam. of 25 mm (1 in) diam.			
492																Release from hole with eff. diam. of 50 mm (2 in) diam.			
493																Release from hole with eff. diam. of 100 mm (4 in) diam.			
494																	Manual Valves: 6"≤D<12"		
495																	Catastrophic Rupture		
496																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
497																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
498																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
499																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
500																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
501																		Manual Valves - Cryogenic: 6"≤D<12"	
502																		Catastrophic Rupture	
503																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
504																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
505																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
506																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
507																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
508																		Manual Valves - Non-cryogenic: 6"≤D<12"	
509																		Catastrophic Rupture	
510																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
511																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
512																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
513																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
514																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
515																	Actuated Valves: 6"≤D<12"		
516																	Catastrophic Rupture		
517																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
518																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
519																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
520																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
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523																		Catastrophic Rupture	
524																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
525																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
526																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
527																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
528																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
529																		Actuated Valves - Non-cryogenic: 6"≤D<12"	
530																		Catastrophic Rupture	
531																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
532																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
533																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
534																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
535																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
536																Valve: 12"≤D<20"			
537																Catastrophic Rupture			
538																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
539																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
540																Release from hole with eff. diam. of 25 mm (1 in) diam.			
541																Release from hole with eff. diam. of 50 mm (2 in) diam.			
542																Release from hole with eff. diam. of 100 mm (4 in) diam.			
543																	Manual Valves: 12"≤D<20"		
544																	Catastrophic Rupture		
545																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
546																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
547																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
548																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
549																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
550																		Manual Valves - Cryogenic: 12"≤D<20"	
551																		Catastrophic Rupture	
552																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
553																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
554																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
555																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
556																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
557																		Manual Valves - Non-cryogenic: 12"≤D<20"	
558																		Catastrophic Rupture	
559																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
560																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
561																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
562																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
563																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
564																	Actuated Valves: 12"≤D<20"		
565																	Catastrophic Rupture		
566																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
567																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
568																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
569																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
570																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
571																		Actuated Valves - Cryogenic: 12"≤D<20"	
572																		Catastrophic Rupture	
573																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
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575																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
576																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
577																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
578																		Actuated Valves - Non-cryogenic: 12"≤D<20"	
579																		Catastrophic Rupture	
580																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
581																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
582																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
583																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
584																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
585																Valve: 20"≤D<40"			
586																Catastrophic Rupture			
587																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
588																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			

Appendix D: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential SubCategory3	Potential SubCategory4
589																Release from hole with eff. diam. of 25 mm (1 in) diam.			
590																Release from hole with eff. diam. of 50 mm (2 in) diam.			
591																Release from hole with eff. diam. of 100 mm (4 in) diam.			
592																	Manual Valves: 20"≤D<40"		
593																	Catastrophic Rupture		
594																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
595																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
596																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
597																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
598																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
599																		Manual Valves - Cryogenic: 20"≤D<40"	
600																		Catastrophic Rupture	
601																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
602																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
603																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
604																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
605																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
606																		Manual Valves - Non-cryogenic: 20"≤D<40"	
607																		Catastrophic Rupture	
608																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
609																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
610																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
611																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
612																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
613																	Actuated Valves: 20"≤D<40"		
614																	Catastrophic Rupture		
615																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
616																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
617																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
618																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
619																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
620																		Actuated Valves - Cryogenic: 20"≤D<40"	
621																		Catastrophic Rupture	
622																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
623																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
624																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
625																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
626																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
627																		Actuated Valves - Non-cryogenic: 20"≤D<40"	
628																		Catastrophic Rupture	
629																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
630																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
631																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
632																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
633																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
163															Expansion Joint- All diameters				
164	4.00E-03	1.06E-03	1.06E-03			1.06E-03	1.06E-03			1.29E-03	1.29E-03				Catastrophic Rupture				
355															Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
165															Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
356															Release from hole with eff. diam. of 25 mm (1 in) diam.				
357															Release from hole with eff. diam. of 50 mm (2 in) diam.				
358															Release from hole with eff. diam. of 100 mm (4 in) diam.				
166																Expansion Joint- Cryogenic: All diameters			
167																Catastrophic Rupture			
359																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
168																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
360																Release from hole with eff. diam. of 25 mm (1 in) diam.			
361																Release from hole with eff. diam. of 50 mm (2 in) diam.			
362																Release from hole with eff. diam. of 100 mm (4 in) diam.			
169																Expansion Joint- Non Cryogenic: All diameters			
170																Catastrophic Rupture			
363																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
171																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
364																Release from hole with eff. diam. of 25 mm (1 in) diam.			
365																Release from hole with eff. diam. of 50 mm (2 in) diam.			
366																Release from hole with eff. diam. of 100 mm (4 in) diam.			
634																Expansion Joint: 2"≤D<6"			
635																Catastrophic Rupture			
636																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
637																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
638																Release from hole with eff. diam. of 25 mm (1 in) diam.			
639																Release from hole with eff. diam. of 50 mm (2 in) diam.			
640																Release from hole with eff. diam. of 100 mm (4 in) diam.			
641																	Expansion Joint- Cryogenic: 2"≤D<6"		
642																	Catastrophic Rupture		
643																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
644																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
645																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
646																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
647																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
648																	Expansion Joint- Non Cryogenic: 2"≤D<6"		
649																	Catastrophic Rupture		
650																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
651																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
652																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
653																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
654																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
655																Expansion Joint: 6"≤D<12"			
656																Catastrophic Rupture			
657																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
658																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
659																Release from hole with eff. diam. of 25 mm (1 in) diam.			
660																Release from hole with eff. diam. of 50 mm (2 in) diam.			
661																Release from hole with eff. diam. of 100 mm (4 in) diam.			
662																	Expansion Joint- Cryogenic: 6"≤D<12"		
663																	Catastrophic Rupture		
664																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
665																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
666																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
667																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
668																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
669																	Expansion Joint- Non Cryogenic: 6"≤D<12"		
670																	Catastrophic Rupture		
671																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
672																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		

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Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
673																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
674																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
675																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
676																Expansion Joint: 12"≤D<20"			
677																Catastrophic Rupture			
678																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
679																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
680																Release from hole with eff. diam. of 25 mm (1 in) diam.			
681																Release from hole with eff. diam. of 50 mm (2 in) diam.			
682																Release from hole with eff. diam. of 100 mm (4 in) diam.			
683																	Expansion Joint- Cryogenic: 12"≤D<20"		
684																	Catastrophic Rupture		
685																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
686																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
687																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
688																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
689																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
690																	Expansion Joint- Non Cryogenic: 12"≤D<20"		
691																	Catastrophic Rupture		
692																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
693																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
694																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
695																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
696																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
697																Expansion Joint: 20"≤D<40"			
698																Catastrophic Rupture			
699																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
700																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
701																Release from hole with eff. diam. of 25 mm (1 in) diam.			
702																Release from hole with eff. diam. of 50 mm (2 in) diam.			
703																Release from hole with eff. diam. of 100 mm (4 in) diam.			
704																	Expansion Joint- Cryogenic: 20"≤D<40"		
705																	Catastrophic Rupture		
706																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
707																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
708																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
709																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
710																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
711																	Expansion Joint- Non Cryogenic: 20"≤D<40"		
712																	Catastrophic Rupture		
713																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
714																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
715																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
716																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
717																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
172															Gasket Flange- All diameters				
173	3.00E-02	1.95E-05	1.98E-05			2.41E-05	2.46E-05			1.45E-05	1.47E-05				Catastrophic Rupture				
367		9.47E-05	9.47E-05			9.47E-05	9.47E-05			9.47E-05	9.47E-05				Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
174		5.15E-05	5.15E-05			5.15E-05	5.15E-05			5.15E-05	5.15E-05				Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
368		7.49E-06	7.49E-06			7.39E-06	7.39E-06			7.66E-06	7.66E-06				Release from hole with eff. diam. of 25 mm (1 in) diam.				
369		6.24E-06	6.24E-06			6.00E-06	5.99E-06			6.68E-06	6.68E-06				Release from hole with eff. diam. of 50 mm (2 in) diam.				
370		2.66E-06	2.66E-06			2.66E-06	2.66E-06			2.66E-06	2.66E-06				Release from hole with eff. diam. of 100 mm (4 in) diam.				
175																Gasket Flange- Cryogenic: All Diameters			
176																Catastrophic Rupture			
371																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
177																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
372																Release from hole with eff. diam. of 25 mm (1 in) diam.			
373																Release from hole with eff. diam. of 50 mm (2 in) diam.			
374																Release from hole with eff. diam. of 100 mm (4 in) diam.			
178																Gasket Flange- Non Cryogenic: All Diameters			
179		6.28E-06	6.21E-06			6.30E-06	6.21E-06			6.28E-06	6.21E-06					Catastrophic Rupture			
375																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
180																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
376																Release from hole with eff. diam. of 25 mm (1 in) diam.			
377																Release from hole with eff. diam. of 50 mm (2 in) diam.			
378																Release from hole with eff. diam. of 100 mm (4 in) diam.			
718																Gasket Flange: 2"≤D<6"			
719																Catastrophic Rupture			
720																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
721																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
722																Release from hole with eff. diam. of 25 mm (1 in) diam.			
723																Release from hole with eff. diam. of 50 mm (2 in) diam.			
724																Release from hole with eff. diam. of 100 mm (4 in) diam.			
725																	Gasket Flange- Cryogenic: 2"≤D<6"		
726																	Catastrophic Rupture		
727																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
728																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
729																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
730																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
731																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
732																	Gasket Flange- Non Cryogenic: 2"≤D<6"		
733																	Catastrophic Rupture		
734																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
735																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
736																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
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739																Gasket Flange: 6"≤D<12"			
740																Catastrophic Rupture			
741																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
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743																Release from hole with eff. diam. of 25 mm (1 in) diam.			
744																Release from hole with eff. diam. of 50 mm (2 in) diam.			
745																Release from hole with eff. diam. of 100 mm (4 in) diam.			
746																	Gasket Flange- Cryogenic: 6"≤D<12"		
747																	Catastrophic Rupture		
748																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
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752																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
753																	Gasket Flange- Non Cryogenic: 6"≤D<12"		
754																	Catastrophic Rupture		
755																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
756																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		

Appendix D: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
757																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
758																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
759																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
760																Gasket Flange: 12"≤D<20"			
761																Catastrophic Rupture			
762																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
763																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
764																Release from hole with eff. diam. of 25 mm (1 in) diam.			
765																Release from hole with eff. diam. of 50 mm (2 in) diam.			
766																Release from hole with eff. diam. of 100 mm (4 in) diam.			
767																	Gasket Flange- Cryogenic: 12"≤D<20"		
768																	Catastrophic Rupture		
769																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
770																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
771																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
772																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
773																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
774																	Gasket Flange- Non Cryogenic: 12"≤D<20"		
775																	Catastrophic Rupture		
776																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
777																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
778																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
779																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
780																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
781																Gasket Flange: 20"≤D<40"			
782																Catastrophic Rupture			
783																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
784																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
785																Release from hole with eff. diam. of 25 mm (1 in) diam.			
786																Release from hole with eff. diam. of 50 mm (2 in) diam.			
787																Release from hole with eff. diam. of 100 mm (4 in) diam.			
788																	Gasket Flange- Cryogenic: 20"≤D<40"		
789																	Catastrophic Rupture		
790																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
791																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
792																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
793																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
794																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
795																	Gasket Flange- Non Cryogenic: 20"≤D<40"		
796																	Catastrophic Rupture		
797																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
798																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
799																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
800																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
801																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
181														Piping: All diameters					
182		2.24E-06	3.04E-06			2.01E-06	2.50E-06			2.86E-06	4.65E-06			Catastrophic Rupture					
183		1.75E-06	1.75E-06			1.58E-06	1.58E-06			2.13E-06	2.13E-06			Release from hole with eff. diam. of 1/3 diam.					
184		8.44E-06	1.02E-05			7.86E-06	9.29E-06			9.65E-06	1.22E-05			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)					
185		9.51E-06	1.23E-05	2.30E-05	2.30E-05	1.05E-05	1.28E-05	2.30E-05	2.30E-05	1.08E-05	1.48E-05	2.30E-05	2.30E-05	Release from hole with eff. diam. of 25mm (1 in)					
186															Piping: d < 50mm (2-inch)				
187	1.00E-06	9.95E-06	9.90E-06			8.47E-06	8.37E-06			1.37E-05	1.38E-05				Catastrophic Rupture				
188															Release from hole with eff. diam. of 1/3 diam.				
189															Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
190	5.00E-06														Release from hole with eff. diam. of 25mm (1 in)				
191																Piping: d < 50mm (2-inch) - Non-Cryogenic			
192		1.21E-05	1.21E-05			1.12E-05	1.12E-05			1.48E-05	1.48E-05					Catastrophic Rupture			
193																Release from hole with eff. diam. of 1/3 diam.			
194																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
195																Release from hole with eff. diam. of 25mm (1 in)			
196																Piping: d < 50mm (2-inch) - Cryogenic			
197																Catastrophic Rupture			
198																Release from hole with eff. diam. of 1/3 diam.			
199																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
200		2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05			Release from hole with eff. diam. of 25mm (1 in)			
201																	Piping: d < 50mm (2-inch) - Cryogenic - VJ PIPING		
202																	Catastrophic Rupture		
203																	Release from hole with eff. diam. of 1/3 diam.		
204																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
205																	Release from hole with eff. diam. of 25mm (1 in)		
206																	Piping: d < 50mm (2-inch) - Cryogenic - NON-VJ PIPING		
207																	Catastrophic Rupture		
208																	Release from hole with eff. diam. of 1/3 diam.		
209																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
210																	Release from hole with eff. diam. of 25mm (1 in)		
211															Piping: 50mm (2-inch) ≤ d < 149mm (6-inch)				
212	5.00E-07	1.85E-06	2.22E-06			1.66E-06	1.84E-06			2.49E-06	3.45E-06				Catastrophic Rupture				
213															Release from hole with eff. diam. of 1/3 diam.				
214															Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
215	2.00E-06														Release from hole with eff. diam. of 25mm (1 in)				
216																Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Non-Cryogenic			
217		2.25E-06	5.61E-06			2.34E-06	5.94E-06			2.25E-06	5.61E-06					Catastrophic Rupture			
218																Release from hole with eff. diam. of 1/3 diam.			
219																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
220																Release from hole with eff. diam. of 25mm (1 in)			
221																Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic			
222																Catastrophic Rupture			
223																Release from hole with eff. diam. of 1/3 diam.			
224																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
225		2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05			Release from hole with eff. diam. of 25mm (1 in)			
226																	Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic - VJ PIPING		
227																	Catastrophic Rupture		
228																	Release from hole with eff. diam. of 1/3 diam.		
229																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
230																	Release from hole with eff. diam. of 25mm (1 in)		
231																	Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic - NON-VJ PIPING		
232																	Catastrophic Rupture		
233																	Release from hole with eff. diam. of 1/3 diam.		
234																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
235																	Release from hole with eff. diam. of 25mm (1 in)		
236															Piping: 150mm (6-inch) ≤ d < 299mm (12-inch)				
237	2.00E-07	7.84E-07	9.85E-07			7.40E-07	8.22E-07			9.68E-07	1.51E-06				Catastrophic Rupture				
238	4.00E-07	4.15E-07	4.15E-07			4.61E-07	4.61E-07			2.73E-07	2.73E-07				Release from hole with eff. diam. of 1/3 diam.				
239															Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
240	7.00E-07														Release from hole with eff. diam. of 25mm (1 in)				

Appendix D: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
241																Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Non-Cryogenic			
242		9.51E-07	2.98E-06			9.11E-07	3.16E-06			9.51E-07	2.98E-06					Catastrophic Rupture			
243																Release from hole with eff. diam. of 1/3 diam.			
244																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
245																Release from hole with eff. diam. of 25mm (1 in)			
246																Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic			
247																Catastrophic Rupture			
248																Release from hole with eff. diam. of 1/3 diam.			
249																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
250		2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05			Release from hole with eff. diam. of 25mm (1 in)			
251																	Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic - VJ PIPING		
252																	Catastrophic Rupture		
253																	Release from hole with eff. diam. of 1/3 diam.		
254																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
255																	Release from hole with eff. diam. of 25mm (1 in)		
256																	Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic - NON-VJ PIPING		
257																	Catastrophic Rupture		
258																	Release from hole with eff. diam. of 1/3 diam.		
259																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
260																	Release from hole with eff. diam. of 25mm (1 in)		
261															Piping: 300mm (12-inch) ≤ d < 499mm (20-inch)				
262	7.00E-08	8.65E-07	1.23E-06			8.45E-07	1.05E-06			9.93E-07	1.74E-06				Catastrophic Rupture				
263	2.00E-07	8.91E-08	8.91E-08			1.05E-07	1.05E-07			4.96E-08	4.97E-08				Release from hole with eff. diam. of 1/3 diam.				
264	4.00E-07	1.12E-07	9.62E-08			1.12E-07	9.60E-08			1.12E-07	9.61E-08				Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
265	5.00E-07	1.93E-06	1.93E-06			1.72E-06	1.72E-06			2.47E-06	2.47E-06				Release from hole with eff. diam. of 25mm (1 in)				
266																Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Non-Cryogenic			
267		8.83E-07	2.93E-06			8.50E-07	3.10E-06			8.83E-07	2.93E-06					Catastrophic Rupture			
268																Release from hole with eff. diam. of 1/3 diam.			
269																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
270																Release from hole with eff. diam. of 25mm (1 in)			
271																Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic			
272																Catastrophic Rupture			
273																Release from hole with eff. diam. of 1/3 diam.			
274																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
275																Release from hole with eff. diam. of 25mm (1 in)			
276																	Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic - VJ PIPING		
277																	Catastrophic Rupture		
278																	Release from hole with eff. diam. of 1/3 diam.		
279																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
280																	Release from hole with eff. diam. of 25mm (1 in)		
281																	Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic - NON-VJ PIPING		
282																	Catastrophic Rupture		
283																	Release from hole with eff. diam. of 1/3 diam.		
284																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
285																	Release from hole with eff. diam. of 25mm (1 in)		
286															Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch)				
287	2.00E-08	7.64E-07	9.99E-07			7.61E-07	8.23E-07			9.32E-07	1.51E-06				Catastrophic Rupture				
288	1.00E-07	4.45E-08	4.46E-08			5.20E-08	5.21E-08			2.56E-08	2.56E-08				Release from hole with eff. diam. of 1/3 diam.				
289	2.00E-07	2.37E-07	2.37E-07			2.75E-07	2.75E-07			1.41E-07	1.41E-07				Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
290	4.00E-07	9.31E-07	1.87E-06			8.94E-07	1.66E-06			1.00E-06	2.39E-06				Release from hole with eff. diam. of 25mm (1 in)				
291																Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Non-Cryogenic			
292		8.45E-07	2.68E-06			8.72E-07	2.84E-06			8.45E-07	2.68E-06					Catastrophic Rupture			
293																Release from hole with eff. diam. of 1/3 diam.			
294																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
295																Release from hole with eff. diam. of 25mm (1 in)			
296																Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic			
297																Catastrophic Rupture			
298																Release from hole with eff. diam. of 1/3 diam.			
299																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
300																Release from hole with eff. diam. of 25mm (1 in)			
301																	Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic - VJ PIPING		
302																	Catastrophic Rupture		
303																	Release from hole with eff. diam. of 1/3 diam.		
304																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
305																	Release from hole with eff. diam. of 25mm (1 in)		
306																	Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic - NON-VJ PIPING		
307																	Catastrophic Rupture		
308																	Release from hole with eff. diam. of 1/3 diam.		
309																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
310																	Release from hole with eff. diam. of 25mm (1 in)		

Appendix E: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11 Except "OREDA '15", "CCPS '89" and "INL CHEM '95"

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
1														Ambient Atm. Storage Tanks					
2		3.45E-06	4.89E-06			3.45E-06	4.90E-06			4.74E-06	4.90E-06			Catastrophic Failure, Release to Atmosphere					
3		9.98E-05	9.98E-05			9.98E-05	9.98E-05			9.98E-05	9.98E-05			Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
4		2.50E-03	2.50E-03			2.50E-03	2.50E-03			2.50E-03	2.50E-03			Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
5														Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
6														Refrigerated Atm. Storage Tanks (Typ. Single Shell)					
7		5.00E-06	5.00E-06			5.00E-06	5.00E-06			5.00E-06	5.00E-06			Catastrophic Failure, Release to Atmosphere					
8														Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
9														Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
10		1.26E-03	1.26E-03			1.26E-03	1.26E-03			1.26E-03	1.26E-03			Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
11														Cryogenic Atm. Storage Tanks					
12		4.60E-06	4.60E-06	5.25E-06	5.25E-06	4.22E-06	4.22E-06	5.17E-06	5.17E-06	6.65E-06	6.65E-06	5.25E-06	5.25E-06	Catastrophic Failure, Release to Atmosphere					
311		6.86E-05	6.86E-05	1.89E-05	1.89E-05	5.36E-05	5.36E-05	1.89E-05	1.89E-05	6.86E-05	6.86E-05	1.89E-05	1.89E-05	Catastrophic Failure of Tank Roof					
13		2.90E-05	2.90E-05	1.01E-06	1.01E-06	2.06E-05	2.06E-05	1.01E-06	1.01E-06	2.90E-05	2.90E-05	1.01E-06	1.01E-06	Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
14		2.39E-05	2.39E-05	3.06E-06	3.06E-06	1.75E-05	1.75E-05	3.06E-06	3.06E-06	2.39E-05	2.39E-05	3.06E-06	3.06E-06	Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
15		1.44E-03	1.44E-03			1.44E-03	1.44E-03			1.44E-03	1.44E-03			Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
16															Single Cont. Cryo. Atm. Storage Tanks				
17	5.00E-06	1.15E-05	1.15E-05	2.99E-05	2.99E-05	1.06E-05	1.06E-05	2.99E-05	2.99E-05	1.73E-05	1.73E-05	2.99E-05	2.99E-05		Catastrophic Failure, Release to Atmosphere				
312	1.00E-04	2.00E-04	2.00E-04			2.00E-04	2.00E-04			2.00E-04	2.00E-04				Catastrophic Failure of Tank Roof				
18	8.00E-05	1.00E-04	1.00E-04			1.00E-04	1.00E-04			1.00E-04	1.00E-04				Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
19	2.00E-04	8.00E-05	8.00E-05			8.00E-05	8.00E-05			8.00E-05	8.00E-05				Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
20	1.00E-04	1.19E-03	1.19E-03			1.19E-03	1.19E-03			1.19E-03	1.19E-03				Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
21																Single Cont. Cryo. Atm. Storage Tanks - HC Only (LNG, Ethane, Ethylene) - Self-Supp. Inner Tank			
22																Catastrophic Failure, Release to Atmosphere			
313																Catastrophic Failure of Tank Roof			
23																Release from a hole in inner tank with eff. diam. of 1 m (~3ft)			
24																Release from a hole in inner tank with eff. diam. of .3 m (~1ft)			
25																Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)			
26																Single Cont. Cryo. Atm. Storage Tanks - LIN/LOX/LAR - Self-Supp. Inner Tank			
27		2.20E-05	2.20E-05			2.20E-05	2.20E-05			2.20E-05	2.20E-05					Catastrophic Failure, Release to Atmosphere			
314																Catastrophic Failure of Tank Roof			
28																Release from a hole in inner tank with eff. diam. of 1 m (~3ft)			
29																Release from a hole in inner tank with eff. diam. of .3 m (~1ft)			
30																Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)			
31															Double Cont. Cryo. Atm. Storage Tanks				
32	5.00E-07	3.23E-08	3.23E-08	7.44E-08	7.44E-08	3.19E-08	3.18E-08	7.39E-08	7.39E-08	4.64E-08	4.64E-08	7.44E-08	7.44E-08		Catastrophic Failure, Release to Atmosphere				
315	1.00E-04	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05		Catastrophic Failure of Tank Roof				
33	1.00E-05	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06		Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
34	3.00E-05	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06		Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
35	1.00E-04	1.32E-03	1.32E-03			1.32E-03	1.32E-03			1.32E-03	1.32E-03				Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
36															Full Cont. Cryo. Atm. Storage Tanks				
37	1.00E-08	2.31E-07	2.31E-07	7.47E-07	7.47E-07	2.22E-07	2.22E-07	7.27E-07	7.28E-07	4.02E-07	4.02E-07	7.47E-07	7.47E-07		Catastrophic Failure, Release to Atmosphere				
316	4.00E-05	2.44E-10	2.40E-10	2.43E-10	2.39E-10	2.53E-10	2.43E-10	2.41E-10	2.41E-10	2.41E-10	2.48E-10	2.43E-10	2.44E-10		Catastrophic Failure of Tank Roof				
38	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06		Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
39	3.00E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06		Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
40	1.00E-04	2.40E-03	2.40E-03			2.40E-03	2.40E-03			2.40E-03	2.40E-03				Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
41															Membrane. Cryo. Atm. Storage Tanks				
42		2.11E-06	2.11E-06	4.46E-06	4.46E-06	2.05E-06	2.05E-06	4.46E-06	4.46E-06	3.14E-06	3.14E-06	4.46E-06	4.46E-06		Catastrophic Failure, Release to Atmosphere				
317															Catastrophic Failure of Tank Roof				
43															Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
44															Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
45															Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
46															Process Vessels, Distillation Columns, Heat Exchangers, and Condensers				
47	5.00E-06	1.67E-02	1.94E-02	2.72E-01	2.72E-01	2.09E-02	2.42E-02	2.72E-01	2.72E-01	2.70E-02	3.13E-02	2.72E-01	2.72E-01		Catastrophic Failure (Rupture)				
48	1.00E-04	1.22E-03	1.22E-03			1.26E-03	1.26E-03			1.13E-03	1.13E-03				Release from a hole with eff. diam. of 0.01m (0.4 in)				
802		3.26E-04	3.77E-04			2.94E-04	3.56E-04			4.00E-04	4.27E-04				Release from a hole with eff. diam. of 0.025m (1 in)				
803		1.16E-04	1.16E-04			1.17E-04	1.17E-04			1.22E-04	1.22E-04				Release from a hole with eff. diam. of 0.05m (2 in)				
804		9.97E-05	1.23E-04			8.89E-05	1.16E-04			1.22E-04	1.34E-04				Release from a hole with eff. diam. of 0.10m (4 in)				
49																Process Vessels incl Distillation Columns			
50		2.85E-05	3.31E-05			2.63E-05	2.98E-05			3.93E-05	4.96E-05					Catastrophic Failure (Rupture)			
51		1.94E-04	1.94E-04			1.66E-04	1.66E-04			2.99E-04	2.99E-04					Release from a hole with eff. diam. of 0.01m (0.4 in)			
805		9.47E-05	1.06E-04			8.11E-05	9.24E-05			1.41E-04	1.51E-04					Release from a hole with eff. diam. of 0.025m (1 in)			
806		3.73E-05	3.73E-05			3.87E-05	3.87E-05			4.29E-05	4.28E-05					Release from a hole with eff. diam. of 0.05m (2 in)			
807		4.59E-05	6.06E-05			3.85E-05	5.37E-05			6.53E-05	7.53E-05					Release from a hole with eff. diam. of 0.10m (4 in)			
52																	PVs incl Dist. Columns - Single Wall		
53		2.81E-05	3.44E-05			2.50E-05	2.98E-05			4.09E-05	5.49E-05						Catastrophic Failure (Rupture)		
54		2.22E-04	2.22E-04			1.93E-04	1.93E-04			3.28E-04	3.28E-04						Release from a hole with eff. diam. of 0.01m (0.4 in)		
808		9.47E-05	1.06E-04			8.11E-05	9.24E-05			1.41E-04	1.51E-04						Release from a hole with eff. diam. of 0.025m (1 in)		
809		3.73E-05	3.73E-05			3.87E-05	3.87E-05			4.29E-05	4.29E-05						Release from a hole with eff. diam. of 0.05m (2 in)		
810		4.59E-05	6.06E-05			3.85E-05	5.37E-05			6.53E-05	7.53E-05						Release from a hole with eff. diam. of 0.10m (4 in)		
318																		Pressure Storage Vessels/Tanks (Single Wall)	
319		2.41E-06	2.38E-06			2.55E-06	2.37E-06			2.37E-06	2.28E-06							Catastrophic Failure (Rupture)	
320		1.10E-05	1.10E-05			1.11E-05	1.11E-05			1.07E-05	1.07E-05							Release from a hole with eff. diam. of 0.01m (0.4 in)	
380		4.57E-06	4.57E-06			4.52E-06	4.52E-06			4.69E-06	4.69E-06							Release from a hole with eff. diam. of 0.025m (1 in)	
381		4.99E-06	4.99E-06			4.99E-06	4.99E-06			4.99E-06	4.99E-06							Release from a hole with eff. diam. of 0.05m (2 in)	
382		4.17E-06	4.17E-06			4.17E-06	4.17E-06			4.17E-06	4.17E-06							Release from a hole with eff. diam. of 0.10m (4 in)	
321																		Process Vessels (Single Wall)	
322		8.46E-05	8.46E-05			7.47E-05	7.47E-05			1.17E-04	1.17E-04							Catastrophic Failure (Rupture)	
323		4.28E-04	4.28E-04			3.86E-04	3.86E-04			5.29E-04	5.29E-04							Release from a hole with eff. diam. of 0.01m (0.4 in)	
383		Some cells shaded to																Release from a hole with eff. diam. of 0.025m (1 in)	
384		protect copyrights or																Release from a hole with eff. diam. of 0.05m (2 in)	
386		licensed software																Release from a hole with eff. diam. of 0.10m (4 in)	
55																		Mole Sieve Vessel (Single Wall)	
56																		Catastrophic Failure (Rupture)	
57																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
387																		Release from a hole with eff. diam. of 0.025m (1 in)	
388																		Release from a hole with eff. diam. of 0.05m (2 in)	
389																		Release from a hole with eff. diam. of 0.10m (4 in)	
58																		Distillation Columns (Single Wall)	
59																		Catastrophic Failure (Rupture)	
60		1.00E-04	1.00E-04			1.00E-04	1.00E-04			1.00E-04	1.00E-04							Release from a hole with eff. diam. of 0.01m (0.4 in)	
390																		Release from a hole with eff. diam. of 0.025m (1 in)	
391																		Release from a hole with eff. diam. of 0.05m (2 in)	
392																		Release from a hole with eff. diam. of 0.10m (4 in)	
61																		Separator (Single Wall)	
62																		Catastrophic Failure (Rupture)	
63																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
393																		Release from a hole with eff. diam. of 0.025m (1 in)	
394																		Release from a hole with eff. diam. of 0.05m (2 in)	
395																		Release from a hole with eff. diam. of 0.10m (4 in)	
64																	PVs incl Dist. Columns - Double Wall (cryogenic)		
65																	Catastrophic Failure (Rupture)		
66																	Release from a hole with eff. diam. of 0.01m (0.4 in)		
396																	Release from a hole with eff. diam. of 0.025m (1 in)		
397																	Release from a hole with eff. diam. of 0.05m (2 in)		

Appendix E: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11 Except "OREDA '15", "CCPS '89" and "INL CHEM '95"

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
398																	Release from a hole with eff. diam. of 0.10m (4 in)		
70																	ISO Containers		
71		2.95E-06	2.95E-06			2.95E-06	2.95E-06			2.95E-06	2.95E-06						Catastrophic Failure (Rupture)		
72		6.01E-05	6.01E-05			6.01E-05	6.01E-05			6.01E-05	6.01E-05						Release from a hole with eff. diam. of 0.01m (0.4 in)		
399																	Release from a hole with eff. diam. of 0.025m (1 in)		
400																	Release from a hole with eff. diam. of 0.05m (2 in)		
401																	Release from a hole with eff. diam. of 0.10m (4 in)		
73																Heat Exchangers incl. Condensers			
74		3.35E-02	3.84E-02	2.72E-01	2.72E-01	4.24E-02	4.94E-02	2.72E-01	2.72E-01	4.67E-02	5.07E-02	2.72E-01	2.72E-01			Catastrophic Failure (Rupture)			
75		1.91E-03	1.91E-03			2.09E-03	2.09E-03			1.52E-03	1.52E-03					Release from a hole with eff. diam. of 0.01m (0.4 in)			
402		4.64E-04	5.44E-04			4.37E-04	5.44E-04			5.11E-04	5.44E-04					Release from a hole with eff. diam. of 0.025m (1 in)			
403		1.56E-04	1.56E-04			1.56E-04	1.56E-04			1.56E-04	1.56E-04					Release from a hole with eff. diam. of 0.05m (2 in)			
404		1.17E-04	1.41E-04			1.07E-04	1.36E-04			1.38E-04	1.49E-04					Release from a hole with eff. diam. of 0.10m (4 in)			
76																	Fired Heat Exchangers		
77		2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01				Catastrophic Failure (Rupture)		
78																	Release from a hole with eff. diam. of 0.01m (0.4 in)		
405																	Release from a hole with eff. diam. of 0.025m (1 in)		
406																	Release from a hole with eff. diam. of 0.05m (2 in)		
407																	Release from a hole with eff. diam. of 0.10m (4 in)		
324																		Submerged Combustion Vaporizers	
325		2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01	2.72E-01					Catastrophic Failure (Rupture)	
326																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
408																		Release from a hole with eff. diam. of 0.025m (1 in)	
409																		Release from a hole with eff. diam. of 0.05m (2 in)	
410																		Release from a hole with eff. diam. of 0.10m (4 in)	
79																	Non-Fired Heat Exchangers incl. Condensers		
80		1.16E-04	1.34E-04			1.02E-04	1.20E-04			1.55E-04	1.67E-04						Catastrophic Failure (Rupture)		
81		2.02E-03	2.02E-03			2.25E-03	2.25E-03			1.56E-03	1.56E-03						Release from a hole with eff. diam. of 0.01m (0.4 in)		
411		4.64E-04	5.44E-04			4.37E-04	5.44E-04			5.11E-04	5.44E-04						Release from a hole with eff. diam. of 0.025m (1 in)		
412		1.56E-04	1.56E-04			1.56E-04	1.56E-04			1.56E-04	1.56E-04						Release from a hole with eff. diam. of 0.05m (2 in)		
413		1.17E-04	1.41E-04			1.07E-04	1.36E-04			1.38E-04	1.49E-04						Release from a hole with eff. diam. of 0.10m (4 in)		
82																		Shell & Tube Heat Exchangers	
83		7.50E-05	8.30E-05			6.83E-05	7.66E-05			9.51E-05	9.87E-05							Catastrophic Failure (Rupture)	
84		1.16E-03	1.16E-03			1.24E-03	1.24E-03			9.97E-04	9.97E-04							Release from a hole with eff. diam. of 0.01m (0.4 in)	
414		3.42E-04	3.94E-04			3.25E-04	3.94E-04			3.73E-04	3.94E-04							Release from a hole with eff. diam. of 0.025m (1 in)	
415		1.01E-04	1.01E-04			1.01E-04	1.01E-04			1.01E-04	1.01E-04							Release from a hole with eff. diam. of 0.05m (2 in)	
416		6.91E-05	8.13E-05			6.25E-05	7.72E-05			8.29E-05	8.90E-05							Release from a hole with eff. diam. of 0.10m (4 in)	
85																			Tube-side Heat Exchangers (HC in tube)
86		9.74E-05	8.85E-05			9.55E-05	8.42E-05			1.08E-04	9.79E-05								Catastrophic Failure (Rupture)
87																			Release from a hole with eff. diam. of 0.01m (0.4 in)
417																			Release from a hole with eff. diam. of 0.025m (1 in)
418																			Release from a hole with eff. diam. of 0.05m (2 in)
419																			Release from a hole with eff. diam. of 0.10m (4 in)
88																			Shell-side Heat Exchangers (HC in shell)
89		7.25E-05	1.03E-04			6.37E-05	9.75E-05			9.37E-05	1.14E-04								Catastrophic Failure (Rupture)
90																			Release from a hole with eff. diam. of 0.01m (0.4 in)
420																			Release from a hole with eff. diam. of 0.025m (1 in)
421																			Release from a hole with eff. diam. of 0.05m (2 in)
422																			Release from a hole with eff. diam. of 0.10m (4 in)
91																		Plate Heat Exchangers	
92		2.36E-04	2.36E-04			1.99E-04	1.99E-04			3.48E-04	3.48E-04							Catastrophic Failure (Rupture)	
93																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
423																		Release from a hole with eff. diam. of 0.025m (1 in)	
424																		Release from a hole with eff. diam. of 0.05m (2 in)	
425																		Release from a hole with eff. diam. of 0.10m (4 in)	
94																		Air Cooled (Fin Fan) Heat Exchangers	
95		3.00E-05	4.87E-05			2.59E-05	4.87E-05			3.95E-05	4.87E-05							Catastrophic Failure (Rupture)	
96																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
426																		Release from a hole with eff. diam. of 0.025m (1 in)	
427																		Release from a hole with eff. diam. of 0.05m (2 in)	
428																		Release from a hole with eff. diam. of 0.10m (4 in)	
97																		Printed Heat Exchangers	
98																		Catastrophic Failure (Rupture)	
99																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
429																		Release from a hole with eff. diam. of 0.025m (1 in)	
430																		Release from a hole with eff. diam. of 0.05m (2 in)	
431																		Release from a hole with eff. diam. of 0.10m (4 in)	
100																		Plate-Fin Heat Exchangers	
101																		Catastrophic Failure (Rupture)	
102																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
432																		Release from a hole with eff. diam. of 0.025m (1 in)	
433																		Release from a hole with eff. diam. of 0.05m (2 in)	
434																		Release from a hole with eff. diam. of 0.10m (4 in)	
103																		Ambient Vaporizer Heat Exchangers	
104																		Catastrophic Failure (Rupture)	
105																		Release from a hole with eff. diam. of 0.01m (0.4 in)	
435																		Release from a hole with eff. diam. of 0.025m (1 in)	
436																		Release from a hole with eff. diam. of 0.05m (2 in)	
437																		Release from a hole with eff. diam. of 0.10m (4 in)	
106															Truck Transfer Arm				
107	3.00E-04	1.51E-05	1.51E-05			1.51E-05	1.51E-05			1.51E-05	1.51E-05				Rupture of transfer arm				
108	3.00E-03	2.09E-04	2.09E-04			2.09E-04	2.09E-04			2.09E-04	2.09E-04				Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
109																Truck Transfer Arm - Cryogenic			
110																Rupture of transfer arm			
111																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
112																Truck Transfer Arm - Non-cryogenic			
113																Rupture of transfer arm			
114																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
115															Ship Transfer Arm				
116	2.00E-05	1.03E-03	1.11E-03			1.02E-03	1.11E-03			1.03E-03	1.11E-03				Rupture of transfer arm				
117	2.00E-04	1.89E-02	1.89E-02			1.89E-02	1.89E-02			1.89E-02	1.89E-02				Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
118																Ship Transfer Arm - Cryogenic			
119																Rupture of transfer arm			
120																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
121																Ship Transfer Arm - Non-cryogenic			
122																Rupture of transfer arm			
123																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
124															Truck Transfer Hose				
125	4.00E-02	4.90E-03	4.90E-03			5.09E-03	5.09E-03			5.10E-03	5.10E-03				Rupture of transfer hose				
126	4.00E-01	2.82E-02	2.82E-02			2.82E-02	2.82E-02			2.82E-02	2.82E-02				Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
127																Truck Transfer Hose - Cryogenic			
128																Rupture of transfer hose			
129																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
130																Truck Transfer Hose - Non-cryogenic			
131		4.00E-04	4.00E-04			4.00E-04	4.00E-04			4.00E-04	4.00E-04					Rupture of transfer hose			

Appendix E: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11 Except "OREDA '15", "CCPS '89" and "INL CHEM '95"

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
132																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
133															Ship Transfer Hose				
134		2.71E-03	4.00E-03			2.61E-03	4.00E-03			2.71E-03	4.00E-03				Rupture of transfer hose				
135		4.00E-02	4.00E-02			4.00E-02	4.00E-02			4.00E-02	4.00E-02				Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)				
136																Ship Transfer Hose - Cryogenic			
137																Rupture of transfer hose			
138																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
139																Ship Transfer Hose - Non-cryogenic			
140																Rupture of transfer hose			
141																Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in)			
142															Valve: All diameters				
143	9.00E-06	1.44E-05	1.44E-05			1.52E-05	1.53E-05			1.47E-05	1.47E-05				Catastrophic Rupture				
327		2.01E-04	2.01E-04			2.01E-04	2.01E-04			2.01E-04	2.01E-04				Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
144															Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
328															Release from hole with eff. diam. of 25 mm (1 in) diam.				
329															Release from hole with eff. diam. of 50 mm (2 in) diam.				
330															Release from hole with eff. diam. of 100 mm (4 in) diam.				
145																Manual Valves: All diameters			
146		8.54E-06	8.05E-06			9.60E-06	8.96E-06			8.54E-06	8.05E-06					Catastrophic Rupture			
331																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
147																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
332																Release from hole with eff. diam. of 25 mm (1 in) diam.			
333																Release from hole with eff. diam. of 50 mm (2 in) diam.			
334																Release from hole with eff. diam. of 100 mm (4 in) diam.			
148																	Manual Valves - Cryogenic: All diameters		
149																	Catastrophic Rupture		
335																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
150																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
336																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
337																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
338																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
151																	Manual Valves - Non-cryogenic: All diameters		
152		6.38E-06	5.82E-06			6.61E-06	5.83E-06			6.38E-06	5.82E-06						Catastrophic Rupture		
339																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
153																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
340																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
341																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
342																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
154																Actuated Valves: All diameters			
155		2.11E-05	2.18E-05			2.23E-05	2.33E-05			2.11E-05	2.18E-05					Catastrophic Rupture			
343															Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
156															Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
344															Release from hole with eff. diam. of 25 mm (1 in) diam.				
345															Release from hole with eff. diam. of 50 mm (2 in) diam.				
346															Release from hole with eff. diam. of 100 mm (4 in) diam.				
157																	Actuated Valves - Cryogenic: All diameters		
158																	Catastrophic Rupture		
347																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
159																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
348																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
349																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
350																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
160																	Actuated Valves - Non-cryogenic: All diameters		
161		2.11E-05	2.18E-05			2.23E-05	2.33E-05			2.11E-05	2.18E-05						Catastrophic Rupture		
351																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
162																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
352																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
353																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
354																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
438																Valve: 2"≤D<6"			
439																Catastrophic Rupture			
440																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
441																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
442																Release from hole with eff. diam. of 25 mm (1 in) diam.			
443																Release from hole with eff. diam. of 50 mm (2 in) diam.			
444																Release from hole with eff. diam. of 100 mm (4 in) diam.			
445																	Manual Valves: 2"≤D<6"		
446																	Catastrophic Rupture		
447																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
448																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
449																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
450																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
451																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
452																		Manual Valves - Cryogenic: 2"≤D<6"	
453																		Catastrophic Rupture	
454																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
455																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
456																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
457																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
458																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
459																		Manual Valves - Non-cryogenic: 2"≤D<6"	
460																		Catastrophic Rupture	
461																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
462																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
463																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
464																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
465																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
466																	Actuated Valves: 2"≤D<6"		
467																	Catastrophic Rupture		
468																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
469																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
470																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
471																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
472																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
473																		Actuated Valves - Cryogenic: 2"≤D<6"	
474																		Catastrophic Rupture	
475																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
476																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
477																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
478																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
479																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
480																		Actuated Valves - Non-cryogenic: 2"≤D<6"	
481																		Catastrophic Rupture	
482																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
483																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	

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484																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
485																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
486																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
487																Valve: 6"≤D<12"			
488																Catastrophic Rupture			
489																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
490																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
491																Release from hole with eff. diam. of 25 mm (1 in) diam.			
492																Release from hole with eff. diam. of 50 mm (2 in) diam.			
493																Release from hole with eff. diam. of 100 mm (4 in) diam.			
494																	Manual Valves: 6"≤D<12"		
495																	Catastrophic Rupture		
496																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
497																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
498																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
499																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
500																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
501																		Manual Valves - Cryogenic: 6"≤D<12"	
502																		Catastrophic Rupture	
503																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
504																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
505																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
506																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
507																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
508																		Manual Valves - Non-cryogenic: 6"≤D<12"	
509																		Catastrophic Rupture	
510																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
511																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
512																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
513																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
514																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
515																	Actuated Valves: 6"≤D<12"		
516																	Catastrophic Rupture		
517																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
518																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
519																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
520																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
521																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
522																		Actuated Valves - Cryogenic: 6"≤D<12"	
523																		Catastrophic Rupture	
524																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
525																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
526																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
527																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
528																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
529																		Actuated Valves - Non-cryogenic: 6"≤D<12"	
530																		Catastrophic Rupture	
531																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
532																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
533																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
534																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
535																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
536																Valve: 12"≤D<20"			
537																Catastrophic Rupture			
538																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
539																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
540																Release from hole with eff. diam. of 25 mm (1 in) diam.			
541																Release from hole with eff. diam. of 50 mm (2 in) diam.			
542																Release from hole with eff. diam. of 100 mm (4 in) diam.			
543																	Manual Valves: 12"≤D<20"		
544																	Catastrophic Rupture		
545																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
546																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
547																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
548																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
549																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
550																		Manual Valves - Cryogenic: 12"≤D<20"	
551																		Catastrophic Rupture	
552																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
553																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
554																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
555																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
556																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
557																		Manual Valves - Non-cryogenic: 12"≤D<20"	
558																		Catastrophic Rupture	
559																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
560																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
561																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
562																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
563																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
564																	Actuated Valves: 12"≤D<20"		
565																	Catastrophic Rupture		
566																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
567																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
568																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
569																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
570																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
571																		Actuated Valves - Cryogenic: 12"≤D<20"	
572																		Catastrophic Rupture	
573																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
574																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
575																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
576																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
577																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
578																		Actuated Valves - Non-cryogenic: 12"≤D<20"	
579																		Catastrophic Rupture	
580																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
581																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
582																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
583																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
584																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
585																Valve: 20"≤D<40"			
586																Catastrophic Rupture			
587																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
588																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			

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589																Release from hole with eff. diam. of 25 mm (1 in) diam.			
590																Release from hole with eff. diam. of 50 mm (2 in) diam.			
591																Release from hole with eff. diam. of 100 mm (4 in) diam.			
592																	Manual Valves: 20"≤D<40"		
593																	Catastrophic Rupture		
594																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
595																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
596																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
597																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
598																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
599																		Manual Valves - Cryogenic: 20"≤D<40"	
600																		Catastrophic Rupture	
601																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
602																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
603																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
604																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
605																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
606																		Manual Valves - Non-cryogenic: 20"≤D<40"	
607																		Catastrophic Rupture	
608																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
609																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
610																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
611																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
612																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
613																	Actuated Valves: 20"≤D<40"		
614																	Catastrophic Rupture		
615																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
616																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
617																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
618																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
619																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
620																		Actuated Valves - Cryogenic: 20"≤D<40"	
621																		Catastrophic Rupture	
622																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
623																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
624																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
625																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
626																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
627																		Actuated Valves - Non-cryogenic: 20"≤D<40"	
628																		Catastrophic Rupture	
629																		Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
630																		Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
631																		Release from hole with eff. diam. of 25 mm (1 in) diam.	
632																		Release from hole with eff. diam. of 50 mm (2 in) diam.	
633																		Release from hole with eff. diam. of 100 mm (4 in) diam.	
163															Expansion Joint- All diameters				
164	4.00E-03	1.06E-03	1.06E-03			1.06E-03	1.06E-03			1.29E-03	1.29E-03				Catastrophic Rupture				
355															Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
165															Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
356															Release from hole with eff. diam. of 25 mm (1 in) diam.				
357															Release from hole with eff. diam. of 50 mm (2 in) diam.				
358															Release from hole with eff. diam. of 100 mm (4 in) diam.				
166																Expansion Joint- Cryogenic: All diameters			
167																Catastrophic Rupture			
359																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
168																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
360																Release from hole with eff. diam. of 25 mm (1 in) diam.			
361																Release from hole with eff. diam. of 50 mm (2 in) diam.			
362																Release from hole with eff. diam. of 100 mm (4 in) diam.			
169																Expansion Joint- Non Cryogenic: All diameters			
170																Catastrophic Rupture			
363																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
171																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
364																Release from hole with eff. diam. of 25 mm (1 in) diam.			
365																Release from hole with eff. diam. of 50 mm (2 in) diam.			
366																Release from hole with eff. diam. of 100 mm (4 in) diam.			
634																Expansion Joint: 2"≤D<6"			
635																Catastrophic Rupture			
636																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
637																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
638																Release from hole with eff. diam. of 25 mm (1 in) diam.			
639																Release from hole with eff. diam. of 50 mm (2 in) diam.			
640																Release from hole with eff. diam. of 100 mm (4 in) diam.			
641																	Expansion Joint- Cryogenic: 2"≤D<6"		
642																	Catastrophic Rupture		
643																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
644																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
645																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
646																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
647																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
648																	Expansion Joint- Non Cryogenic: 2"≤D<6"		
649																	Catastrophic Rupture		
650																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
651																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
652																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
653																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
654																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
655																Expansion Joint: 6"≤D<12"			
656																Catastrophic Rupture			
657																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
658																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
659																Release from hole with eff. diam. of 25 mm (1 in) diam.			
660																Release from hole with eff. diam. of 50 mm (2 in) diam.			
661																Release from hole with eff. diam. of 100 mm (4 in) diam.			
662																	Expansion Joint- Cryogenic: 6"≤D<12"		
663																	Catastrophic Rupture		
664																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
665																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
666																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
667																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
668																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
669																	Expansion Joint- Non Cryogenic: 6"≤D<12"		
670																	Catastrophic Rupture		
671																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
672																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		

Appendix E: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11 Except "OREDA '15", "CCPS '89" and "INL CHEM '95"

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
673																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
674																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
675																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
676																Expansion Joint: 12"≤D<20"			
677																Catastrophic Rupture			
678																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
679																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
680																Release from hole with eff. diam. of 25 mm (1 in) diam.			
681																Release from hole with eff. diam. of 50 mm (2 in) diam.			
682																Release from hole with eff. diam. of 100 mm (4 in) diam.			
683																	Expansion Joint- Cryogenic: 12"≤D<20"		
684																	Catastrophic Rupture		
685																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
686																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
687																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
688																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
689																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
690																	Expansion Joint- Non Cryogenic: 12"≤D<20"		
691																	Catastrophic Rupture		
692																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
693																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
694																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
695																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
696																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
697																Expansion Joint: 20"≤D<40"			
698																Catastrophic Rupture			
699																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
700																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
701																Release from hole with eff. diam. of 25 mm (1 in) diam.			
702																Release from hole with eff. diam. of 50 mm (2 in) diam.			
703																Release from hole with eff. diam. of 100 mm (4 in) diam.			
704																	Expansion Joint- Cryogenic: 20"≤D<40"		
705																	Catastrophic Rupture		
706																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
707																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
708																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
709																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
710																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
711																	Expansion Joint- Non Cryogenic: 20"≤D<40"		
712																	Catastrophic Rupture		
713																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
714																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
715																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
716																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
717																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
172															Gasket Flange- All diameters				
173	3.00E-02	1.98E-05	1.98E-05			2.46E-05	2.46E-05			1.47E-05	1.47E-05				Catastrophic Rupture				
367		9.47E-05	9.47E-05			9.47E-05	9.47E-05			9.47E-05	9.47E-05				Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
174		5.15E-05	5.15E-05			5.15E-05	5.15E-05			5.15E-05	5.15E-05				Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
368		7.49E-06	7.49E-06			7.39E-06	7.39E-06			7.66E-06	7.66E-06				Release from hole with eff. diam. of 25 mm (1 in) diam.				
369		6.24E-06	6.24E-06			6.00E-06	6.00E-06			6.68E-06	6.68E-06				Release from hole with eff. diam. of 50 mm (2 in) diam.				
370		2.66E-06	2.66E-06			2.66E-06	2.66E-06			2.66E-06	2.66E-06				Release from hole with eff. diam. of 100 mm (4 in) diam.				
175																Gasket Flange- Cryogenic: All Diameters			
176																Catastrophic Rupture			
371																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
177																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
372																Release from hole with eff. diam. of 25 mm (1 in) diam.			
373																Release from hole with eff. diam. of 50 mm (2 in) diam.			
374																Release from hole with eff. diam. of 100 mm (4 in) diam.			
178																Gasket Flange- Non Cryogenic: All Diameters			
179		6.21E-06	6.21E-06			6.21E-06	6.21E-06			6.21E-06	6.21E-06					Catastrophic Rupture			
375																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
180																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
376																Release from hole with eff. diam. of 25 mm (1 in) diam.			
377																Release from hole with eff. diam. of 50 mm (2 in) diam.			
378																Release from hole with eff. diam. of 100 mm (4 in) diam.			
718																Gasket Flange: 2"≤D<6"			
719																Catastrophic Rupture			
720																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
721																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
722																Release from hole with eff. diam. of 25 mm (1 in) diam.			
723																Release from hole with eff. diam. of 50 mm (2 in) diam.			
724																Release from hole with eff. diam. of 100 mm (4 in) diam.			
725																	Gasket Flange- Cryogenic: 2"≤D<6"		
726																	Catastrophic Rupture		
727																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
728																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
729																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
730																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
731																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
732																	Gasket Flange- Non Cryogenic: 2"≤D<6"		
733																	Catastrophic Rupture		
734																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
735																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
736																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
737																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
738																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
739																Gasket Flange: 6"≤D<12"			
740																Catastrophic Rupture			
741																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
742																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
743																Release from hole with eff. diam. of 25 mm (1 in) diam.			
744																Release from hole with eff. diam. of 50 mm (2 in) diam.			
745																Release from hole with eff. diam. of 100 mm (4 in) diam.			
746																	Gasket Flange- Cryogenic: 6"≤D<12"		
747																	Catastrophic Rupture		
748																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
749																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
750																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
751																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
752																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
753																	Gasket Flange- Non Cryogenic: 6"≤D<12"		
754																	Catastrophic Rupture		
755																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
756																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		

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757																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
758																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
759																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
760																Gasket Flange: 12"≤D<20"			
761																Catastrophic Rupture			
762																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
763																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
764																Release from hole with eff. diam. of 25 mm (1 in) diam.			
765																Release from hole with eff. diam. of 50 mm (2 in) diam.			
766																Release from hole with eff. diam. of 100 mm (4 in) diam.			
767																	Gasket Flange- Cryogenic: 12"≤D<20"		
768																	Catastrophic Rupture		
769																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
770																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
771																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
772																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
773																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
774																	Gasket Flange- Non Cryogenic: 12"≤D<20"		
775																	Catastrophic Rupture		
776																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
777																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
778																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
779																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
780																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
781																Gasket Flange: 20"≤D<40"			
782																Catastrophic Rupture			
783																Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
784																Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
785																Release from hole with eff. diam. of 25 mm (1 in) diam.			
786																Release from hole with eff. diam. of 50 mm (2 in) diam.			
787																Release from hole with eff. diam. of 100 mm (4 in) diam.			
788																	Gasket Flange- Cryogenic: 20"≤D<40"		
789																	Catastrophic Rupture		
790																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
791																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
792																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
793																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
794																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
795																	Gasket Flange- Non Cryogenic: 20"≤D<40"		
796																	Catastrophic Rupture		
797																	Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
798																	Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
799																	Release from hole with eff. diam. of 25 mm (1 in) diam.		
800																	Release from hole with eff. diam. of 50 mm (2 in) diam.		
801																	Release from hole with eff. diam. of 100 mm (4 in) diam.		
181														Piping: All diameters					
182		2.29E-06	3.51E-06			2.03E-06	2.95E-06			2.88E-06	5.39E-06			Catastrophic Rupture					
183		1.75E-06	1.75E-06			1.58E-06	1.58E-06			2.13E-06	2.13E-06			Release from hole with eff. diam. of 1/3 diam.					
184		8.44E-06	1.02E-05			7.86E-06	9.29E-06			9.65E-06	1.22E-05			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)					
185		9.51E-06	1.23E-05	2.30E-05	2.30E-05	1.05E-05	1.28E-05	2.30E-05	2.30E-05	1.08E-05	1.48E-05	2.30E-05	2.30E-05	Release from hole with eff. diam. of 25mm (1 in)					
186															Piping: d < 50mm (2-inch)				
187	1.00E-06	1.16E-05	1.16E-05			1.01E-05	1.01E-05			1.59E-05	1.59E-05				Catastrophic Rupture				
188															Release from hole with eff. diam. of 1/3 diam.				
189															Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
190	5.00E-06														Release from hole with eff. diam. of 25mm (1 in)				
191																Piping: d < 50mm (2-inch) - Non-Cryogenic			
192		1.21E-05	1.21E-05			1.12E-05	1.12E-05			1.48E-05	1.48E-05					Catastrophic Rupture			
193																Release from hole with eff. diam. of 1/3 diam.			
194																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
195																Release from hole with eff. diam. of 25mm (1 in)			
196																Piping: d < 50mm (2-inch) - Cryogenic			
197																Catastrophic Rupture			
198																Release from hole with eff. diam. of 1/3 diam.			
199																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
200		2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05	2.29E-05			Release from hole with eff. diam. of 25mm (1 in)			
201																	Piping: d < 50mm (2-inch) - Cryogenic - VJ PIPING		
202																	Catastrophic Rupture		
203																	Release from hole with eff. diam. of 1/3 diam.		
204																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
205																	Release from hole with eff. diam. of 25mm (1 in)		
206																	Piping: d < 50mm (2-inch) - Cryogenic - NON-VJ PIPING		
207																	Catastrophic Rupture		
208																	Release from hole with eff. diam. of 1/3 diam.		
209																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
210																	Release from hole with eff. diam. of 25mm (1 in)		
211															Piping: 50mm (2-inch) ≤ d < 149mm (6-inch)				
212	5.00E-07	1.85E-06	2.43E-06			1.64E-06	2.03E-06			2.47E-06	3.82E-06				Catastrophic Rupture				
213															Release from hole with eff. diam. of 1/3 diam.				
214															Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
215	2.00E-06														Release from hole with eff. diam. of 25mm (1 in)				
216																Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Non-Cryogenic			
217		2.25E-06	5.61E-06			2.34E-06	5.94E-06			2.25E-06	5.61E-06					Catastrophic Rupture			
218																Release from hole with eff. diam. of 1/3 diam.			
219																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
220																Release from hole with eff. diam. of 25mm (1 in)			
221																Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic			
222																Catastrophic Rupture			
223																Release from hole with eff. diam. of 1/3 diam.			
224																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
225		2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05	2.31E-05			Release from hole with eff. diam. of 25mm (1 in)			
226																	Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic - VJ PIPING		
227																	Catastrophic Rupture		
228																	Release from hole with eff. diam. of 1/3 diam.		
229																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
230																	Release from hole with eff. diam. of 25mm (1 in)		
231																	Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic - NON-VJ PIPING		
232																	Catastrophic Rupture		
233																	Release from hole with eff. diam. of 1/3 diam.		
234																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
235																	Release from hole with eff. diam. of 25mm (1 in)		
236															Piping: 150mm (6-inch) ≤ d < 299mm (12-inch)				
237	2.00E-07	6.81E-07	1.13E-06			6.11E-07	9.55E-07			8.16E-07	1.77E-06				Catastrophic Rupture				
238	4.00E-07	4.15E-07	4.15E-07			4.61E-07	4.61E-07			2.73E-07	2.73E-07				Release from hole with eff. diam. of 1/3 diam.				
239															Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
240	7.00E-07														Release from hole with eff. diam. of 25mm (1 in)				

Appendix E: "Perceived Relevancy" Results with Table 12 Weighting Factors Applied and Using All References "Specifically Included in Analysis" in Table 11 Except "OREDA '15", "CCPS '89" and "INL CHEM '95"

Index	CURRENT PHMSA FRT SPEC	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example A: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example B: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=ALL; PSL=ALL; AFS=LNG; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=ALL; DT=ALL	Example C: Mean Failure Rate/Year for Case: SFS=LNG; PSL=ALL; AFS=LNG; DT=ALL	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
241																Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Non-Cryogenic			
242		9.51E-07	2.98E-06			9.11E-07	3.16E-06			9.51E-07	2.98E-06					Catastrophic Rupture			
243																Release from hole with eff. diam. of 1/3 diam.			
244																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
245																Release from hole with eff. diam. of 25mm (1 in)			
246																Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic			
247																Catastrophic Rupture			
248																Release from hole with eff. diam. of 1/3 diam.			
249																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
250		2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05	2.30E-05			Release from hole with eff. diam. of 25mm (1 in)			
251																	Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic - VJ PIPING		
252																	Catastrophic Rupture		
253																	Release from hole with eff. diam. of 1/3 diam.		
254																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
255																	Release from hole with eff. diam. of 25mm (1 in)		
256																	Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic - NON-VJ PIPING		
257																	Catastrophic Rupture		
258																	Release from hole with eff. diam. of 1/3 diam.		
259																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
260																	Release from hole with eff. diam. of 25mm (1 in)		
261															Piping: 300mm (12-inch) ≤ d < 499mm (20-inch)				
262	7.00E-08	7.36E-07	1.45E-06			6.82E-07	1.27E-06			8.16E-07	2.06E-06				Catastrophic Rupture				
263	2.00E-07	8.91E-08	8.91E-08			1.05E-07	1.05E-07			4.96E-08	4.96E-08				Release from hole with eff. diam. of 1/3 diam.				
264	4.00E-07	1.12E-07	9.61E-08			1.12E-07	9.62E-08			1.12E-07	9.62E-08				Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
265	5.00E-07	1.93E-06	1.93E-06			1.72E-06	1.72E-06			2.47E-06	2.47E-06				Release from hole with eff. diam. of 25mm (1 in)				
266																Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Non-Cryogenic			
267		8.83E-07	2.93E-06			8.50E-07	3.10E-06			8.83E-07	2.93E-06					Catastrophic Rupture			
268																Release from hole with eff. diam. of 1/3 diam.			
269																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
270																Release from hole with eff. diam. of 25mm (1 in)			
271																Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic			
272																Catastrophic Rupture			
273																Release from hole with eff. diam. of 1/3 diam.			
274																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
275																Release from hole with eff. diam. of 25mm (1 in)			
276																	Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic - VJ PIPING		
277																	Catastrophic Rupture		
278																	Release from hole with eff. diam. of 1/3 diam.		
279																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
280																	Release from hole with eff. diam. of 25mm (1 in)		
281																	Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic - NON-VJ PIPING		
282																	Catastrophic Rupture		
283																	Release from hole with eff. diam. of 1/3 diam.		
284																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
285																	Release from hole with eff. diam. of 25mm (1 in)		
286															Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch)				
287	2.00E-08	6.19E-07	1.19E-06			5.73E-07	9.98E-07			7.41E-07	1.81E-06				Catastrophic Rupture				
288	1.00E-07	4.45E-08	4.45E-08			5.20E-08	5.20E-08			2.56E-08	2.56E-08				Release from hole with eff. diam. of 1/3 diam.				
289	2.00E-07	2.37E-07	2.37E-07			2.75E-07	2.75E-07			1.41E-07	1.41E-07				Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
290	4.00E-07	9.31E-07	1.87E-06			8.94E-07	1.66E-06			1.00E-06	2.39E-06				Release from hole with eff. diam. of 25mm (1 in)				
291																Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Non-Cryogenic			
292		8.45E-07	2.68E-06			8.72E-07	2.84E-06			8.46E-07	2.68E-06					Catastrophic Rupture			
293																Release from hole with eff. diam. of 1/3 diam.			
294																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
295																Release from hole with eff. diam. of 25mm (1 in)			
296																Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic			
297																Catastrophic Rupture			
298																Release from hole with eff. diam. of 1/3 diam.			
299																Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
300																Release from hole with eff. diam. of 25mm (1 in)			
301																	Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic - VJ PIPING		
302																	Catastrophic Rupture		
303																	Release from hole with eff. diam. of 1/3 diam.		
304																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
305																	Release from hole with eff. diam. of 25mm (1 in)		
306																	Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic - NON-VJ PIPING		
307																	Catastrophic Rupture		
308																	Release from hole with eff. diam. of 1/3 diam.		
309																	Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
310																	Release from hole with eff. diam. of 25mm (1 in)		

Appendix F: "Wisdom of the Crowd" Results with Table 14 Weighting Factors Applied and Using All Refernces "Specifically Included in Analysis" on Table 11

Index	CURRENT PHMSA FRT SPEC	Example 1 Wgtg: Uniform	Example 2 Wgtg.	Example 3 Wgtg.	Example 4 Wgtg.	Example 5 Wgtg: 100% "HSE FRED JUN '12"	Example 6 Wgtg: 100% "RIVM BEVI '09"	Example 7 Wgtg: 100% "LNE '09"	Example 8 Wgtg: 100% "IOGP 434-1 & 434-3"	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
1										Ambient Atm. Storage Tanks					
2		1.66E-03	9.44E-04	6.68E-06	4.36E-06	4.89E-06				Catastrophic Failure, Release to Atmosphere					
3		9.98E-05	9.98E-05	9.98E-05	9.98E-05	9.98E-05				Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
4		2.50E-03	2.50E-03	2.50E-03	2.50E-03	2.50E-03				Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
5										Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
6										Refrigerated Atm. Storage Tanks (Typ. Single Shell)					
7		2.10E-03	1.36E-03	4.98E-06	4.98E-06			4.98E-06		Catastrophic Failure, Release to Atmosphere					
8										Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
9										Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
10		1.26E-03	2.40E-03	2.40E-03	2.40E-03			2.40E-03		Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
11										Cryogenic Atm. Storage Tanks					
12		6.66E-04	3.33E-04	6.45E-06	7.98E-06	1.56E-05	1.25E-06	1.72E-07	5.32E-06	Catastrophic Failure, Release to Atmosphere					
311		7.71E-05	7.71E-05	7.71E-05	7.71E-05	7.71E-05				Catastrophic Failure of Tank Roof					
13		3.37E-05	3.37E-05	3.37E-05	3.37E-05	3.37E-05				Release from a hole in inner tank with eff. diam. of 1 m (~3ft)					
14		2.74E-05	2.74E-05	2.74E-05	2.74E-05	2.74E-05				Release from a hole in inner tank with eff. diam. of .3 m (~1ft)					
15		1.44E-03	1.44E-03	1.44E-03	1.44E-03		1.00E-04	2.40E-03		Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)					
16											Single Cont. Cryo. Atm. Storage Tanks				
17	5.00E-06	1.05E-03	5.36E-04	1.62E-05	1.97E-05	3.08E-05	5.09E-06	4.84E-07	1.59E-05		Catastrophic Failure, Release to Atmosphere				
312	1.00E-04	2.00E-04	2.00E-04	2.00E-04	2.00E-04	2.00E-04					Catastrophic Failure of Tank Roof				
18	8.00E-05	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04					Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
19	2.00E-04	8.00E-05	8.00E-05	8.00E-05	8.00E-05	8.00E-05					Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
20	1.00E-04	1.19E-03	1.19E-03	1.19E-03	1.19E-03		1.00E-04	2.40E-03			Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
21												Single Cont. Cryo. Atm. Storage Tanks - HC Only (LNG, Ethane, Ethylene) - Self-Supp. Inner Tank			
22		8.63E-03	8.63E-03									Catastrophic Failure, Release to Atmosphere			
313												Catastrophic Failure of Tank Roof			
23												Release from a hole in inner tank with eff. diam. of 1 m (~3ft)			
24												Release from a hole in inner tank with eff. diam. of .3 m (~1ft)			
25												Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)			
26												Single Cont. Cryo. Atm. Storage Tanks - LIN/LOX/LAR - Self-Supp. Inner Tank			
27		2.20E-05	2.20E-05	2.20E-05	2.20E-05	2.20E-05						Catastrophic Failure, Release to Atmosphere			
314												Catastrophic Failure of Tank Roof			
28												Release from a hole in inner tank with eff. diam. of 1 m (~3ft)			
29												Release from a hole in inner tank with eff. diam. of .3 m (~1ft)			
30												Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)			
31											Double Cont. Cryo. Atm. Storage Tanks				
32	5.00E-07	3.23E-08	3.21E-08	3.36E-08	3.44E-08	5.49E-08	1.21E-08	9.47E-09	2.29E-08		Catastrophic Failure, Release to Atmosphere				
315	1.00E-04	4.03E-05	4.03E-05	4.03E-05	4.03E-05	4.03E-05					Catastrophic Failure of Tank Roof				
33	1.00E-05	1.02E-06	1.02E-06	1.02E-06	1.02E-06	1.02E-06					Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
34	3.00E-05	3.09E-06	3.09E-06	3.09E-06	3.09E-06	3.09E-06					Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
35	1.00E-04	1.32E-03	1.32E-03	1.32E-03	1.32E-03		1.00E-04	2.40E-03			Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
36											Full Cont. Cryo. Atm. Storage Tanks				
37	1.00E-08	2.54E-07	2.06E-07	1.75E-07	1.02E-07	5.10E-08	1.66E-08	1.10E-08	1.15E-08		Catastrophic Failure, Release to Atmosphere				
316	4.00E-05	2.42E-10	2.45E-10	2.49E-10	2.42E-10	2.47E-10					Catastrophic Failure of Tank Roof				
38	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06					Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
39	3.00E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06	3.03E-06					Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
40	1.00E-04	2.40E-03	2.40E-03	2.40E-03	2.40E-03			2.40E-03			Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
41											Membrane. Cryo. Atm. Storage Tanks				
42		2.23E-06	1.90E-06	1.82E-06	1.33E-06		7.46E-09		1.15E-08		Catastrophic Failure, Release to Atmosphere				
317											Catastrophic Failure of Tank Roof				
43											Release from a hole in inner tank with eff. diam. of 1 m (~3ft)				
44											Release from a hole in inner tank with eff. diam. of .3 m (~1ft)				
45											Release from a hole in inner tank with eff. diam. of 0.01 m (0.4 in)				
46											Process Vessels, Distillation Columns, Heat Exchangers, and Condensers				
47	5.00E-06	1.34E-02	1.77E-02	1.85E-02	2.40E-02	2.98E-06	2.12E-05	8.96E-06	4.93E-07		Catastrophic Failure (Rupture)				
48	1.00E-04	1.22E-03	1.41E-03	1.36E-03	1.35E-03	2.57E-05	4.58E-04	5.33E-03	1.05E-03		Release from a hole with eff. diam. of 0.01m (0.4 in)				
802		3.00E-04	2.47E-04	2.21E-04	1.09E-04	4.98E-06		5.94E-06	5.28E-04		Release from a hole with eff. diam. of 0.025m (1 in)				
803		1.03E-04	9.20E-05	7.29E-05	4.99E-06	4.99E-06					Release from a hole with eff. diam. of 0.05m (2 in)				
804		9.59E-05	8.69E-05	8.61E-05	6.77E-05			1.60E-05	1.47E-04		Release from a hole with eff. diam. of 0.10m (4 in)				
49												Process Vessels incl Distillation Columns			
50		3.01E-03	1.68E-03	8.58E-04	2.72E-06	2.98E-06	3.50E-06	1.76E-06	4.94E-07			Catastrophic Failure (Rupture)			
51		1.66E-04	1.45E-04	1.20E-04	5.62E-05	2.57E-05	7.30E-05	6.39E-05	2.99E-04			Release from a hole with eff. diam. of 0.01m (0.4 in)			
805		7.98E-05	5.83E-05	4.71E-05	1.84E-05	4.98E-06		5.94E-06	1.95E-04			Release from a hole with eff. diam. of 0.025m (1 in)			
806		2.82E-05	2.28E-05	1.62E-05	4.99E-06	4.99E-06						Release from a hole with eff. diam. of 0.05m (2 in)			
807		4.37E-05	4.22E-05	4.24E-05	3.47E-05				5.28E-05			Release from a hole with eff. diam. of 0.10m (4 in)			
52													PVs incl Dist. Columns - Single Wall		
53		3.91E-03	1.99E-03	1.01E-03	2.67E-06	2.99E-06	3.50E-06	1.76E-06	4.93E-07				Catastrophic Failure (Rupture)		
54		1.90E-04	1.54E-04	1.28E-04	5.54E-05	1.00E-05	7.30E-05	6.39E-05	2.99E-04				Release from a hole with eff. diam. of 0.01m (0.4 in)		
808		7.98E-05	5.83E-05	4.71E-05	1.84E-05	4.98E-06		5.94E-06	1.95E-04				Release from a hole with eff. diam. of 0.025m (1 in)		
809		2.82E-05	2.28E-05	1.62E-05	4.99E-06	4.99E-06							Release from a hole with eff. diam. of 0.05m (2 in)		
810		4.37E-05	4.22E-05	4.24E-05	3.47E-05				5.28E-05				Release from a hole with eff. diam. of 0.10m (4 in)		
318														Pressure Storage Vessels/Tanks (Single Wall)	
319		1.63E-05	8.92E-06	3.45E-06	1.94E-06	2.99E-06	4.86E-07	3.57E-07	4.93E-07					Catastrophic Failure (Rupture)	
320		1.08E-05	1.07E-05	1.06E-05	1.04E-05	1.00E-05	9.98E-06	1.20E-05	1.20E-05					Release from a hole with eff. diam. of 0.01m (0.4 in)	
380		4.54E-06	4.16E-06	4.27E-06	4.30E-06	4.98E-06		1.08E-06	7.20E-06					Release from a hole with eff. diam. of 0.025m (1 in)	
381		4.99E-06	4.99E-06	4.99E-06	4.99E-06	4.99E-06								Release from a hole with eff. diam. of 0.05m (2 in)	
382		4.17E-06	4.17E-06	4.17E-06	4.17E-06				4.17E-06					Release from a hole with eff. diam. of 0.10m (4 in)	
321														Process Vessels (Single Wall)	
322		7.79E-05	5.75E-05	5.04E-05	4.11E-06		4.99E-06	3.18E-06						Catastrophic Failure (Rupture)	
323		4.00E-04	3.41E-04	3.17E-04	1.54E-04		9.99E-05	1.20E-04	5.60E-04					Release from a hole with eff. diam. of 0.01m (0.4 in)	
383		Some cells shaded to						1.10E-05	3.50E-04					Release from a hole with eff. diam. of 0.025m (1 in)	
384		protect copyrights or												Release from a hole with eff. diam. of 0.05m (2 in)	
386		licensed software							1.10E-04					Release from a hole with eff. diam. of 0.10m (4 in)	
55														Mole Sieve Vessel (Single Wall)	
56														Catastrophic Failure (Rupture)	
57														Release from a hole with eff. diam. of 0.01m (0.4 in)	
387														Release from a hole with eff. diam. of 0.025m (1 in)	

Appendix F: "Wisdom of the Crowd" Results with Table 14 Weighting Factors Applied and Using All Refernces "Specifically Included in Analysis" on Table 11

Index	CURRENT PHMSA FRT SPEC	Example 1 Wgtg: Uniform	Example 2 Wgtg.	Example 3 Wgtg.	Example 4 Wgtg.	Example 5 Wgtg: 100% "HSE FRED JUN '12"	Example 6 Wgtg: 100% "RIVM BEVI '09"	Example 7 Wgtg: 100% "LNE '09"	Example 8 Wgtg: 100% "IOGP 434-1 & 434-3"	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
388														Release from a hole with eff. diam. of 0.05m (2 in)	
389														Release from a hole with eff. diam. of 0.10m (4 in)	
58														Distillation Columns (Single Wall)	
59							4.98E-06							Catastrophic Failure (Rupture)	
60		1.00E-04	1.00E-04	1.00E-04	1.00E-04		1.00E-04							Release from a hole with eff. diam. of 0.01m (0.4 in)	
390														Release from a hole with eff. diam. of 0.025m (1 in)	
391														Release from a hole with eff. diam. of 0.05m (2 in)	
392														Release from a hole with eff. diam. of 0.10m (4 in)	
61														Separator (Single Wall)	
62														Catastrophic Failure (Rupture)	
63														Release from a hole with eff. diam. of 0.01m (0.4 in)	
393														Release from a hole with eff. diam. of 0.025m (1 in)	
394														Release from a hole with eff. diam. of 0.05m (2 in)	
395														Release from a hole with eff. diam. of 0.10m (4 in)	
64													PVs incl Dist. Columns - Double Wall (cryogenic)		
65													Catastrophic Failure (Rupture)		
66													Release from a hole with eff. diam. of 0.01m (0.4 in)		
396													Release from a hole with eff. diam. of 0.025m (1 in)		
397													Release from a hole with eff. diam. of 0.05m (2 in)		
398													Release from a hole with eff. diam. of 0.10m (4 in)		
70													ISO Containers		
71		2.95E-06	2.95E-06	2.95E-06	2.95E-06	2.95E-06							Catastrophic Failure (Rupture)		
72		6.01E-05	6.01E-05	6.01E-05	6.01E-05	6.01E-05							Release from a hole with eff. diam. of 0.01m (0.4 in)		
399													Release from a hole with eff. diam. of 0.025m (1 in)		
400													Release from a hole with eff. diam. of 0.05m (2 in)		
401													Release from a hole with eff. diam. of 0.10m (4 in)		
73												Heat Exchangers incl. Condensers			
74		2.47E-02	3.40E-02	3.84E-02	7.10E-02		5.01E-05	1.63E-05				Catastrophic Failure (Rupture)			
75		2.03E-03	2.70E-03	2.89E-03	4.47E-03		1.00E-03	1.33E-02	1.33E-03			Release from a hole with eff. diam. of 0.01m (0.4 in)			
402		4.56E-04	4.23E-04	4.28E-04	4.95E-04				6.54E-04			Release from a hole with eff. diam. of 0.025m (1 in)			
403		1.56E-04	1.56E-04	1.56E-04								Release from a hole with eff. diam. of 0.05m (2 in)			
404		1.13E-04	1.01E-04	9.92E-05	7.55E-05			1.60E-05	1.87E-04			Release from a hole with eff. diam. of 0.10m (4 in)			
76													Fired Heat Exchangers		
77		2.72E-01	2.72E-01	2.72E-01	2.72E-01								Catastrophic Failure (Rupture)		
78													Release from a hole with eff. diam. of 0.01m (0.4 in)		
405													Release from a hole with eff. diam. of 0.025m (1 in)		
406													Release from a hole with eff. diam. of 0.05m (2 in)		
407													Release from a hole with eff. diam. of 0.10m (4 in)		
324														Submerged Combustion Vaporizers	
325		2.72E-01	2.72E-01	2.72E-01	2.72E-01									Catastrophic Failure (Rupture)	
326														Release from a hole with eff. diam. of 0.01m (0.4 in)	
408														Release from a hole with eff. diam. of 0.025m (1 in)	
409														Release from a hole with eff. diam. of 0.05m (2 in)	
410														Release from a hole with eff. diam. of 0.10m (4 in)	
79													Non-Fired Heat Exchangers incl. Condensers		
80		7.64E-03	3.91E-03	2.30E-03	3.04E-05		5.01E-05	1.63E-05					Catastrophic Failure (Rupture)		
81		2.17E-03	2.70E-03	2.89E-03	4.47E-03		1.00E-03	1.33E-02	1.33E-03				Release from a hole with eff. diam. of 0.01m (0.4 in)		
411		4.56E-04	4.23E-04	4.28E-04	4.95E-04				6.54E-04				Release from a hole with eff. diam. of 0.025m (1 in)		
412		1.56E-04	1.56E-04	1.56E-04									Release from a hole with eff. diam. of 0.05m (2 in)		
413		1.13E-04	1.01E-04	9.92E-05	7.56E-05			1.60E-05	1.87E-04				Release from a hole with eff. diam. of 0.10m (4 in)		
82														Shell & Tube Heat Exchangers	
83		1.06E-03	6.37E-04	4.09E-04	2.61E-05		5.00E-05	1.29E-05						Catastrophic Failure (Rupture)	
84		1.21E-03	1.40E-03	1.47E-03	2.07E-03		1.00E-03	6.00E-03	9.97E-04					Release from a hole with eff. diam. of 0.01m (0.4 in)	
414		3.37E-04	3.11E-04	3.15E-04	3.80E-04				4.79E-04					Release from a hole with eff. diam. of 0.025m (1 in)	
415		1.01E-04	1.01E-04	1.01E-04										Release from a hole with eff. diam. of 0.05m (2 in)	
416		6.62E-05	5.75E-05	5.60E-05	3.95E-05			1.60E-05	1.16E-04					Release from a hole with eff. diam. of 0.10m (4 in)	
85															Tube-side Heat Exchangers (HC in tube)
86		4.92E-04	4.18E-04	3.17E-04											Catastrophic Failure (Rupture)
87									8.81E-04						Release from a hole with eff. diam. of 0.01m (0.4 in)
417									4.00E-04						Release from a hole with eff. diam. of 0.025m (1 in)
418															Release from a hole with eff. diam. of 0.05m (2 in)
419									9.10E-05						Release from a hole with eff. diam. of 0.10m (4 in)
88															Shell-side Heat Exchangers (HC in shell)
89		9.38E-05	8.14E-05	7.54E-05	4.01E-05		5.00E-05								Catastrophic Failure (Rupture)
90							1.00E-03		1.10E-03						Release from a hole with eff. diam. of 0.01m (0.4 in)
420									5.61E-04						Release from a hole with eff. diam. of 0.025m (1 in)
421															Release from a hole with eff. diam. of 0.05m (2 in)
422									1.40E-04						Release from a hole with eff. diam. of 0.10m (4 in)
91														Plate Heat Exchangers	
92		2.58E-02	1.10E-02	5.95E-03	3.73E-05		5.01E-05	2.01E-05						Catastrophic Failure (Rupture)	
93							1.00E-03	1.80E-02	2.80E-03					Release from a hole with eff. diam. of 0.01m (0.4 in)	
423									1.60E-03					Release from a hole with eff. diam. of 0.025m (1 in)	
424														Release from a hole with eff. diam. of 0.05m (2 in)	
425									4.80E-04					Release from a hole with eff. diam. of 0.10m (4 in)	
94														Air Cooled (Fin Fan) Heat Exchangers	
95														Catastrophic Failure (Rupture)	
96									4.90E-04					Release from a hole with eff. diam. of 0.01m (0.4 in)	
426									2.40E-04					Release from a hole with eff. diam. of 0.025m (1 in)	
427														Release from a hole with eff. diam. of 0.05m (2 in)	
428		3.34E-05	3.04E-05	3.08E-05	3.15E-05				5.99E-05					Release from a hole with eff. diam. of 0.10m (4 in)	
97														Printed Heat Exchangers	
98														Catastrophic Failure (Rupture)	
99														Release from a hole with eff. diam. of 0.01m (0.4 in)	
429														Release from a hole with eff. diam. of 0.025m (1 in)	
430														Release from a hole with eff. diam. of 0.05m (2 in)	
431														Release from a hole with eff. diam. of 0.10m (4 in)	

Appendix F: "Wisdom of the Crowd" Results with Table 14 Weighting Factors Applied and Using All Refernces "Specifically Included in Analysis" on Table 11

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100														Plate-Fin Heat Exchangers	
101														Catastrophic Failure (Rupture)	
102														Release from a hole with eff. diam. of 0.01m (0.4 in	
432														Release from a hole with eff. diam. of 0.025m (1 in	
433														Release from a hole with eff. diam. of 0.05m (2 in	
434														Release from a hole with eff. diam. of 0.10m (4 in	
103														Ambient Vaporizer Heat Exchangers	
104														Catastrophic Failure (Rupture)	
105														Release from a hole with eff. diam. of 0.01m (0.4 in	
435														Release from a hole with eff. diam. of 0.025m (1 in	
436														Release from a hole with eff. diam. of 0.05m (2 in	
437														Release from a hole with eff. diam. of 0.10m (4 in	
106											Truck Transfer Arm				
107	3.00E-04	1.51E-05	2.26E-05	2.38E-05	2.71E-05		3.01E-05	3.01E-05			Rupture of transfer arm				
108	3.00E-03	2.09E-04	3.00E-04	3.00E-04	3.00E-04		3.00E-04	2.99E-04			Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in				
109												Truck Transfer Arm - Cryogenic			
110												Rupture of transfer arm			
111												Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in			
112												Truck Transfer Arm - Non-cryogenic			
113												Rupture of transfer arm			
114												Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in			
115											Ship Transfer Arm				
116	2.00E-05	1.07E-03	1.16E-04	9.42E-05	5.41E-05		2.99E-05	3.00E-05			Rupture of transfer arm				
117	2.00E-04	1.89E-02	3.00E-04	3.00E-04	3.00E-04		3.00E-04	3.00E-04			Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in				
118												Ship Transfer Arm - Cryogenic			
119												Rupture of transfer arm			
120												Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in			
121												Ship Transfer Arm - Non-cryogenic			
122												Rupture of transfer arm			
123												Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in			
124											Truck Transfer Hose				
125	4.00E-02	1.86E-02	1.17E-02	7.06E-03	2.43E-03	4.00E-04	4.00E-03	4.00E-03			Rupture of transfer hose				
126	4.00E-01	2.82E-02	4.00E-02	4.00E-02	4.00E-02		4.00E-02	4.00E-02			Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in				
127												Truck Transfer Hose - Cryogenic			
128												Rupture of transfer hose			
129												Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in			
130												Truck Transfer Hose - Non-cryogenic			
131		4.00E-04	4.00E-04	4.00E-04	4.00E-04	4.00E-04						Rupture of transfer hose			
132												Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in			
133											Ship Transfer Hose				
134		2.88E-03	3.56E-03	3.77E-03	4.00E-03		4.00E-03	4.00E-03			Rupture of transfer hose				
135		4.00E-02	4.00E-02	4.00E-02	4.00E-02		4.00E-02	4.00E-02			Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in				
136												Ship Transfer Hose - Cryogenic			
137												Rupture of transfer hose			
138												Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in			
139												Ship Transfer Hose - Non-cryogenic			
140												Rupture of transfer hose			
141												Release from hole with eff. diam. of 10% diam. with max.of 50mm (2 in			
142											Valve: All diameters				
143	9.00E-06	1.16E-03	7.55E-04	5.06E-04	8.70E-06						Catastrophic Rupture				
327		2.01E-04	2.01E-04	2.01E-04	2.00E-04	2.00E-04					Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
144											Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
328											Release from hole with eff. diam. of 25 mm (1 in) diam.				
329											Release from hole with eff. diam. of 50 mm (2 in) diam.				
330											Release from hole with eff. diam. of 100 mm (4 in) diam.				
145												Manual Valves: All diameters			
146		2.07E-04	1.30E-04	3.79E-05								Catastrophic Rupture			
331												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
147												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
332												Release from hole with eff. diam. of 25 mm (1 in) diam.			
333												Release from hole with eff. diam. of 50 mm (2 in) diam.			
334												Release from hole with eff. diam. of 100 mm (4 in) diam.			
148													Manual Valves - Cryogenic: All diameters		
149													Catastrophic Rupture		
335													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
150													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
336													Release from hole with eff. diam. of 25 mm (1 in) diam.		
337													Release from hole with eff. diam. of 50 mm (2 in) diam.		
338													Release from hole with eff. diam. of 100 mm (4 in) diam.		
151													Manual Valves - Non-cryogenic: All diameters		
152		5.82E-05	3.33E-05	2.31E-05									Catastrophic Rupture		
339													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
153													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
340													Release from hole with eff. diam. of 25 mm (1 in) diam.		
341													Release from hole with eff. diam. of 50 mm (2 in) diam.		
342													Release from hole with eff. diam. of 100 mm (4 in) diam.		
154												Actuated Valves: All diameters			
155		5.55E-05	4.25E-05	3.51E-05								Catastrophic Rupture			
343												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
156												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
344												Release from hole with eff. diam. of 25 mm (1 in) diam.			
345												Release from hole with eff. diam. of 50 mm (2 in) diam.			
346												Release from hole with eff. diam. of 100 mm (4 in) diam.			
157													Actuated Valves - Cryogenic: All diameters		
158													Catastrophic Rupture		
347													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		

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159													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
348													Release from hole with eff. diam. of 25 mm (1 in) diam.		
349													Release from hole with eff. diam. of 50 mm (2 in) diam.		
350													Release from hole with eff. diam. of 100 mm (4 in) diam.		
160													Actuated Valves - Non-cryogenic: All diameters		
161		5.55E-05	4.25E-05	3.51E-05									Catastrophic Rupture		
351													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
162													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
352													Release from hole with eff. diam. of 25 mm (1 in) diam.		
353													Release from hole with eff. diam. of 50 mm (2 in) diam.		
354													Release from hole with eff. diam. of 100 mm (4 in) diam.		
438												Valve: 2"≤D<6"			
439												Catastrophic Rupture			
440												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
441												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
442												Release from hole with eff. diam. of 25 mm (1 in) diam.			
443												Release from hole with eff. diam. of 50 mm (2 in) diam.			
444												Release from hole with eff. diam. of 100 mm (4 in) diam.			
445													Manual Valves: 2"≤D<6"		
446													Catastrophic Rupture		
447													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
448													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
449													Release from hole with eff. diam. of 25 mm (1 in) diam.		
450													Release from hole with eff. diam. of 50 mm (2 in) diam.		
451													Release from hole with eff. diam. of 100 mm (4 in) diam.		
452														Manual Valves - Cryogenic: 2"≤D<6"	
453														Catastrophic Rupture	
454														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
455														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
456														Release from hole with eff. diam. of 25 mm (1 in) diam.	
457														Release from hole with eff. diam. of 50 mm (2 in) diam.	
458														Release from hole with eff. diam. of 100 mm (4 in) diam.	
459														Manual Valves - Non-cryogenic: 2"≤D<6"	
460														Catastrophic Rupture	
461														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
462														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
463														Release from hole with eff. diam. of 25 mm (1 in) diam.	
464														Release from hole with eff. diam. of 50 mm (2 in) diam.	
465														Release from hole with eff. diam. of 100 mm (4 in) diam.	
466													Actuated Valves: 2"≤D<6"		
467													Catastrophic Rupture		
468													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
469													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
470													Release from hole with eff. diam. of 25 mm (1 in) diam.		
471													Release from hole with eff. diam. of 50 mm (2 in) diam.		
472													Release from hole with eff. diam. of 100 mm (4 in) diam.		
473														Actuated Valves - Cryogenic: 2"≤D<6"	
474														Catastrophic Rupture	
475														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
476														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
477														Release from hole with eff. diam. of 25 mm (1 in) diam.	
478														Release from hole with eff. diam. of 50 mm (2 in) diam.	
479														Release from hole with eff. diam. of 100 mm (4 in) diam.	
480														Actuated Valves - Non-cryogenic: 2"≤D<6"	
481														Catastrophic Rupture	
482														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
483														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
484														Release from hole with eff. diam. of 25 mm (1 in) diam.	
485														Release from hole with eff. diam. of 50 mm (2 in) diam.	
486														Release from hole with eff. diam. of 100 mm (4 in) diam.	
487												Valve: 6"≤D<12"			
488												Catastrophic Rupture			
489												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
490												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
491												Release from hole with eff. diam. of 25 mm (1 in) diam.			
492												Release from hole with eff. diam. of 50 mm (2 in) diam.			
493												Release from hole with eff. diam. of 100 mm (4 in) diam.			
494													Manual Valves: 6"≤D<12"		
495													Catastrophic Rupture		
496													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
497													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
498													Release from hole with eff. diam. of 25 mm (1 in) diam.		
499													Release from hole with eff. diam. of 50 mm (2 in) diam.		
500													Release from hole with eff. diam. of 100 mm (4 in) diam.		
501														Manual Valves - Cryogenic: 6"≤D<12"	
502														Catastrophic Rupture	
503														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
504														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
505														Release from hole with eff. diam. of 25 mm (1 in) diam.	
506														Release from hole with eff. diam. of 50 mm (2 in) diam.	
507														Release from hole with eff. diam. of 100 mm (4 in) diam.	
508														Manual Valves - Non-cryogenic: 6"≤D<12"	
509														Catastrophic Rupture	
510														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
511														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
512														Release from hole with eff. diam. of 25 mm (1 in) diam.	

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513														Release from hole with eff. diam. of 50 mm (2 in) diam.	
514														Release from hole with eff. diam. of 100 mm (4 in) diam.	
515													Actuated Valves: 6"≤D<12"		
516													Catastrophic Rupture		
517													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
518													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
519													Release from hole with eff. diam. of 25 mm (1 in) diam.		
520													Release from hole with eff. diam. of 50 mm (2 in) diam.		
521													Release from hole with eff. diam. of 100 mm (4 in) diam.		
522														Actuated Valves - Cryogenic: 6"≤D<12"	
523														Catastrophic Rupture	
524														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
525														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
526														Release from hole with eff. diam. of 25 mm (1 in) diam.	
527														Release from hole with eff. diam. of 50 mm (2 in) diam.	
528														Release from hole with eff. diam. of 100 mm (4 in) diam.	
529														Actuated Valves - Non-cryogenic: 6"≤D<12"	
530														Catastrophic Rupture	
531														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
532														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
533														Release from hole with eff. diam. of 25 mm (1 in) diam.	
534														Release from hole with eff. diam. of 50 mm (2 in) diam.	
535														Release from hole with eff. diam. of 100 mm (4 in) diam.	
536												Valve: 12"≤D<20"			
537												Catastrophic Rupture			
538												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
539												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
540												Release from hole with eff. diam. of 25 mm (1 in) diam.			
541												Release from hole with eff. diam. of 50 mm (2 in) diam.			
542												Release from hole with eff. diam. of 100 mm (4 in) diam.			
543													Manual Valves: 12"≤D<20"		
544													Catastrophic Rupture		
545													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
546													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
547													Release from hole with eff. diam. of 25 mm (1 in) diam.		
548													Release from hole with eff. diam. of 50 mm (2 in) diam.		
549													Release from hole with eff. diam. of 100 mm (4 in) diam.		
550														Manual Valves - Cryogenic: 12"≤D<20"	
551														Catastrophic Rupture	
552														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
553														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
554														Release from hole with eff. diam. of 25 mm (1 in) diam.	
555														Release from hole with eff. diam. of 50 mm (2 in) diam.	
556														Release from hole with eff. diam. of 100 mm (4 in) diam.	
557														Manual Valves - Non-cryogenic: 12"≤D<20"	
558														Catastrophic Rupture	
559														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
560														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
561														Release from hole with eff. diam. of 25 mm (1 in) diam.	
562														Release from hole with eff. diam. of 50 mm (2 in) diam.	
563														Release from hole with eff. diam. of 100 mm (4 in) diam.	
564													Actuated Valves: 12"≤D<20"		
565													Catastrophic Rupture		
566													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
567													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
568													Release from hole with eff. diam. of 25 mm (1 in) diam.		
569													Release from hole with eff. diam. of 50 mm (2 in) diam.		
570													Release from hole with eff. diam. of 100 mm (4 in) diam.		
571														Actuated Valves - Cryogenic: 12"≤D<20"	
572														Catastrophic Rupture	
573														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
574														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
575														Release from hole with eff. diam. of 25 mm (1 in) diam.	
576														Release from hole with eff. diam. of 50 mm (2 in) diam.	
577														Release from hole with eff. diam. of 100 mm (4 in) diam.	
578														Actuated Valves - Non-cryogenic: 12"≤D<20"	
579														Catastrophic Rupture	
580														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
581														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
582														Release from hole with eff. diam. of 25 mm (1 in) diam.	
583														Release from hole with eff. diam. of 50 mm (2 in) diam.	
584														Release from hole with eff. diam. of 100 mm (4 in) diam.	
585												Valve: 20"≤D<40"			
586												Catastrophic Rupture			
587												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
588												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
589												Release from hole with eff. diam. of 25 mm (1 in) diam.			
590												Release from hole with eff. diam. of 50 mm (2 in) diam.			
591												Release from hole with eff. diam. of 100 mm (4 in) diam.			
592													Manual Valves: 20"≤D<40"		
593													Catastrophic Rupture		
594													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
595													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
596													Release from hole with eff. diam. of 25 mm (1 in) diam.		
597													Release from hole with eff. diam. of 50 mm (2 in) diam.		
598													Release from hole with eff. diam. of 100 mm (4 in) diam.		

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Index	CURRENT PHMSA FRT SPEC	Example 1 Wgtg: Uniform	Example 2 Wgtg.	Example 3 Wgtg.	Example 4 Wgtg.	Example 5 Wgtg: 100% "HSE FRED JUN '12"	Example 6 Wgtg: 100% "RIVM BEVI '09"	Example 7 Wgtg: 100% "LNE '09"	Example 8 Wgtg: 100% "IOGP 434-1 & 434-3"	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
599														Manual Valves - Cryogenic: 20"≤D<40"	
600														Catastrophic Rupture	
601														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
602														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
603														Release from hole with eff. diam. of 25 mm (1 in) diam.	
604														Release from hole with eff. diam. of 50 mm (2 in) diam.	
605														Release from hole with eff. diam. of 100 mm (4 in) diam.	
606														Manual Valves - Non-cryogenic: 20"≤D<40"	
607														Catastrophic Rupture	
608														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
609														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
610														Release from hole with eff. diam. of 25 mm (1 in) diam.	
611														Release from hole with eff. diam. of 50 mm (2 in) diam.	
612														Release from hole with eff. diam. of 100 mm (4 in) diam.	
613													Actuated Valves: 20"≤D<40"		
614													Catastrophic Rupture		
615													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
616													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
617													Release from hole with eff. diam. of 25 mm (1 in) diam.		
618													Release from hole with eff. diam. of 50 mm (2 in) diam.		
619													Release from hole with eff. diam. of 100 mm (4 in) diam.		
620														Actuated Valves - Cryogenic: 20"≤D<40"	
621														Catastrophic Rupture	
622														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
623														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
624														Release from hole with eff. diam. of 25 mm (1 in) diam.	
625														Release from hole with eff. diam. of 50 mm (2 in) diam.	
626														Release from hole with eff. diam. of 100 mm (4 in) diam.	
627														Actuated Valves - Non-cryogenic: 20"≤D<40"	
628														Catastrophic Rupture	
629														Release from hole with eff. diam. of 2 mm (0.08 in) diam.	
630														Release from hole with eff. diam. of 10 mm (0.4 in) diam.	
631														Release from hole with eff. diam. of 25 mm (1 in) diam.	
632														Release from hole with eff. diam. of 50 mm (2 in) diam.	
633														Release from hole with eff. diam. of 100 mm (4 in) diam.	
163											Expansion Joint- All diameters				
164	4.00E-03	1.71E-03	1.50E-03	1.29E-03	8.76E-04						Catastrophic Rupture				
355											Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
165											Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
356											Release from hole with eff. diam. of 25 mm (1 in) diam.				
357											Release from hole with eff. diam. of 50 mm (2 in) diam.				
358											Release from hole with eff. diam. of 100 mm (4 in) diam.				
166												Expansion Joint- Cryogenic: All diameters			
167												Catastrophic Rupture			
359												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
168												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
360												Release from hole with eff. diam. of 25 mm (1 in) diam.			
361												Release from hole with eff. diam. of 50 mm (2 in) diam.			
362												Release from hole with eff. diam. of 100 mm (4 in) diam.			
169												Expansion Joint- Non Cryogenic: All diameters			
170												Catastrophic Rupture			
363												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
171												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
364												Release from hole with eff. diam. of 25 mm (1 in) diam.			
365												Release from hole with eff. diam. of 50 mm (2 in) diam.			
366												Release from hole with eff. diam. of 100 mm (4 in) diam.			
634												Expansion Joint: 2"≤D<6"			
635												Catastrophic Rupture			
636												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
637												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
638												Release from hole with eff. diam. of 25 mm (1 in) diam.			
639												Release from hole with eff. diam. of 50 mm (2 in) diam.			
640												Release from hole with eff. diam. of 100 mm (4 in) diam.			
641													Expansion Joint- Cryogenic: 2"≤D<6"		
642													Catastrophic Rupture		
643													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
644													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
645													Release from hole with eff. diam. of 25 mm (1 in) diam.		
646													Release from hole with eff. diam. of 50 mm (2 in) diam.		
647													Release from hole with eff. diam. of 100 mm (4 in) diam.		
648													Expansion Joint- Non Cryogenic: 2"≤D<6"		
649													Catastrophic Rupture		
650													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
651													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
652													Release from hole with eff. diam. of 25 mm (1 in) diam.		
653													Release from hole with eff. diam. of 50 mm (2 in) diam.		
654													Release from hole with eff. diam. of 100 mm (4 in) diam.		
655												Expansion Joint: 6"≤D<12"			
656												Catastrophic Rupture			
657												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
658												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
659												Release from hole with eff. diam. of 25 mm (1 in) diam.			
660												Release from hole with eff. diam. of 50 mm (2 in) diam.			
661												Release from hole with eff. diam. of 100 mm (4 in) diam.			
662													Expansion Joint- Cryogenic: 6"≤D<12"		
663													Catastrophic Rupture		

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664													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
665													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
666													Release from hole with eff. diam. of 25 mm (1 in) diam.		
667													Release from hole with eff. diam. of 50 mm (2 in) diam.		
668													Release from hole with eff. diam. of 100 mm (4 in) diam.		
669													Expansion Joint- Non Cryogenic: 6"≤D<12"		
670													Catastrophic Rupture		
671													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
672													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
673													Release from hole with eff. diam. of 25 mm (1 in) diam.		
674													Release from hole with eff. diam. of 50 mm (2 in) diam.		
675													Release from hole with eff. diam. of 100 mm (4 in) diam.		
676												Expansion Joint: 12"≤D<20"			
677												Catastrophic Rupture			
678												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
679												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
680												Release from hole with eff. diam. of 25 mm (1 in) diam.			
681												Release from hole with eff. diam. of 50 mm (2 in) diam.			
682												Release from hole with eff. diam. of 100 mm (4 in) diam.			
683													Expansion Joint- Cryogenic: 12"≤D<20"		
684													Catastrophic Rupture		
685													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
686													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
687													Release from hole with eff. diam. of 25 mm (1 in) diam.		
688													Release from hole with eff. diam. of 50 mm (2 in) diam.		
689													Release from hole with eff. diam. of 100 mm (4 in) diam.		
690													Expansion Joint- Non Cryogenic: 12"≤D<20"		
691													Catastrophic Rupture		
692													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
693													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
694													Release from hole with eff. diam. of 25 mm (1 in) diam.		
695													Release from hole with eff. diam. of 50 mm (2 in) diam.		
696													Release from hole with eff. diam. of 100 mm (4 in) diam.		
697												Expansion Joint: 20"≤D<40"			
698												Catastrophic Rupture			
699												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
700												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
701												Release from hole with eff. diam. of 25 mm (1 in) diam.			
702												Release from hole with eff. diam. of 50 mm (2 in) diam.			
703												Release from hole with eff. diam. of 100 mm (4 in) diam.			
704													Expansion Joint- Cryogenic: 20"≤D<40"		
705													Catastrophic Rupture		
706													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
707													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
708													Release from hole with eff. diam. of 25 mm (1 in) diam.		
709													Release from hole with eff. diam. of 50 mm (2 in) diam.		
710													Release from hole with eff. diam. of 100 mm (4 in) diam.		
711													Expansion Joint- Non Cryogenic: 20"≤D<40"		
712													Catastrophic Rupture		
713													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
714													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
715													Release from hole with eff. diam. of 25 mm (1 in) diam.		
716													Release from hole with eff. diam. of 50 mm (2 in) diam.		
717													Release from hole with eff. diam. of 100 mm (4 in) diam.		
172											Gasket Flange- All diameters				
173	3.00E-02	4.73E-05	2.91E-05	2.32E-05	8.75E-05						Catastrophic Rupture				
367		9.47E-05	9.73E-05	9.70E-05	5.09E-05				5.09E-05		Release from hole with eff. diam. of 2 mm (0.08 in) diam.				
174		5.15E-05	5.15E-05	5.15E-05							Release from hole with eff. diam. of 10 mm (0.4 in) diam.				
368		7.43E-06	7.31E-06	7.05E-06	5.03E-06	5.03E-06					Release from hole with eff. diam. of 25 mm (1 in) diam.				
369		6.09E-06	5.77E-06	5.12E-06	9.46E-08	9.47E-08					Release from hole with eff. diam. of 50 mm (2 in) diam.				
370		2.66E-06	2.66E-06	2.66E-06							Release from hole with eff. diam. of 100 mm (4 in) diam.				
175												Gasket Flange- Cryogenic: All Diameters			
176												Catastrophic Rupture			
371												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
177												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
372												Release from hole with eff. diam. of 25 mm (1 in) diam.			
373												Release from hole with eff. diam. of 50 mm (2 in) diam.			
374												Release from hole with eff. diam. of 100 mm (4 in) diam.			
178												Gasket Flange- Non Cryogenic: All Diameters			
179		6.68E-06	6.44E-06	6.35E-06								Catastrophic Rupture			
375												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
180												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
376												Release from hole with eff. diam. of 25 mm (1 in) diam.			
377												Release from hole with eff. diam. of 50 mm (2 in) diam.			
378												Release from hole with eff. diam. of 100 mm (4 in) diam.			
718												Gasket Flange: 2"≤D<6"			
719												Catastrophic Rupture			
720												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
721												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
722												Release from hole with eff. diam. of 25 mm (1 in) diam.			
723												Release from hole with eff. diam. of 50 mm (2 in) diam.			
724												Release from hole with eff. diam. of 100 mm (4 in) diam.			
725													Gasket Flange- Cryogenic: 2"≤D<6"		
726													Catastrophic Rupture		
727													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
728													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		

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729													Release from hole with eff. diam. of 25 mm (1 in) diam.		
730													Release from hole with eff. diam. of 50 mm (2 in) diam.		
731													Release from hole with eff. diam. of 100 mm (4 in) diam.		
732													Gasket Flange- Non Cryogenic: 2"≤D<6"		
733													Catastrophic Rupture		
734													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
735													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
736													Release from hole with eff. diam. of 25 mm (1 in) diam.		
737													Release from hole with eff. diam. of 50 mm (2 in) diam.		
738													Release from hole with eff. diam. of 100 mm (4 in) diam.		
739												Gasket Flange: 6"≤D<12"			
740												Catastrophic Rupture			
741												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
742												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
743												Release from hole with eff. diam. of 25 mm (1 in) diam.			
744												Release from hole with eff. diam. of 50 mm (2 in) diam.			
745												Release from hole with eff. diam. of 100 mm (4 in) diam.			
746													Gasket Flange- Cryogenic: 6"≤D<12"		
747													Catastrophic Rupture		
748													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
749													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
750													Release from hole with eff. diam. of 25 mm (1 in) diam.		
751													Release from hole with eff. diam. of 50 mm (2 in) diam.		
752													Release from hole with eff. diam. of 100 mm (4 in) diam.		
753													Gasket Flange- Non Cryogenic: 6"≤D<12"		
754													Catastrophic Rupture		
755													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
756													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
757													Release from hole with eff. diam. of 25 mm (1 in) diam.		
758													Release from hole with eff. diam. of 50 mm (2 in) diam.		
759													Release from hole with eff. diam. of 100 mm (4 in) diam.		
760												Gasket Flange: 12"≤D<20"			
761												Catastrophic Rupture			
762												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
763												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
764												Release from hole with eff. diam. of 25 mm (1 in) diam.			
765												Release from hole with eff. diam. of 50 mm (2 in) diam.			
766												Release from hole with eff. diam. of 100 mm (4 in) diam.			
767													Gasket Flange- Cryogenic: 12"≤D<20"		
768													Catastrophic Rupture		
769													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
770													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
771													Release from hole with eff. diam. of 25 mm (1 in) diam.		
772													Release from hole with eff. diam. of 50 mm (2 in) diam.		
773													Release from hole with eff. diam. of 100 mm (4 in) diam.		
774													Gasket Flange- Non Cryogenic: 12"≤D<20"		
775													Catastrophic Rupture		
776													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
777													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
778													Release from hole with eff. diam. of 25 mm (1 in) diam.		
779													Release from hole with eff. diam. of 50 mm (2 in) diam.		
780													Release from hole with eff. diam. of 100 mm (4 in) diam.		
781												Gasket Flange: 20"≤D<40"			
782												Catastrophic Rupture			
783												Release from hole with eff. diam. of 2 mm (0.08 in) diam.			
784												Release from hole with eff. diam. of 10 mm (0.4 in) diam.			
785												Release from hole with eff. diam. of 25 mm (1 in) diam.			
786												Release from hole with eff. diam. of 50 mm (2 in) diam.			
787												Release from hole with eff. diam. of 100 mm (4 in) diam.			
788													Gasket Flange- Cryogenic: 20"≤D<40"		
789													Catastrophic Rupture		
790													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
791													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
792													Release from hole with eff. diam. of 25 mm (1 in) diam.		
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794													Release from hole with eff. diam. of 100 mm (4 in) diam.		
795													Gasket Flange- Non Cryogenic: 20"≤D<40"		
796													Catastrophic Rupture		
797													Release from hole with eff. diam. of 2 mm (0.08 in) diam.		
798													Release from hole with eff. diam. of 10 mm (0.4 in) diam.		
799													Release from hole with eff. diam. of 25 mm (1 in) diam.		
800													Release from hole with eff. diam. of 50 mm (2 in) diam.		
801													Release from hole with eff. diam. of 100 mm (4 in) diam.		
181										Piping: All diameters					
182		3.06E-06	2.50E-06	2.12E-06	5.30E-07	3.58E-07	4.66E-07	2.56E-08	1.72E-05	Catastrophic Rupture					
183		1.65E-06	1.35E-06	1.11E-06	4.74E-07	2.29E-07			7.42E-06	Release from hole with eff. diam. of 1/3 diam.					
184		8.07E-06	7.71E-06	7.75E-06	2.59E-06		2.59E-06			Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)					
185		8.42E-06	9.18E-06	8.79E-06	6.86E-06	1.60E-06				Release from hole with eff. diam. of 25mm (1 in)					
186											Piping: d < 50mm (2-inch)				
187	1.00E-06	9.25E-06	7.87E-06	6.83E-06	1.99E-06	1.01E-06	9.93E-07	2.54E-08	2.69E-05		Catastrophic Rupture				
188											Release from hole with eff. diam. of 1/3 diam.				
189							5.09E-06				Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
190	5.00E-06					5.01E-06					Release from hole with eff. diam. of 25mm (1 in)				
191												Piping: d < 50mm (2-inch) - Non-Cryogenic			
192		1.05E-05	8.22E-06	7.10E-06	5.07E-07		9.93E-07	2.54E-08				Catastrophic Rupture			
193												Release from hole with eff. diam. of 1/3 diam.			

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194							5.09E-06					Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
195												Release from hole with eff. diam. of 25mm (1 in)			
196												Piping: d < 50mm (2-inch) - Cryogenic			
197												Catastrophic Rupture			
198												Release from hole with eff. diam. of 1/3 diam.			
199												Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
200		2.29E-05	2.29E-05	2.29E-05	2.29E-05							Release from hole with eff. diam. of 25mm (1 in)			
201													Piping: d < 50mm (2-inch) - Cryogenic - VJ PIPING		
202													Catastrophic Rupture		
203													Release from hole with eff. diam. of 1/3 diam.		
204													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
205													Release from hole with eff. diam. of 25mm (1 in)		
206													Piping: d < 50mm (2-inch) - Cryogenic - NON-VJ PIPING		
207													Catastrophic Rupture		
208													Release from hole with eff. diam. of 1/3 diam.		
209													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
210													Release from hole with eff. diam. of 25mm (1 in)		
211											Piping: 50mm (2-inch) ≤ d < 149mm (6-inch)				
212	5.00E-07	2.49E-06	2.13E-06	1.81E-06	5.44E-07	4.88E-07	3.08E-07	2.36E-08	7.70E-06		Catastrophic Rupture				
213									7.42E-06		Release from hole with eff. diam. of 1/3 diam.				
214							2.02E-06				Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
215	2.00E-06					1.04E-06					Release from hole with eff. diam. of 25mm (1 in)				
216												Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Non-Cryogenic			
217		2.10E-06	2.04E-06	1.90E-06	2.91E-08			2.35E-08				Catastrophic Rupture			
218												Release from hole with eff. diam. of 1/3 diam.			
219												Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
220												Release from hole with eff. diam. of 25mm (1 in)			
221												Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic			
222												Catastrophic Rupture			
223												Release from hole with eff. diam. of 1/3 diam.			
224												Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
225		2.31E-05	2.31E-05	2.31E-05	2.31E-05							Release from hole with eff. diam. of 25mm (1 in)			
226													Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic - VJ PIPING		
227													Catastrophic Rupture		
228													Release from hole with eff. diam. of 1/3 diam.		
229													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
230													Release from hole with eff. diam. of 25mm (1 in)		
231													Piping: 50mm (2-inch) ≤ d < 149mm (6-inch) - Cryogenic - NON-VJ PIPING		
232													Catastrophic Rupture		
233													Release from hole with eff. diam. of 1/3 diam.		
234													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
235													Release from hole with eff. diam. of 25mm (1 in)		
236											Piping: 150mm (6-inch) ≤ d < 299mm (12-inch)				
237	2.00E-07	1.73E-06	1.30E-06	1.01E-06	1.40E-07	1.96E-07		3.36E-08			Catastrophic Rupture				
238	4.00E-07	4.28E-07	3.85E-07	3.90E-07	4.32E-07	3.91E-07					Release from hole with eff. diam. of 1/3 diam.				
239											Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
240	7.00E-07					7.21E-07					Release from hole with eff. diam. of 25mm (1 in)				
241												Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Non-Cryogenic			
242		9.18E-07	9.78E-07	9.46E-07	2.89E-08			3.36E-08				Catastrophic Rupture			
243												Release from hole with eff. diam. of 1/3 diam.			
244												Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
245												Release from hole with eff. diam. of 25mm (1 in)			
246												Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic			
247												Catastrophic Rupture			
248												Release from hole with eff. diam. of 1/3 diam.			
249												Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
250		2.30E-05	2.30E-05	2.30E-05	2.30E-05							Release from hole with eff. diam. of 25mm (1 in)			
251													Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic - VJ PIPING		
252													Catastrophic Rupture		
253													Release from hole with eff. diam. of 1/3 diam.		
254													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
255													Release from hole with eff. diam. of 25mm (1 in)		
256													Piping: 150mm (6-inch) ≤ d < 299mm (12-inch) - Cryogenic - NON-VJ PIPING		
257													Catastrophic Rupture		
258													Release from hole with eff. diam. of 1/3 diam.		
259													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
260													Release from hole with eff. diam. of 25mm (1 in)		
261											Piping: 300mm (12-inch) ≤ d < 499mm (20-inch)				
262	7.00E-08	1.99E-06	1.39E-06	1.04E-06	8.58E-08	7.20E-08		2.35E-08			Catastrophic Rupture				
263	2.00E-07	9.94E-08	1.16E-07	1.39E-07	1.94E-07	1.94E-07					Release from hole with eff. diam. of 1/3 diam.				
264	4.00E-07	1.12E-07	1.10E-07	1.04E-07							Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
265	5.00E-07	1.79E-06	1.57E-06	1.24E-06	4.95E-07	4.95E-07					Release from hole with eff. diam. of 25mm (1 in)				
266												Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Non-Cryogenic			
267		8.55E-07	9.29E-07	9.38E-07	2.64E-08			2.35E-08				Catastrophic Rupture			
268												Release from hole with eff. diam. of 1/3 diam.			
269												Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
270												Release from hole with eff. diam. of 25mm (1 in)			
271												Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic			
272												Catastrophic Rupture			
273												Release from hole with eff. diam. of 1/3 diam.			
274												Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
275												Release from hole with eff. diam. of 25mm (1 in)			
276													Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic - VJ PIPING		
277													Catastrophic Rupture		
278													Release from hole with eff. diam. of 1/3 diam.		
279													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		

Appendix F: "Wisdom of the Crowd" Results with Table 14 Weighting Factors Applied and Using All Refernces "Specifically Included in Analysis" on Table 11

Index	CURRENT PHMSA FRT SPEC	Example 1 Wgtg: Uniform	Example 2 Wgtg.	Example 3 Wgtg.	Example 4 Wgtg.	Example 5 Wgtg: 100% "HSE FRED JUN '12"	Example 6 Wgtg: 100% "RIVM BEVI '09"	Example 7 Wgtg: 100% "LNE '09"	Example 8 Wgtg: 100% "IOGP 434-1 & 434-3"	Super Category Comparison	Current FRT Category	Potential SubCategory1	Potential SubCategory2	Potential Subcategory3	Potential SubCategory4
280													Release from hole with eff. diam. of 25mm (1 in)		
281													Piping: 300mm (12-inch) ≤ d < 499mm (20-inch) - Cryogenic - NON-VJ PIPING		
282													Catastrophic Rupture		
283													Release from hole with eff. diam. of 1/3 diam.		
284													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
285													Release from hole with eff. diam. of 25mm (1 in)		
286											Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch)				
287	2.00E-08	1.89E-06	1.17E-06	8.38E-07	4.69E-08	4.05E-08	9.39E-08	2.14E-08			Catastrophic Rupture				
288	1.00E-07	4.95E-08	5.74E-08	6.87E-08	9.51E-08	9.51E-08					Release from hole with eff. diam. of 1/3 diam.				
289	2.00E-07	2.62E-07	3.02E-07	3.24E-07	4.89E-07		4.89E-07				Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)				
290	4.00E-07	9.07E-07	9.80E-07	1.05E-06	4.32E-07	4.32E-07					Release from hole with eff. diam. of 25mm (1 in)				
291												Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Non-Cryogenic			
292		8.01E-07	8.21E-07	8.38E-07	2.69E-08			2.14E-08				Catastrophic Rupture			
293												Release from hole with eff. diam. of 1/3 diam.			
294												Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
295												Release from hole with eff. diam. of 25mm (1 in)			
296												Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic			
297												Catastrophic Rupture			
298												Release from hole with eff. diam. of 1/3 diam.			
299												Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)			
300												Release from hole with eff. diam. of 25mm (1 in)			
301													Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic - VJ PIPING		
302													Catastrophic Rupture		
303													Release from hole with eff. diam. of 1/3 diam.		
304													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
305													Release from hole with eff. diam. of 25mm (1 in)		
306													Piping: 500mm (20-inch) ≤ d < 1000 mm (40-inch) - Cryogenic - NON-VJ PIPING		
307													Catastrophic Rupture		
308													Release from hole with eff. diam. of 1/3 diam.		
309													Release from hole with effective diameter of 10% diameter, up to 50mm (2-inches)		
310													Release from hole with eff. diam. of 25mm (1 in)		

Appendix G: Excerpts from *Analysis of LNG Peakshaving Facility Release Prevention Systems (PNL-4153)*

The following excerpts from *Analysis of LNG Peakshaving Facility Release Prevention Systems* by Pelto, P.J., Baker, E.G., Powers, T.B., Schreiber, A.M., Hoggs, J.M., and Daling, P.M. of Pacific Northwest Laboratory, PNL-4153, 1982 ("PNL PSRP '82") are provided directly in this Final Report for the reader's convenience.

TABLE 3. Generic Failure Rates for Components of LNG Peakshaving Facilities

Component	Failure Mode	Faults/Hr	Reference
Pump	Rupture	1×10^{-8}	(SAI 1975, Browning 1978)
	Fails to Stop	1×10^{-7}	(Welker 1976)
Compressor	Rupture	1×10^{-8}	(SAI 1975, Browning 1978)
	Fails to Run Normally	3×10^{-4}	(Welker 1979)
Vaporizer	Tube or Panel Rupture	1×10^{-4}	(Welker 1979)
	Control System Failure	1×10^{-3}	(Welker 1979)
Pipe Section >3 in dia.	Rupture	1×10^{-10}	(USNRC 1975)
Storage Tank	Rupture	1×10^{-9} 1×10^{-10}	(SAI 1975, Atallah 1980)
	Cold Spot	1×10^{-5}	(Welker 1979)
Valve	Rupture	1×10^{-9}	(USNRC 1975, Welker 1979)
	Fails Closed or Is Misdirected Toward Closed	5×10^{-5}	(Lees 1973, Lawley 1974, Browning 1973)
	Fails Open or Is Misdirected Toward Open	5×10^{-5}	(Lees 1973, Lawley 1974, Browning 1973)
Expansion Joints	Rupture	1×10^{-7}	(Welker 1976, SAI 1975)
Pipe Fittings (flanges, elbows, tees, etc.)	Rupture	1×10^{-8}	(USNRC 1975)
Loading Arm	Rupture	3×10^{-7}	(Welker 1976, SAI 1975)
Sensors/Detectors			
Flow	Fail Dangerously	2×10^{-4}	(Lees 1973, Lawley 1974, Browning 1973, 1978, Anyakora 1971)
Level	Fail Dangerously	2×10^{-4}	(Lees 1973, Lawley 1974, Browning 1973, 1978, Anyakora 1971)
Pressure	Fail Dangerously	1×10^{-4}	(Lees 1973, Kletz 1977, Anyakora 1971)
Temperature	Fail Dangerously	1×10^{-4}	(Lees 1973, Browning 1978, Anyakora 1971)
Combustible Gas	Fail Dangerously	4×10^{-5}	(Welker 1979, St. John 1978)
UV Radiation	Fail Dangerously	1×10^{-4}	(Welker 1976, 1979, Lees 1973, Anyakora 1971)
Low Temperature	Fail Dangerously	1×10^{-4}	--

TABLE 3. (contd)

Component	Failure Mode	Faults/Hr	Reference
Controller, Limit Switch (decision-making unit)	Fail Dangerously	3×10^{-5}	(Lees 1973, Browning 1973, 1978, Anyakora 1971, Fisher 1973)
Alarm	Fails to Operate	5×10^{-5}	(SAI 1975, Lawley 1974, Browning 1978)
Relief Valve	Fails to Open	1×10^{-6}	(Lawley 1974, Kletz 1972, 1977, USNRC 1975)
	Opens Prematurely	1×10^{-5}	(Lawley 1974, USNRC 1975)
ESD Circuitry (based on failure of a relay to energize or to open)	Fails to Energize	1×10^{-5}	(USNRC 1975, Welker 1976, Lees 1973, Anyakora 1971)
	Fails to De-energize (fail-safe system)	1×10^{-7}	(USNRC 1975, Welker 1976, Lees 1973, Anyakora 1971)
Operator[(a)]	Fails to Respond Correctly to Changes in Important Process Variable, Complex System	3×10^{-1}	(Kletz 1972, 1973, 1975)
	Fails to Respond Correctly to Changes in Important Process Variables, Simple System	$3. \times 10^{-2}$	(Lawley 1974, Kletz 1973, 1975)
	Fails to Respond Promptly and Correctly to Emergency Alarms, Simple System	1×10^{-2}	(Kletz 1975)
	Monitor or Inspection Error, Fails to Notice a Release, or Severe Equipment Problems	1×10^{-1}	(Welker 1976, Kletz 1972, 1973, 1975)
	Fails to Follow Standard Operating Procedure, Testing, or Maintenance Procedures	5×10^{-2}	(Kletz 1972, 1973, 1975)

(a) Faults per demand.

More often than not in our analysis the top event was a large release of LNG from a particular system. After selecting the top event the analyst systematically works backward to identify component faults (basic events), which could cause or contribute to the undesired top event.

Standard symbols shown in Figure 2 are used to express the relationship of individual component failures (basic events) to the overall system failure (top event). Multiple events which individually cause or contribute to the top event are connected by an OR gate. Events which must occur concurrently in order to cause or contribute to the top event are connected by an AND gate.

TABLE 7. Summary of Results of LNG Peakshaving Facility Release Scenario Analysis

Release Scenarios	Expected No. of Events Per Year	Release Occurrs And Is Not Stopped in 1 Min. by ESD Expected No. of Events Per Year	Maximum Release Size (Equivalent Gallons of LNG) 1 Min.	10 Min.	Material Released	Critical System Components
Storage System						
Gross Failure of Storage Tank	1×10^{-5}	-	-	1.5×10^{7}	LNG	Storage Tank
Storage Tank Is Overfilled	3×10^{-4}	-	(a)	(a)	Natural Gas/LNG	Operator, Level Detectors
Storage Tank Is Over-pressured and Relief Valves Open	1	-	5-2400(b)	50-24000(b)	Natural Gas	Pressure Detector, Pressure Controller, Operator
Storage Tank Is Over-pressured and Relief Valves Fail	1×10^{-6}		95-285(c)	1.1×10^{6} - 3.4×10^{6}(c)	Natural Gas/LNG	Relief Valves
Storage Tank Is Under-pressured and Relief Valves Open	5×10^{-3}		-	-		Pressure Detector, Pressure Controller
Storage Tank Is Under-pressured and Relief Valves Fail	5×10^{-9}		95-285(c)	1.1×10^{6} - 3.4×10^{6}(c)	Natural Gas/LNG	Relief Valves
Rupture of Storage Tank Inlet Line	5×10^{-4}	6×10^{-4}	50	500	LNG	Expansion Joint, Operator
Rupture of Storage Tank Outlet Line	5×10^{-5}	1×10^{-5}	28000	280000	LNG	Expansion Joint, Internal Valve, Operator
Rupture of Pump Discharge Line	2×10^{-3}	2×10^{-5}	625	6250	LNG	Expansion Joint, Operator

4.3

TABLE 7. con't

Vaporizer Section						
Vaporizer Tube (Sub. Comb.) Rupture	1×10^{-1}	1×10^{-3}	1250	12500	Natural Gas/LNG	Heat Exchanger Tubes, Operator
Rupture of Vaporizer Outlet Line from Cold Gas (Vaporizer Control Failure)	9×10^{-2}	9×10^{-4}	1250	12500	Natural Gas/LNG	Vaporizer Outlet Temp. Controller, Operator
Transportation and Transfer						
Rupture of 3" Liquid Loading Line During Loading	1×10^{-4}	2×10^{-6}	460	3600	LNG	Expansion Joints, Transfer Pump Operator, Gas Detectors
Rupture of 3" Liquid Unloading Line During Unloading	6×10^{-5}	1×10^{-6}	870	8200	LNG	Expansion Joints, Operator, Gas Detectors
Rupture of 350 gpm Sendout Pump During Loading	1×10^{-4}	1×10^{-5}	1800	18200	LNG	Transfer Pump, Gas Detectors, Flow Detector, Operator
Rupture of 2" Vapor Return Line During Loading	1×10^{-4}	2×10^{-6}	1100 ft^3	11000 ft^3	Natural Gas	Expansion Joints, Operator, Gas Detectors
Rupture of Flexible Metal Hose During Load/Unload	6×10^{-4} 3×10^{-4}	1×10^{-5} 6×10^{-6}	Load: 470 Unload: 1600	Load: 3600 Unload: 10500	LNG LNG	Flexible Hose, Connectors, Operator
Rupture of Pressure Buildup Coil During Unloading	6×10^{-7}	6×10^{-9}	200	2000	LNG	Valves, Operator
Trailer Accidents	1.7×10^{-2}	-	10500	-	LNG	Driver, Double-Walled Tank, Pressure Relief Devices

(a) Could cause failure of outer shell and roof. Failure of inner tank possible.
(b) Lower number is typical of vapor generation rate during filling. Higher number is maximum relief valve capacity.
(c) Will cause rupture of outer tank roof/wall joint. Failure of inner tank is unlikely. Release rate is for an open top tank for 200 hours (time to pump tank down).

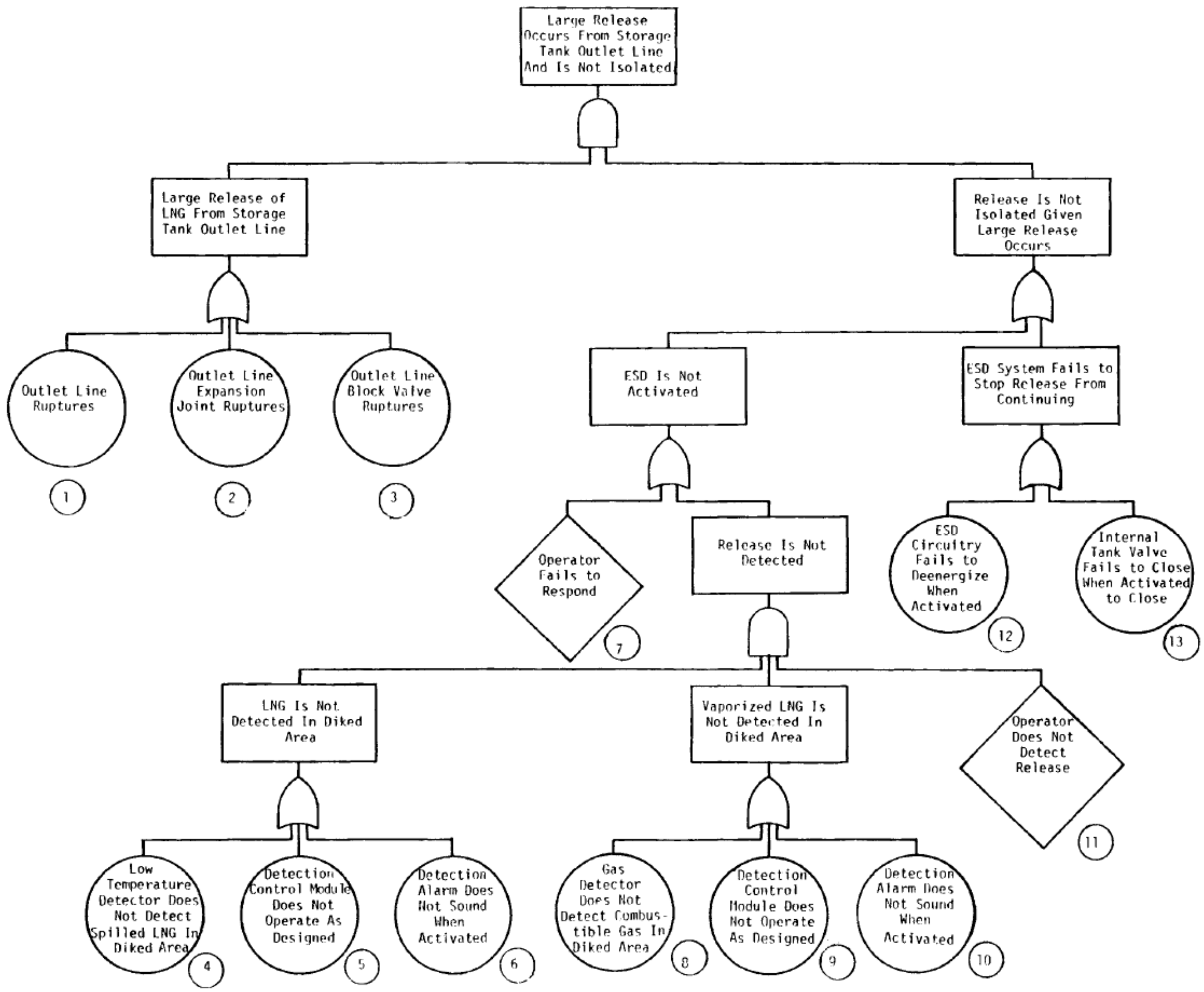


FIGURE B.8 Fault Tree for a Large Release from the Storage Tank Outlet Line (Supporting Calculations in Table B.7)

TABLE B.7. Supporting Calculations for Large Release from Storage Tank Outlet Line (See Figure B.8)

		λ (Faults/Hr)	τ or t (Hr)	$\bar{a}$ (Faults)
Basic Events:				
1	Outlet line ruptures (5 sections)[(a)]	$5\ (1 \times 10^{-10})$	t = 480	2.4×10^{-7}
2	Outlet line expansion joint ruptures[(a)]	1×10^{-7}	t = 480	4.8×10^{-5}
3	Outlet line block valve ruptures[(a)]	1×10^{-9}	t = 480	4.8×10^{-7}
4	Low temperature detector does not detect spilled LNG in diked area[(b)]	1×10^{-4}	1000	1×10^{-1}
5	Detection control module does not operate as designed[(b)]	3×10^{-5}	1000	3×10^{-2}
6	Detection alarm does not sound when activated[(c)]	5×10^{-5}	80	4×10^{-3}
7	Operator fails to respond[(d)]			1×10^{-2}
8	Gas detector does not detect combustible gas in diked area[(b)]	4×10^{-5}	1000	4×10^{-2}
9	Detection control module does not operate as designed[(b)]	3×10^{-5}	1000	3×10^{-2}
10	Detection alarm does not sound when activated[(c)]	5×10^{-5}	80	4×10^{-3}
11	Operator does not detect release[(d)]			1×10^{-1}
12	ESD circuitry fails to deenergize when activated[(b)]	1×10^{-7}	1000	1×10^{-4}
13	Internal tank valve fails to close when activated to close[(e)]	5×10^{-5}	4000	2×10^{-1}

TABLE B.7. Contd

Calculations:

14 ENF(expected number of failures) = (1) + (2) + (3)
$= (2.4 \times 10^{-7}/yr + 4.8 \times 10^{-5}/yr + 4.8 \times 10^{-7}/yr) = 4.9 \times 10^{-5}/yr$

15 Release is not isolated = [((4) + (5) + (6)) ((8) + (9) + (10)) ((11)) + (7) + (12) + (13)] = $[(1 \times 10^{-1} + 3 \times 10^{-2} + 4 \times 10^{-3}) (4 \times 10^{-2} + 3 \times 10^{-2} + 4 \times 10^{-3}) (1 \times 10^{-1}) + 1 \times 10^{-2} + 1 \times 10^{-4} + 2 \times 10^{-1}] = 2.1 \times 10^{-1}$/demand

TOP EVENT = (14) * (15) = 1.0×10^{-5}/year

(a) t = mission time of 20 days/year = 480 hours/year
(b) Detectors, control modules, and ESD circuitry are on a three month test interval for an assumed combined detection plus repair time of 2000 hours and a mean dead time of 1000 hours.
(c) Alarms are tested weekly for an assumed combined detection plus repair time of 160 hours and a mean dead time of 80 hours.
(d) Faults per demand.
(e) Internal tank valve is tested once a year for an assumed combined detection time and repair time of 8000 hours and a mean dead time of 4000 hours.

Rupture of an outlet LNG line will occur about 5×10^{-5} times per year. If the sendout system is shut down and the release isolated in 1 minute, 28,000 gallons would be spilled. If the system is not shut down for 10 minutes, 280,000 gallons would be released. This will occur 2×10^{-1} per demand, resulting in a probability of about 1×10^{-5} per year for this scenario. If an outlet line ruptures, gas detectors and LTDs in the storage tank dike area will warn the operator that an emergency condition exists and the operator would then have to activate the ESD. A fault tree for the rupture of a storage outlet line is shown in Figure C.8. If the internal valve did not close, the contents of the whole tank would be released up to 348,000 bbls.

TABLE B.16. Supporting Calculations for Release from Storage Tank Outlet Line with Alternative Design of In-Tank Pumps (See Figure B.18)

		λ (Faults/Hr)	τ (Hr)	$\bar{a}$ (Probability)
Basic Events:				
1	Outlet line ruptures (17 sections)	$(17)(1 \times 10^{-10})$		
2	Outlet line expansion joint ruptures (2 joints)	$(2)(1 \times 10^{-7})$		
3	Outlet line block valve ruptures (2 valves)	$(2)(1 \times 10^{-9})$		
4	Low temperature detector does not detect spilled LNG in diked area[a]	1×10^{-4}	1000	1×10^{-1}
5	Detection control module does not operate as designed[a]	3×10^{-5}	1000	3×10^{-2}
6	Detection alarm does not sound when activated[b]	5×10^{-5}	80	4×10^{-3}
7	Operator fails to respond[c]			1×10^{-2}
8	Gas detector does not detect combustible gas in diked area[a]	4×10^{-5}	1000	4×10^{-2}
9	Detection control module does not operate as designed[a]	3×10^{-5}	1000	3×10^{-2}
10	Detection alarm does not sound when activated[b]	5×10^{-5}	80	4×10^{-3}
11	Operator does not detect release[c]			1×10^{-1}
12	ESD circuitry fails to deenergize when activated[a]	1×10^{-7}	1000	1×10^{-4}
13	Pump A fails to stop[e]	1×10^{-7}	4000	4×10^{-4}
14	Block valve A fails to close[a]	5×10^{-5}	1000	5×10^{-2}
15	Pump B fails to stop[e]	1×10^{-7}	4000	4×10^{-4}
16	Block valve B fails to close[a]	5×10^{-5}	1000	5×10^{-2}

TABLE B.16. Contd

	λ (Faults/Hr)	τ (Hr)	$\bar{a}$ (Probability)
Basic Events:			
17 LNG is being pumped to the vaporizers[d]	480 hr/8760 hr = 5.5×10^{-2}		

Calculations:

18 Minimum Cut Set for Outlet Line Rupture

This assumes that an outlet line rupture is downstream of the pumps and block valves therefore a release will continue if both pumps and block valves fail to stop or close respectively.

① [(④ + ⑤ + ⑥) (⑧ + ⑨ + ⑩) (⑪) + ⑦ + ⑫
+ (⑬ * ⑭) + (⑮ * ⑯)] ⑰ = $(1.7 \times 10^{-9}$/hr)
(8760 hrs/yr)[f] $[(1 \times 10^{-1} + 3 \times 10^{-2} + 4 \times 10^{-3})$ $(4 \times 10^{-2}$
$+ 3 \times 10^{-2} + 4 \times 10^{-3})$ $(1 \times 10^{-1}) + 1 \times 10^{-2} + 1 \times 10^{-4}$
$+ (4 \times 10^{-4} * 5 \times 10^{-2}) + (4 \times 10^{-4} * 5 \times 10^{-2})]$ (5.5×10^{-2})
$= 9.1 \times 10^{-9}$/yr

19 Minimum Cut Set for Outlet Line Expansion Joint Rupture

(2A) = Hazard rate expansion Joint A = 1×10^{-7}/hr
(2B) = Hazard rate expansion Joint B = 1×10^{-7}/hr

This assumes that the expansion joints are upstream of the block valves therefore is expansion joint A ruptures block valve A won't be involved in stopping flow by path 1 but it will be possible to stop flow by path 2. Vice-versa for expansion joint B.

⑰ { ② [(④ + ⑤ + ⑥) (⑧ + ⑨ + ⑩) (⑪) + ⑦ + ⑫]
+ (2A) [⑬ + ⑭ ⑮ ⑯] + (2B) [⑮ + ⑬ ⑭ ⑯]} = (5.5×10^{-2})
{$(2 \times 10^{-7}$/hr) (8760 hr/yr)[f] $[(1 \times 10^{-1} + 3 \times 10^{-2} + 4 \times 10^{-3})$
$* (4 \times 10^{-2} + 3 \times 10^{-2} + 4 \times 10^{-3})$ $(1 \times 10^{-1}) + 1 \times 10^{-2}$
$+ 1 \times 10^{-4}]$ + $(1 \times 10^{-7}$/hr) (8760 hr/yr)[f] $[4 \times 10^{-4}$
$+ (5 \times 10^{-2} * 4 \times 10^{-4} * 5 \times 10^{-2})]$ + $(1 \times 10^{-7}$/hr)
(8760 hr/yr)[f] $[4 \times 10^{-4} + (4 \times 10^{-4} * 5 \times 10^{-2} * 5 \times 10^{-2})]$}
$= 1.1 \times 10^{-6}$/yr

B.56

TABLE B.16. Contd

Calculations:

20 Minimum Cut Set for Outlet Line Block Valve Rupture

3A = Hazard rate block valve A rupture = 1×10^{-9}/hr

3B = Hazard rate block valve B rupture = 1×10^{-9}/hr

This calculation is based on the fact that if block valve A ruptures then block valve A won't be involved in ESD shutdown by either path 1 or 2. Vice-versa for block valve B.

$$⑰ \{ ③ [(④ + ⑤ + ⑥)(⑧ + ⑨ + ⑩)(⑪) + ⑦ + ⑫] + Ⓐ[⑬ + ⑮ * ⑯] + Ⓑ[⑮ + ⑬ * ⑭]\}$$

$$= (5.5 \times 10^{-2}) \{(2 \times 10^{-9}/hr)(8760\ hr/yr)^{(f)} [(1 \times 10^{-1} + 3 \times 10^{-2} + 4 \times 10^{-3}) * (4 \times 10^{-2} + 3 \times 10^{-2} + 4 \times 10^{-3}) (1 \times 10^{-1}) + 1 \times 10^{-2} + 1 \times 10^{-4}] + (1 \times 10^{-9}/hr) (8760\ hr/yr)^{(f)} [4 \times 10^{-4} + (4 \times 10^{-4}) (5 \times 10^{-2})] + (1 \times 10^{-9}/hr) (8760\ hr/yr)^{(f)} [4 \times 10^{-4} + (4 \times 10^{-4}) (5 \times 10^{-2})]\} = 1.1 \times 10^{-8}/yr$$

$$\text{TOP EVENT} = ⑱ + ⑲ + ⑳ = 9.1 \times 10^{-9}/yr + 1.1 \times 10^{-6}/yr + 1.1 \times 10^{-8}/yr = 1.1 \times 10^{-6}/yr$$

(a) Detectors, control modules, ESD Circuitry, and block valves are tested on a three month test interval for an assumed combined detection plus repair time of 2000 hours and a mean dead time of 1000 hours.
(b) Alarms are on a weekly test interval for an assumed combined detection plus repair time of 160 hours and a mean dead time of 80 hours.
(c) Faults per demand.
(d) LNG is being pumped to vaporizers 20 days/year or 480 hours/year.
(e) Pumps are assumed to be tested once a year for an assumed combined detection plus repair time of 8000 hours and a mean dead time of 4000 hours.
(f) Multiplication by 8760 hours per year is to convert the λ = faults/hour to λ = faults/year.

TABLE B.17. Supporting Calculations for Release from Storage Tank Outlet Line with Alternative Design of a Double Ply Expansion Joint (See Figure B.19)

		λ (Faults/Hr)	τ or t (Hr)	$\bar{a}$ (Probability)
Basic Events:				
1	Outlet line ruptures (5 sections)	$(5)(1 \times 10^{-10})$		
2a	First expansion joint ruptures	1×10^{-7}		
2b	Second (outer) expansion joint ruptures[(a)]	1×10^{-7}	t = 8760	8.8×10^{-4}
3	Outlet line block valve ruptures	1×10^{-9}		
4	Low temperature detector does not detect spilled LNG in diked area[(b)]	1×10^{-4}	1000	1×10^{-1}
5	Detection control module does not operate as designed[(b)]	3×10^{-5}	1000	3×10^{-2}
6	Detection alarm does not sound when activated[(c)]	5×10^{-5}	80	4×10^{-3}
7	Operator fails to respond[(d)]			1×10^{-2}
8	Gas detector does not detect combustible gas in diked area[(b)]	4×10^{-5}	1000	4×10^{-2}
9	Detection control module does not operate as designed[(b)]	3×10^{-5}	1000	3×10^{-2}
10	Detection alarm does not sound when activated[(c)]	5×10^{-5}	80	4×10^{-3}
11	Operator does not detect release[(d)]			1×10^{-1}
12	ESD circuitry fails to deenergize when activated[(b)]	1×10^{-7}	1000	1×10^{-4}
13	Internal tank valve fails to close when activated to close[(e)]	5×10^{-5}	4000	2×10^{-1}

TABLE B.17. Contd

Calculations:

14 ENF(expected number of failures) = (1) + ((2a) * (2b)) + (3)
= (8760 hr/yr)[(f)] [5×10^{-10}/hr + (1×10^{-7}/hr * 8.8×10^{-4})
+ 1×10^{-9}/hr] = 1.4×10^{-5}/yr

15 Release is not isolated given Large Release Occurs = [((4) + (5) + (6))
((8) + (9) + (10)) ((11)) + (7) + (12) + (13)] = [(1×10^{-1} + 3×10^{-2}
+ 4×10^{-3}) (4×10^{-2} + 3×10^{-2} + 4×10^{-3}) (1×10^{-1})
+ 1×10^{-2} + 1×10^{-4} + 2×10^{-1}] = 2.1×10^{-1}/demand)

TOP EVENT = (14) * (15) = (1.4×10^{-5}/year) (2.1×10^{-1}/demand)
= 2.9×10^{-6}/year

(a) The mission time for the second (outer) expansion joint is assumed to be one year = 8760 hours.
(b) Detectors, control modules, and ESD circuitry are on a three month test interval for an assumed combined detection plus repair time of 2000 hours and a mean dead time of 1000 hours.
(c) Alarms are tested weekly for an assumed combined detection plus repair time of 160 hours and a mean dead time of 80 hours.
(d) Faults per demand.
(e) Internal tank valve is tested once a year for an assumed combined detection plus repair time of 8000 hours and a mean dead time of 4000 hours.
(f) Multiplication by 8760 hours per year is to convert the λ = faults/hr to λ = faults/yr.

Release Calculations Tank Outlet Line Rupture

Based on a hydrostatic pressure due to 100' of LNG (from top of inner tank to level of break) causing flow speed of 80 ft/sec or flow through 12" pipe of 470 gallons/second:

- Assuming a one minute release:
  28,000 gallons of LNG released.
- Assuming a 10 minute release:
  280,000 gallons of LNG released.

TABLE B.18. Supporting Calculations for Release from Storage Tank Outline Line (Bottom Withdrawal) with Alternative Design of a Block Valve Upstream as well as Downstream of the Expansion Joint (See Figure B.20)

		λ (Faults/Hr)	τ (Hr)	$\bar{a}$ (Probability)
Basic Events:				
1	Outlet line ruptures (5 sections)	$(5)(1 \times 10^{-10})$		
2a	Outlet line expansion joint ruptures	1×10^{-7}		
3a	Outlet line upstream block valve ruptures	1×10^{-9}		
3b	Outlet line downstream block valve ruptures	1×10^{-9}		
4	Low temperature detector does not detect spilled LNG in diked area(a)	1×10^{-4}	1000	1×10^{-1}
5	Detection control module does not operate as designed(a)	3×10^{-5}	1000	3×10^{-2}
6	Detection alarm does not sound when activated(b)	5×10^{-5}	80	4×10^{-3}
7	Operator fails to respond(c)			1×10^{-2}
8	Gas detector does not detect combustible gas in diked area(a)	4×10^{-5}	1000	4×10^{-2}
9	Detection control module does not operate as designed(a)	3×10^{-5}	1000	3×10^{-2}
10	Detection alarm does not sound when activated(b)	5×10^{-5}	80	4×10^{-3}
11	Operator does not detect release(c)			1×10^{-1}
12	ESD circuitry fails to deenergize when activated( )	1×10^{-7}	1000	1×10^{-4}
13	Internal tank valve fails to close when activated to close(d)	5×10^{-5}	4000	2×10^{-1}

TABLE B.18. Contd

		λ (Faults/Hr)	τ (Hr)	$\bar{a}$ (Probability)
Basic Events:				
14	Block valve before the expansion joint fails to close[a]	5×10^{-5}	1000	5×10^{-2}
15	Block valve after the expansion joint fails to close[e]	5×10^{-5}	500	2.5×10^{-2}

Calculations:

16 Cut Set for Outlet Line Rupture

This assumes that an outlet line rupture is downstream of all the expansion joint and block valves.

$$(1) [((4) + (5) + (6)) ((8) + (9) + (10)) ((11)) + (7) + (12) + ((13) * (14) * (15))] = (5 \times 10^{-10}/\text{hr}) (8760 \text{ hr/yr}) [(1 \times 10^{-1} + 3 \times 10^{-2} + 4 \times 10^{-3}) (4 \times 10^{-2} + 3 \times 10^{-2} + 4 \times 10^{-3}) (1 \times 10^{-1}) + 1 \times 10^{-2} + 1 \times 10^{-4} + (2 \times 10^{-1} * 5 \times 10^{-2} * 2.5 \times 10^{-2})] = 5.0 \times 10^{-8}/\text{yr}$$

17 Cut Set for Expansion Joint Failure

$$(2) [((4) + (5) + (6)) ((8) + (9) + (10)) ((11)) + (7) + (12) + ((13) * (14))] = (1 \times 10^{-7}/\text{hr}) (8760 \text{ hr/yr}) [(1 \times 10^{-1} + 3 \times 10^{-2} + 4 \times 10^{-3}) (4 \times 10^{-2} + 3 \times 10^{-2} + 4 \times 10^{-3}) (1 \times 10^{-1}) + 1 \times 10^{-2} + 1 \times 10^{-4} + (2 \times 10^{-1} * 5 \times 10^{-2})] = 1.8 \times 10^{-5}/\text{yr}$$

TABLE B.17. Contd

Calculations:

18 Cut Set for Upstream Block Valve Rupture

This assumes that once a block valve ruptures the fact that it could still close has no effect on system.

(3a) [((4) + (5) + (6)) ((8) + (9) + (10)) ((11)) + (7) + (12) + (13))]
$= (1 \times 10^{-9}/hr)\ (8760\ hr/yr)\ [(1 \times 10^{-1} + 3 \times 10^{-2} + 4 \times 10^{-3})$
$(4 \times 10^{-3})\ (4 \times 10^{-2} + 3 \times 10^{-2} + 4 \times 10^{-3})\ (1 \times 10^{-1})$
$+ 1 \times 10^{-2} + 1 \times 10^{-4} + 2 \times 10^{-1}] = 1.8 \times 10^{-6}/yr$

19 Cut Set for Downstream Block Valve Rupture

This assumes that once a block valve rupture the fact that it could still close has no effect on the system.

(3b) [((4) + (5) + (6)) ((8) + (9) + (10)) ((11)) + (7) + (12) + (13)
* (14))] $= (1 \times 10^{-9}/hr)\ (8760\ hr/yr)\ [(1 \times 10^{-1} + 3 \times 10^{-2}$
$+ 4 \times 10^{-3})\ (4 \times 10^{-2} + 3 \times 10^{-2} + 4 \times 10^{-3})\ (1 \times 10^{-1})$
$+ 1 \times 10^{-2} + (2 \times 10^{-1} * 5 \times 10^{-2})] = 1.8 \times 10^{-7}/yr$

TOP EVENT = (16) + (17) + (18) + (19) $= 5.0 \times 10^{-8}/yr + 1.8 \times 10^{-5}/yr$
$+ 1.8 \times 10^{-6}/yr + 1.8 \times 10^{-7}/yr = 2.0 \times 10^{-5}/yr$

(a) Detectors, control modules, ESD circuitry, and the upstream block valve are on a three month test interval for an assumed combined detection plus repair time of 2000 hours and a mean dead time of 1000 hours.
(b) Alarms are on a weekly test interval for an assumed combined detection plus repair time of 160 hours and a mean dead time of 80 hours.
(c) Faults per demand.
(d) The internal tank valve is tested once a year for an assumed combined detection and repair time of 8000 hours and a mean dead time of 4000 hours.
(e) The block valve downstream of the expansion joint is assumed to be always closed except for the ∿20 days/year when vaporizaton is assumed to occur. Thus the block valve has a mission time of ∿20 days or an assumed time of 500 hours to develop a fault not to close.
(f) Multiplication by 8760 hours per year is to convert the λ = faults/hr to λ = faults/yr.

Appendix H: Excerpts from *Analysis of LNG Import Terminal Release Prevention Systems (PNL-4152)*

The following excerpts from *Analysis of LNG Import Terminal Release Prevention Systems* by Baker, E.G. of Pacific Northwest Laboratory, PNL-4152, 1982 ("PNL ITRP '82") are provided directly in this Final Report for the reader's convenience.

TABLE 3.3. Generic Failure Rates for Components of LNG Import Terminals

Component	Failure Mode	Faults/Hr	Reference
Pump	Rupture	1×10^{-8}	(SAI 1975, Browning 1978)
	Fails to Stop	1×10^{-7}	(Welker 1976)
Compressor	Rupture	1×10^{-8}	(SAI 1975, Browning 1978)
	Fails to Run Normally	3×10^{-4}	(Welker 1979)
Vaporizer	Tube or Panel Rupture	1×10^{-5}	(Welker 1979)
	Control System Failure	1×10^{-4}	(Welker 1979)
Pipe Section >3 in dia.	Rupture	1×10^{-10}	(USNRC 1975)
Storage Tank	Rupture	1×10^{-9} 1×10^{-10}	(SAI 1975, Atullah 1980)
	Cold Spot	1×10^{-5}	(Welker 1979)
Valve	Rupture	1×10^{-9}	(USNRC 1975, Welker 1979)
	Fails Closed or Is Misdirected Toward Closed	5×10^{-5}	(Lees 1973, Lawley 1974, Browning 1973)
	Fails Open or Is Misdirected Toward Open	5×10^{-5}	(Lees 1973, Lawley 1974, Browning 1973)
Expansion Joints	Rupture	1×10^{-7}	(Welker 1976, SAI 1975)
Pipe Fittings (flanges, elbows, tees, etc.)	Rupture	1×10^{-8}	(USNRC 1975)
Loading Arm	Rupture	3×10^{-7}	(Welker 1976, SAI 1975)
Sensors/Detectors			
Flow	Fail Dangerously	2×10^{-4}	(Lees 1973, Lawley 1974, Browning 1973, 1978, Anyakora 1971)
Level	Fail Dangerously	2×10^{-4}	(Lees 1973, Lawley 1974, Browning 1973, 1978, Anyakora 1971)
Pressure	Fail Dangerously	1×10^{-4}	(Lees 1973, Kletz 1977, Anyakora 1971)
Temperature	Fail Dangerously	1×10^{-4}	(Lees 1973, Browning 1978, Anyakora 1971)
Combustible Gas	Fail Dangerously	4×10^{-5}	(Welker 1979, St. John 1978)
UV Radiation	Fail Dangerously	1×10^{-4}	(Welker 1976, 1979, Lees 1973, Anyakora 1971)
Low Temperature	Fail Dangerously	1×10^{-4}	--

TABLE 3.3. (contd)

Component	Failure Mode	Faults/Hr	Reference
Controller, Limit Switch (decision-making unit)	Fail Dangerously	3×10^{-5}	(Lees 1973, Browning 1973, 1978, Anyakora 1971, Fisher 1973)
Alarm	Fails to Operate	5×10^{-5}	(SAI 1975, Lawley 1974, Browning 1978)
Relief Valve	Fails to Open	1×10^{-6}	(Lawley 1974, Kletz 1972, 1977, USNRC 1975)
	Opens Prematurely	1×10^{-5}	(Lawley 1974, USNRC 1975)
ESD Circuitry (based on failure of a relay to energize or to open)	Fails to Energize	1×10^{-5}	(USNRC 1975, Welker 1976, Lees 1973, Anyakora 1971)
	Fails to De-energize (fail-safe system)	1×10^{-7}	(USNRC 1975, Welker 1976, Lees 1973, Anyakora 1971)
Operator[(a)]	Fails to Respond Correctly to Changes in Important Process Variable, Complex System	3×10^{-1}	(Kletz 1972, 1973, 1975)
	Fails to Respond Correctly to Changes in Important Process Variables, Simple System	3×10^{-1}	(Lawley 1974, Kletz 1973, 1975)
	Fails to Respond Promptly and Correctly to Emergency Alarms, Simple System	1×10^{-2}	(Kletz 1975)
	Monitor or Inspection Error, Fails to Notice a Release, or Severe Equipment Problems	1×10^{-1}	(Welker 1976, Kletz 1972, 1973, 1975)
	Fails to Follow Standard Operating Procedure, Testing, or Maintenance Procedures	5×10^{-2}	(Kletz 1972, 1973, 1975)

(a) Faults per demand.

TABLE 4.1. Summary of Results of LNG Import Terminal Release Scenario Analysis

Release Scenarios	Expected Number of Events per Year	Release Occurs and Is Not Stopped in 1 Minute by ESD Expected Number of Events per Year	Maximum Release Size (Equivalent Gallons of LNG) 1 Minute	10 Minutes	Material Release	Critical System Components
Marine Terminal and Unloading System						
1. Rupture of Loading Arm or Components During Unloading	2×10^{-3}	2×10^{-5}	15,000	130,000	LNG	Loading Arm, Swivel Joints, Operator
2. Rupture of Main Transfer Line or Components During Unloading	4×10^{-3}	1×10^{-6}	500,000	970,000	LNG	Expansion Joints
Storage System						
3. Gross Failure of a Storage Tank	1×10^{-5}	--	--	23,000,000	LNG	Storage Tanks
4. Storage Tank Is Overfilled	2×10^{-3}	--	--(a)	--(a)	Natural Gas/LNG	Level Detectors and Transmitters, Filling Valve, Operator
5. Storage Tank Is Overpressured During Filling and Vent/Relief Valves Open	5×10^{-1}	--	400-4,000(b)	4,000-40,000(b)	Natural Gas	Pressure Detector, Pressure Contoller, Operator
5a. Storage Tank Is Overpressured During Filling and Vent/Relief Valves Fail	1×10^{-6}(d)	--	200-600(c)	1,200,000-3,500,000(c)	Natural Gas/LNG	Vent/Relief Valves
6. Storage Tank Is Underpressured and Vacuum Relief Valves Open	2×10^{-3}	--	--	--	--	Pressure Controller, Pressure Detector
6a. Storage Tank Is Underpressured and Vacuum Relief Valves Fail	1×10^{-8}(e)	--	200-600(c)	1,200,000-3,500,000(c)	Natural Gas/LNG	Vent/Relief Valves
7. Rupture of Storage Tank Inlet Line	2×10^{-6}	4×10^{-8}	61,000	538,000	LNG	Filling Valves, Pipe Fittings, Operator
8. Rupture of Storage Tank Outlet Line	3×10^{-5}	5×10^{-7}	5,000	41,000	LNG	Outlet Valves, Pipe Fittings, Operator
9. Rupture of Secondary Pump or Associated Piping and Valves	2×10^{-3}	3×10^{-5}	5,000	41,000	LNG	Secondary Pumps, Section and Discharge Valves
Vaporization Section						
10. Vaporizer Tube (Sub. Comb.) or Plate (Open Rack) Rupture	5×10^{-1}	5×10^{-2}	1,700	4,100	Natural Gas/LNG	Heat Exhanger Tubes or Plates
11. Rupture of Vaporizer Outlet Line From Cold Gas (Vaporizer Contol Failure)	8×10^{-2}	8×10^{-4}	2,000	11,000	Natural Gas/LNG	Temperature Control System, Temperature Detectors, Operator
12. Rupture of Main Vaporizer Header and Gas Line to the Pipeline	1×10^{-4}	1×10^{-6}	16,000	83,000	Natural Gas	Piping

(a) Could cause failure of outer shell and roof. Failure of inner tank is possible.
(b) Lower number is typical vapor generation rate during filling. Higher number is maximum relief valve capacity.
(c) Will cause rupture of outer tank roof/wall joint. Failure of inner tank is unlikely. Release rate is for an open top tank for 100 hours (time to pump out the tank is full).
(d) Assumes four relief valves or the vent valve required to relieve pressure.
(e) Assumes only one vacuum relief valve is necessary to equalize pressure.

4.3

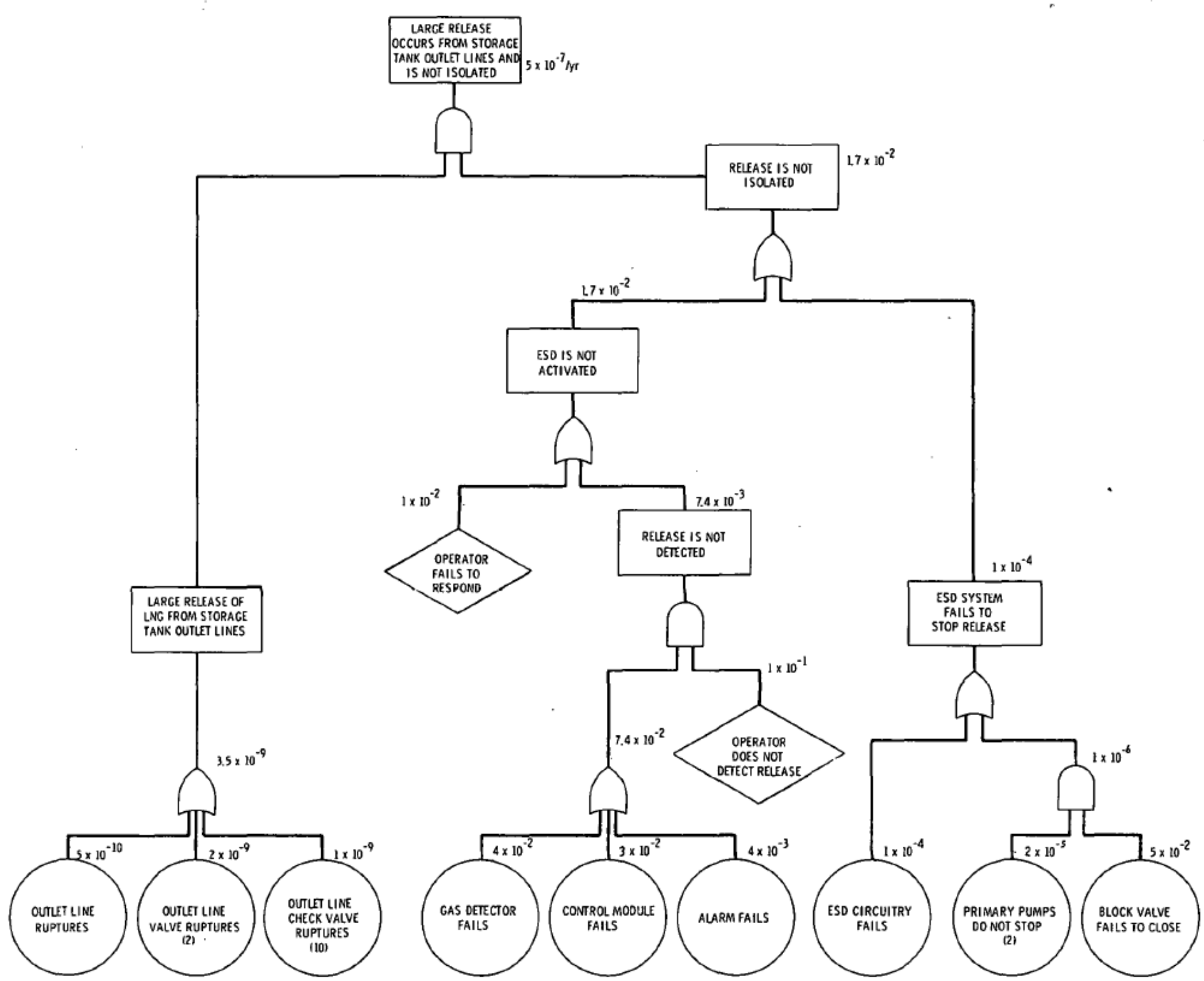


FIGURE B.11. Fault Tree for Large Release from Storage Tank Outlet Lines

TABLE B.8. Supporting Calculations for Large Release from Storage Tank Outlet Lines Fault Tree

Large Release From Storage Tank Outlet Lines

Gas Detector System	λ	τ	$\bar{a}$
Gas detector fails	4×10^{-5}	1000	4×10^{-2}
Control module fails	3×10^{-5}	1000	3×10^{-2}
Alarm fails	5×10^{-5}	80	4×10^{-3}
			7.4×10^{-2}

ESD System			
ESD circuitry fails	1×10^{-7}	1000	1×10^{-4}
Primary pumps do not stop (2)	2×10^{-7}	100	2×10^{-5}
Block valve fails to close	5×10^{-5}	1000	5×10^{-2}
			1×10^{-6}
ESD system fails to stop release			1×10^{-4}

Expected number of failures	3.5×10^{-9}/hr = 3.1×10^{-5}/yr
Release is not isolated	1.7×10^{-2}/demand (5×10^{-7}/yr)

TABLE B.12. Supporting Calculations for Main Transfer Line Rupture (Double Ply Expansion Joints) Fault Tree

Rupture of Main Transfer Line During Filling (Double Ply Expansion Joints)

1. Assume if one ply is faulty unloading operations are stopped and do not resume until repaired so $\tau = 0$
2. If not detected by the pressure sensor the fault is not repairable
3. Longest the fault will go undected is equal to the pressure sensor test interval so τ avg = 1000 hrs (3 month test interval)

	λ	τ	$\bar{a}$
Expansion joint 1 fails	1×10^{-7}		
Pressure sensor fails	1×10^{-4}	1000	0.1
Pressure switch fails	3×10^{-5}	1000	3×10^{-2}
Alarm fails	5×10^{-5}	80	4×10^{-3}
			.13
Expansion joint 1 fails and fault is undetected	1.4×10^{-8}	1000	1.4×10^{-5}
Expansion joint 2 fails during loading	1×10^{-7}		

$$enf = \lambda T = 1 \times 10^{-7} \text{ (1500 hrs/yr)}$$

$$enf = 1.5 \times 10^{-4}/yr$$

Expected number of failures during loading per expansion joint $= 1.4 \times 10^{-5} (1.5 \times 10^{-4}) = 2 \times 10^{-9}$

x 25 expansion joints $= 5 \times 10^{-8}$/year

Other failure modes (pipe and valve rupture) $= 3 \times 10^{-5}$/yr

TABLE B.13. Supporting Calculations for Main Transfer Line Rupture (Double Wall Pipe) Fault Tree

Rupture of Main Transfer Line During Filling (Double Wall Pipe)

1. If fault develops in either line the system is shutdown
2. The longest a fault will go undetected is equal to the sensor test interval so τ avg = 1000 hrs (3 month test interval)

	λ	τ	$\bar{a}$
Inner pipe component fails (expansion joint)	2.5×10^{-6}		
Gas detector fails	4×10^{-5}	1000	4×10^{-2}
Limit switch fails	3×10^{-5}	1000	3×10^{-2}
Alarm fails	5×10^{-5}	80	4×10^{-3}
Operator fails to shutdown			1×10^{-2}
			8.4×10^{-2}
Inner pipe component fails and is not detected	2.1×10^{-7}	1000	2.1×10^{-7}
Outer pipe component fails	2.5×10^{-6}		
Pressure sensor fails	1×10^{-4}	1000	0.1
Limit switch fails	3×10^{-5}	1000	3×10^{-2}
Alarm fails	5×10^{-5}	80	4×10^{-3}
Operator fails to shutdown			1×10^{-2}
			.14
Outer pipe component fails and is not detected	3.5×10^{-7}	1000	3.5×10^{-4}

$$enf_K = \int rof_K \, dT = a_K \Sigma \frac{\lambda_i}{\bar{a}_i} dT = 2.1 \times 10^{-4}(3.5 \times 10^{-4}) \quad \frac{2.1 \times 10^{-7}}{2.1 \times 10^{-4}} \quad \frac{3.5 \times 10^{7}}{3.5 \times 10^{-4}}$$

$$= \int_0^{1500 \text{ hrs}} 7.4 \times 10^{-8} \; (2 \times 10^{-3}) \; dT = 2.2 \times 10^{-7}/yr$$

TABLE B.14. Supporting Calculations for Main Transfer Line Rupture (double wall pipe-outer pipe is vapor return)

Rupture of Main Transfer Line During Filling
(Double wall pipe - outer pipe used as vapor return line)

	λ	τ	$\bar{a}$
Outer pipe components fails	2.5×10^{-6}	0	0
Inner pipe component fails	2.5×10^{-6}	100	2.5×10^{-4}

$$\text{Expected number of failures} = 2.5 \times 10^{-6}/\text{hr} \quad (2.5 \times 10^{-4}) \ (1500 \text{ hrs/yr})$$
$$\cong 1 \times 10^{-6}/\text{yr}$$

Appendix I: Excerpts from *LNG Terminal Risk Assessment Study for Oxnard, California (SAI-75-615-LJ)*

The following excerpts from the *LNG Terminal Risk Assessment Study for Oxnard, California,* prepared for Western LNG Terminal Co. by Science Applications Inc., SAI-75-615-LJ, Dec. 22, 1975 ("SAI '75") are provided directly in this Final Report for the reader's convenience. Table 3.1 summarizes the failure rate database used, and Figure 3.16 shows the FTA that is described in the following excerpt from Section 3.5 "Probabilistic Estimates of Hazards" on p. 3-35:

> The results of the study show that the largest probability, 4.0 x 10^{-6}/year, for a leak of LNG under normal operations occurs for a major rupture of one of the storage tanks. This probability reflects the compounding of a mean failure rate of 1.0 x 10^{-6}/tank-year from the data base for a single tank failure. Such a high probability is strictly applicable only to pressure vessels exposed to a high-pressure environment but was used because no other information was available.

Table 3.1 Failure Rate Data Base

Failure Modes	Mean Failure Rate or Demand Probability
Valve Ruptures	1.0 x 10^{-8}/hour
Tank Ruptures	1.0 x 10^{-6}/year
Connection Flange Ruptures	1.0 x 10^{-8}/hour
Swivel Ruptures	1.0 x 10^{-8}/hour
Expansion Joint Ruptures	1.0 x 10^{-8}/hour
Compressor Ruptures	1.0 x 10^{-8}/hour
Pump Ruptures	1.0 x 10^{-8}/hour
Relief Valve Fails to Open on Demand	1.0 x 10^{-5}/demand
Relief Valve Opens early	1.0 x 10^{-5}/hour
Automated Valve Fails to Open on Demand	1.0 x 10^{-3}/demand
Electronic System Fails	1.0 x 10^{-6}/hour
Automatic Shutdown Device Fails	1.0 x 10^{-4}/demand
Electric Motor Fails	1.0 x 10^{-3}/demand
Shutdown Device Fails on Demand	1.0 x 10^{-4}/demand
Operator Fails to Observe	1.0 x 10^{-3}/demand
Operator Fails to Take Action	3.0 x 10^{-4}/demand
Operator Fails to Observe Audible Alarm	3.0 x 10^{-4}/demand
Audible Alarm Fails on Demand	1.0 x 10^{-5}/demand
>6-inch Pipe Rupture*	1.8 x 10^{-9}/foot-year

*This value is obtained from the values in WASH-1400 by scaling from the estimated lengths of plant piping on which the estimates are based.

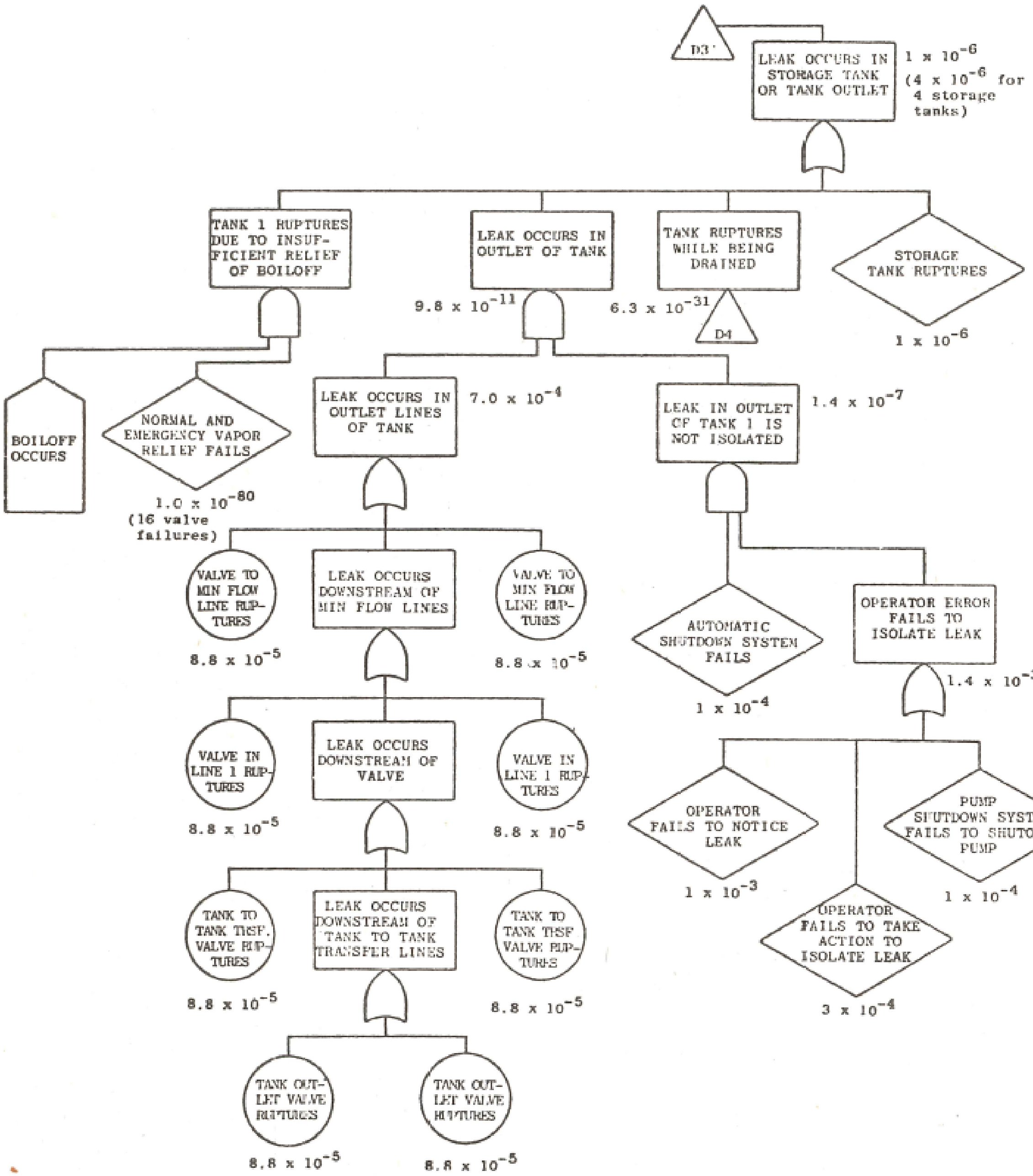


Figure 3.16. Fault Tree for Leak in Storage Tank or Tank Outlet

3-28

Appendix J: Analysis of PHMSA's Onshore Natural Gas Transmission Pipeline Incident Data

GTI analyzed the incidents and population data sets between 2002-2015 recorded in PHMSA's Natural Gas Transmission and Gathering incident and annual reports. GTI's analysis built upon the methodology contained in the 2015 analysis of PHMSA's Onshore Natural Gas Transmission data by Chio Lam, *Statistical Analyses of Historical Pipeline Incident Data with Application to the Risk Assessment of Onshore Natural Gas Transmission Pipelines*, Master of Science Thesis, The University of Western Ontario, July 2015 ("PHMSA NGT LAM '15"). In this report, PHMSA's Natural Gas Transmission report data is abbreviated as PHMSA NGT.

As in Lam's analysis, GTI's analysis of rupture rates focused on on-shore Natural Gas Transmission incident and population data, and excluded consideration of: gathering line incidents and population; and off-shore natural gas transmission incidents and population data. As in Lam's analysis, an analysis of leak (vs. rupture) incidents was not performed since only incidents that meet the reporting threshold of US 49 CFR Section 191.3 are represented in the data, whereas it is expected that all ruptures are reportable incidents. Gathering line rupture data was not analyzed since a substantial amount of gathering pipeline materials are non-steel, whereas virtually all transmission piping is steel; for example, in the 2015 population data set, 9.11% of gathering pipeline materials are non-steel and 99.46% of transmission pipelines are steel.

In total, we analyzed three cases and included additional subsets of incident data which are defined below as Cases 1, 2 and 3, in order to build upon the methodology used by Lam:

Data Entry	PHMSA NGT GTI CASE 1	PHMSA NGT GTI CASE 2	PHMSA NGT GTI CASE 3
ONSHORE	INCLUDE	INCLUDE	INCLUDE
PIPE(PIPE BODY or PIPE SEAM)	INCLUDE	INCLUDE	INCLUDE
TRANSMISSION SYSTEM	INCLUDE	INCLUDE	INLCUDE
PIPING on COMPRESSOR STATION & STORAGE	INCLUDE	INCLUDE	INCLUDE
TRANSMISSION LINE OF DISTRIBUTION SYSTEM	EXCLUDE	INCLUDE	INCLUDE
WELD, INCLUDING HEAT-AFFECTED ZONE	EXCLUDE	EXCLUDE	INCLUDE*
Purpose of Analysis	Believed by GTI to Provide a Direct Comparison with LAM's Thesis	Intermediate Results	Final Results "PHMSA NGT GTI '16"

Table J.1.1: Data extraction for different cases

* Includes 5 rupture incidents in the 2010-2015 data set, all of which are categorized in "Weld Subtype" as "Pipe Girth Weld"

First, we compared the total mileage with PHMSA NGT and the PHMSA NGT online data (http://www.phmsa.dot.gov/pipeline/library/data-stats/annual-report-mileage-for-natural-gas-transmission-and-gathering-systems) and showed good agreement:

YEAR	PHMSA NGT Annual Report Online[1]	PHMSA NGT GTI Analysis	PHMSA NGT LAM '15 (Figure 2.1 in LAM's Thesis)
2002	477621.7	476420.5	476490.6
2003	475382.8	475374.4	475348.4
2004	477864.2	477869.3	477963.8
2005	474413.0	470079.8	470093.9
2006	472651.5	472697.1	472745.1
2007	474636.3	474640.6	474716.3
2008	478383.4	478389.0	478476.7
2009	481135.2	481125.2	481163.5
2010	481747.7	481760.5	479949.8
2011	482344.3	482350.6	480525.4
2012	480481.7	480533.3	479633.7
2013	480103.6	480110.1	479064.1

Table J.2.1: Total transmission mileage (in km)

The total mileage for each year was computed using the summation of mileage for each diameter in the population data. Mileage data reported to NPS≤4" was applied in this analysis as 2"≤NPS≤4". This was considered a reasonable approximation since only 3 of the 37 incidents (i.e. 8.1%) reported during 2010-2015 for pipe diameter ≤ 4" were for pipe diameters < 2", which provides an indication of the underlying distribution of all piping ≤ 4"; in addition, all piping ruptures reported during 2010-2015 were ≥ 2" in diameter.

Second, we replicated the results of Master's Thesis by Chio Lam and showed good agreement with our Case 1 results.

Lam, Chio, *Statistical Analyses of Historical Pipeline Incident Data with Application to the Risk Assessment of Onshore Natural Gas Transmission Pipelines*, Master of Science Thesis, The University of Western Ontario, July 2015 ["PHMSA NGT LAM '15]

Diameter (inch)	PHMSA NGT LAM'15	PHMSA NGT GTI CASE 1	PHMSA NGT GTI CASE 2	PHMSA NGT GTI CASE 3
Unknown	0.40%	0.43%	0.40%	0.39%
0<d≤4	8.60%	8.86%	8.80%	8.93%
4<d≤10	22.20%	22.25%	22.20%	21.94%
10<d≤20	38.60%	38.23%	38.60%	37.67%
20<d≤8	15.30%	15.33%	15.80%	16.70%
28<d	14.90%	14.90%	14.20%	14.37%

Table J.2.2: Distribution of all incidents by diameter (2002-2013)

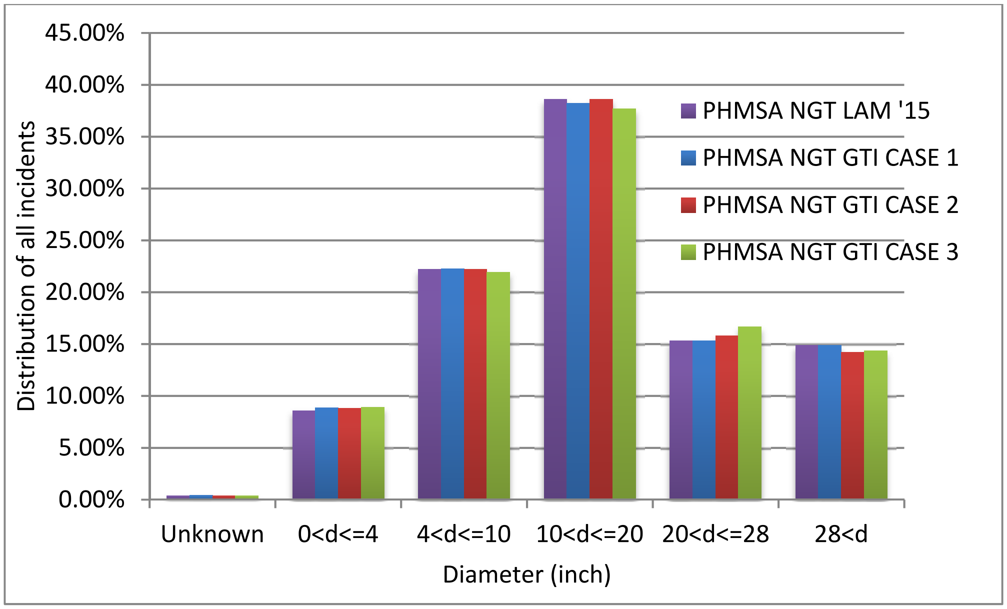


Figure J.2.2: Distribution of all incidents by diameter (2002-2013)

Diameter (inch)	PHMSA NGT LAM'15	PHMSA NGT GTI CASE 1	PHMSA NGT GTI CASE 2	PHMSA NGT GTI CASE 3
0<d≤4	2.20E-05	2.22e-5	2.46e-5	2.67e-5
4<d≤10	3.00E-05	2.96e-5	3.12e-5	3.12e-5
10<d≤20	4.60E-05	4.65e-5	5.00e-5	5.06e-5
20<d≤8	2.50E-05	2.49e-5	2.81e-5	3.02e-5
28<d	2.00E-05	2.00e-5	2.00e-5	2.06e-5

Table J.2.3: Onshore rupture rates/km-year by diameter (2002-2013)

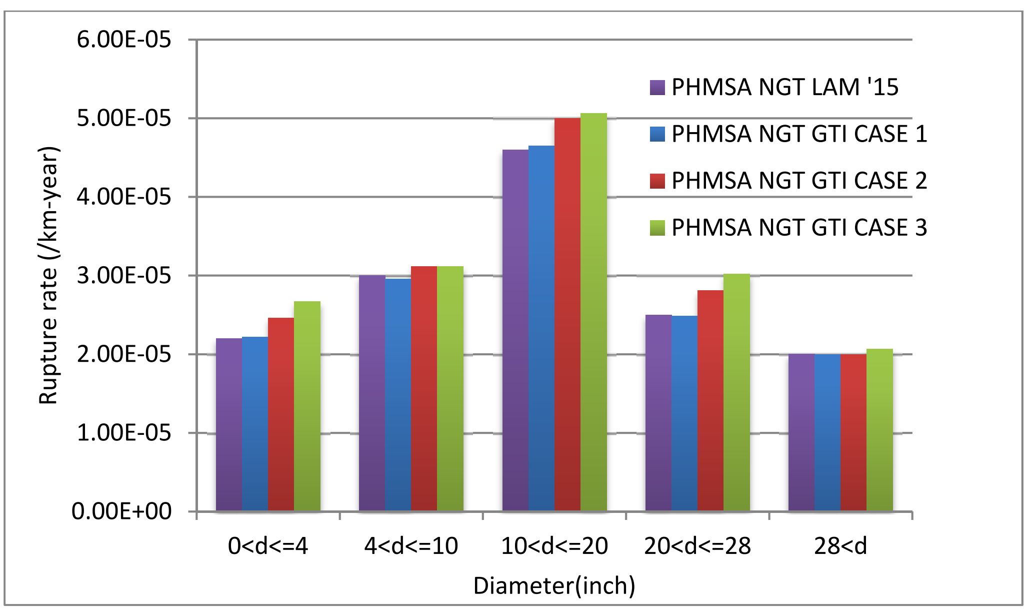
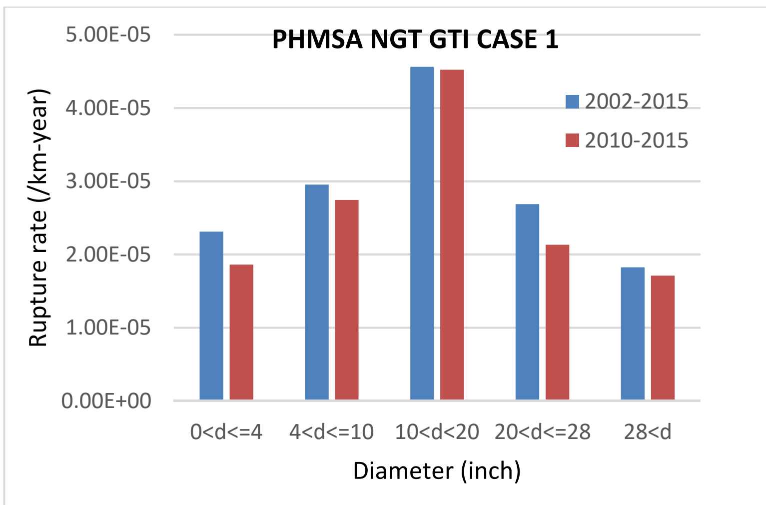


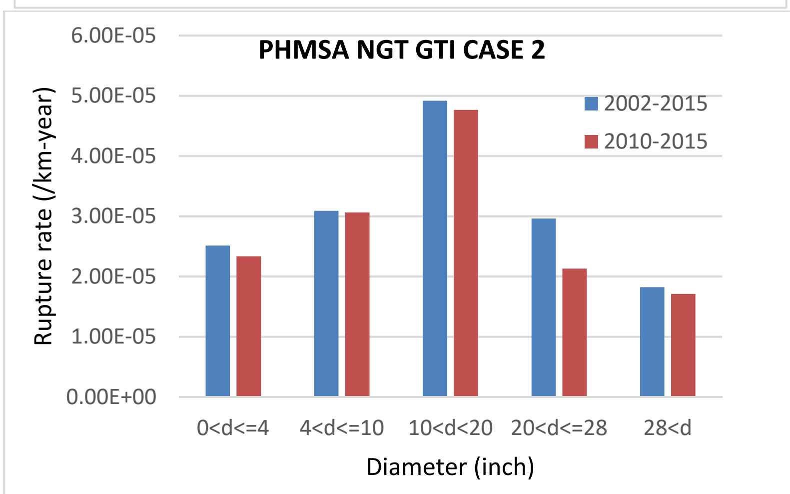
Figure J.2.3: Onshore rupture rates/km-year by diameter (2002-2013)

Third, we confirmed that the rupture rates from 2002 – 2015 are quite similar to the rupture rates from 2010 – 2015 for three analysis cases. Thus, the 2010-15 incident data is quite representative of the 2002-2015 incident data.

Diameter (inch)	PHMSA NGT GTI CASE 1		PHMSA NGT GTI CASE 2		PHMSA NGT GTI CASE 3	
	2002 – 2015	2010-2015	2002 – 2015	2010-2015	2002 – 2015	2010-2015
0<d≤4	2.31E-05	1.86E-05	2.51e-5	2.33e-5	2.69e-5	2.33e-5
4<d≤10	2.95E-05	2.74E-05	3.09e-5	3.06e-5	3.09e-5	3.06e-5
10<d≤0	4.56E-05	4.52E-05	4.92e-5	4.77e-5	4.97e-5	4.89e-5
20<d≤28	2.68E-05	2.13E-05	2.96e-5	2.13e-5	3.14e-5	2.55e-5
28<d	1.82E-05	1.71E-05	1.82e-5	1.71e-5	1.99e-5	2.10e-5

Table J.3.1: Onshore rupture rates/km-year by diameter





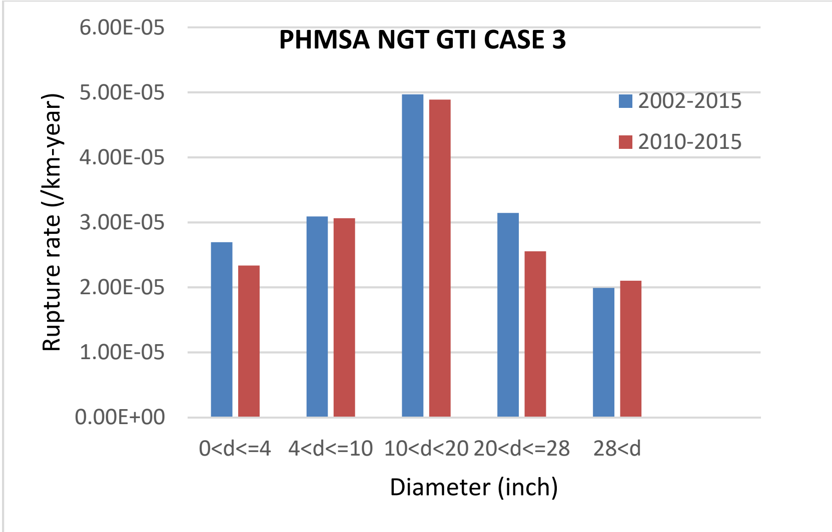


Figure J.3.1: Onshore rupture rates/km-year by diameter

Fourth, we considered only the pipeline rupture data from 2010 to 2015 in order calculate the rupture rates for the diameter ranges in Table 4.1 that match the diameter ranges in the FRT. The data from 2002 – 2009 could not be included in this manner because it does not contain actual pipeline diameters (and instead only provides a range of diameters such as 0<d<=4, 4<d<=10, 10<d<=20, 20<d<=28 and 28<d).

Diameter (inch)	PHMSA NGT GTI CASE 1	PHMSA NGT GTI CASE 2	PHMSA NGT GTI CASE 3
0≤d<2			
2≤d<6	2.31E-05	2.78E-05	2.78E-05
6≤d<12	2.91E-05	3.23E-05	3.23E-05
12≤d<20	3.68E-05	4.03E-05	4.20E-05
20≤d<40	2.68E-05	2.68E-05	2.96E-05

Table J.4.1: Onshore rupture rates/km-year by FRT category diameter (2010-15)

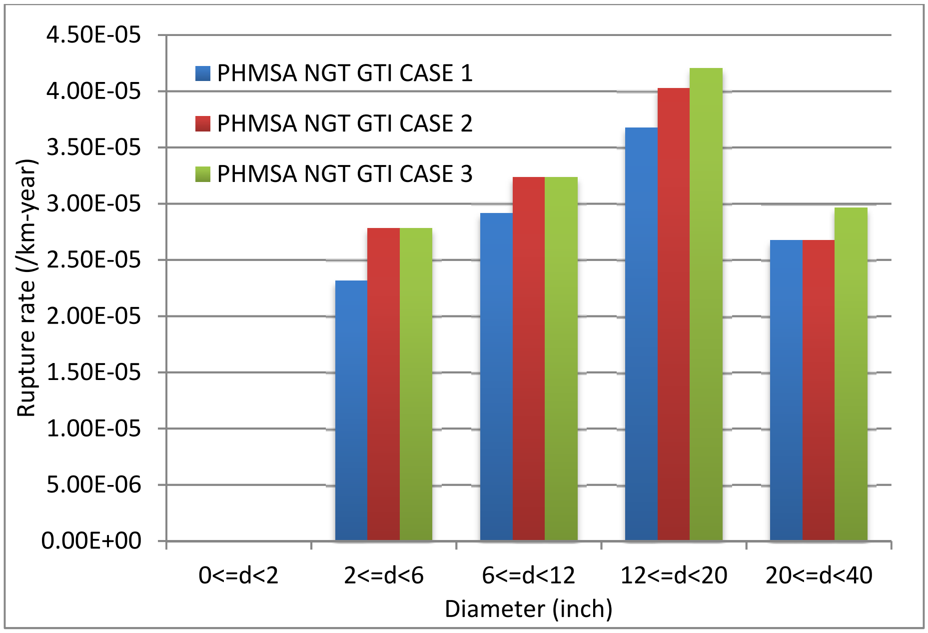


Figure J.4.1: Rupture rates/km-year by FRT category diameter (2010-2015)

The Case 3 results shown in Table J.4.1 above were entered into the database for this project as "PHMSA NGT GTI '16".

As an additional clarification, no ruptures of valves are identified in this 2010-2015 database.

Appendix K: Analysis of PHMSA's Onshore Hazardous Liquids Pipeline Accident Data

GTI analyzed the accident (referred to as incident hereafter in this appendix) and population data sets between 2010-2015 recorded in PHMSA's Hazardous Liquids accident and annual reports, to provide directly comparable data to our analysis of on-shore natural gas transmission pipeline ruptures during 2010-15 as summarized in Appendix J.

In total, we analyzed two cases with different subsets of onshore rupture incidents data as shown in Table K.1.1. One case included those incidents occurring onshore and pipe related (pipe body or pipe seam) or weld, including the heat affected zone but excluded those occurring on piping at pump/meter station and terminal/tank farm. Another case included those incidents occurring onshore and pipe related (pipe body or pipe seam) or weld, including the heat affected zone and also included piping at pump/meter station and terminal/tank farm. In this report, PHMSA Hazardous Liquid is abbreviated as PHMSA HL.

Data Entry	PHMSA HL GTI CASE 1	PHMSA HL GTI CASE 2
ONSHORE	INCLUDE	INCLUDE
PIPE(PIPE BODY or PIPE SEAM)	INCLUDE	INCLUDE
WELD, INCLUDING HEAT-AFFECTED ZONE	INCLUDE	INCLUDE
PUMP/METER STATION	EXCLUDE	INCLUDE
TERMINAL/TANK FARM	EXCLUDE	INCLUDE

Table K.1.1: Data extraction for Case 1 and Case 2

First, we compared the total mileage with PHMSA NGT and the PHMSA HL online data (http://www.phmsa.dot.gov/pipeline/library/data-stats/annual-report-mileage-for-hazardous-liquid-or-carbon-dioxide-systems) and found good agreement as shown below in the first two columns of Table K.2.1. The total mileage for each year was computed using the summation of mileage for each dimeter in the population data. Column 3 of Table K.2.1 also shows the mileage contained in PHMSA's Natural Gas Transmission reports, to provide an understanding of the comparative sizes of these two databases.

Year	PHMSA HL GTI	PHMSA HL Online[1]	PHMSA NGT GTI
2010	284514.1	292864.5	481760.5
2011	287247.5	295429.7	482350.6
2012	291921.9	299679.8	480533.3
2013	301735.9	309642.7	480110.1
2014	313150.2	321305.1	479457.4
2015	327165.0	335523.0	478389.9

Table K.2.1: Total transmission mileage (in km)

Second, we computed the breakdown of the number of onshore rupture incidents by predominant commodity carried in the pipeline.

Predominant Commodity	Number of Rupture Incidents	
	PHMSA HL GTI CASE 1	PHMSA HL GTI CASE 2
Crude Oil	12	19
HVL	15	15
Non-HVL	12	13
CO2	1	1

Table K.3.1: Breakdown of the number of onshore rupture incidents by predominant commodity (2010-2015)

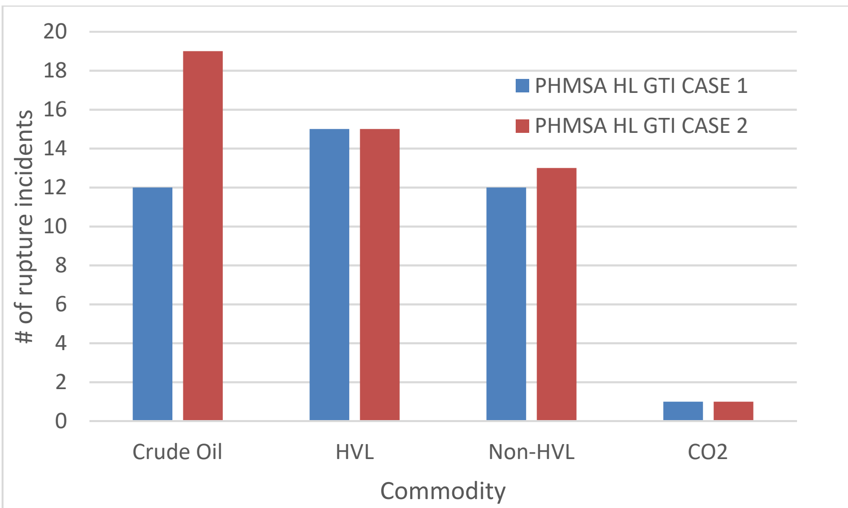


Figure K.3.1: Breakdown of the number of onshore rupture incidents by predominant commodity (2010-2015)

Third, we computed the rupture rates by predominant commodity carried, and confirmed that there were not substantial (e.g. >5x) differences in overall rupture rates for the different predominant commodities carried.

Predominant Commodity	Rupture Rate (/km-year)	
	PHMSA HL GTI CASE 1	PHMSA HL GTI CASE 2
Crude Oil	2.21E-05	3.58E-05
HVL	2.53E-05	2.53E-05
Non-HVL	1.95E-05	2.11E-05
CO2	2.00E-05	2.00E-05

Table K.4.1: Onshore rupture rates/km-year by commodity (2010-2015)

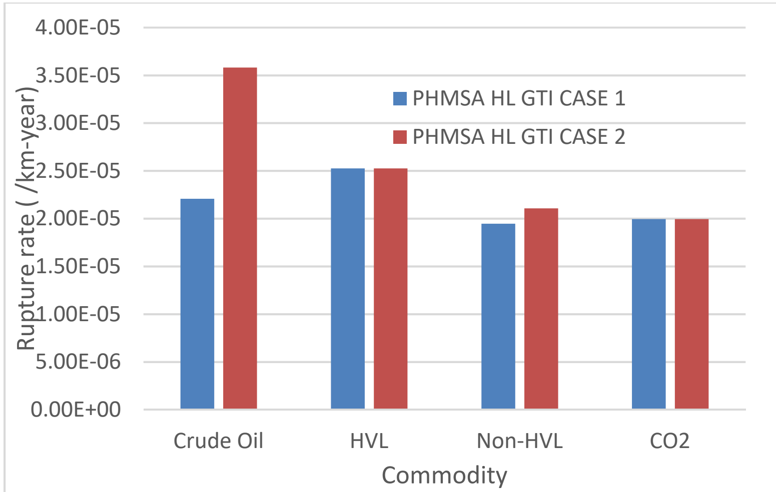


Figure K.4.1: Onshore rupture rates/km-year by commodity (2010-2015)

Fourth, we computed the rupture rates by diameter ranges that match those in the FRT for all of the data in the dataset (i.e. including all predominant commodity carried). The Case 2 results shown in Table K.5.1 above were entered into the database for this project as "PHMSA HL GTI '16". As an additional clarification, one valve rupture is identified in this 2010-2015 database (in crude oil service) but the valve size is unidentified and the "Rupture Details" column identifies that "DIAPHRAGM WAS CRACKED. REPLACED DIAPHRAGM"; this sole valve rupture was not included in the analysis but if it had it would increase the rate by 2% (i.e. 49/48).

Diameter (inch)	Rupture Rate (/km-year)	
	PHMSA HL GTI CASE 1	PHMSA HL GTI CASE 2
0≤d<2		
2≤d<6	3.95e-5	3.95e-5
6≤d<12	2.22e-5	2.45e-5
12≤d<20	1.37e-5	2.01e-5
20≤d<40	3.51e-5	3.90e-5

Table K.5.1: Onshore rupture rates/km-year by FRT diameter category (2010-2015)

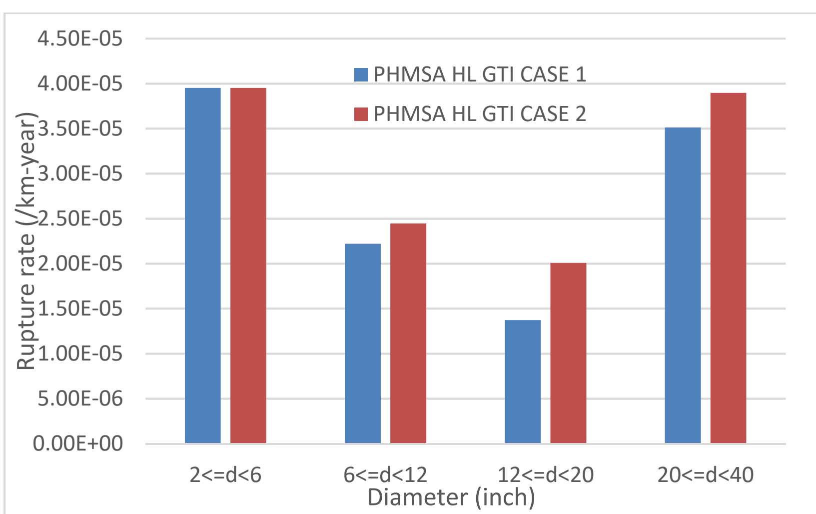


Figure K.5.1: Onshore rupture rates/km-year by FRT diameter ranges (2010-2015)

Fifth, for PHMSA's and FERC's additional information we computed the rupture rates by any diameter broken down by commodity for case 1.

Diameter (inch)	Rupture Rated (All Commodities)	Breakdown by Commodity	Rupture Rates (Breakdown by Commodity)
0≤d<2			
2≤ d< 6	3.95E-05	Crude Oil	1.30e-5
		HVL	1.34e-5
		Non-HVL	0
		CO2	1.31e-5
6≤d<12	2.22E-05	Crude Oil	2.23e-6
		HVL	1.12e-5
		Non-HVL	8.80e-6
		CO2	0
12≤d<20	1.37E-05	Crude Oil	1.78e-6
		HVL	5.63e-6
		Non-HVL	6.32e-6
		CO2	0
20≤d<40	3.51E-05	Crude Oil	2.85e-5
		HVL	2.94e-6
		Non-HVL	3.70e-6
		CO2	0

Table K.6.1: Onshore rupture rates/km-year by FRT diameter category; breakdown by commodity (2010-2015)

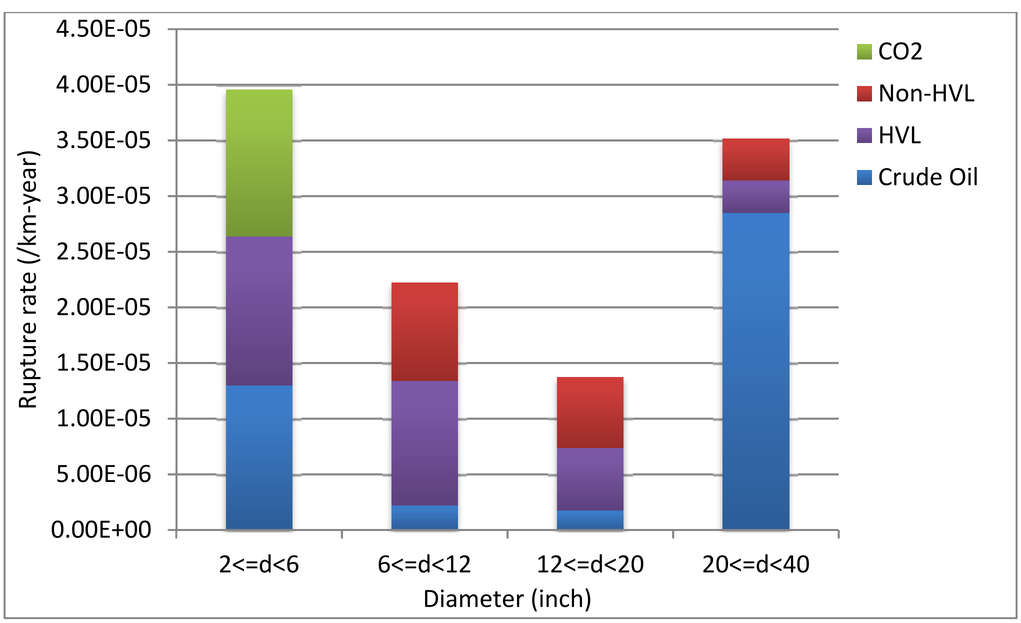


Figure K.6.1: Onshore rupture rates/km-year by FRT diameter category; breakdown by commodity (2010-2015)

Sixth, for PHMSA's and FERC's additional information we computed the rupture rates by FRT diameter category broken down by commodity for case 2.

Diameter (inch)	Rupture Rated (All Commodities)	Breakdown by Commodity	Rupture Rates (Breakdown by Commodity)
0≤d<2			
2≤ d< 6	3.95E-05	Crude Oil	1.30e-5
		HVL	1.34e-5
		Non-HVL	0
		CO2	1.31e-5
6≤d<12	2.45E-05	Crude Oil	4.49e-6
		HVL	1.12e-5
		Non-HVL	8.80e-6
		CO2	0
12≤d<20	2.01E-05	Crude Oil	5.98e-6
		HVL	5.63e-6
		Non-HVL	8.46e-6
		CO2	0
20≤d<40	3.90E-05	Crude Oil	3.23e-5
		HVL	2.94e-6
		Non-HVL	3.70e-6
		CO2	0

Table K.7.1: Onshore rupture rates/km-year by FRT diameter category; breakdown by commodity (2010-2015)

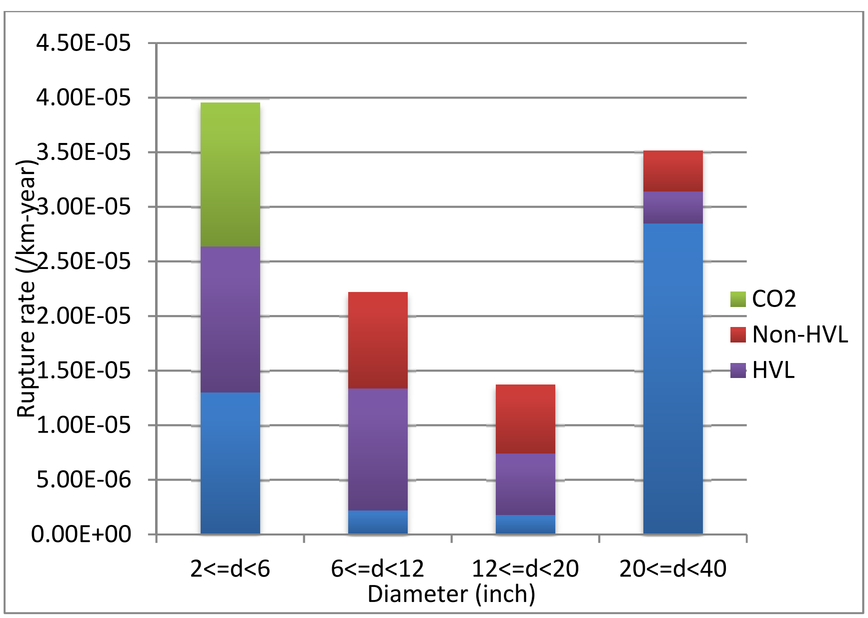


Figure K.7.1: Onshore rupture rates/km-year by FRT diameter category; breakdown by commodity (2010-2015)

Appendix L: Visualization of UK HSE Hydrocarbon Releases Database (HCRD)

The UK HSE Hydrocarbon Releases Database (HCRD) System is one often-cited equipment failure rate database for oil and gas, CPI and related applications. The HCRD System has continuously collected reliability data from UK off-shore oil and gas operations since 1992. The HCRD database is the basis for DNV's commercial LEAK software that estimates piping and equipment leak frequencies, as described in "DNV FFG HCRD '13".

GTI generated the figures in this Appendix directly from the data in the HCRD from fiscal years 1992/1993 to 2015/2016, in order to help PHMSA and FERC better understand the distribution of some of the components and leak incidents from this large public database. GTI used the data that is publicly available in Microsoft Excel® files entitled "Offshore Hydrocarbon Population Data 1992 - 2015" and "Offshore Hydrocarbon Releases 1992 – 2015" which are available as of the date of this report at http://www.hse.gov.uk/offshore/statistics.htm.

The HCRD uses the term "Pressure Vessel" for equipment that is in service such as a: knock-out drum, reboiler, separator, or other. Because these uses are primarily process-related we use the terminology "Pressure (Process) Vessel" in this Appendix for this class of equipment in the HCRD.

1. <u>Piping</u>

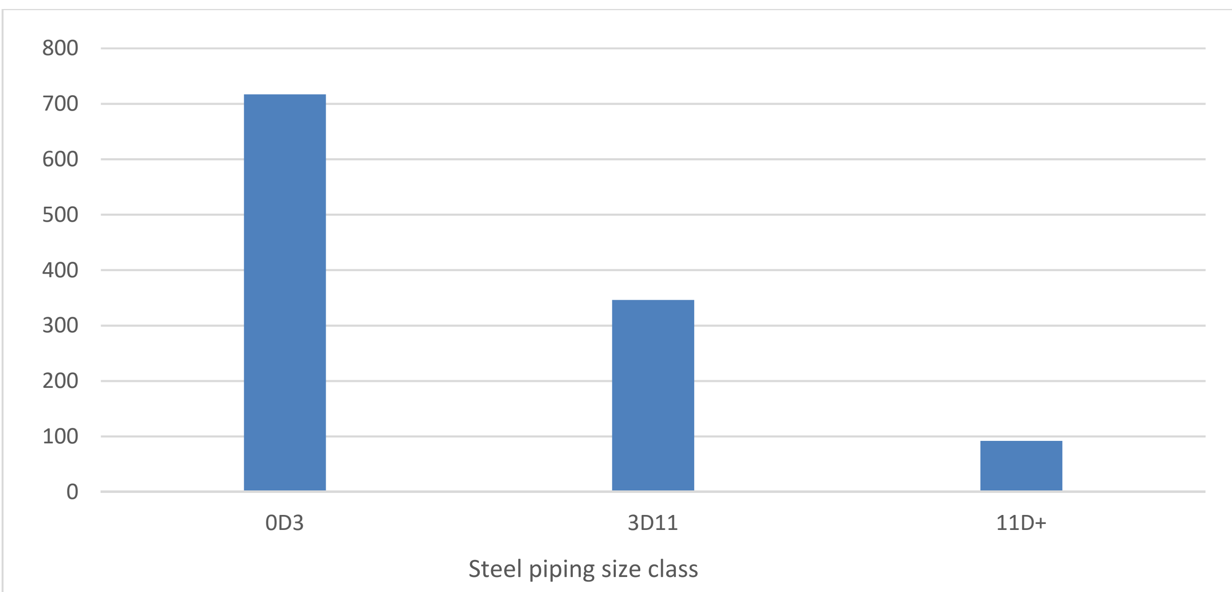


Figure L.1: Number of steel piping leak incidents reported by size category (D≤3", 3"<D≤11", D>11")

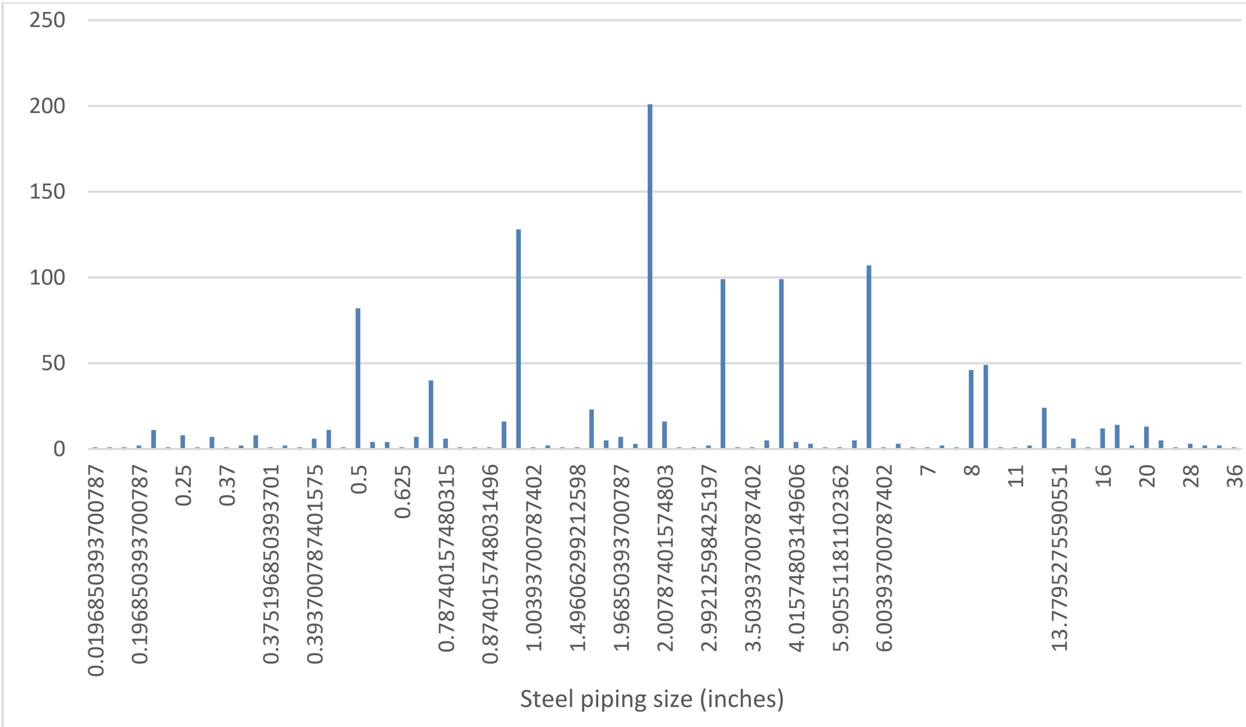


Figure L.2: Number of steel piping leak incidents reported by size (inches)

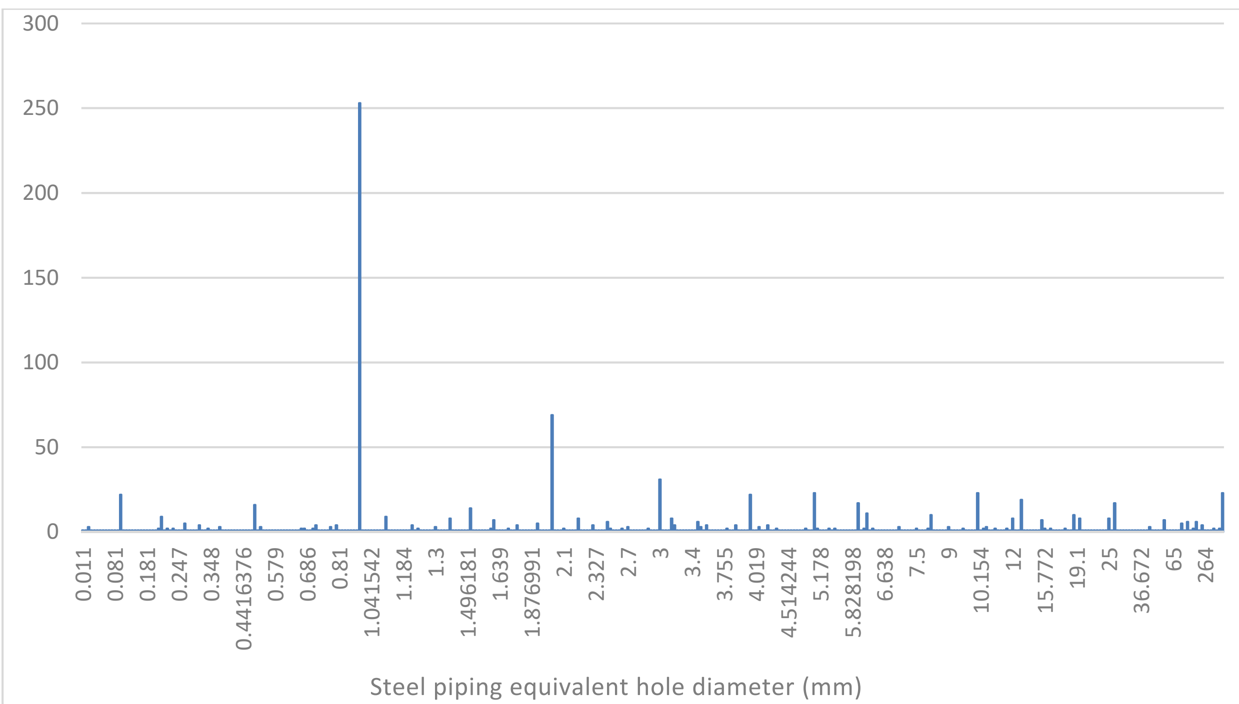


Figure L.3: Number of steel piping holes by equivalent hole diameter (mm)

2. Flanges

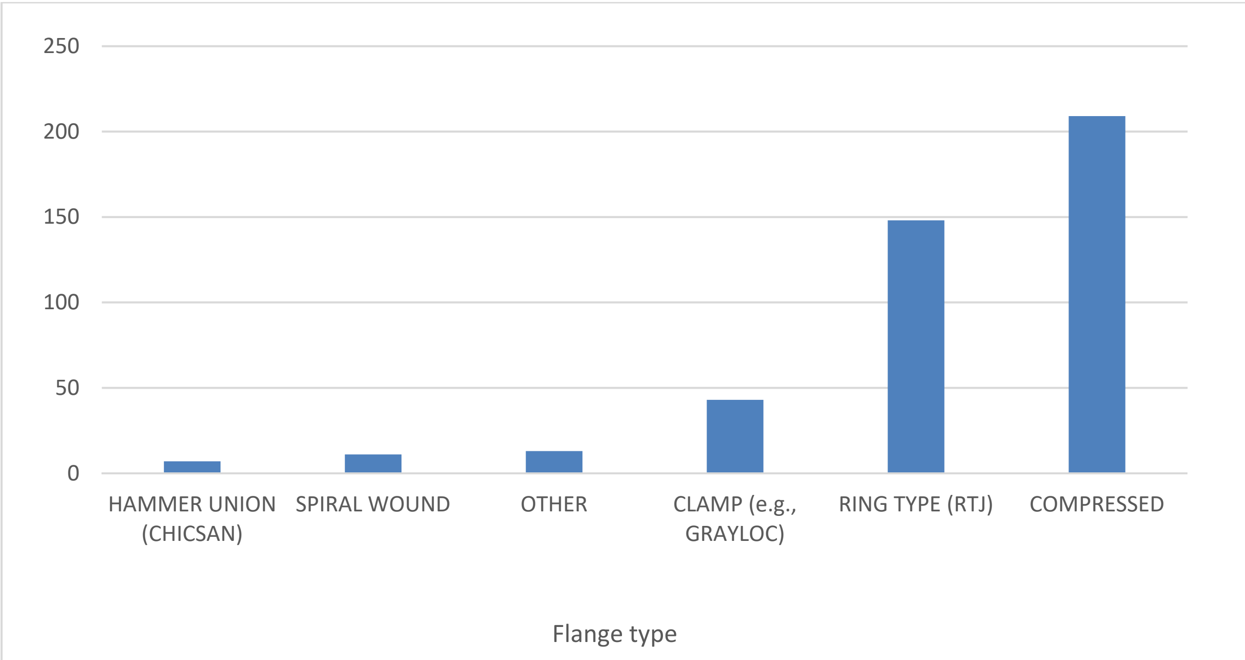


Figure L.4: Number of flange leak incidents reported by type

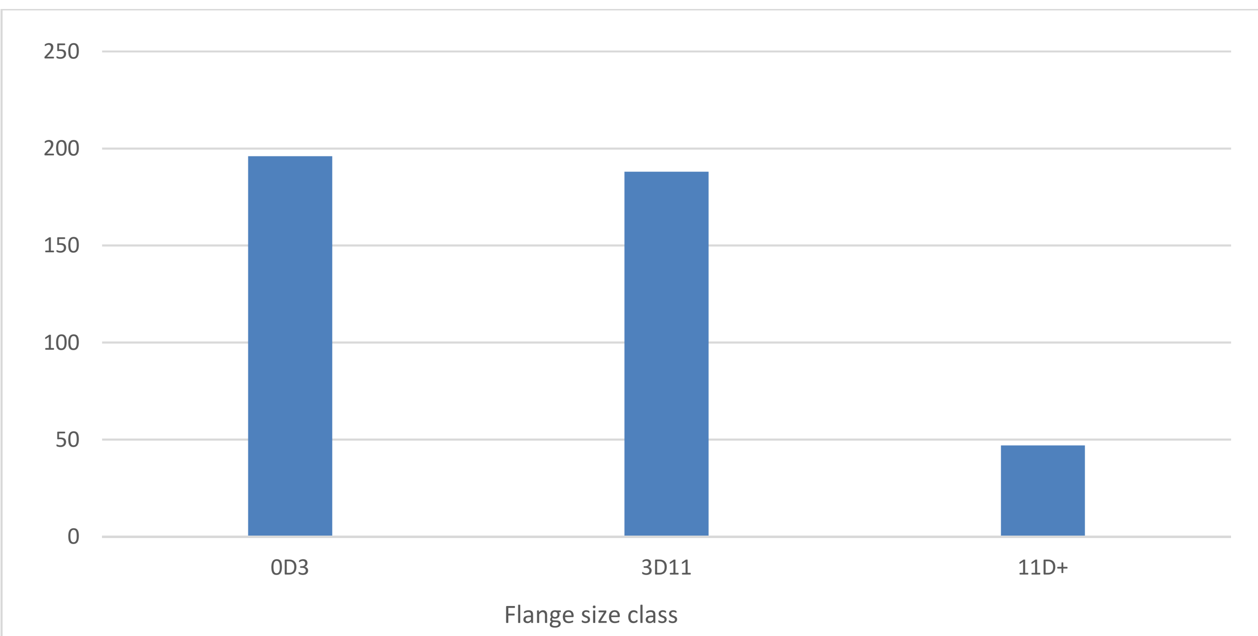


Figure L.5: Number of flange leak incidents reported by size category (D≤3", 3"<D≤11", D>11")

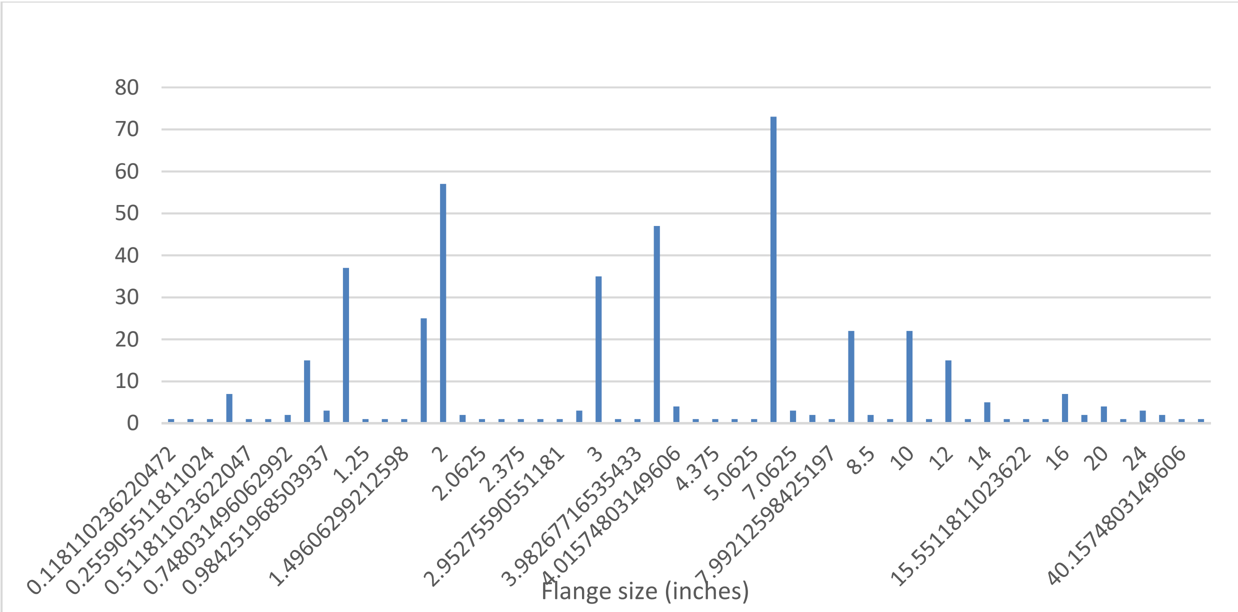


Figure L.6: Number of flange leak incidents reported by size (inches)

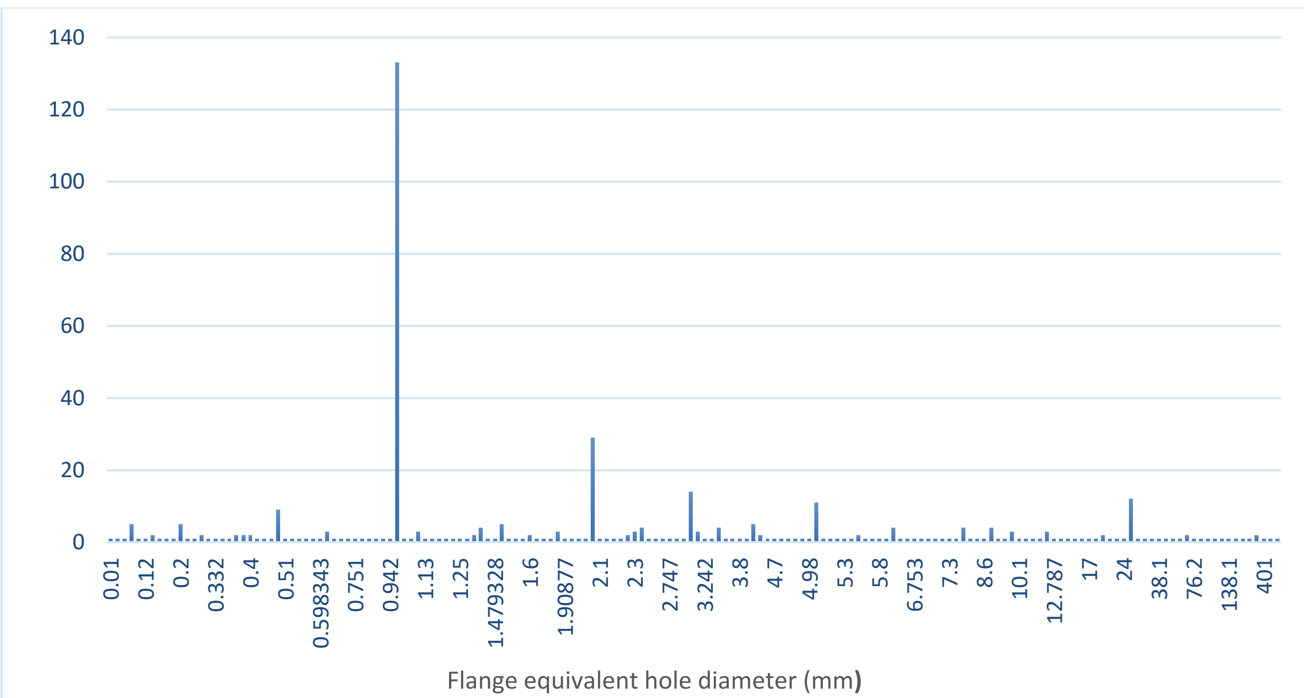


Figure L.7: Number of flange holes by equivalent hole diameter (mm)

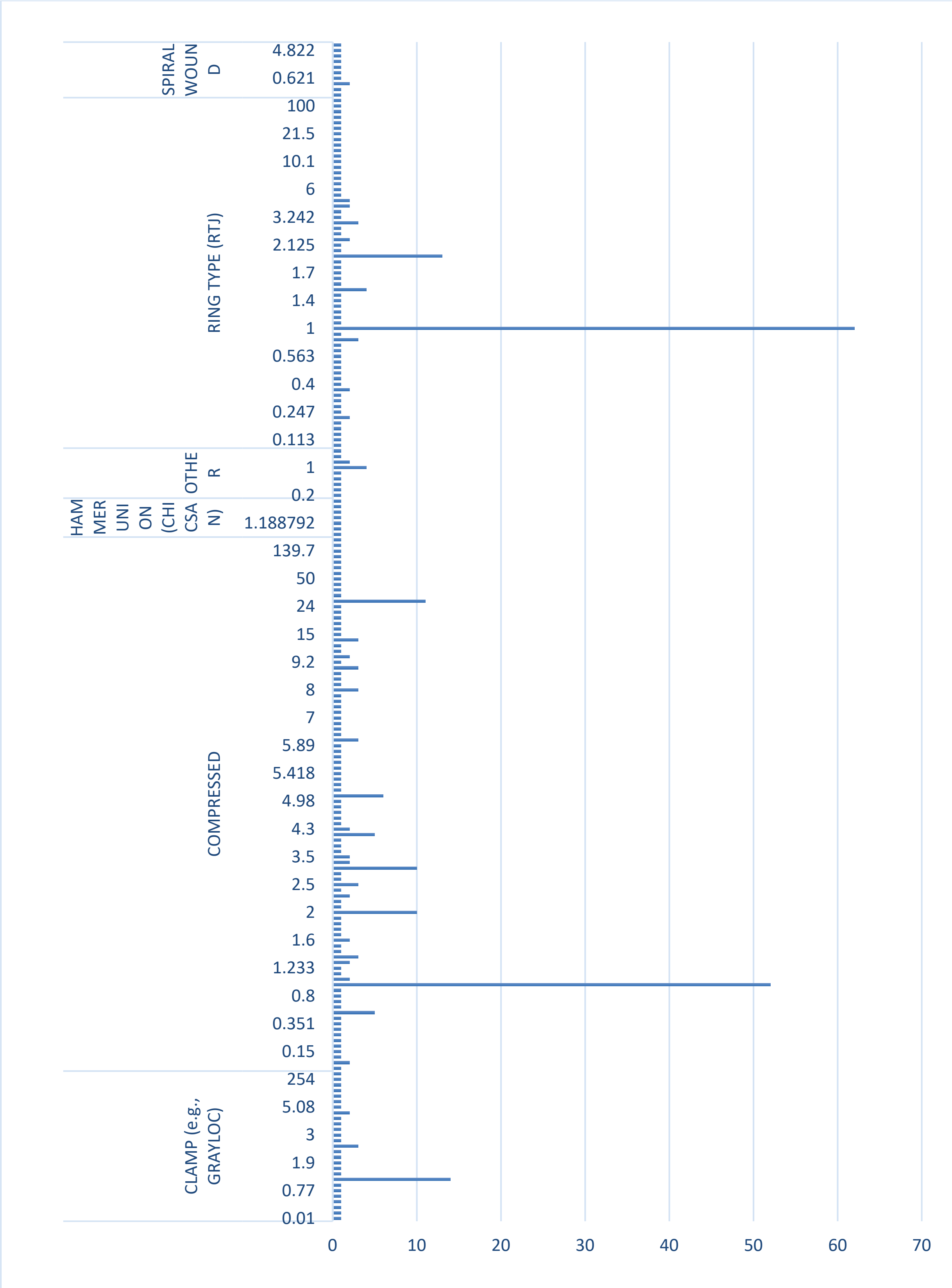


Figure L.8: Number of flange holes by equivalent hole diameter (mm) and type

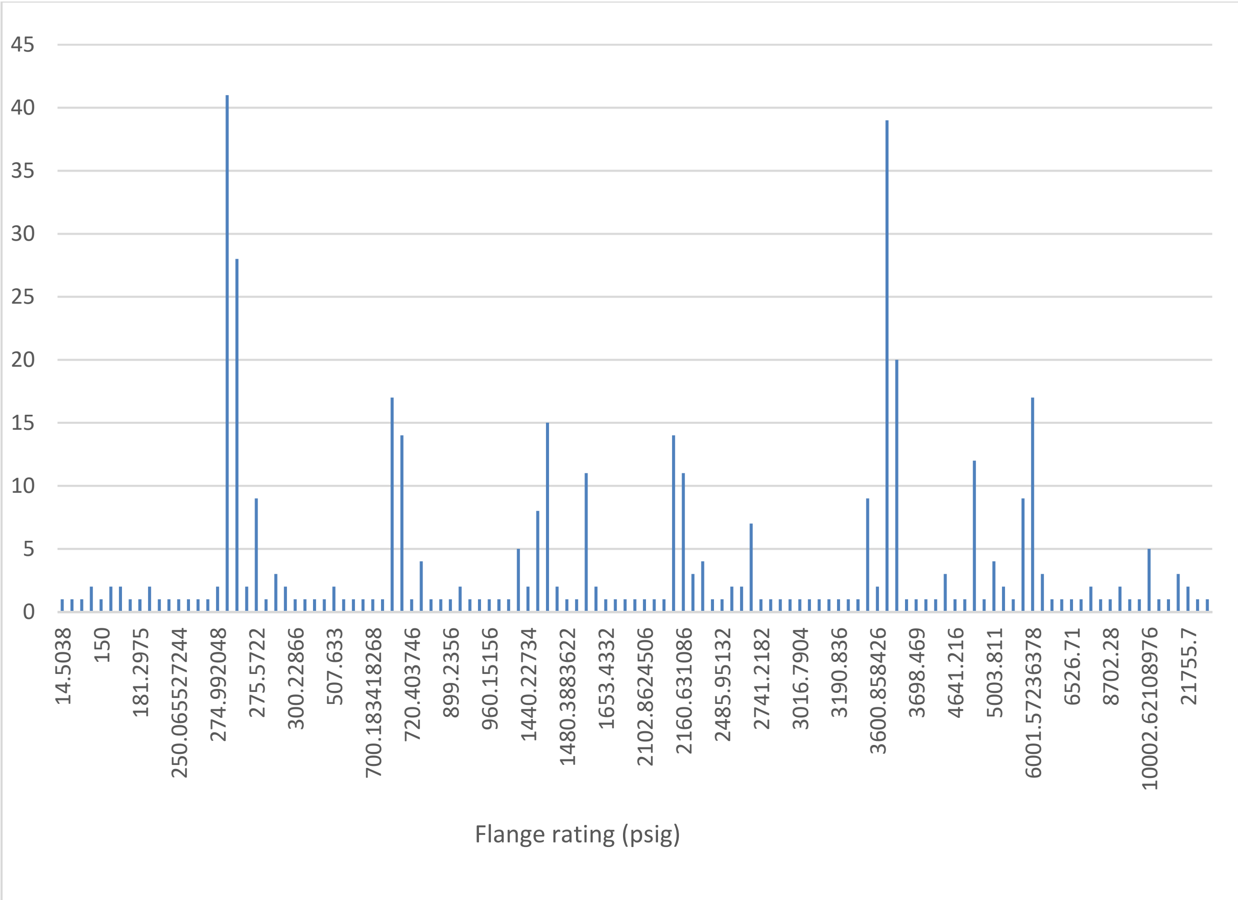


Figure L.9: Number of flange leak incidents reported by rating (psig)

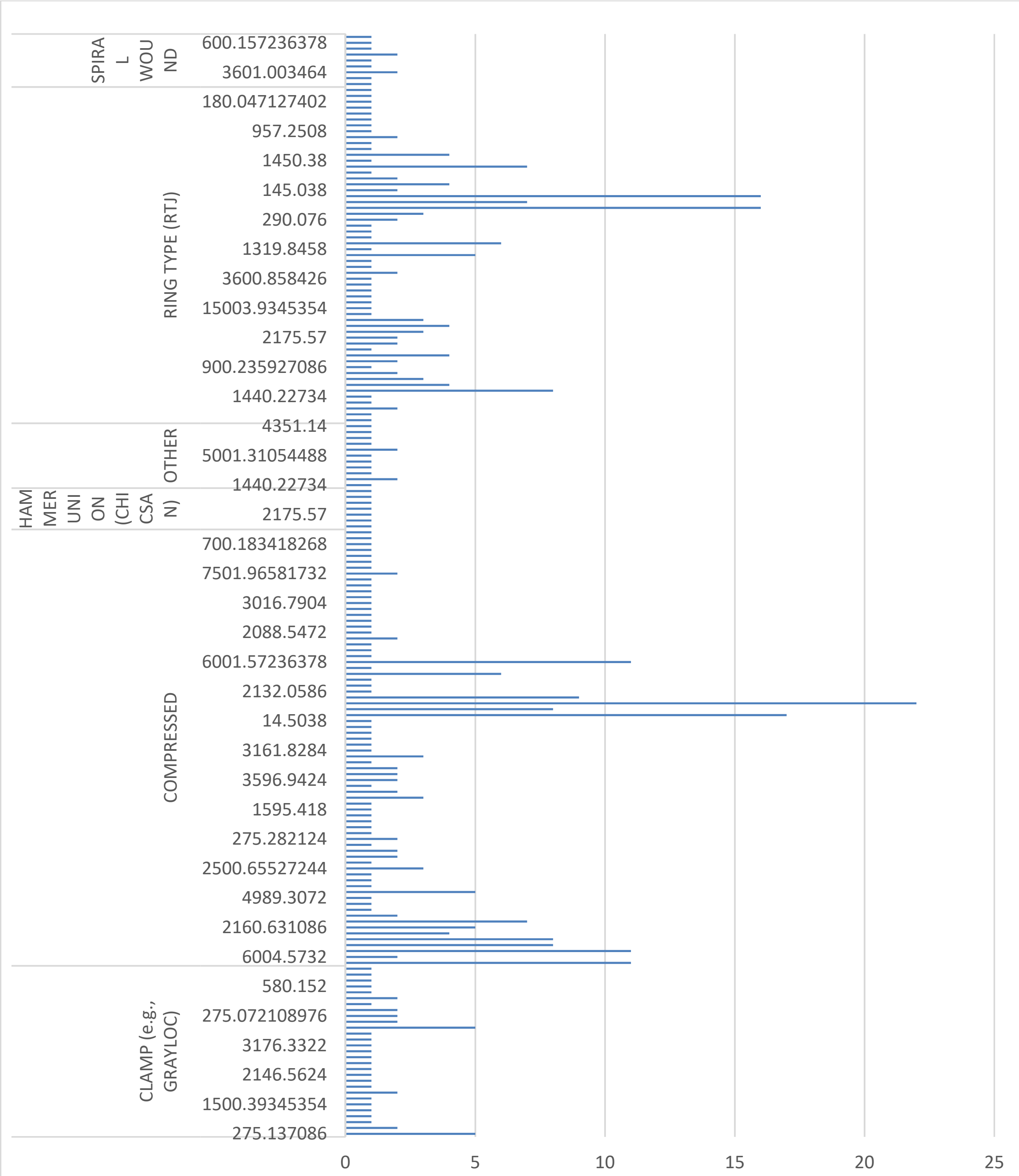


Figure L.10: Number of flange ratings by rating (psig) and type

3. <u>Actuated Valve</u>

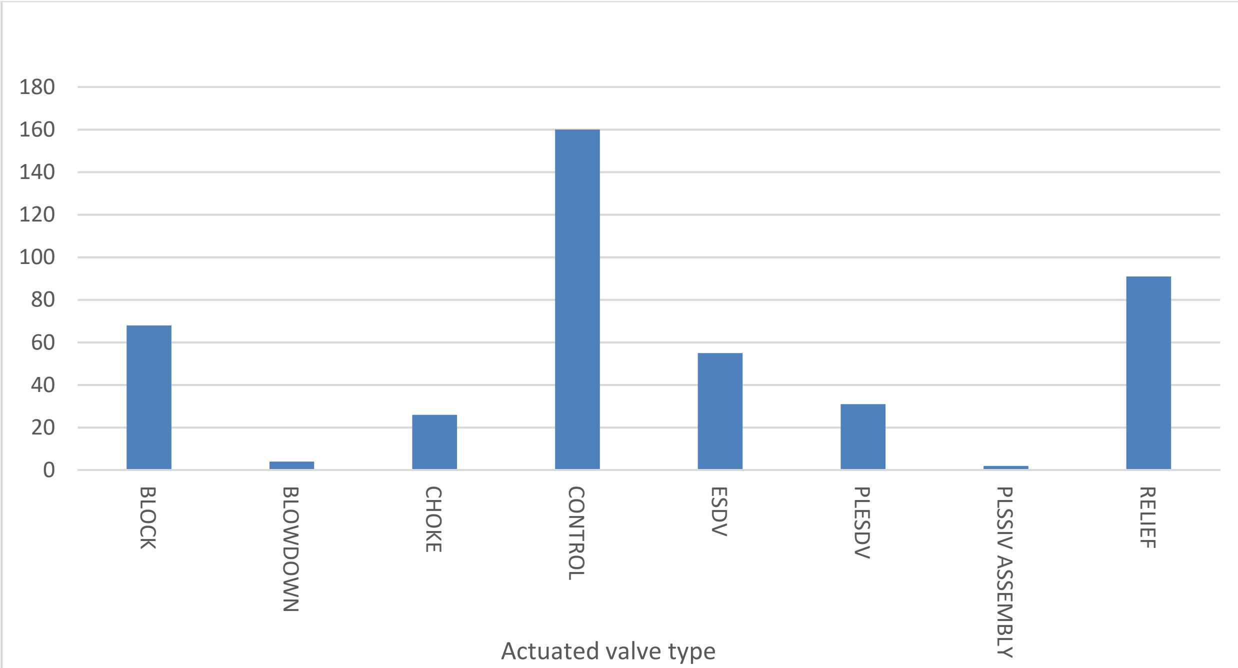


Figure L.11: Number of actuated valve leak incidents reported by type

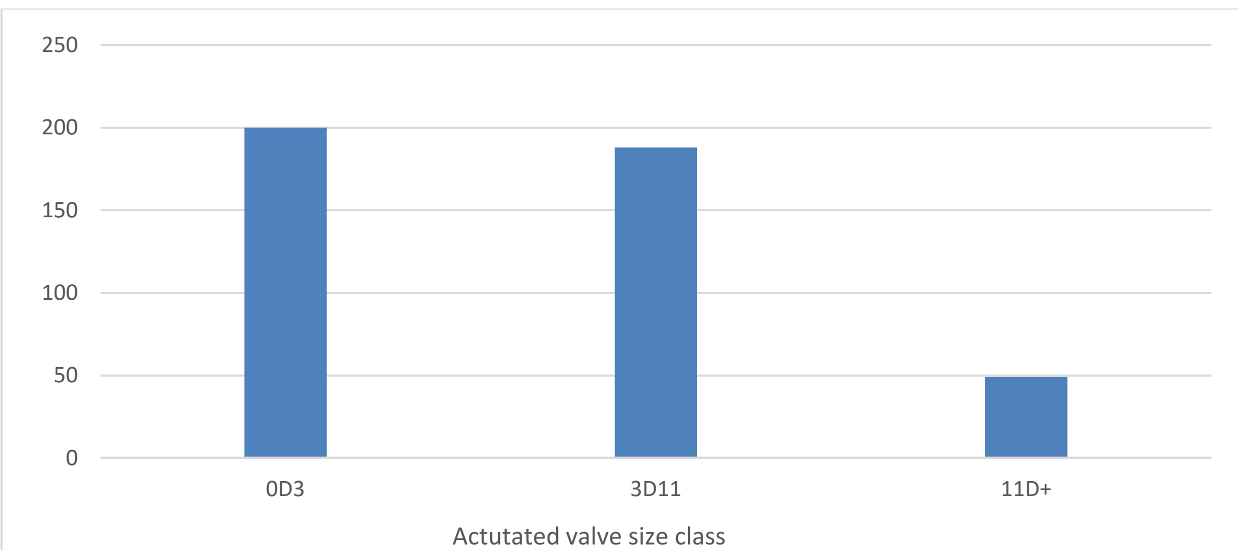


Figure L.12: Number of actuated valve leak incidents reported by size category (D≤3", 3"<D≤11", D>11")

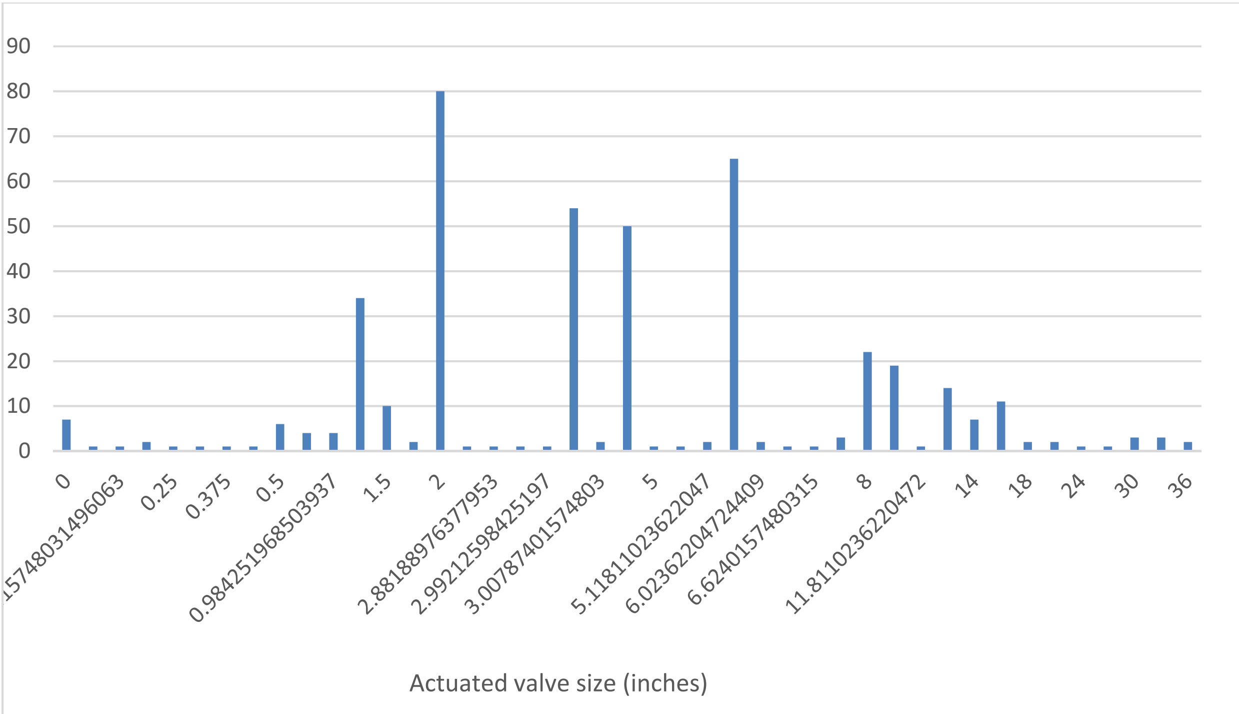


Figure L.13: Number of actuated valve leak incidents reported by size (inches)

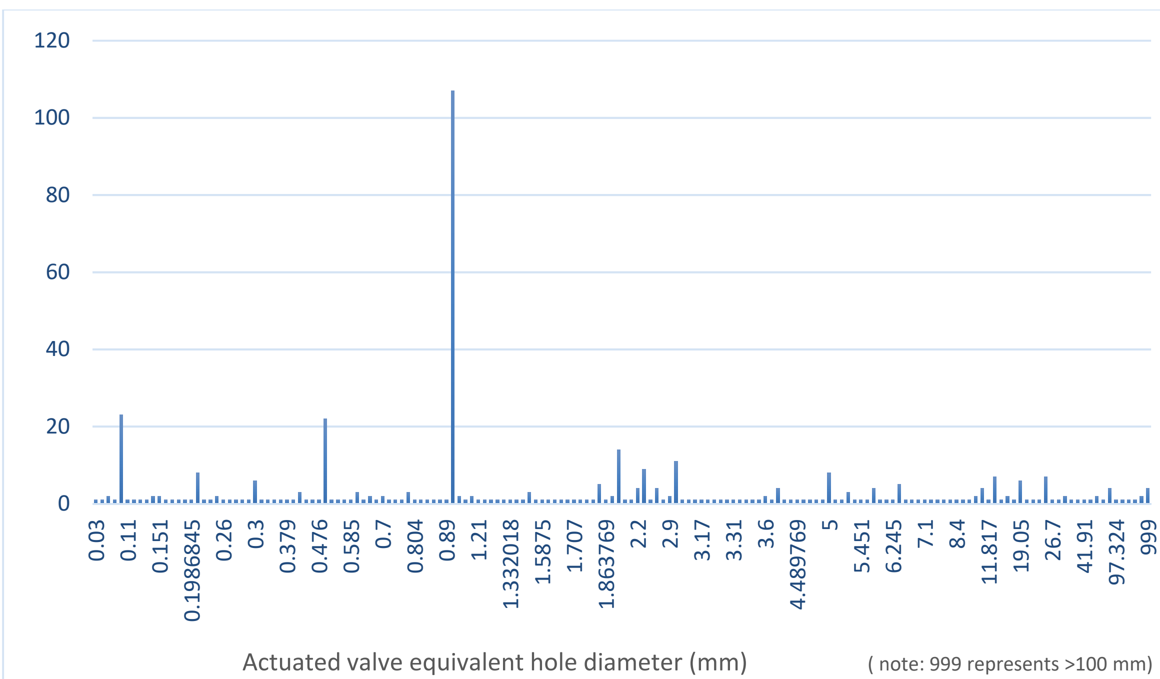


Figure L.14: Number of actuated valve holes by equivalent hole diameter (mm)

4. Manual Valve

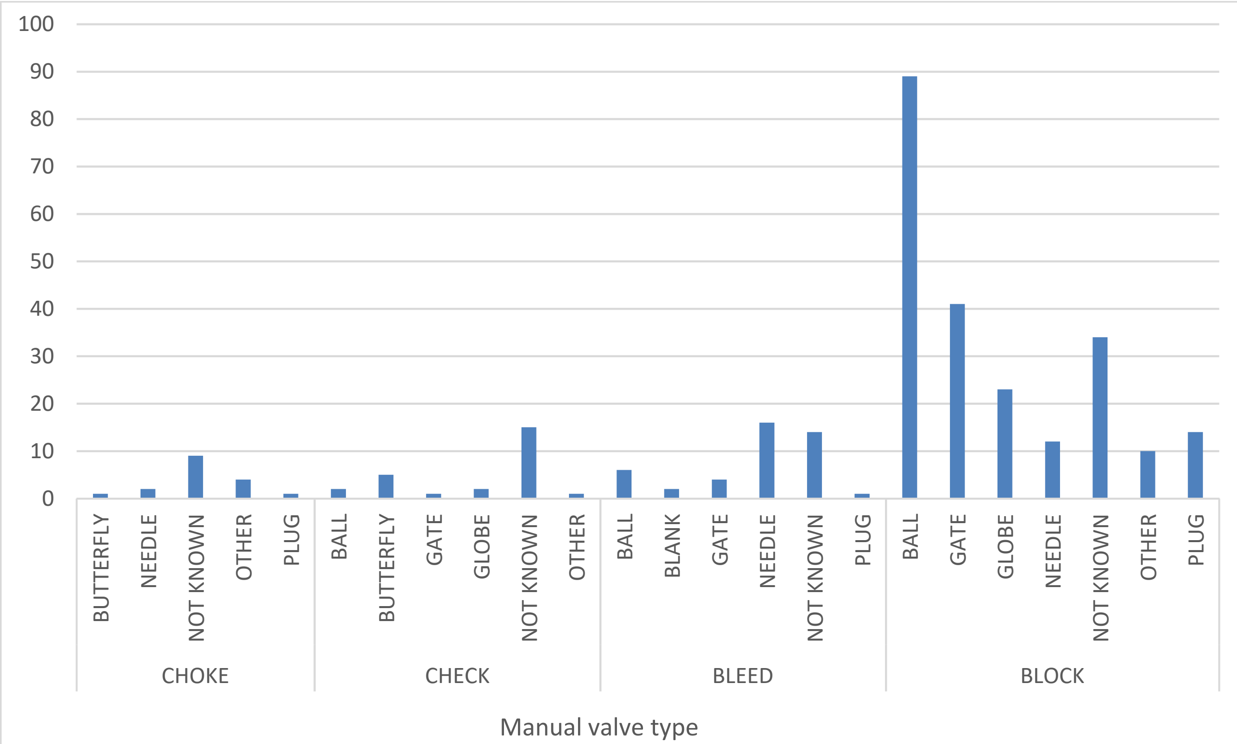


Figure L.15: Number of manual valve leak incidents reported by type

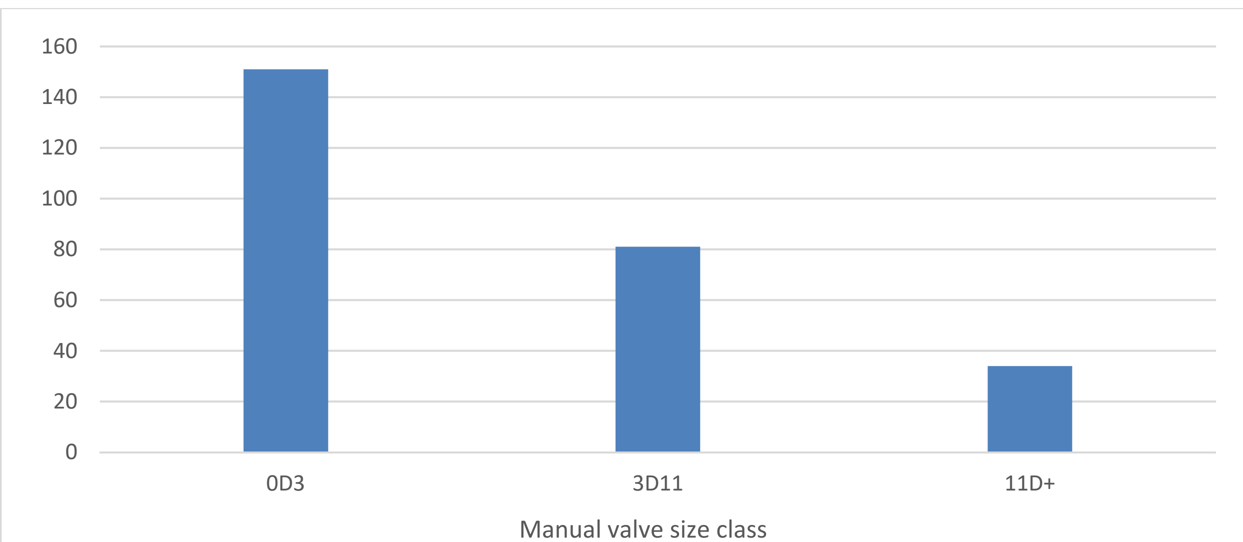


Figure L.16: Number of manual valve leak incidents reported by size category (D≤3", 3"<D≤11", D>11")

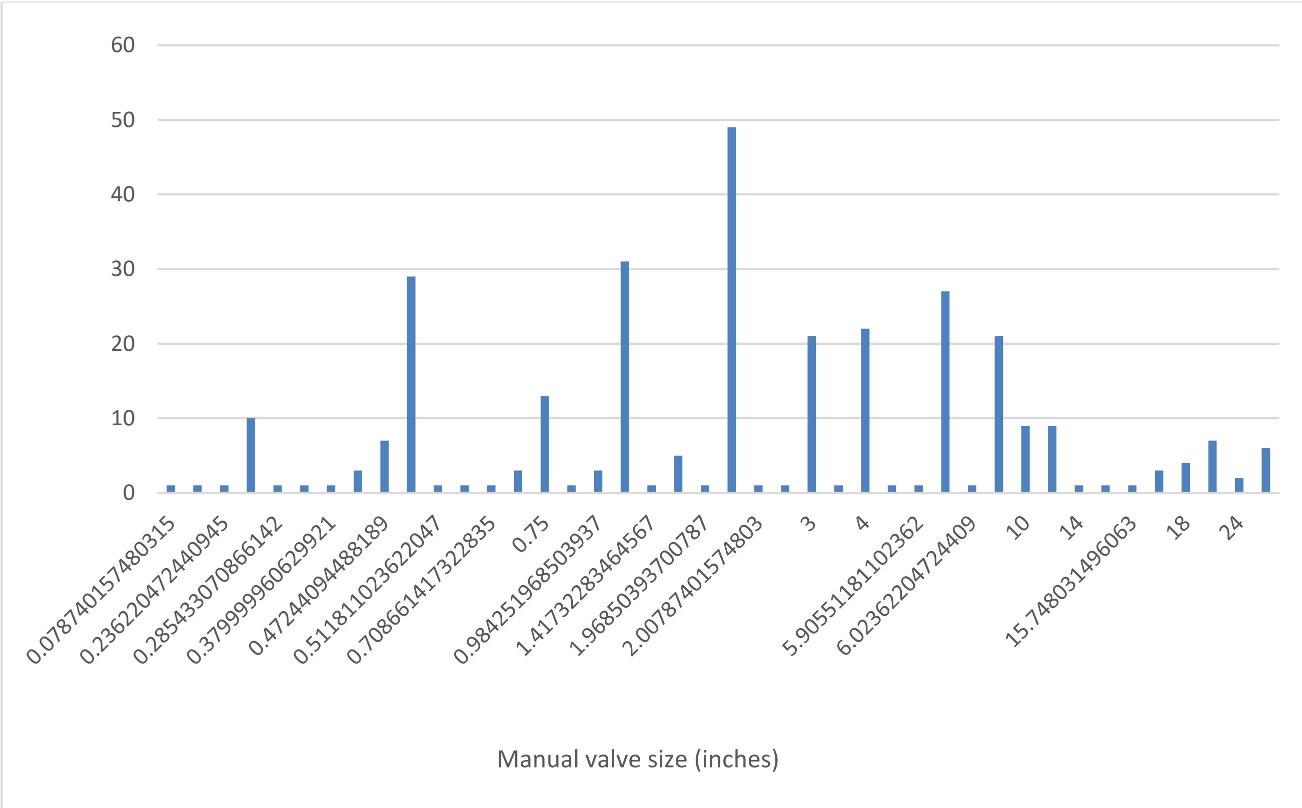


Figure L.17: Number of manual valve leak incidents reported by size (inches)

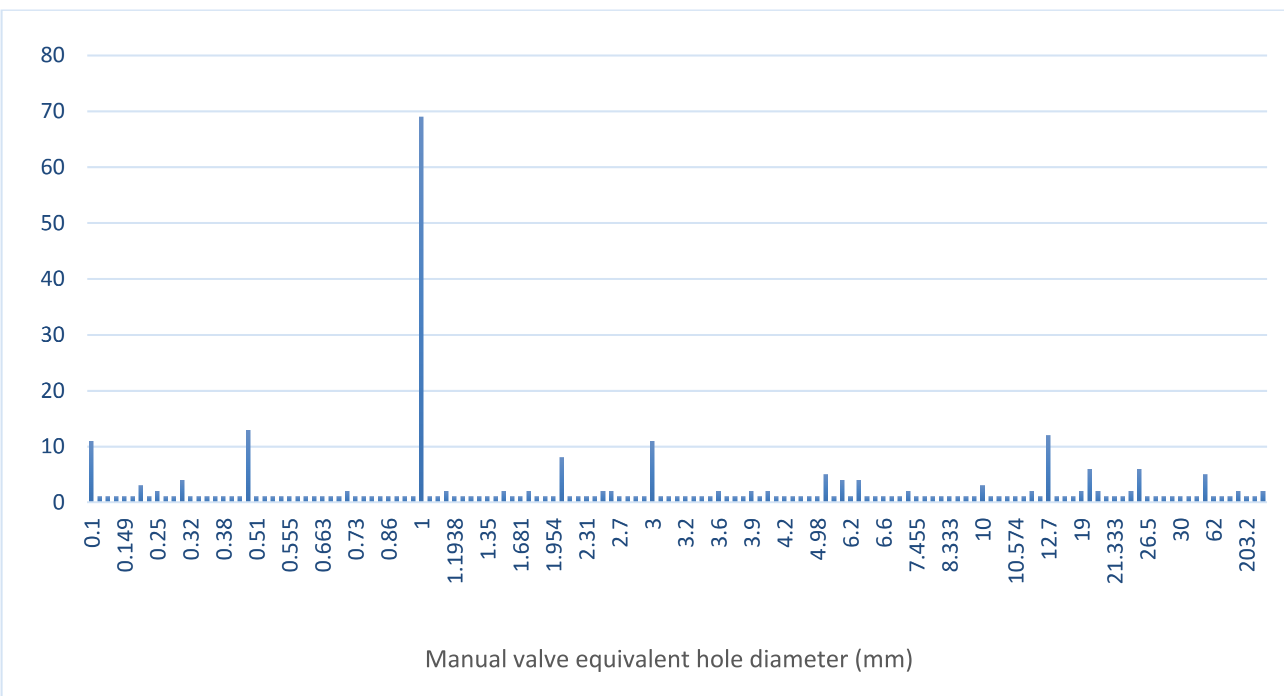


Figure L.18: Number of manual valve holes by equivalent hole diameter (mm)

5. Heat Exchanger

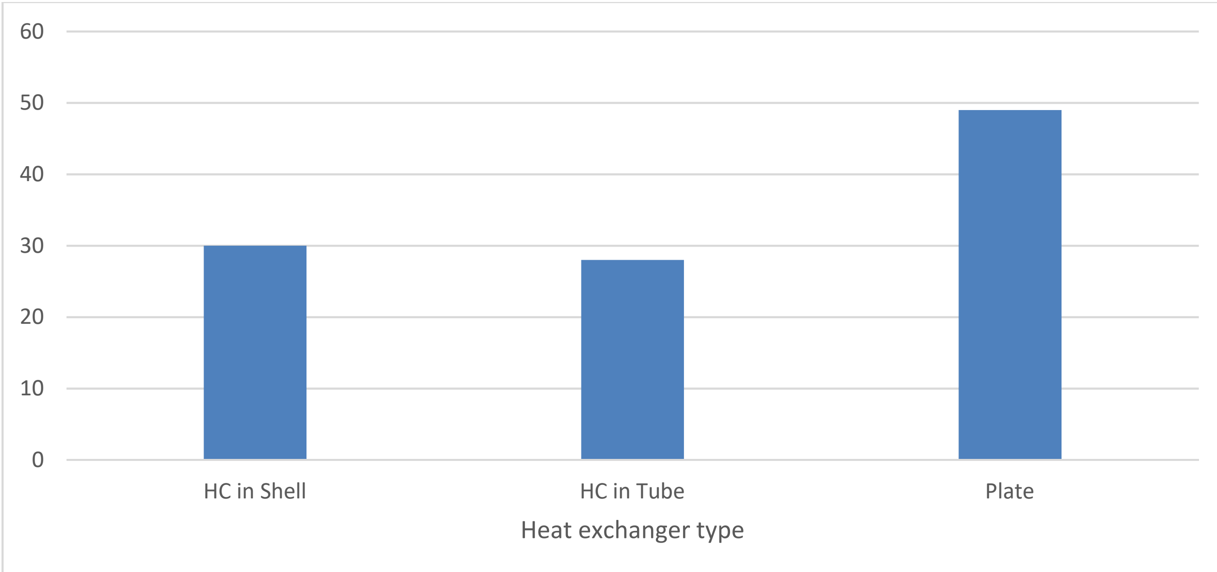


Figure L.19: Number of heat exchanger leak incidents by type

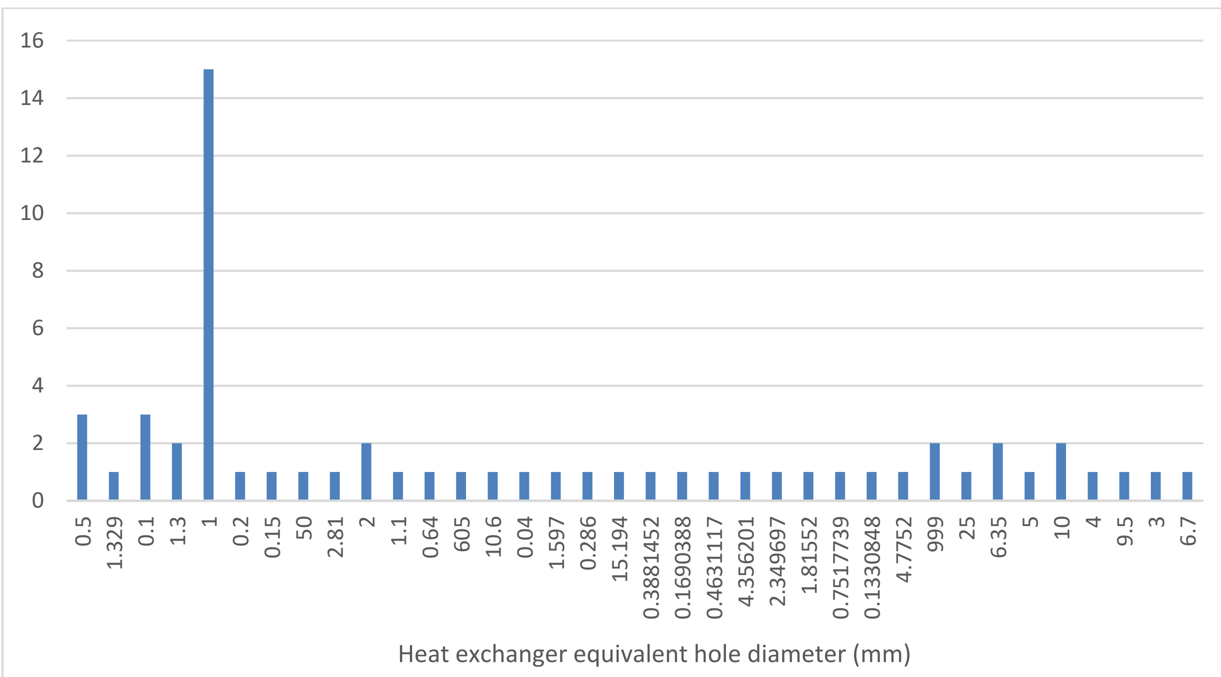


Figure L.20: Number of heat exchanger leak incidents by hole diameter (mm)

6. Fin Fan Coolers

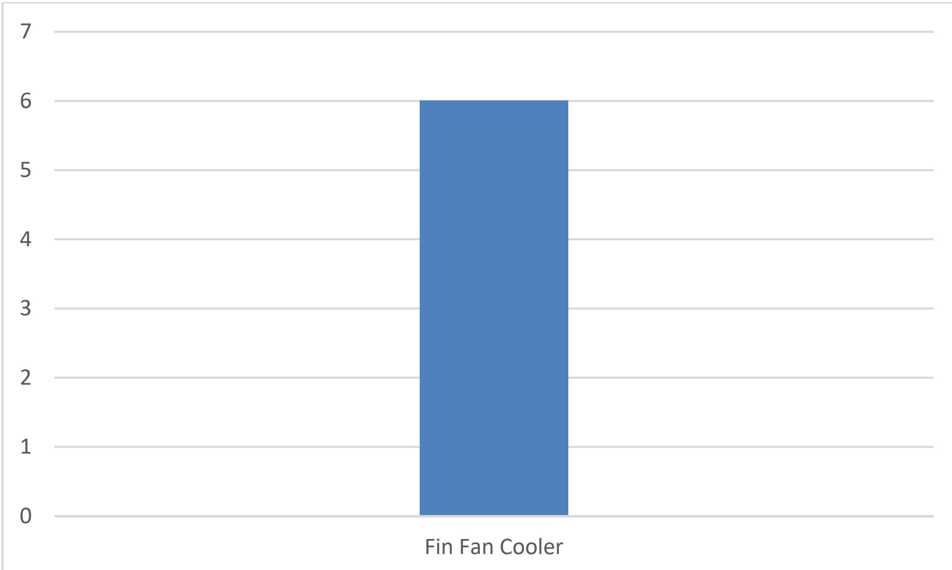


Figure L.21: Number of fin fan cooler leak incidents

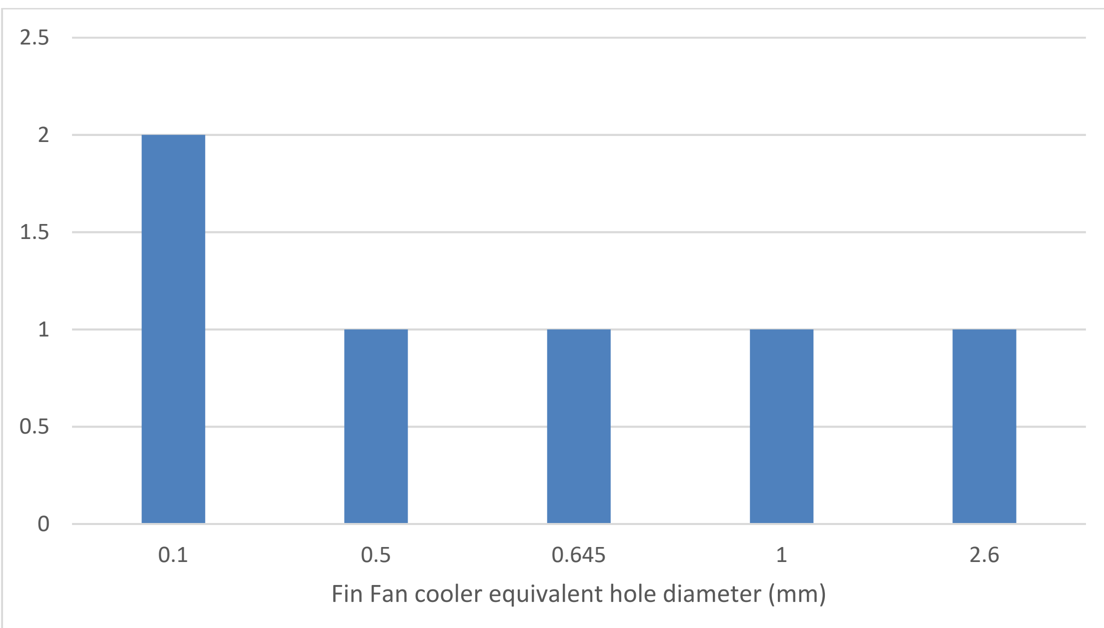


Figure L.22: Number of fin fan cooler leak incidents by hole diameter (mm)

7. Pressure (Process) Vessels

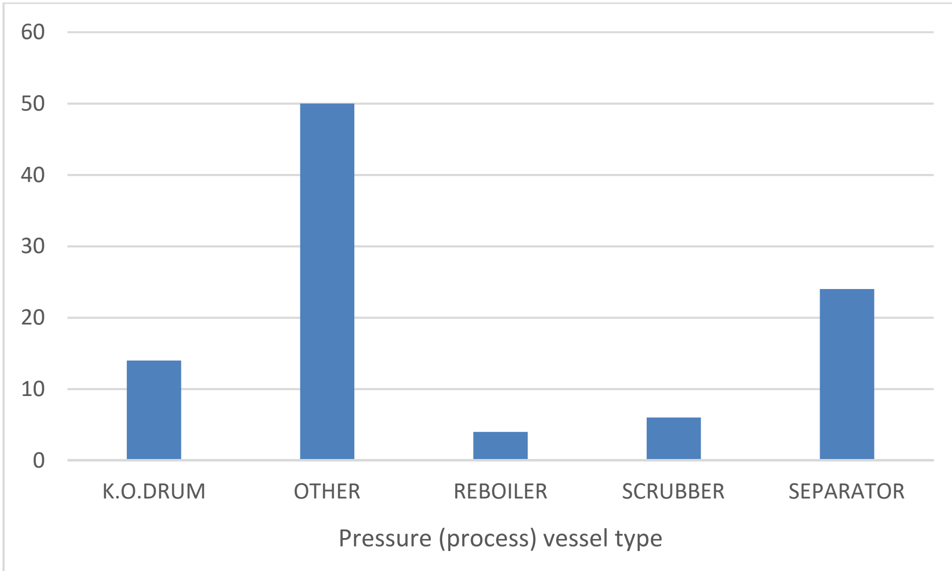


Figure L.23: Number of pressure (process) vessel leak incidents by type

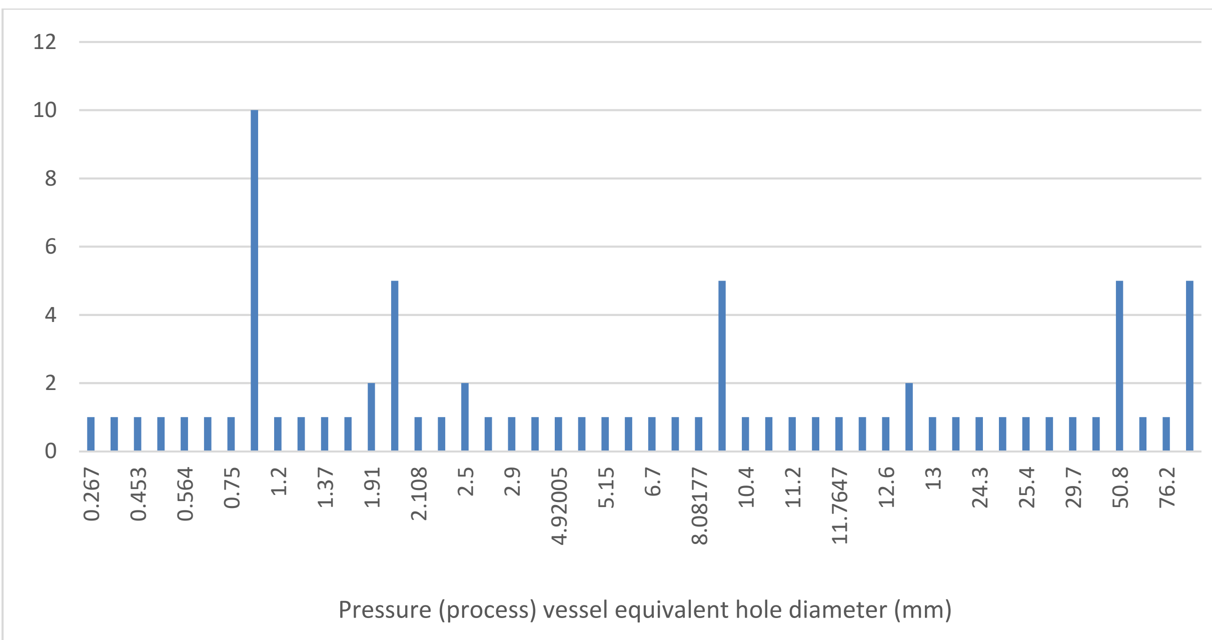


Figure L.24: Number of pressure (process) vessel leak incidents by hole diameter (mm)

Comment re: HCRD Equipment Counts

GTI concurs with the following statement made by DNV on p. 5 of "DNV FFG HCRD '13" that there are uncertainties associated with the equipment count in the HCRD (which of course directly impacts the calculation of failure frequencies from the HCRD database):

> Determining the number of leaks that have occurred off-shore provides only one part of the data that is required to calculate leak frequency. The number of different types of equipment offshore has also been recorded and quantified since 1992, although HSE has recorded no change in the equipment count since 2003 (Regarding system and equipment population data, HSE notes that the responsibility for maintaining the currency of this data rests with duty holders. The population data in HCRD is provided by duty holders on a voluntary database and it is not HSE's role to update, or verify this particular data. Use of this population data would need to be made with caution). It is questionable that the amount of equipment has remained the same offshore since 2003. Maintaining an accurate equipment count is not straightforward, for example the count of equipment on mobile rigs would require the database operators to keep track of the position of MOUs and their movements. The equipment count on the UKCS is provided by the operators on a voluntary database and it is not part of HSE's role to monitor or verify the equipment count. Therefore there are uncertainties associated with the equipment count.

As one example, the population of steel piping in the HCRD database is illustrated below:

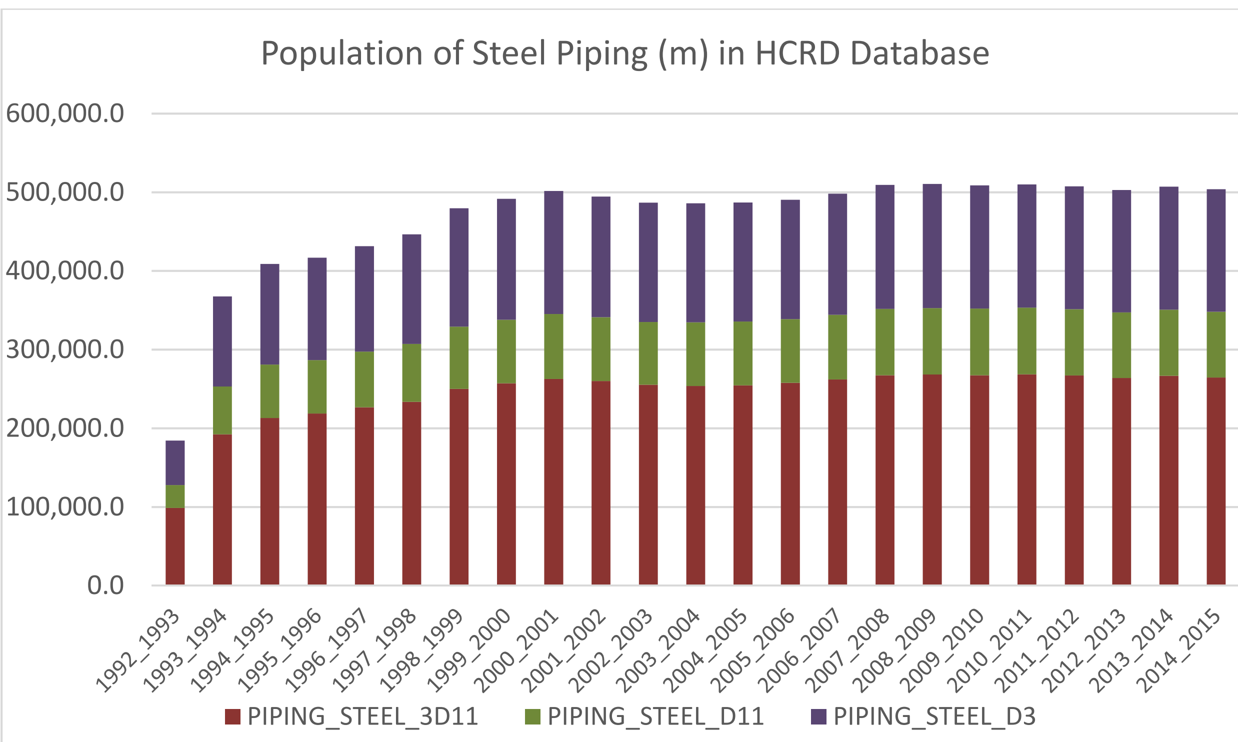
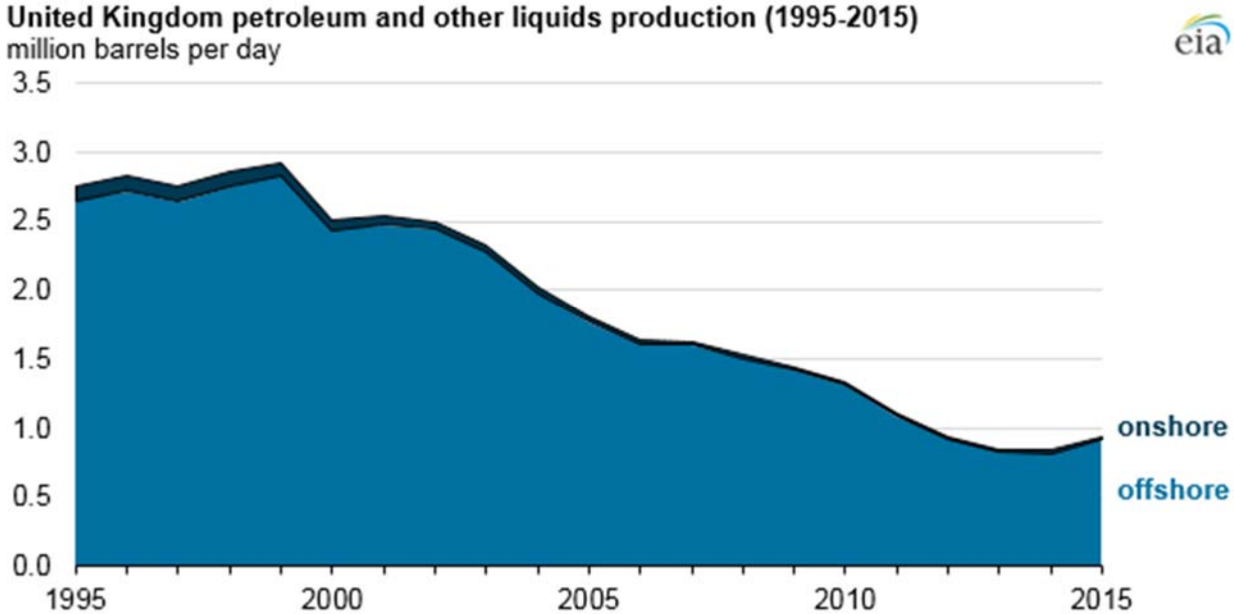


Figure L.25 Population of Steel Piping in HCRD Database

In comparson, total UK petroleum and other liquids production has declined approximately 60% since 2000, according to a 2016 analysis by the U.S. Energy Information Administration:[69]



Appendix M: Cumulative Leak Frequency Curves Developed from UK HSE Hydrocarbon Releases Database (HCRD)

GTI developed cumulative failure frequency curves for flanges, heat exchangers, piping-steel, pressure (process) vessels, fin fan coolers, actuated valves, and manual valves in the UK HCRD database in order to help enhance PHMSA's and FERC's understanding of this database. GTI used the data that is publicly available in Microsoft Excel® files entitled "Offshore Hydrocarbon Population Data 1992 - 2015" and "Offshore Hydrocarbon Releases 1992 – 2015" which are available as of the date of this report at http://www.hse.gov.uk/offshore/statistics.htm.

GTI analyzed the raw data in this public database and calculated cumulative failure rate distribution curves by considering the total leak incidents and the total equipment populations over the each of the years from 1992/1993 to 2015/2016. The results are illustrated in the graphs below where x-axis represents a hole size diameter and y-axis represents the cumulative failure rate of a leak hole that is equal to or greater than that diameter. The cumulative leak frequencies provided in Appendix M were calculated directly from all of the raw data, and do not incorporate any differentiation of type of leak (e.g. "Full Pressure" versus "Zero Pressure" leaks).

The HCRD uses the term "Pressure Vessel" for equipment that is in service such as a: knock-out drum, reboiler, separator, or other. Because these uses are primarily process-related we use the terminology "Pressure (Process) Vessel" in this Appendix for this class of equipment in the HCRD.

There are 2401 leak incidents involving these equipment categories from 1992/1993 to 2015/2016, out of which 52 incidents (i.e., 2.2%) do not provide hole size diameter data. In order to determine total failure frequencies more accurately, we included these 52 incidents and applied them uniformly across the failure rate distribution generated from the incidents in their respective equipment categories that did have hole size data. As shown below, the Pressure (Process) Vessels category was by far the equipment category most impacted, with with 22 of 99 entries (22.2%) lacking hole size data.

Equipment	Number of incidents with no hole size
Flanges	0 out of 430
Heat exchangers	2 out of 107
Piping - steel	22 out of 1012
Pressure (Process) vessels	22 out of 99
Fin Fan coolers	0 out of 6
Valve actuated	4 out of 438
Valve manual	2 out of 309

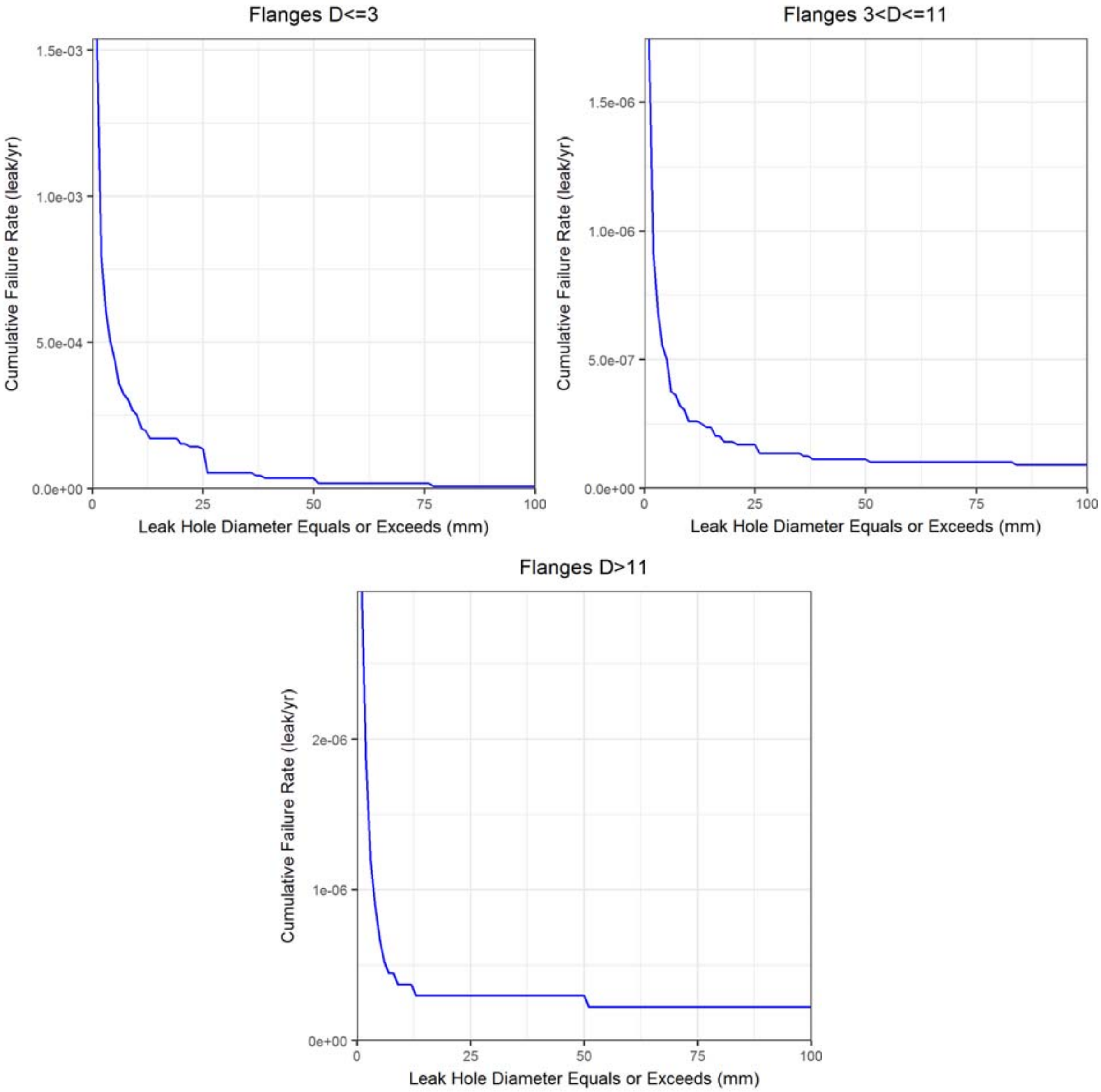
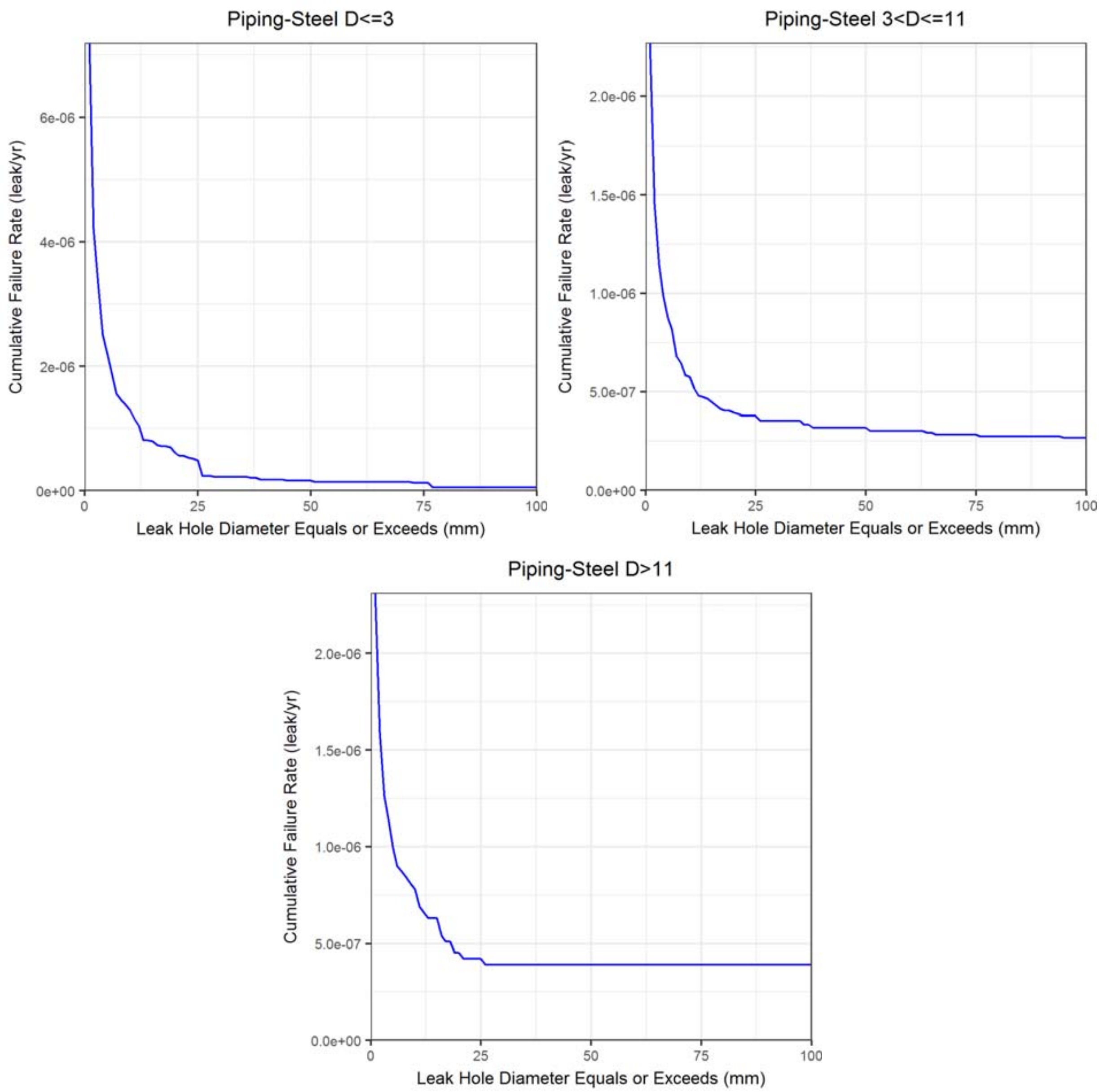
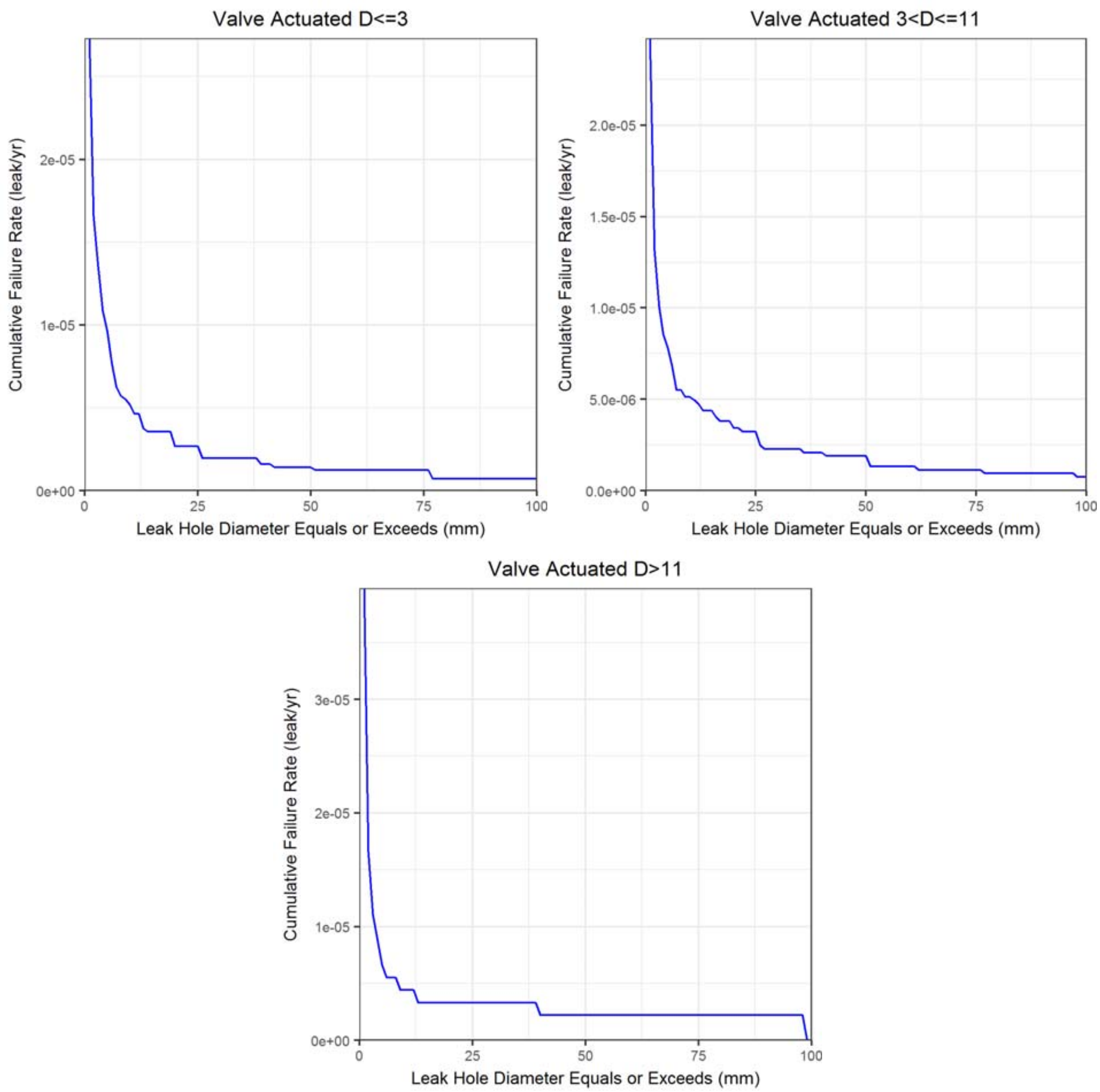


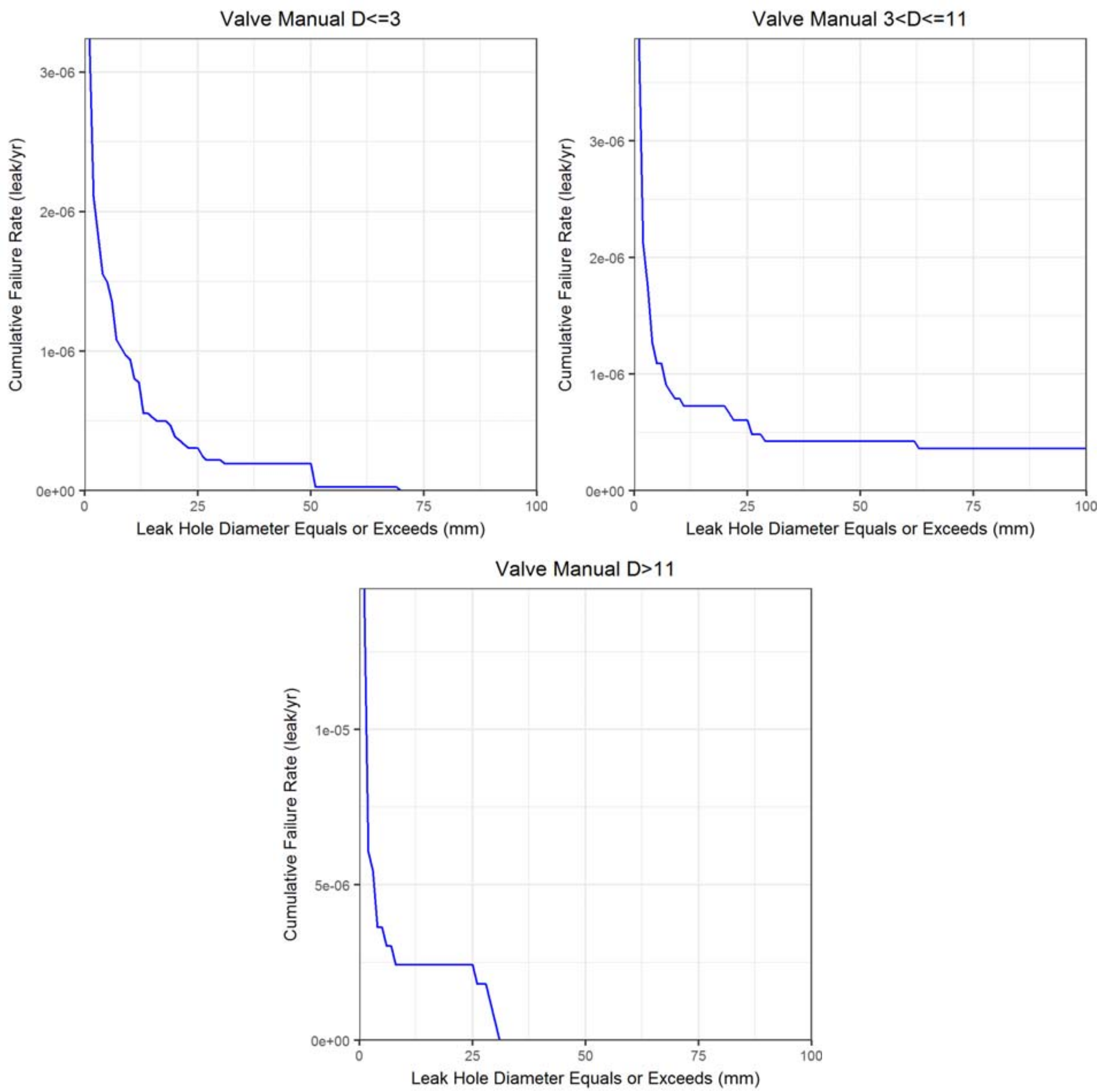
Figure M.1: Cumulative Failure Rate of Flanges by size category (D≤3”, 3”<D≤11”, D>11”)



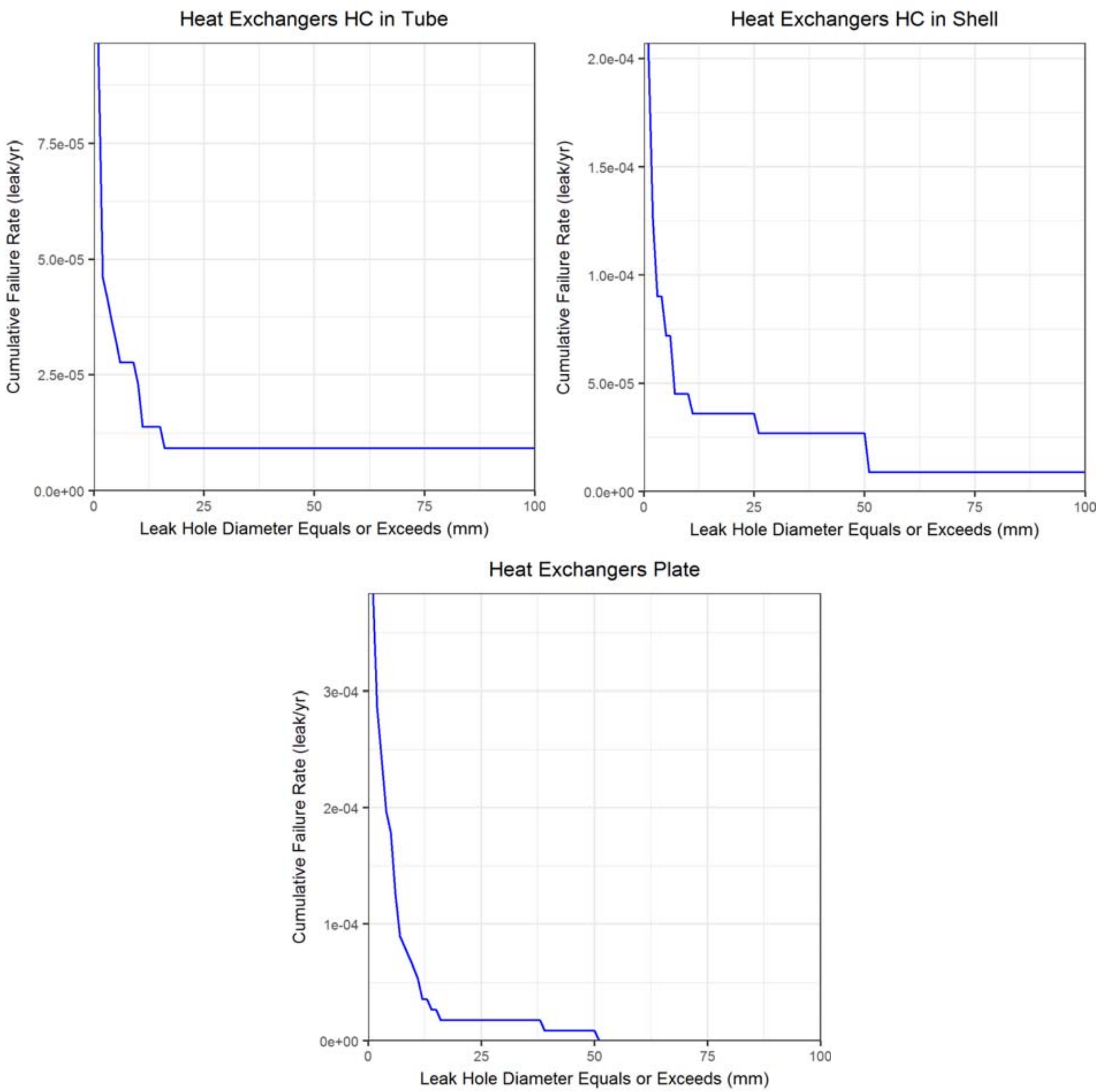
Figures M.2: Cumulative Failure Rate of Piping – Steel by size category (D≤3”, 3”<D≤11”, D>11”)



Figures M.3: Cumulative Failure Rate of Actuated Valves by size category (D≤3”, 3”<D≤11”, D>11”)



Figures M.4: Cumulative Failure Rate of Manual Valves by size category (D≤3", 3"<D≤11", D>11")



Figures M.5: Cumulative Failure Rate of Heat Exchangers by Heat Exchanger Type (excludes Fin-Fan)

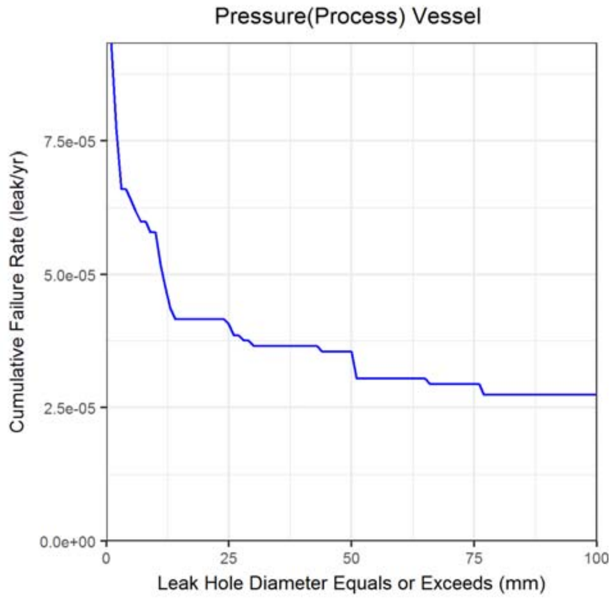


Figure M.6: Cumulative Failure Rate of Pressure (Process) Vessels

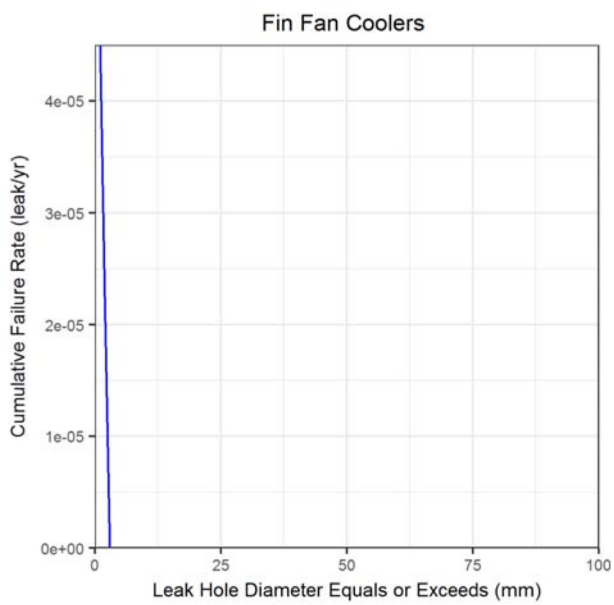


Figure M.7: Cumulative Failure Rate of Fin Fan Coolers

Appendix N: Subject Matter Experts Contacted in Addition to Technical Advisory Panel

The purpose of Task 4 of the project was to contact Subject Matter Experts (SMEs) and other stakeholders beyond the project's Technical Advisory Panel (TAP), in order to ensure that no significant existing failure rate data sources were overlooked and to gather additional key input into this PHMSA-funded project. The project targeted to contact a representative sampling of at least 15 entities beyond those in the TAP, such as additional pipeline companies and operators of LNG facilities, operators of related process facilities (e.g. industrial gas, chemical processing, etc.), standard-developing organizations, and perhaps a representative major oil and gas company. The goal was to seek their voluntary input and insights into this project, our analysis, and failure rate data sources (and inquire if they have proprietary data that they may publically share under this or subsequent research).

For this task the project team leveraged its contacts in the LNG industry through its long history in LNG. In addition, the project team leveraged major events such as: the LNG18 conference in Perth, Australia during April 2016 (this tri-annual conference is one of the largest LNG conferences held in the world, with approximately 6,000 attendees); meetings of the American Gas Association's Supplemental Gas Technical Committee during 2016 (this committee includes LNG plant peak shaving plant management personnel, LNG export facility personnel, LNG-focused engineering firms, LNG equipment manufacturers, and others); and Natural Gas for High Horsepower (HHP) Summits and Expositions. By leveraging these LNG-related events in an opportunistic manner, the project team was able to personally discuss LNG equipment failure rate data issues and PHMSA's project with a diverse number of individuals at key companies.

More than 50 SMEs were contacted. They represented global perspective and expertise as operators of LNG plants and related process facilities, pipeline companies, LNG equipment manufacturers, LNG facility and storage tank designers and builders, and others.
All of the following SMEs were contacted by email, and most also in person:

1. **AGL Resources,** Managing Director Storage & Peaking Services
2. **Air Liquide Global E&C Solutions**, LNG Product Manager and also LNG Technology Lead
3. **Air Products and Chemicals Inc. (APCI),** General Manager Global LNG & CyroMachinery Division, and also Manager LNG Mechanical Design Engineering
4. **Applied Cryo Technologies,** Chief Operating Officer
5. **Baltimore Gas & Electric Co.,** Senior Engineering Technical Specialist
6. **Bechtel**, Engineering Manager, Tank Business Line
7. **Bestobell Valves, div. of Parker Hannifin,** Product Manager and also Business Development Manager
8. **Black & Veatch Corp.,** Vice President - LNG Technology, B&V Energy
9. **Braemar Engineering,** Vice President LNG Technical Services
10. **British Compressed Gas Association,** Technical Manager
11. **CB&I,** Senior Vice President of LNG
12. **Chart Industries,** Vice President of Sales, LNG and also Vice President of Engineering
13. **Cheniere LNG O&M Services, LLC**, Vice President, Government and Regulatory

Affairs, and also Principal Process Engineer

14. **Chevron Energy Technology Pty Ltd.,** Perth Global Technology Centre Manager
15. **Compressed Gas Association,** Technical Manager
16. **ConocoPhillips,** Licensing Director, LNG Technology and Licensing
17. **Cryosys,** President
18. **Dominion Cove Point**, Vice President - LNG Operations, and also Director - Liquefaction
19. **EcoElectrica L.P.**, Plant Manager
20. **EMCO Wheaton by Gardner Denver**, Engineering Manager
21. **Elengy, a company of GDF Suez,** Head of LNG Technical Department
22. **Evergas,** Senior LNG Operations Manager
23. **European Industrial Gas Association,** Deputy General Secretary
24. **Excelerate Energy LP,** Senior Vice President, Operations
25. **ExxonMobil Development Company,** Risk and Loss Prevention Engineer
26. **Fluor,** Technical Director, Process Engineering and Senior Fellow, LNG & Gas Processing
27. **FMC Technologies,** Business Development Manager, Loading Systems
28. **Freeport LNG Development, LP,** FERC Compliance Manager - Liquefaction
29. **GTT**, Structure Engineer and also Business Development Manager
30. **Hitachi High-Tech AW Cryo, Inc.,** President
31. **INOXCVA,** President and CEO
32. **International Group of Liquefied Natural Gas Importers (GIIGNL),** Technical Study Group Lead
33. **Jereh Group,** Deputy Director
34. **Kawasaki Heavy Industries,** Manager Overseas Sales Section, Cryogenic Storage System Sales Department
35. **Kellogg Brown & Root (KBR),** Director LNG and FLNG Engineering and Construction
36. **Korea Gas Research Institute,** Head
37. **Linde AG Engineering Division,** Executive Vice President, LNG and Natural Gas Plants
38. **Matrix Service,** Senior Director, Business Development
39. **Perma-Pipe Inc.,** Division Vice President, Oil & Gas
40. **Petronas**, Head - Performance, Portfolio & Governance, Technology, Technical Global
41. **Petronet LNG Limited**, General Manager – Maintenance
42. **PHPK Technologies**, Director of Sales and Marketing
43. **RegO Products,** Director of Sales
44. **Shell Global Solutions International BV**, Global Manager - LNG Market Access and also Distribution Engineering Manager - LNG Market Access
45. **Society of International Gas Tanker and Terminal Operators Ltd (SIGGTO),** General Manager
46. **Stabilis Energy,** Vice President, Plant Construction/Business Development
47. **Technodyne International Ltd.,** Founder and past Technical Director
48. **Tokyo Boeki Machinery Ltd. (Niigata Loading Systems, Ltd.),** Subsection Chief, Overseas Plant Equipment Group
49. **Toyo Kanetsu K.K. (TKK),** Sales Department
50. **U.S. Coast Guard, Liquefied Gas Carrier National Center of Excellence**, Detachment Chief
51. **Valco Group,** Director Australia

52. **Wartsila North America,** Gas Initiatives Vice President
53. **Woodside Energy Ltd.**, VP Technology

Appendix O: Acronyms

Acronyms often used in this report and in the referenced literature are listed below. See also Section 3 for acronyms of references as used in this project.

Acronym	Description (using English translations)
AGA	American Gas Association
AGS	Dutch Hazardous Substance Council
AHJ	Authority Having Jurisdiction
AIChE	American Institute of Chemical Engineers
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BEVI	Dutch External Safety Decree for Establishments
BCF	Billion Cubic Feet of Natural Gas
BCGA	British Compressed Gas Association
BAC	Break-Away Coupling
BRZO	Dutch Hazards of Major Accidents (risks) Decree
CCPS	AIChE Center for Chemical Process Safety
CEN	European Norm (i.e., European Community standard)
CFR	U.S. Code of Federal Regulations
CGA	Compressed Gas Association
CH-IV	CH-IV International Inc.
COMAH	Control of Major Accident Hazards
COTP	USCG Captain of the Port
CPI	Chemical Process Industry
CSA	CSA Group (formerly Canadian Standards Association)
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DNV	Det Norske Veritas
EGIG	European Gas pipeline Incident data Group
EIGA	European Industrial Gas Association
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ERC	Emergency Release Coupling
ERP	Emergency Response Plan
ERS	Emergency Release System
ESD	Emergency Shutdown system
FERC	U.S. Federal Energy Regulatory Commission
F-N	Frequency-Number of Fatalities
FRED	Failure Rate and Event Data
FRT	Failure Rate Table
FSRU	Floating Storage and Regasification Unit

FSU	Floating Storage Unit
FTA	Fault Tree Analysis
GIIGNL	International Group of LNG Importers Ltd.
GRI	Gas Research Institute
GTI	Gas Technology Institute (formerly GRI and Institute of Gas Technology)
HAZID	Hazard Identification analysis
HAZOP	Hazard and Operability analysis
HCRD	UK Hydrocarbon Releases Database System
HSE	UK Health and Safety Executive
HSL	UK Health and Safety Laboratory (of HSE Science Division)
IMDG Code	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
INL	Idaho National Laboratory
IOGP	International Association of Oil & Gas Producers (formerly OGP)
IR	Individual Risk
ISO	International Organization for Standardization
LNE	Flemish Environment, Nature and Energy Department
LNG	Liquefied Natural Gas
LNGC	LNG carrier
LPG	Liquefied Petroleum Gas
MARAD	U.S. DOT Maritime Administration
NB	Nominal Bore
NFPA	National Fire Protection Association
NG	Natural Gas
NVIC	USCG Navigation and Vessel Inspection Circular
OCIMF	Oil Company International Marine Forum
OREDA	Offshore and Onshore Reliability Data project
PERC	Powered Emergency Release Coupling
PGS	Dutch Publication Series on Dangerous Substances
PHMSA	U.S. DOT Pipeline and Hazardous Materials Safety Administration
PNL	Pacific Northwest Laboratory
PS	Peak Shaving LNG Plant
QRA	Quantitative Risk Assessment
RAM	Reliability Availability Maintenance analysis
RIVM	Dutch National Institute of Public Health and the Environment
SALS	Single Accidental Leakage Source
SIGTTO	Society of International Gas Tanker and Terminal Operators
SINTEF	Norwegian Foundation for Scientific and Industrial Research
SME	Subject Matter Expert
SR	Societal Risk
TNO	Dutch Organization for Applied Scientific Research
USCG	U.S. Coast Guard

Appendix P: Bibliography

The following references were evaluated for relevancy to this research during project DTPH56-15-T-00008. The abbreviated name that is [included in brackets] is used elsewhere in this project, including in the project's database.

Additional Failure Rate Quantitative Data References Evaluated for Relevancy to Components in PHMSA's LNG Failure Rate Table:

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