



CGA TR-7—2023 METHODOLOGY TO DETERMINE PIPING FAILURE RATES FOR NONTOXIC CRYOGENIC INDUSTRIAL GAS SUPPLY SYSTEMS WITH PIPE SIZE UP TO 6 INCHES

FIRST EDITION

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Work Item 22-60
Process Safety Committee

FIRST EDITION: 2023

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Contents	Page
1 Executive summary	1
2 Introduction and problem statement.....	2
3 Recent History of some relevant failure frequencies studies	3
4 Framing a useful conclusion for failure frequencies	4
4.1 Source	4
4.2 Data filtering	4
4.3 Small sizes	5
4.4 Normalized and formula driven.....	5
5 Formulation of the failure frequency guidance for small scale	7
5.1 General considerations for failure rates.....	11
5.2 Setting up a set of equivalent lengths for piping components.	12
5.3 Hose examples.....	15
6 Comparison to other methodologies	16
7 Anticipated practice for use of the proposed failure frequency in risk-informed methods	23
8 References	31

Tables

Table 1—Equivalent length of various equipment.....	1
Table 2—HCRD equipment types.....	7
Table 3—Selected pipe and tubing types	7
Table 4—Selected mechanical joint types	7
Table 5—Selected dynamic seal types	8
Table 6—Data used in affirming annual failure rate equation	9
Table 7—Table of equivalent lengths.....	15
Table 8—Key for Figures 16 through 19	22
Table 9—Example equipment count	23
Table 10—Frequency calculations initial example	24
Table 11—Rank order of failure frequencies	25
Table 12—Range summaries of failure frequencies	26
Table 13—Example equipment count updated	26
Table 14—Frequency calculations updated example	27
Table 15—Rank order of failure frequencies updated	28
Table 16—Range summaries of failure frequencies updated	29
Table 17—Equipment count and equivalent length determination.....	30
Table 18—Updated equipment count and equivalent lengths	31

Figures

Figure 1—Loss of containment fishbone diagram.....	6
Figure 2—Hole size distribution for pipe less than 3 in (equipment type 1)	9
Figure 3—Piping annual failure rate plot.....	10
Figure 4—Numeric substitution for Equation 5.6 for hole sizes between 3 mm and 10 mm on a 50-mm pipe..	10
Figure 5—Numeric substitution for Equation 5.6 for hole sizes between 3 mm and 50 mm on a 50-mm pipe..	11
Figure 6—Nominal annual failure rate	12
Figure 7—Equivalent length determinations	13
Figure 8—Example of equivalent length for a dynamic seal	13
Figure 9—Development of make and break equation.....	14
Figure 10—Substitution for Equation 5.2.2 for a failure rate of 1 per 4 weeks.....	15
Figure 11—Hose example 1	15
Figure 12—Hose example 2	16
Figure 13—Hose example 3	16

Figure 14—Hose example 4	16
Figure 15—Hose example with comparison to FERC.....	16
Figure 16—Pipe cumulative annual failure rate ([1/m-yr])	18
Figure 17—Valve cumulative annual failure rate ([1/ yr])	19
Figure 18—Flange cumulative annual failure rate ([1/yr])	20
Figure 19—Hose cumulative annual failure rate ([1/m-yr])	21
Figure 20—Individual risk at range plot.....	26
Figure 21—Individual risk at range plot updated.....	29
Figure 22—Application of Miner’s Rule	30
Figure 23—Application of Miner’s Rule updated.....	31

Appendices

Appendix A—Data sorts (Normative).....	33
Appendix B—Hole distribution plots (Normative).....	50

Appendix Tables

Table A-1—Instruments	33
Table A-2—Pipe less than 3 in.....	34
Table A-3—3 in <Pipe<11	36
Table A-4—11 in <Pipe	37
Table A-5—Flanges<3 in	37
Table A-6—3 in <flanges<11 in.....	38
Table A-7—Flanges>11 in	38
Table A-8—All flanges	39
Table A-9—Manual valves	41
Table A-10—Auto valves	42
Table A-11—All valves	43
Table A-12—Centrifugal compressors	1
Table A-13—Reciprocating compressors	1
Table A-14—Centrifugal pumps	1
Table A-15—Reciprocating pumps	46
Table A-16—All dynamic seals	47

Appendix Figures

Figure B-1—Equipment type 0-3, piping	50
Figure B-2—Equipment type 4-7, flanges	51
Figure B-3—Equipment type 8-12, dynamic seals.....	52
Figure B-4—Equipment type 13-15, valves	53

1 Executive summary

This technical report applies to 300 series austenitic stainless steel piping up to and including 6 inches in diameter, suitable for nontoxic cryogenic service, and where the design pressure stress of pipe and tube does not exceed one half of the basic allowable stress.

Small scale industrial gas installations, and in particular ones for cryogenic service, need reasonable equipment failure rates to drive risk informed frameworks for siting and guideline setbacks. Current failure rate guidance does not fit well for small scale and is unnecessarily conservative. The study of recent efforts in this area demonstrates interest but no useful guidance on approaches.

Such guidance should be practical in its application and transparent in its design basis. The publicly available Hydrocarbon Release Database (HSE Hydrocarbon Release Database, www.hse.gov.uk/offshore/statistics) (HCRD) for leak rates is used to generate a universal failure rate equation that has small scale and cryogenic considerations included [1].¹

$$FF_{\text{cryo}}(d1, d2, D) = \left[\frac{1}{1 + \left(\frac{\frac{d2}{\text{mm}}}{1.5} \right)^{-1.5}} - \frac{1}{1 + \left(\frac{\frac{d1}{\text{mm}}}{1.5} \right)^{-1.5}} \right] \cdot \left[\left(2.539 + 25.2 \cdot e^{\frac{-D}{29.412}} \right) \cdot 10^{-5} \right] \cdot 40\% \cdot \frac{1}{\text{m} \cdot \text{yr}}$$

Additionally, a simplified approach to estimate equipment limits is developed that allows for quick estimates of system aggregate risks using an equivalent length approach.

Table 1—Equivalent length of various equipment

Equipment type	Equivalent length (m)	Notes
Pipe or tube (per meter)	1	Welded joints are assumed to be part of this equipment type and are not subject to additional equivalent length consideration
Static mechanical joints (each)	1	These are mechanical seals held in place by some threaded, bolted, crimped, or swaged joint
Valves (each)	2	This is for any valve that has a body seal and packing. Features such as flanged inlets, 2-piece bodies, etc. do not require additional equivalent length. Automatic valves that have more than 96 full cycles (full return to starting position as in open to closed and returning to open) in an 8-hour period shall be evaluated as a dynamic seal at the nominal diameter of the shaft being sealed.
Hose not under flexure (per meter)	20	Hoses are assumed to be stainless steel, corrugated, and reinforced with a stainless-steel braid and properly maintained in accordance with CGA P-82, <i>Standard for Maintenance of Transfer Hoses</i> [2].
Dynamic seals and hoses (bellows) under flexure (each)	$350 - 349 \cdot e^{\left(\frac{-\text{cycles}}{10^7} \right)}$	This equivalent length should be added to the aggregate of shaft diameters for valves, pumps, and compressors. For hoses in flexure, they should be aggregated against the full inside diameter of the hose corrugation. Cycles= the annual number of full design cycles. When less than full cycle range can be demonstrated, the annual number of full cycles can be pro-rated accordingly.
Make-and-break connections (each)	$350 - 349 \cdot e^{\left(\frac{-\text{breaks}}{10^2} \right)}$	This equivalent length should be added to the aggregate for the full piping diameter being assessed Breaks= the annualized number of connect breaks.

¹ References are shown by bracketed numbers and are listed in order of appearance in the reference section.

When compared to traditionally approaches to risk-informed methods, the proposed method simplifies the number of iterations required, improves both the accuracy, and reduces the subjectivity.

2 Introduction and problem statement

Small scale industrial installations for industrial gases have generally been guided by codes and standards that prescribe setbacks to property lines and other safety critical objects by way of tables. These tables are often generated by committee where the basis of the prescriptive requirements can be lost to history.

More recently there is a move to a risk basis for small scale setback requirements. Risk is determined by the consequence of a release multiplied by the probability of such a release. When the full details of a site are documented, a risk-based approach can be taken adding up all potential leak consequences and the probability of each such leak. These can then be rank ordered by either range or persons affected and the aggregate probabilities then totaled. Such a detailed process is often referred to as quantitative risk analysis (QRA).

Large scale industrial sites use QRAs to qualify the risk-based siting. This process requires a detailed understanding of the system layout and component positions. Additionally, failure frequency data is used to characterize the likelihood and size of unintended holes, typically modeled as round holes. This failure data is collected and summarized into component types and size bundles that do not lend themselves to properly modeling smaller scale piping systems.

Many industrial gas systems have smaller scale piping systems and can be in “near retail” or “light industrial” areas where available setbacks are much smaller. Near retail or light industrial areas are defined as areas where the size of the piping and major equipment in the designed system are same or larger than any adjacent or neighboring systems. Neighboring or adjacent systems of larger diameter or larger components where the maintenance setbacks or defined risk area overlaps would disqualify the site as near retail or light industrial. Additionally, near retail areas are often inherently closer to the public.

Smaller system siting is also driven by either prescriptive or deterministic methods found in standards. A risk-informed basis to drive such standards development is desired. Risk-informed methods imply that many of the details are assumed or given simplified proxy equivalents. In this way, a quick and conservative method can be developed that is appropriate for smaller scale installations. Further, such a risk-informed system would be best suited if the amount of equipment allowed could be compared to the available setback. Such an analysis would require generalized leak frequencies to reduce the number of varying components and associated component-dependent leak frequency assumptions.

The use of available failure frequency approaches for small scale industrial gas systems that are in light industrial or near retail locations present several challenges. First, the traditional filtering of hole sizes for guidance typically does not include any reports for holes sizes smaller than 1 mm. While this is reasonable for larger systems, holes on the order of 1mm and smaller are relevant for systems demanding very short setbacks. Secondly, the size of equipment in industrial gas systems may all be less than 2 in nominal size. In most guidance documents the piping and equipment sizes reported on are greater than 2 in, and they defer to an “instrumentation” category which offers no further delineation on equipment type or size. Thirdly, small scale systems are cited by standards which are historically prescriptive and table drive. Migration to a risk-informed method would necessarily be based on anticipated equipment limits and not on a detailed design. This makes the what-if scenarios for design and siting of small scale much more difficult as existing guidance has unique recommendations for a wide range of discrete types. A methodology that would allow for a generalized equipment limits would be necessary for setting the basis for updating table based and deterministic methods currently used for small scale.

This study focused on the development of loss-of-containment frequencies for piping systems (piping components, rotating equipment, and controls) used in small scale industrial gas (typically cryogenic) applications. The study included the following four key attributes:

- Source—The data source was publicly available and accordingly reproducible;
- Data filtering—The data sorting and filtering was for small scale industrial gas piping equipment types;

- Small sizes—Small scale sizes and equipment types were well modeled and appropriate for determining setbacks needed for light industrial and near retail application; and
- Normalized and formula-driven—Equipment types and sizes were normalized which in turn simplified the risk analysis necessary for a risk-informed approach.

This technical report applies to metallic piping up to 6 inches in diameter, suitable for nontoxic cryogenic service, and where the design pressure stress of pipe and tube does not exceed one half of the basic allowable stress.

3 Recent History of some relevant failure frequencies studies

In 2007 Sandia National Labs conducted a study for the purposes of revising setback distances for gaseous hydrogen. This study culminated in a 2009 report by LaChance and Houf [3]. This work also is the basis for gaseous hydrogen setback as represented in NFPA 2 [4]. In this study the lack of data for smaller scale release probabilities was noted and led to a Bayesian statistical analysis intended to affirm a relatively small data set accumulated by industrial gas participants. The approach uses existing “data” noted as priors. When such data has subjective influences (as when the data is already filtered and sorted based on alternate assumptions), they are considered uninformed, and the results become questionable. Recognized and noted as such in the report, the analysis represented the best available options for evaluation. The rates developed were on the order of 2 decades lower than the priors used in the analysis. The analysis did not explore any relationships with component size and concluded that a percent area for a hole on the order of 3% of the inside area of the pipe was a reasonably proxy for full component examples studied.

In 2010, the Det Norske Veritas (DNV) produced a failure frequency database that leveraged the HCRD maintained by HSE in the UK [5, 1]. In this publication, the data used is from specific release data from offshore equipment collected between 1992 and 2010. The data is presented in table form. A leak table is presented for each equipment type. The categories for data collection are intended for large scale systems and for QRAs. The use of a formula interpretation is reserved for the DNV commercial software “LEAK”.

Also, in 2010 the International Association of Oil and Gas Producers published OGP Risk Assessment Data Directory report no. 434-1 [6]. As in the DNV publication, the HCRD is used as the data set and only release tables by hole range are presented. Formula equivalents are not published, and the sizes are bundled typically for equipment between 50 mm to 150 mm in the smallest range apart from a broad category of “instrument connections.” The publication does note potential corrections for improvements in corrosion mitigations for embrittlement and for thinning yet falls short of any specificity.

In 2012 the Federal Energy Regulatory Commission (FERC) in coordination with the Pipeline and Hazardous Material Safety Administration (PHMSA) presented a guidance recommendation for liquefied natural gas facilities [7]. This guidance focused on leak frequencies with a single largest accidental release (SLAR) criteria of 3.5×10^{-5} . A summary table was developed after review of numerous databases. The study shows the wide variation across differing databases, which in some cases is by 2 or more orders of magnitude. A wide-ranging averaging effort, informed by department experience, results in a release rate table. The bundled sizes and minimal hole size distribution make the table difficult to use in small scale application. Additionally, the rate proposed for flanges and flexible hoses are singular and conservative and inconsistent with industrial gas experience.

In 2012, the National Fire Protection Association (NFPA) updates NFPA 59A, *Standard for the Production, Storage, and handling of Liquefied Natural Gas (LNG)*, to the 2013 ed. created a performance based (QRA guidance) chapter, which gives only a full rupture rate for piping [8]. NFPA 55, *Compressed Gases and Cryogenic Fluids Code* 2013 ed. adopts the work from Sandia completed in 2009 using a 1.5 safety factor and a 3% area hole size for gaseous hydrogen [9, 4].

In 2017 the Gas Technology Institute, under contract by PHMSA, completed a report on the evaluation of the failure rate table proposed by FERC /PHMSA in 2012 [10]. The report generally affirms the table narrowly as reasonably based on the intended use in evaluating Single Largest Accidental Release Scenarios (SLARS) with a 3.5×10^{-5} criteria. In the intended use, potential releases that can be demonstrated as less likely than 3.5×10^{-5} /yr can be excluded from a credible SLAR. The report does note the conservative nature of the hose releases as being on the order of 2 decades too likely. The report also attempts a Bayesian analysis. Like the

Sandia work, the priors are noted as being uninformed. This report notes the HCRD database as the most complete and publicly accessible set of data.

In June of 2017 the most recent edition of the UK Health and Safety Executive (HSE) guidance is published [11]. HSE Failure Rate and Event Data for use within Risk Assessments chapter 6K covers event data, human factors, and failure rates. Mechanical failure rates for components are represented in Section 1.2 and pipework is in section FR1.3. This publication does not rely on a single database, but rather summarizes expert opinion on a range of data sources that are noted in the publication. An earlier version of this publication is also used in the FERC guidance from 2012 and GTI report published earlier in 2017. The format for the reported failure rates varies from component type to component type and is in tabled formats. This can make combinations of component types in a system more difficult to interpret. The failure rates shown are among the lowest in publication and are clearly intended for land-based installations.

In 2018, the 2019 edition of NFPA 59A is published. This revision includes a failure frequency table that is principally based on the PHMSA/FERC table affirmed by the GTI report. Additionally, the 2019 edition includes a new chapter (Chapter 17) that addresses the siting for small-scale LNG systems. The risk-informed basis for the development of the setbacks in the small-scale chapter were developed by a committee assigned task group led by PHMSA. The failure frequency assumptions used in that work are as outlined in this report. NFPA 59A does not represent the failure frequencies used in the small-scale work explicitly, only the summary conclusions of the analysis [8].

In 2019, the IOGP updated the process release frequency publication from 2010 [12]. In this updated report, formulas are reported in addition to the tables. LNG applications noted as small scale and cryogenic suggested to be 40%-65% of presented values, but no further recommendations are provided. Two HCRD data sets are represented. Data from the last 10 years show reductions in failure rates over the comprehensive data sets that include data from 1992. More recent data does not have reported population data needed for objective annualized failure rates. The recommended size range continues to only go down to 2 inches, relegating smaller sizes to “instrument connections.”

In 2020 Marx and Ishii published “A new look at release event frequencies” [13]. In this report, the HCRD database is again leveraged. Missing population data from 2016 and beyond was filled in by extrapolation. A typical filtering approach was used that only looked at hole sizes greater than 1 mm diameter and to exclude pressures less than 0.1 barg. As was done in support of the 2019 small scale chapter, hole distributions were examined and then applied to the annualized failure rate by each reported equipment type. Formulas are provided to estimate the accumulated failure frequencies. The equipment categories in the HCRD only support size distinctions in piping and then only to a lower bundle of 3 in to 11 in. Equipment smaller than 3 in was summarized as an equipment type “instrumentation.”

4 Framing a useful conclusion for failure frequencies

Examining the key attributes identified for success against the referenced history on the subject, we can set a path for development of a useful failure frequency approach for small scale industrial gas risk-informed work.

4.1 Source

The data source was publicly available and accordingly reproducible.

The use of the HCRD is widely recognized and in the public domain [1]. Its use will allow for reproducibility and transparency. Only the data that has reported populations will be used. Based on the OGP analysis this should result in conservative numbers and retain objectivity. Fiscal years are used since they are full 12 months in all cases (starting April 1). This includes years 1992-1993 through 2014-2015. 2016 data is preliminary and not included in this effort.

4.2 Data filtering

The data sorting and filtering was for small scale industrial gas piping equipment types.

The database offered a broad range of sorting fields. Most of these fields are useful for the intended purpose of tracking release amounts and operation responses. For our purpose, we needed to look at the data that showed equipment failure as the cause. The following sorting filters were used to narrow the release results.

For the purposes of small scale, hole sizes of less than 1 mm were relevant. Accordingly, hole size limitation were limited to holes smaller than 0.1 mm. This increased the hole size count. Smaller holes were not expected to be ignitable.

Operational cause was set to “no” to count only equipment failures and not human or maintenance failures.

Defining the loss of containment (LOC) consequence is fundamental to risk assessment to any size system. Such LOC's are commonly sorted by means of a fishbone diagram. As illustrated in Figure 1, such an approach is used to define two major categories of LOC root causes, non-operational and operational.

Non-operational causes are rooted in behaviors established prior to putting the system in to operation. They are typically mitigated by adherence to established codes and standards. The adherence to these established norms is assumed in this study. Operational causes are the balance of potential causes that are difficult or impossible to predict. Mitigations here are based on reducing the likelihood of the initiating event like controlling the potential for corrosion or impact.

Only releases at pressures greater than 1 barg were included. This was done to exclude maintenance failures. Additionally, lower pressure releases were anticipated to be caused by environmental influences like impact from maintenance equipment since pressure stresses are low. For this database, the offshore environment and working conditions were understood to be more extreme than the environment expected for light industrial and near retail exposures.

4.3 Small sizes

Small scale sizes and equipment types were well modeled and appropriate for determining setbacks needed for light industrial and near retail application.

The influence of equipment size in annualized failure rates can be examined. Finding a generalized trend across the reported equipment sizes can help with a generalized curve. This will allow for more resolution for failure rates for equipment smaller than 2 in.

4.4 Normalized and formula driven

Equipment types and sizes were normalized which in turn simplified the risk analysis necessary for a risk-informed approach.

A single formula approach can enable useful Risk-Informed studies. Compromises in perceived accuracy of results needs to be balanced against known wide variation and uncertainty in the data and reporting structures. A common hole size distribution, in combination with a generalized annual failure rate by equipment size, acted as the basis for frequency estimates. Equipment types can then be compared against their independent annualized failure rates and reasonable equivalents lengths determined.

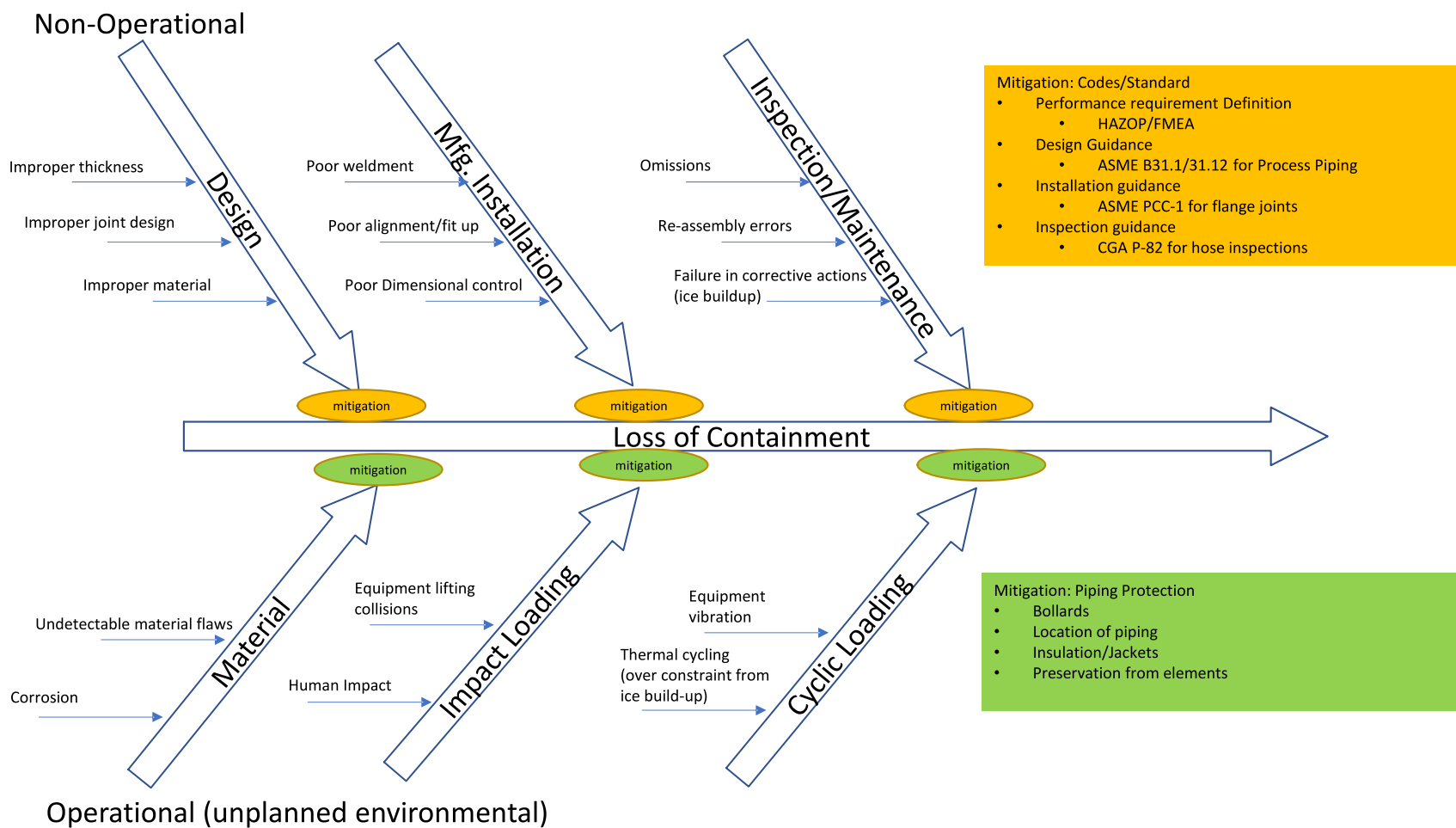


Figure 1—Loss of containment fishbone diagram

5 Formulation of the failure frequency guidance for small scale

The highlighted set shown in Table 2 were used as the small scale equipment. For statistical significance reasons, single and double seal pumps, actuated valves, and manual valves were combined. Additionally, summary categories of all “flanges”, “shaft seals,” and “valves” are represented.

Table 2—HCRD equipment types

Equipment	Equipment	Equipment	Equipment
VALVEACTUATE_ESDV_D3	PUMPS_CENTRIFUGAL_DOUBLESEAL	BOPSTACKS_SUBSEA	PIPELINES_FLEXIBLE_12D16
VALVEACTUATE_PLESDV_12D16	PUMPS_CENTRIFUGAL_SINGLESEAL	BOPSTACKS_SURFACE	PIPELINES_FLEXIBLE_4D8
VALVEACTUATE_PLESDV_4D8	PUMPS_RECIPROCATIN_DOUBLESEAL	COMPRESSORS_CENTRIFUGAL	PIPELINES_FLEXIBLE_8D12
VALVEACTUATE_PLESDV_8D12	PUMPS_RECIPROCATIN_SINGLESEAL	COMPRESSORS_RECIPROCATIN	PIPELINES_FLEXIBLE_D16
VALVEACTUATE_PLESDV_D16	RISERS_FLEXIBLE_12D16	CRUDEOILSTOR	PIPELINES_FLEXIBLE_D4
VALVEACTUATE_PLESDV_D4	RISERS_FLEXIBLE_4D8	DEGASSERS	PIPELINES_STEEL_12D16
VALVEACTUATE_PLSSIVASSEMB_12D16	RISERS_FLEXIBLE_8D12	DIVERTERS	PIPELINES_STEEL_4D8
VALVEACTUATE_PLSSIVASSEMB_4D8	RISERS_FLEXIBLE_D16	DRAIN_OPENING	PIPELINES_STEEL_8D12
VALVEACTUATE_PLSSIVASSEMB_8D12	RISERS_FLEXIBLE_D4	DRAIN_PLUG	PIPELINES_STEEL_D16
VALVEACTUATE_PLSSIVASSEMB_D16	RISERS_STEEL_12D16	EXPANDERS	PIPELINES_STEEL_D4
VALVEACTUATE_PLSSIVASSEMB_D4	RISERS_STEEL_4D8	FILTERS	PIPING_FLEXIBLE_3D11
VALVEACTUATE_RELIEF_3D11	RISERS_STEEL_8D12	FINFANCOOLER	PIPING_FLEXIBLE_D11
VALVEACTUATE_RELIEF_D11	RISERS_STEEL_D16	FLANGES_3D11	PIPING_FLEXIBLE_D3
VALVEACTUATE_RELIEF_D3	RISERS_STEEL_D4	FLANGES_D11	PIPING_STEEL_3D11
VALVEMANUAL_BLEED	TURBINES_DUALFUEL	FLANGES_D3	PIPING_STEEL_D11
VALVEMANUAL_BLOCK_3D11	TURBINES_GAS	HEATEXCHANGE_HCINSHLL	PIPING_STEEL_D3
VALVEMANUAL_BLOCK_D11	VALVEACTUATE_BLOCK_3D11	HEATEXCHANGE_HCINTUBE	PRESSUREVESS_HORIZONTAL_ADSORBER
VALVEMANUAL_BLOCK_D3	VALVEACTUATE_BLOCK_D11	HEATEXCHANGE_PLATE	PRESSUREVESS_HORIZONTAL_KODRUM
VALVEMANUAL_CHECK_3D11	VALVEACTUATE_BLOCK_D3	INSTRUMENTS	PRESSUREVESS_HORIZONTAL_OTHER
VALVEMANUAL_CHECK_D11	VALVEACTUATE_BLOWDOWN_3D11	MUDSHALE_PUMPS	PRESSUREVESS_HORIZONTAL_REBOILER
VALVEMANUAL_CHECK_D3	VALVEACTUATE_BLOWDOWN_D11	MUDSHALE_SHAKERS	PRESSUREVESS_HORIZONTAL_SCRUBBER
VALVEMANUAL_CHOKE_3D11	VALVEACTUATE_BLOWDOWN_D3	MUDSHALE_TANKS	PRESSUREVESS_HORIZONTAL_SEPARATOR
VALVEMANUAL_CHOKE_D11	VALVEACTUATE_CHOKE_3D11	PIGLAUNCHERS_12D16	PRESSUREVESS_HORIZONTAL_STABILISER
VALVEMANUAL_CHOKE_D3	VALVEACTUATE_CHOKE_D11	PIGLAUNCHERS_8D12	PRESSUREVESS_VERTICAL_ADSORBER
WELLHEADS_5000psiP1000	VALVEACTUATE_CHOKE_D3	PIGLAUNCHERS_D16	PRESSUREVESS_VERTICAL_KODRUM
WELLHEADS_P10000psi	VALVEACTUATE_CONTROL_3D11	PIGLAUNCHERS_D8	PRESSUREVESS_VERTICAL_OTHER
WELLHEADS_P5000psiP345b	VALVEACTUATE_CONTROL_D11	PIGRECEIVERS_12D16	PRESSUREVESS_VERTICAL_REBOILER
XMASTREES_5000psiP1000	VALVEACTUATE_CONTROL_D3	PIGRECEIVERS_8D12	PRESSUREVESS_VERTICAL_SCRUBBER
XMASTREES_P5000psiP345b	VALVEACTUATE_ESDV_3D11	PIGRECEIVERS_D16	PRESSUREVESS_VERTICAL_SEPARATOR
	VALVEACTUATE_ESDV_D11	PIGRECEIVERS_D8	PRESSUREVESS_VERTICAL_STABILISER

The first group shown in Table 3 was used to evaluate the basic failure frequency for steel pipe and tube. The equipment type “instruments” was included. The unit measure on instruments is taken as a per meter assumption for this stage and is later affirmed to be reasonable based on the study of equipment that represent mechanical static joints.

Table 3—Selected pipe and tubing types

INSTRUMENTS	$d < 20 \text{ mm}$
PIPING_STEEL_D3	$20 \text{ mm} < d < 78 \text{ mm}$
PIPING_STEEL_3D11	$78 \text{ mm} < d < 200 \text{ mm}$
PIPING_STEEL_D11	$200 \text{ mm} < d < 600 \text{ mm}$

The next set shown in Table 4 are equipment groups that are static mechanical seals or predominantly mechanical seals (consideration for automatic valves).

Table 4—Selected mechanical joint types

FLANGES_D3
FLANGES_3D11
FLANGES_D11
All flanges
Auto Valve
Man Valve
All valves

The last group shown in Table 5 is for high frequency shaft seals.

Table 5—Selected dynamic seal types

COMPRESSORS_CENTRIFUGAL
COMPRESSORS_RECIPROCATIN
PUMP_CENTRIFUGAL
PUMP_RECIPROCATIN
All shaft seals

For each of these groups the data as filtered is combined and rank ordered by size. This data is shown in Appendix A.

For each set the hole size and failure count is summarized and the cumulative frequency is tabulated to generate a hole size distribution that will then be multiplied by the annualized failure rate for all holes. This is then curve fit to a normal distribution of Equation 5.1.

$$f(x, a, b) := \frac{1}{1 + \left(\frac{x}{a}\right)^{-b}} \quad (5.1)$$

The basic failure frequency is estimated using the first sets of failure data. A standard distribution is shown in Equations 5.2 and 5.3 as good approximations for the individual data sets.

$$Hdist(d, eq) := \frac{1}{1 + \left(\frac{d}{a_{eq}}\right)^{-b_{eq}}} \quad Hdist_std(d) := \frac{1}{1 + \left(\frac{d}{1.5}\right)^{-1.5}} \quad (5.2 \text{ and } 5.3)$$

Where:

- d is the hole size in mm.
- eq is an index value used to identify the equipment type data set

Hole size distributions are compiled in Appendix B.

By inspection you can see that the hole size distribution is well approximated by the standard equation across the full range of nominal pipe and tubing sizes as compared to the equipment specific values for the parameters a_{eq} and b_{eq} . As shown in Figure 2, eq=1 is the index for pipe less than 3 in diameter. In these plots, the x axis is the reported equivalent hole size in mm and the y axis is the cumulative distribution. The “eq” variable seen by the plots in a simple index used in the manipulations of the curve fits.

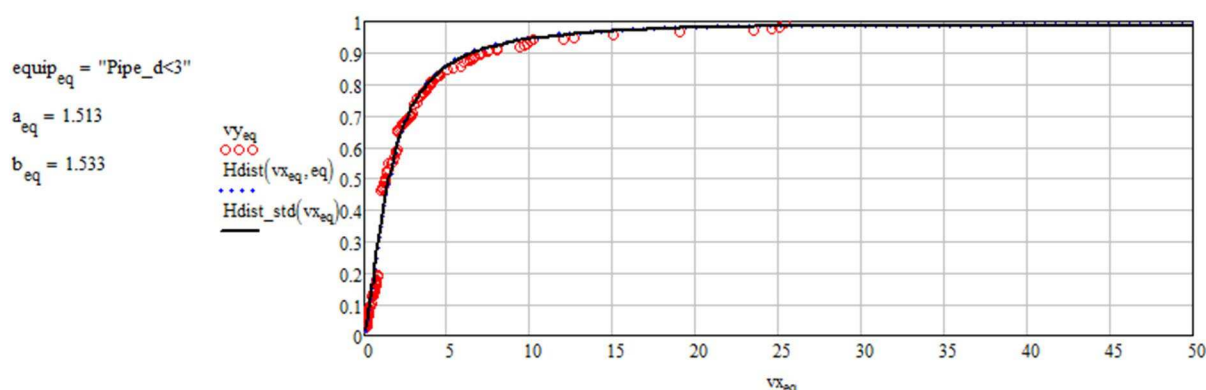


Figure 2—Hole size distribution for pipe less than 3 in (equipment type 1)

To get the full annual frequency for a given nominal pipe size, the annual failure rate must be included. The total population data is bundled into the mentioned size categories as shown in Table 6 for annual failure rate (AFR) for equipment types 0 through 3. To estimate the frequency for a discrete nominal pipe size the annualized data needs a general equation that when integrated for averages will generate the statistical data shown in the tables. This is accomplished by developing an annualized failure rate equation that when integrated to find the equivalent average it matches the reported data. The HCRD database only reports equipment size in the binned ranges. This forces some decisions on diameter assumptions within the equipment types that would best represent the data. Diameter limits are chosen as reasonable for the reported equipment type and 20 mm is chosen for instrumentation. Most guidelines note piping to 1 in and some 1/2 in pipe. Smaller systems would then be diameters up to 1/2 in pipe or nominally 20 mm. By examining the pipe and tubing data sets (see Appendix A) for equipment types 0-3 we find the annualized leak rates per equipment type.

Table 6—Data used in affirming annual failure rate equation

$equip_0 = \text{"Instrument Conn."}$	$Population_0 := 1507450 \text{ m}\cdot\text{yr}$	$Failures_0 := 313$	$D1 := 1$	
$equip_1 = \text{"Pipe_d<3"}$	$Population_1 := 3327753 \text{ m}\cdot\text{yr}$	$Failures_1 := 269$	$D2 := 20$	$AFR_0 = 2.076 \times 10^{-4}$
$equip_2 = \text{"Pipe_3<d<11"}$	$Population_2 := 5629717 \text{ m}\cdot\text{yr}$	$Failures_2 := 164$	$D3 := 78$	$AFR_1 = 8.084 \times 10^{-5}$
$equip_3 = \text{"Pipe_d>11"}$	$Population_3 := 1772071 \text{ m}\cdot\text{yr}$	$Failures_3 := 45$	$D4 := 200$	$AFR_2 = 2.949 \times 10^{-5}$
			$D5 := 600$	$AFR_3 = 2.539 \times 10^{-5}$

AFR = Annual failure rate

D1 - A necessary lower bound to execute the evaluation of the equation by integration.

Equation 5.4 was developed and adjusted such that the integrated values between the ranges for equipment types 0 through 3 match the statistical data. The utility of the equation is then demonstrated for equipment type based on the integration between the estimated representative diameters and then compared to the calculated annual failure rate by type.

$$AFR_HCRD_pipe(D) := \left(2.539 + 25.2 \cdot e^{\frac{-D}{29.412}} \right) \cdot 10^{-5} \quad (5.4)$$

The equation driven integrated average is then compared to the data set driven annual failure rate, as shown in Equation 5.5.

$$AFR_{avg}(D1,D2) := \frac{\int_{D1}^{D2} AFR_{HCRD_pipe}(D) dD}{D2 - D1} \quad (5.5)$$

The balance suggests a reasonable distribution of equipment size impact to annual failure rate. In Equation 5.5, the diameter is presented in mm and the failure rate is in (m-yr)⁻¹ as plotted in Figure 4.0.2. Notably the “D”s in this integration are equipment sizes and not hole sizes. For proper comparison to the equipment type “bins” the ranges are the limits of the “bin” sizes.

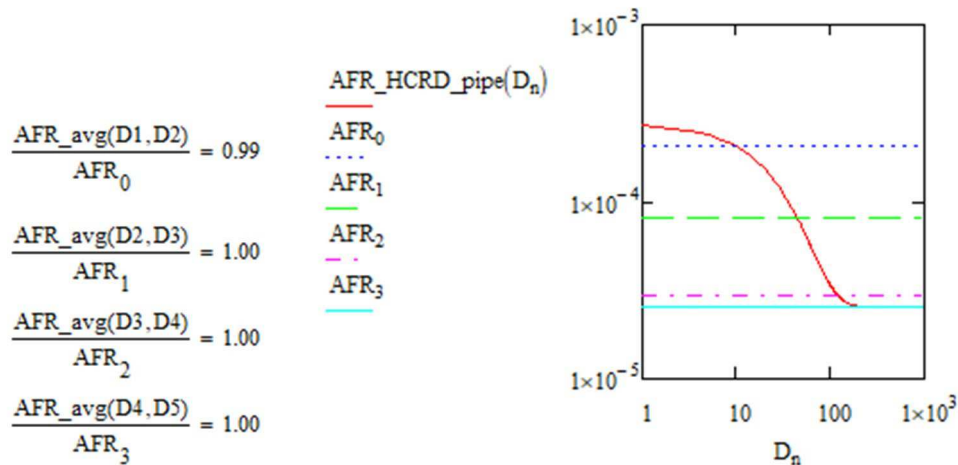


Figure 3—Piping annual failure rate plot

The general equation for annual failure rate in (m-yr)⁻¹ for a hole size between d1 and d2 given a nominal diameter of D is presented below in Equation 5.6. All diameters are in mm.

$$FF(d1, d2, D) = \left[\frac{1}{1 + \left(\frac{d2}{1.5} \right)^{-1.5}} - \frac{1}{1 + \left(\frac{d1}{1.5} \right)^{-1.5}} \right] \cdot \left[\left(2.539 + 25.2 \cdot e^{\frac{-D}{29.412}} \right) \cdot 10^{-5} \right] \cdot \frac{1}{m \cdot yr} \quad (5.6)$$

For example, Figure 4 shows the numeric substitution given a pipe size with inside diameter of 50 mm, the AFR for hole sizes between 3 mm and 10 mm would be predicted to be as shown in Figure 4.

$$\left[\frac{1}{1 + \left(\frac{10}{1.5} \right)^{-1.5}} - \frac{1}{1 + \left(\frac{3}{1.5} \right)^{-1.5}} \right] \cdot \left[\left(2.539 + 25.2 \cdot e^{\frac{-50}{29.412}} \right) \cdot 10^{-5} \right] = 1.474 \times 10^{-5} \quad \frac{1}{m \cdot yr}$$

Figure 4—Numeric substitution for Equation 5.6 for hole sizes between 3 mm and 10 mm on a 50-mm pipe

The annual failure rate for holes greater than 3 mm can also be directly calculated as well by setting the larger hole limit to the full diameter as shown in Figure 5.

$$\left[\frac{1}{1 + \left(\frac{50}{1.5} \right)^{-1.5}} - \frac{1}{1 + \left(\frac{3}{1.5} \right)^{-1.5}} \right] \cdot \left[\left(2.539 + 25.2 \cdot e^{\frac{-50}{29.412}} \right) \cdot 10^{-5} \right] = 1.829 \times 10^{-5} \quad \frac{1}{\text{m} \cdot \text{yr}}$$

Figure 5—Numeric substitution for Equation 5.6 for hole sizes between 3 mm and 50 mm on a 50-mm pipe

5.1 General considerations for failure rates

The HCRD database is for offshore installations. Many of the noted publications make note of the unique environment that data represents and offer considerations for further failure rate reduction for systems that can be demonstrated to be less harsh. The 2010 references of DNV and OGP both acknowledge land base cryogenic systems as having potentially lower failure frequencies [5, 6]. The DNV conclusion is to not take modifications to failure rates until such time that a statistical basis is established, while the OGP does offer a specific 40%-65% range with a 50% reduction given a “fully justified” consideration. By 2012 the opinion of FERC for land based cryogenic LNG for piping failure rates justifies a substantive reduction in prescribed rates while acknowledging the wide range of published values, including both HCRD offshore based values and HSE land-based values [7]. The FERC table does leave some components like flanges, and hoses at very high values. The GTI report chapter 7 points to potential reductions for the FERC table, namely [10]:

- piping protection;
- piping stability;
- use of stainless steel;
- lack of salt spray and generally corrosive environments;
- inert nature of fluids; and
- increased use of weldments.

The 2019 edition of the OGP, IOGP reaffirms the 50% failure rate reduction language from 2010 and adds a reasoning basis from API 581, by summarizing damage mechanisms reminiscent of the comments from the GTI report, which include the following [12, 14]:

- thinning
- stress corrosion cracking
- external damage
- high temperature hydrogen attack
- mechanical fatigue
- brittle fracture

This 50% reduction on the recommended early data sort is less than applying a 40% reduction on the comprehensive data sort of all data. Steel piping AFR for 2 in steel process pipe for the recommended recent data (2006-2015) is tabulated at $2.5 \times 10^{-5} \text{ (m-yr)}^{-1}$. The suggested value of 50% of 2.5×10^{-5} would be 1.25×10^{-5} . Steel piping AFR for 2 in steel process pipe for all data (1992-2015) is tabulated at $6.0 \times 10^{-5} \text{ (m-yr)}^{-1}$. The proposed AFR for this Technical Report is 40% of only the data that has population data within the HCRD which is conservatively represented by the IOGP all data AFR. Accordingly, 40% of 6.0×10^{-5} is 2.4×10^{-5} which is conservative to the 1.25×10^{-5} suggestion. This means the application of 40% on the proposed data sort is in alignment with IOGP recommendations and conservative to the 2019 edition with respect to mitigation factors.

For small scale cryogenic systems in light industrial or near retail locations, these factors can be assessed as risk mitigating. Nominal pipe schedules result in wall thicknesses that exceed the basic pressure requirements. Piping hoop stresses are generally well below 1/2 of the basic allowable stress level, which precludes risks associated with thinning. Systems fit for cryogenic service are predominantly 300 series austenitic stainless steel, which is inherently resistant to corrosion. It has high toughness, which is useful in fatigue mitigation and limits crack propagations. The light industrial area also reduces the potential for heavy loaded collisions that might otherwise be present in the servicing of adjacent larger equipment. For these reasons a cryogenic risk reduction factor of 40% can reasonably be factored into failure frequency methodology.

$$FF_{\text{cryo}}(d1, d2, D) = \left[\frac{1}{1 + \left(\frac{d2}{1.5} \right)^{-1.5}} - \frac{1}{1 + \left(\frac{d1}{1.5} \right)^{-1.5}} \right] \cdot \left[\left(2.539 + 25.2 \cdot e^{\frac{-D}{29.412}} \right) \cdot 10^{-5} \right] \cdot 40\% \cdot \frac{1}{\text{m} \cdot \text{yr}}$$

Further reduction of failure frequencies may be considered when the piping is substantially protected against an LOC from potential impact and cyclic loads and justified by analysis.

5.2 Setting up a set of equivalent lengths for piping components.

To keep the overall failure frequency of piping systems easy to assess and without extensive interpretation, it is useful to identify other piping components in terms of equivalent length of pipe. The standard equation above is in units per meter-year. First, we can examine the overall hole size distribution as shown in Appendix B.

The standardized hole distribution (shown as H_dist_std in Appendix B plots), which uses the log-logistic coefficients of 1.5 and -1.5 is conservative (predicting nominally large holes) than the equipment specific curve fits. This is evident when surveying the distribution plots in Appendix B, noting the black standard distribution line is lower than the dotted blue line, which is the equipment specific fit. This offers the convenience of maintaining one general curve. The limits of predicted hole sizes in pumps and compressors is clearly a result of the high frequency of shaft seal leaks. The data from these will be characterized as dynamic seals that are intended to be relative to the shaft size and not the nominal equipment size. Flanges and manual valves can be characterized as mechanical static joints.

By comparing the annual failure rate of nominal piping to the annual failure rate of other flanges and manual valves, the equivalent length for failure analysis can be predicted. The nominal annual failure rate, AFR_nom, is the ratio of all tabulated failures for the three pipe size ranges, divided by the aggregate reported population for the three pipe size ranges as shown in Figure 6. Instrument equipment is not included in this nominal rate.

$$AFR_{\text{nom}} := \frac{269 + 166 + 45}{3327753 + 5629717 + 1772071} = 4.474 \times 10^{-5}$$

Figure 6—Nominal annual failure rate

Mechanical joints can be represented by the data sets for flanges and manual valves. Comparing the annual failure rates for these equipment types to the nominal annual rate we can derive an equivalent length. Flanges have a nominal equivalent length of 1 m. The assessment against all valves suggest a valve may be better approximated with an equivalent length of 2 m. As a balance against the uncertainty of valve operation frequency and to account for both body seals and packing seals, the 2-m equivalent is a conservative and easy rule for any basic valve, manual or automatic.

Dynamic seals as represented by the difference of automatic valves to manual valves and by shaft seals vary based on the aggregate cycles of use. A small number of cycles as in an automatic valve would approach 7, while the high-end frequency for a rotating shaft of a pump would reach 350.

Determination of equivalent lengths is shown in Figure 7.

	0	
	"Instrument Conn."	
	"Pipe_d<3"	$Leq_{flange} := \frac{AFR_7}{AFR_{nom}} = 1.07$
	"Pipe_3<d<11"	
	"Pipe_d>11"	
	"Flange_d<3"	$Leq_{Mvalve} := \frac{AFR_{14}}{AFR_{nom}} = 0.852$
	"Flange_3<d<11"	
	"Flange_d<11"	
equip =	"Flange_all"	$Leq_{Avalve} := \frac{AFR_{13}}{AFR_{nom}} = 7.982$
	"Compressor_Cent."	
	"Compressor_Recip"	
	"Pump_Cent"	$Leq_{dynseal} := \frac{AFR_{12}}{AFR_{nom}} = 350.864$
	"Pump_Recip"	
	"Shaft_Seals"	
	"Valve_auto"	
	"Valve_man"	$Leq_{valve} := \frac{AFR_{15}}{AFR_{nom}} = 2.006$
	"Valves_all"	

Figure 7—Equivalent length determinations

A simple equation to predict the equivalent length for dynamic seal is shown in Equation 5.2.1.

$$Leq_{dyn}(\text{cycles}) := 350 - 349 \cdot e^{-\frac{\text{cycles}}{10^7}} \quad (5.2.1)$$

Testing this equation against the practical limits of a modulating automatic valve (once every 3 minutes) and a rotating seal (10 rpm) suggests satisfactory compliance to the computed equivalent lengths. The substitutions shown in Figure 8 confirm a reasonable result.

$$Leq_{dyn}\left(\frac{1}{3 \cdot \text{min}} \cdot \frac{7 \text{ day}}{\text{week}} \cdot \text{yr}\right) = 7.065$$

$$Leq_{dyn}\left(10 \cdot \text{rpm} \cdot \frac{24 \text{ hr}}{\text{day}} \cdot \frac{7 \text{ day}}{\text{week}} \cdot \text{yr}\right) = 337.187$$

Figure 8—Example of equivalent length for a dynamic seal

A special consideration must be made for steel corrugated hose commonly used in cryogenic applications. These hoses are used daily for offloading trailers, filling trailers and transfilling to other equipment (like vehicle fuel tanks). In some cases, hoses are used to affect easy field connections. To make reasonable accommodations, some recognized mitigations should be generally addressed:

- Risk from damage by impact is reduced by the enhanced integrity of the piping and or reduced by applying additional protection to the piping. Affective collision protection should get a failure reduction of 0.10 as recommended by the GTI report page 115 [10]. It would be reasonable to apply such a factor if piping is also located in a way that it is out of any potential impact zone because of its location, say elevated above other activities, or affixed to something that will inherently reduce potential impacts or human interference, such as being attached directly to a storage tank or wall;
- Hoses are inherently riskier than piping since they are thinner and more vulnerable to both impact and corrosion. So, an equivalent length of 20 is applied. Should a hose be protected from impact, the reduction of 0.10 can be applied, reducing the equivalent length to 2, thereby retaining a residual risk adjustment;

- The excessive flexing of a hose may also be present, such events imply a required cycle count to determine a useful equivalent length modifier; and
- Hoses used for transfers typically have a make-break connection. This connection, unlike a dynamic seal, is removed completely on each cycle, exposing the sealing surfaces to debris and ice. Additionally, the proximity of an operator to the make-break connection increases its inherent risk.

Given an equation for a make-break fitting, consistent with the intent of the dynamic seal, a study was conducted against filter housing and pig launchers as shown in Figure 9, since these components include such connections that are put together and taken apart in normal operation.

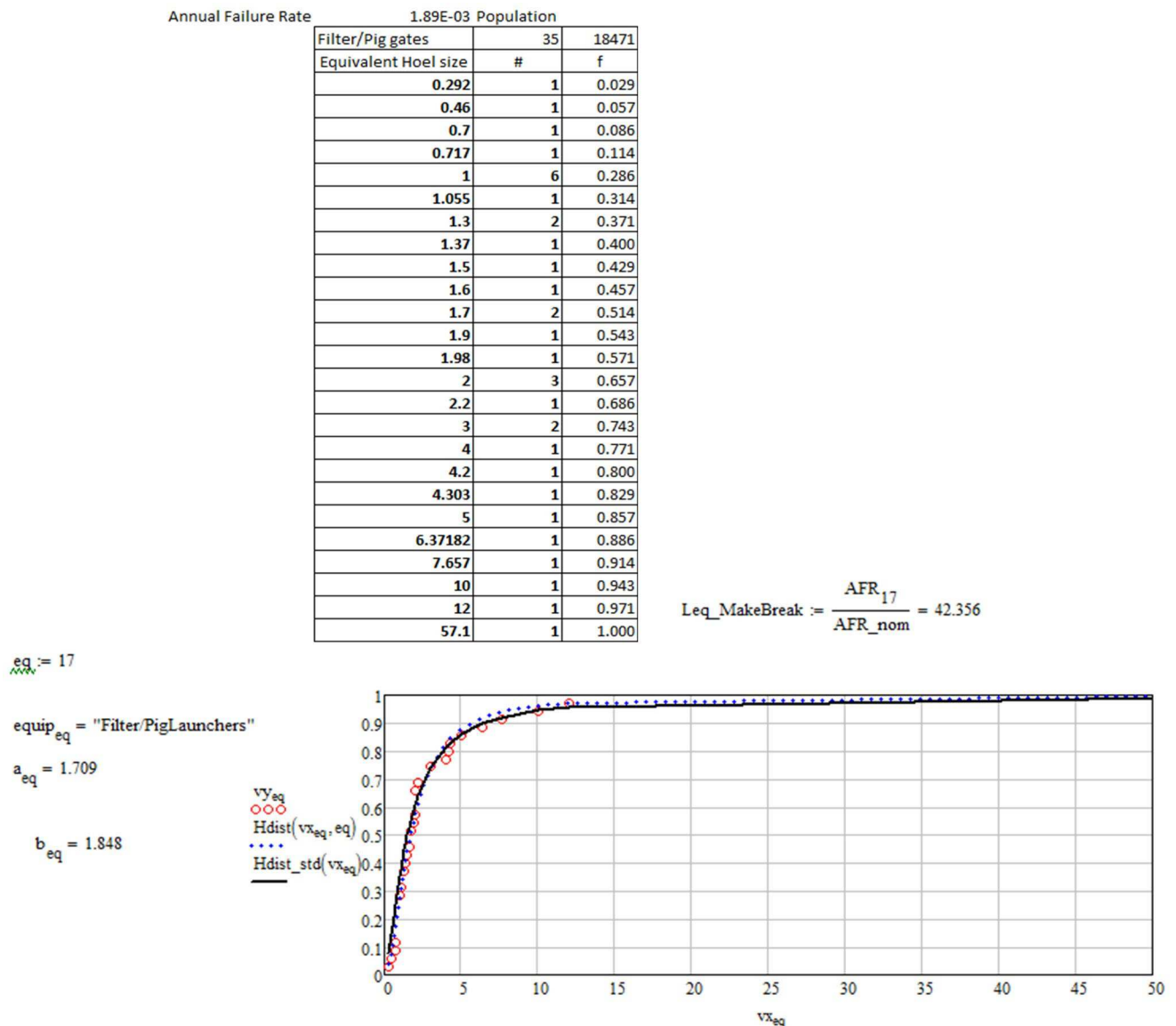


Figure 9—Development of make and break equation

Assigning an anticipated filter/pig launch cycle to once a month, the dynamic seal equation is modified as shown in Equation 5.2.2 and in the substitution shown in Figure 10.

$$Leq_{make_break}(\text{cycles}) := 350 - 349e^{-\frac{\text{cycles}}{10^2}}$$