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LPG Component Leak Frequency Estimation

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ABSTRACT

Liquefied petroleum gas (LPG) is used in heating, cooking, and as a vehicle fuel (called autogas). A safety risk assessment may be needed to assess potential hazard scenarios and inform the regulations, codes, and standards that apply to LPG facilities, such as autogas refueling facilities. The frequency of unintended releases in an LPG system is an important aspect of a system quantitative risk assessment. This report documents estimation of leakage frequencies for individual components of LPG systems. These frequencies are described using uncertainty distributions obtained with Bayesian statistical methods, generic data, and LPG data which were publicly available. There was a lack of LPG data in the literature, so frequencies for most components were developed with generic data and should be used cautiously; without additional information about component leak frequencies in LPG systems, it is not known whether these generic frequencies may be conservative or non-conservative.

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ACRONYMS AND TERMS

Acronym/Term	Definition
CNG	compressed natural gas
LNG	liquefied natural gas
LOX	liquid oxygen
LPG	liquefied petroleum gas
QRA	quantitative risk assessment

1. INTRODUCTION

Liquefied petroleum gas (LPG), or propane gas, is used in heating, cooking, and as a vehicle fuel (called autogas). The infrastructure that supports the transportation and storage of LPG may involve large quantities of the flammable gas. A safety risk assessment may be needed to assess potential hazard scenarios and inform the regulations, codes, and standards that apply to LPG facilities, such as autogas refueling facilities. The frequency of unintended releases in an LPG system is an important aspect of a system quantitative risk assessment (QRA), such as the methodology in the Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) software [1].

The frequencies for possible release scenarios, along with release/behavior models, can be utilized to quantify the risks for LPG facilities. Generally, a QRA is used to quantify the risk associated with unintended releases of LPG, identify significant risk contributors for a given facility, and inform prevention and mitigation strategies for stakeholders. However, not all leak frequencies needed for a QRA are well known and analysts may compensate for this uncertainty by using conservatively high leak frequencies and consequently conservatively high risks. Alternately, requirements for LPG may be based on requirements or risk assessments for another fuel type (such as natural gas, hydrogen, or liquid fuels), meaning the requirements may not be relevant for LPG in particular. Establishing more realistic leak frequencies using available data can improve the accuracy and applicability of these risk assessments.

This report documents estimation of leakage frequencies for individual components of LPG systems for use in a QRA. The Bayesian methodology used to estimate these frequencies has previously been applied by Sandia National Laboratories for gaseous hydrogen [2, 3], liquid hydrogen [4], liquid natural gas, [5], and compressed natural gas [6]. The method combines generic fuel system data with LPG data (where available) to produce estimated leak frequency uncertainty distributions. These distributions provide a median leak frequency which can be used as a point estimate in QRA. The full distributions also include state-of-knowledge uncertainty as well as the variation in leak frequencies that is inherent between sites due to varying ages, designs, operating conditions, maintenance, regulatory region, etc. This allows the distributions to be used for uncertainty analysis.

A detailed literature review was performed (Section 2.1), searching the open literature for LPG-specific leak frequency data. Where LPG data were not available, more generic data were used, attempting to leverage data from other applications and industries (including data for other fuels) and apply those data as appropriate for LPG. The theoretical model to which the collected data were applied is briefly summarized in Section 2.2. Results of the analysis are presented in Section 3, which give recommended leak frequency values for LPG components. Sensitivity studies are presented in Section 4, which address the lack of LPG-specific data by assessing the impact of including or excluding data from other types of fuels.

2. METHODS

This section discusses the data collection (Section 2.1) and theoretical model (Section 2.2) used to develop LPG leak frequencies.

2.1. Data Collection

A literature review was performed to identify leak frequency data applicable to components in LPG systems. Search terms included: LPG, liquid propane gas, Autogas, propane, leak frequency, leak frequencies, risk, and refueling station. References were included if they contained calculated or estimated leak frequencies for filters, flanges, hoses, instruments, joints, loading arms, pipes, pumps, valves, or vessels for propane, LPG, or Autogas. References were also included if they contained leak frequencies that were calculated or estimated using multiple fuel sources, one of which was propane, LPG, or Autogas. References would also have been included if they contained enough information to estimate leak frequencies, such as reporting the number of operating hours and list of leak events. However, no such references were found. To be used with the theoretical model (Section 2.2) references also needed to include a measure of leak size that allowed binning the leak frequencies into 0.01%, 0.1%, 1%, 10%, or 100% fractional leak area bins, and fortunately all references that provided leak frequencies applicable to LPG system components also included sufficient leak size information for binning.

Generic data which were collected and binned for previous leak frequency estimation studies [2, 3, 5, 6] were included in the data search for this analysis. This category of data includes frequencies derived from individual fuel sources or from multiple fuel sources which are published as applicable to generic systems (e.g., hydrocarbon system frequencies derived from offshore oil data, chemical processing frequencies derived from chlorine systems). Generic data were necessary to include because few LPG-applicable data points were found in the literature search; LPG-applicable leak frequencies were only found for vessels. However, data that were applicable to or derived from compressed natural gas (CNG), liquified natural gas (LNG), or liquid oxygen (LOX) were excluded from the data set. These data points were excluded based on engineering judgement that CNG, LNG, and LOX systems are substantially different from LPG systems either due to significantly higher pressure or cryogenic temperatures. Due to the lack of LPG data, however, this judgement could not be quantitatively verified. Similarly, detailed source fuel information was not available for all generic data points, so removing data which specifies CNG, LNG, or LOX as a source fuel may introduce selection bias. Section 4.2 discusses the impact of this judgement on the final LPG leak frequency estimates.

The generic data set included frequencies obtained from onshore and offshore hydrocarbon systems, which can include gaseous and liquid systems [7, 8]. The proportion of gaseous versus liquid system data used to calculate these frequencies was not specified. If the data included significantly more liquid hydrocarbon leaks, it may not be applicable to leaks in LPG systems. The hydrocarbon data was included in the leak frequency estimates and a sensitivity study was performed (Section 4.3) to assess the impact of including this data

Table 2-1 lists the number of data points in each data category from the literature; the data points are listed in Appendix A with information on the source fuels or applicability. The CNG, LNG, or LOX applicable data are not included in the generic data category even if the data were originally published for generic system assessment. The data that were used to produce the final leak frequency estimates for each component are identified with bold and underlining in the table. Only generic data were used to derive frequencies for filters, flanges, hoses, instruments, joints, loading arms, pipes, pumps, and valves. Both generic and LPG-applicable data were used for vessels. Some of the published frequencies for hoses and loading arms were provided as annual frequencies and others were provided as per-transfer frequencies. These data were kept separate; per-year and per-transfer leak frequencies were both estimated.

Most of the vessel data contained enough information to determine if the source fuel system was pressurized or atmospheric. The source fuel pressure was considered as a possible data filter for generic data, but there was insufficient LPG-applicable data to determine the validity of filtering on this criterion, so data from pressurized and atmospheric systems was used (see Section 4.1).

Table 2-1 Number of data points of each data type identified in the literature review

Component	Generic Data		CNG, LNG, or LOX Applicable Data	LPG Applicable Data
	Other	Hydrocarbon		
Filters	**7**	**9**	2	0
Flanges	**17**	**24**	2	0
Hoses	**8 (annual)** **10 (per transfer)**	**24 (annual)**	9 (annual)	0
Instruments	**1**	**7**	0	0
Joints	**2**	0	4	0
Loading Arms	**3 (annual)** **4 (per transfer)**	0	2 (annual) 1 (per transfer)	0
Pipes	**60**	**24**	44	0
Pumps	**26**	**18**	0	0
Valves	**39**	**48**	21	0
Vessels	**49**	**22**	27	**8**

Bold and underlining indicates data included in the recommended leak frequencies.

2.2. Model

Leak frequencies were estimated using a log-linear Bayesian model which describes the log leak frequency as a function of fractional leak area. Fractional leak area is defined by dividing the leak area by the cross-sectional area of the component. The theoretical model has previously been applied to hydrogen systems [2, 3], LNG systems [5], and CNG systems [6] and is depicted in Figure 2-1. The fractional leak area bins are 0.01% (very small), 0.1% (small), 1% (medium), 10% (large), and 100% (rupture). The model predicts a normal distribution of log-leak frequencies for each leak area bin and the distributions are related to each other across the bins via a line through their means. In essence, the average log-leak frequency can be described as a linear function of the leak area bin and uncertainty around that linear function varies between the bins. The linear relationship between the bins allows the model to predict leak frequencies for all of the leak area bins even if there are only data points in some of the bins.

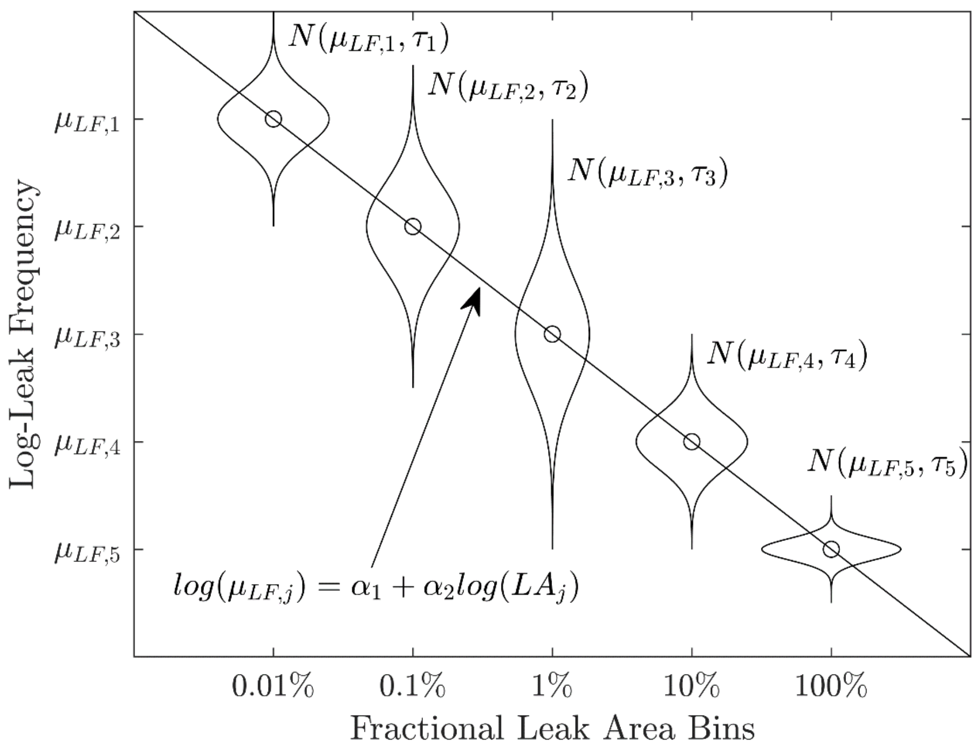

Figure 2-1 Notional depiction of the leak frequency theoretical model as described in [6, 9]

This model was first presented for leak frequency estimation in [2]. It is specified in by

$$\text{Log}(LF_j) \sim N(\mu_{LF,j}, \tau_j) \tag{1}$$

$$\tau_j \sim Gamma(s_j, r_j) \tag{2}$$

$$\text{Log}(\mu_{LF,j}) = \alpha_1 + \alpha_2 \log(LA_j) \tag{3}$$

$$\alpha_1 \sim N(\alpha_{11}, \alpha_{12}) \tag{4}$$

$$\alpha_2 \sim N(\alpha_{21}, \alpha_{22}) \tag{5}$$

where "Gamma" denotes the gamma distribution with the shape and rate parameterization, and "$N(\cdot,\ \cdot)$" denotes the normal distribution with the mean and precision parameterization [10]. This model and its Bayesian foundation are described in additional detail in [4, 6, 9]. It is implemented as a Bayesian hierarchical model [11] with the same uninformed prior distributions as used as in [3, 5, 6]:

$$\tau_j \sim Gamma(5,1) \tag{6}$$

$$\alpha_1 \sim N(0, 10^{-3}) \tag{7}$$

$$\alpha_2 \sim N(0, 10^{-3}) \tag{8}$$

Generic and (for vessels) LPG data were applied to update the prior distributions using JAGS [10] via the **rjags** package in R [12, 13]. Five chains were used, 10^6 samples were used for burn-in, 10^6 samples were used to update the model, and 10^5 samples from each of the five chains were used to sample the final leak frequency estimates and statistics. These sample sizes were previously shown to be more than sufficient to obtain converged mean and percentile estimates for this model [5].

3. RESULTS

This section presents the results from the model update described in Section 2.2. Plots are presented for each component which show the data used to fit the model and the final distributions on log leak frequency estimated during the update (Figure 3-1 through Figure 3-12). The distributions on log leak frequency are defined theoretically as normal distributions, and therefore include infinitely small and infinitely large log leak frequencies. If the distributions are sampled for uncertainty quantification without applying truncation, samples from the tails of the distributions, though uncommon, may result in the use of leak frequencies that are unrealistic. Use of the distributions to quantify uncertainty in risk assessment should include reasonable truncation to avoid unrealistic values from being sampled.

For some components and leak size bins, the lack of data may artificially lower uncertainty; uncertainty estimates from larger data sets are more reliable and uncertainty estimates from small data sets should be used cautiously. This is because the model fits the mean trend and the variation in the data for that bin. If there is only one data point in the bin, there is not much variation for the model to detect; the model can only incorporate variation that exists within the data to which it is fit. This can be seen by comparing the 0.1%, 1%, and 10% bins for filters, for example (Figure 3-1). The 0.1% bin has one data point, which is also the center for that bin. There are no other data points in the bin, which means the model is not given any other information about the variation between sites or between different filter designs. Meaningful variation may exist between sites and filter designs that is missing from the model because it is missing from the data. We can contrast this with the data in the 10% bin. There are two data points in this bin, which provides enough information about variation that widens the distribution for this bin (relative to the data points). This is an improvement in the realism of the estimated variation in leak frequencies but may still be an underestimate due to the limited data size. Finally, we can contrast this with the 1% bin, which has four data points in two clusters (one cluster around the center of the distribution and one cluster in the upper tail). The difference in magnitude between the two clusters of leak frequencies significantly extends the distribution for this bin. Because the data reflect high variability in 1% leak area frequencies for filters, the model reflects high variability in 1% leak frequencies for filters.

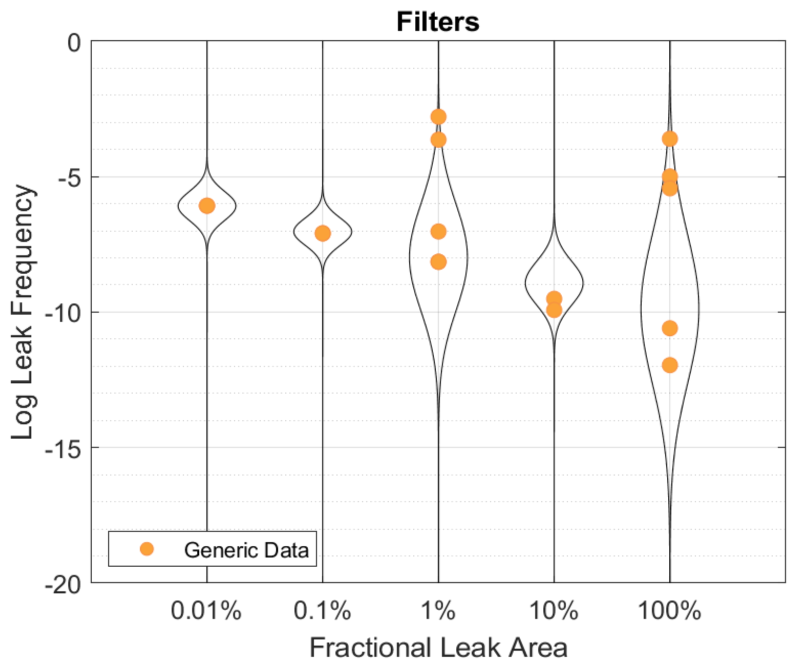

Figure 3-1 Log leak frequency distributions for filters from generic data

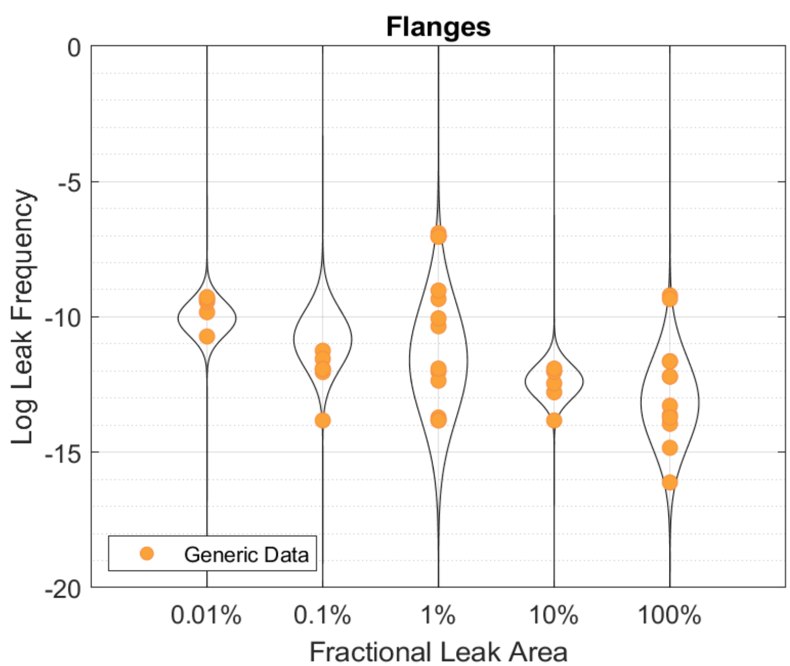

Figure 3-2 Log leak frequency distributions for flanges from generic data

Hoses are unusual relative to the other components because the annual log leak frequencies for hoses (Figure 3-3) increase as a function of fractional leak area. This is not the case for other components and has been observed in previous analyses for other fuels which used much of the same generic data [5, 6]. However, it is also not the case for hoses when the log leak frequencies are estimated per-transfer rather than annually. We do not know why this difference exists for hoses. It is possible that hoses are, in general, more prone to larger leaks because the materials predispose holes in hoses to expand rapidly, so that leaks which start as small leaks more often progress to larger leaks and ruptures by the time they are detected. This may not be seen in the per-transfer leak frequencies due to differences in the materials and design of hoses for stationary installations versus trucks; leaks at stationary installations would be more likely to be tracked per year and leaks originating from trucks would be more likely to be tracked per-transfer. However, we also note that the amount of per-transfer data for hoses is also quite small, so it is possible that the difference in behavior between the two types of leak frequencies for hoses is simply due to insufficient data.

The leak frequency estimates and statistics are shown in Table 3-1. Additional statistics and the parameters of the log-leak frequency distributions are also provided in Appendix B.

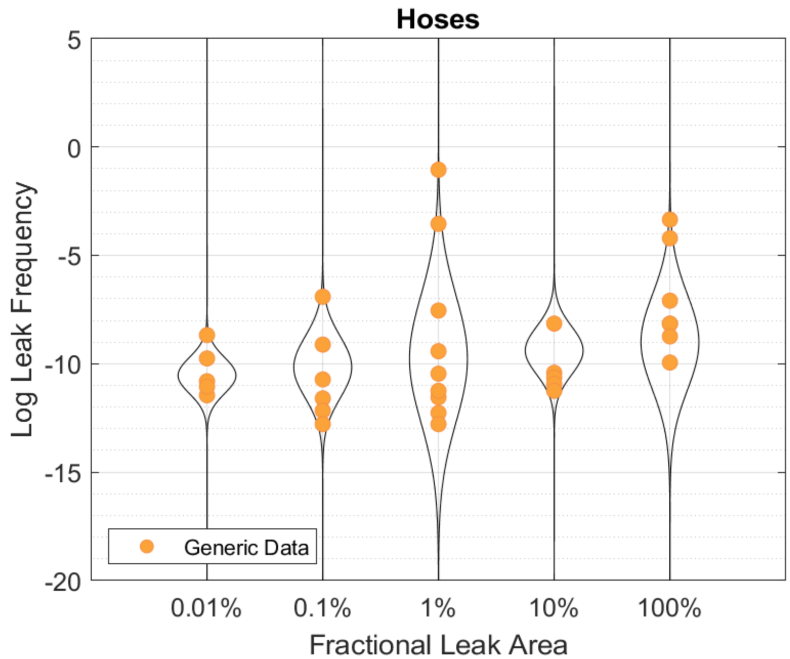

Figure 3-3 Annual log leak frequency distributions for hoses from generic data

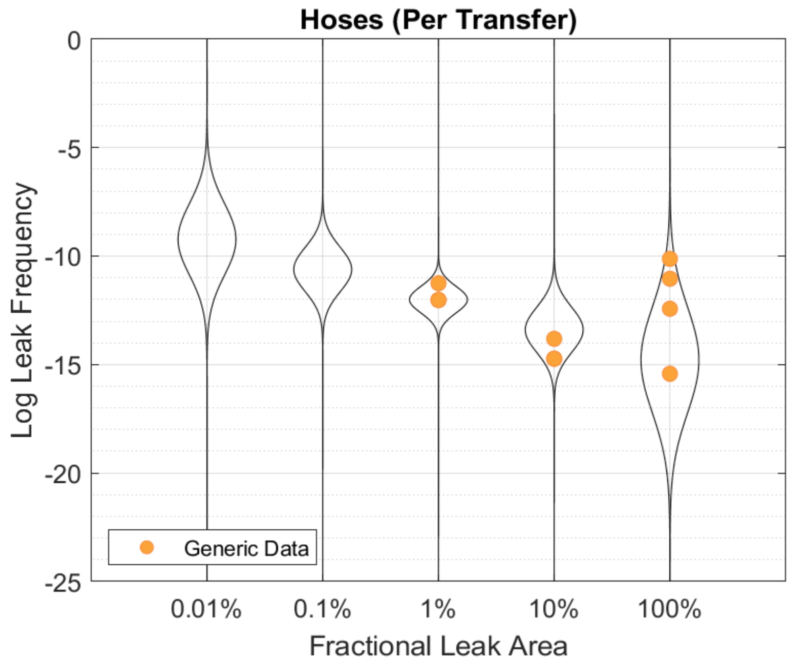

Figure 3-4 Per-transfer log leak frequency distributions for hoses from generic data

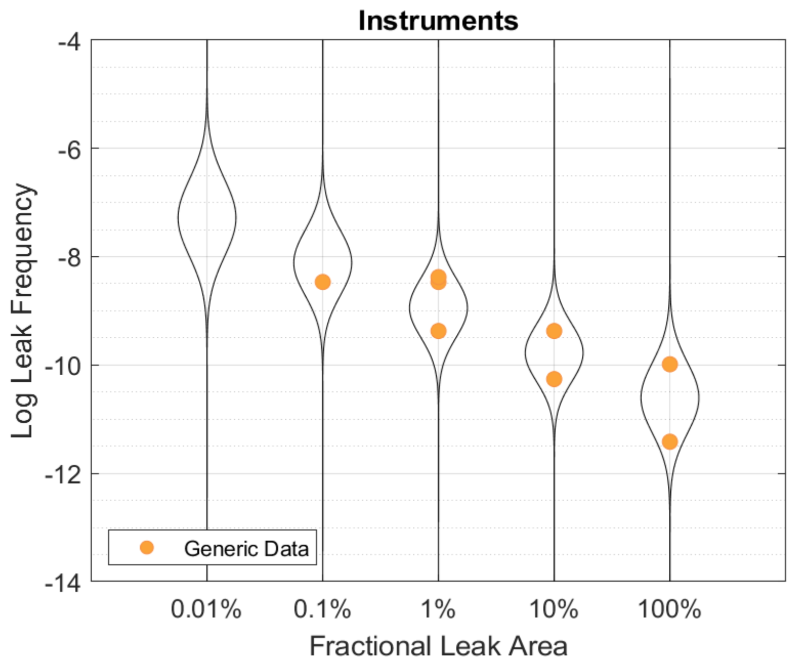

Figure 3-5 Log leak frequency distributions for instruments from generic data

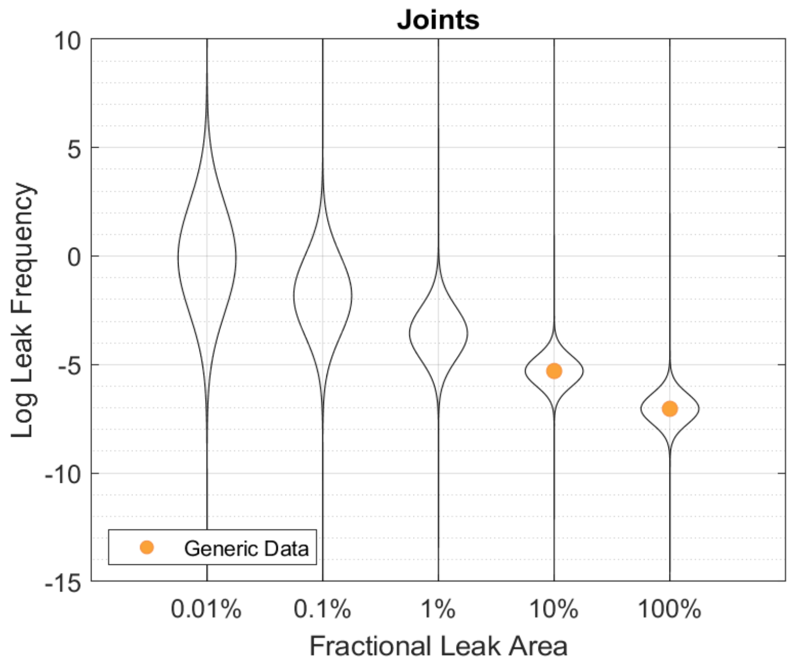

Figure 3-6 Log leak frequency distributions for joints from generic data

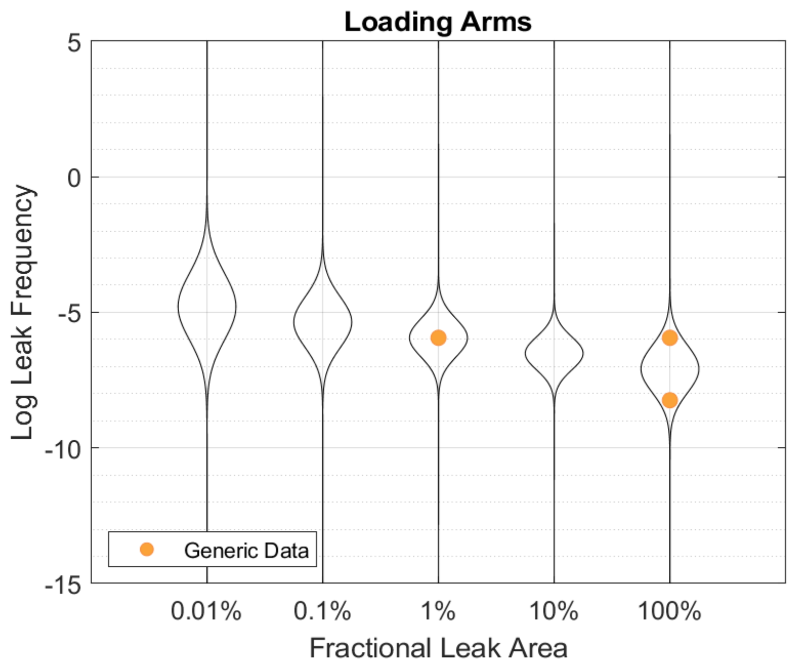

Figure 3-7 Annual log leak frequency distributions for loading arms from generic data

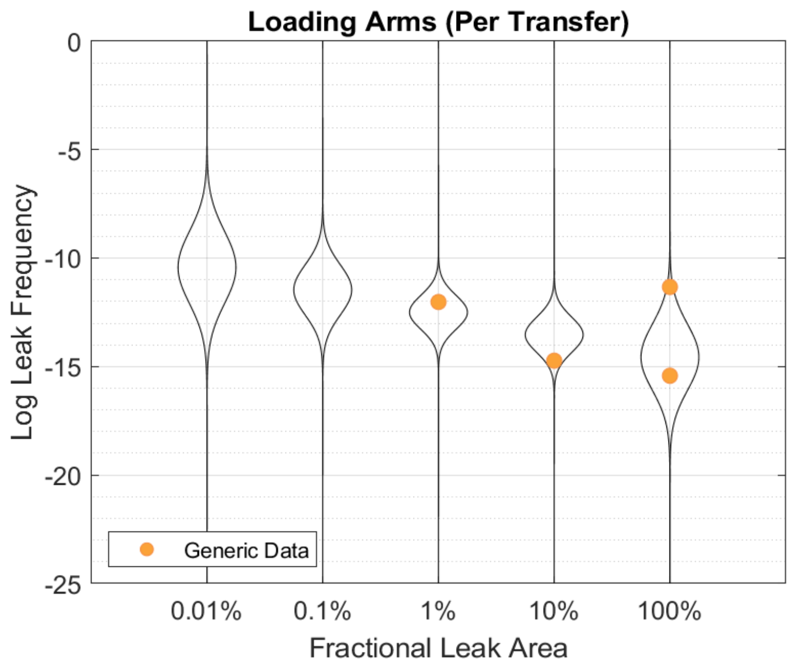

Figure 3-8 Per-transfer log leak frequency distributions for loading arms from generic data

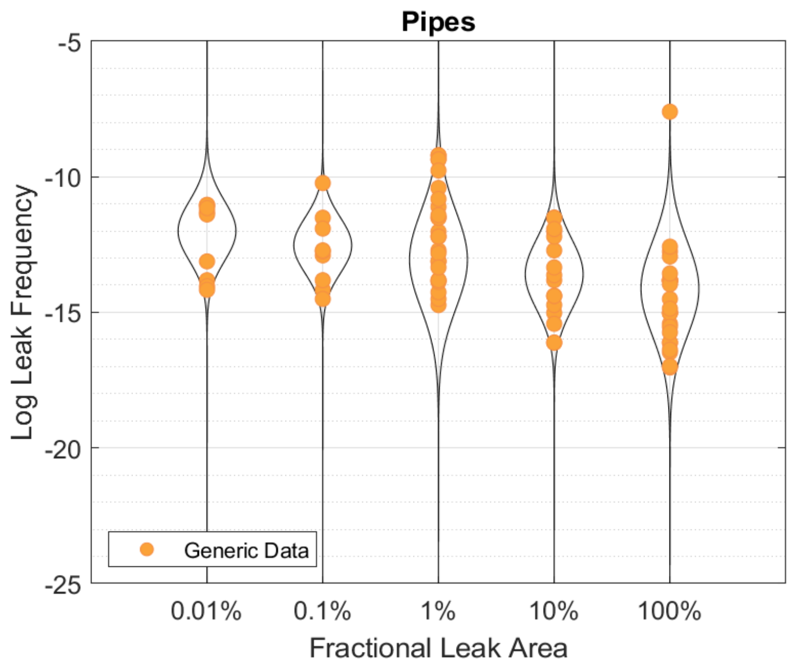

Figure 3-9 Log leak frequency distributions for pipes from generic data

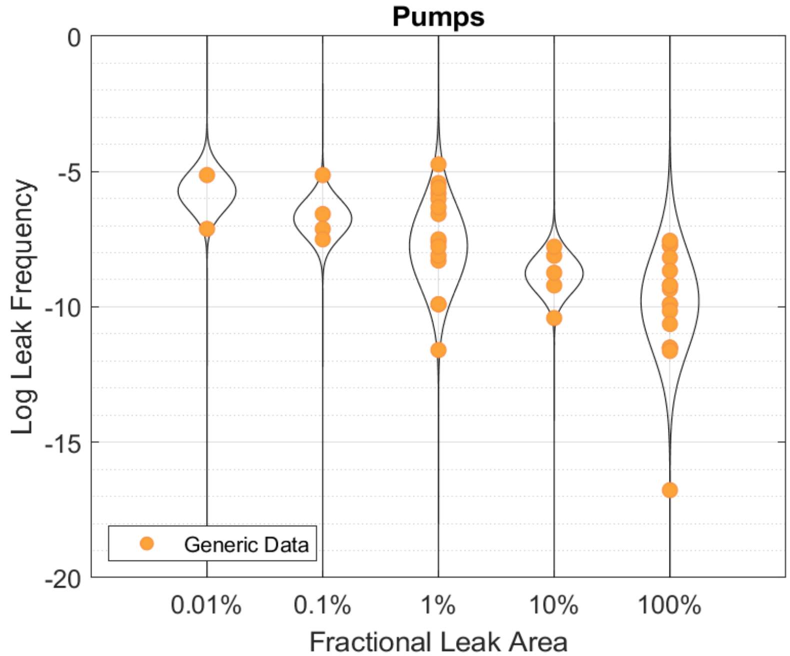

Figure 3-10 Log leak frequency distributions for pumps from generic data

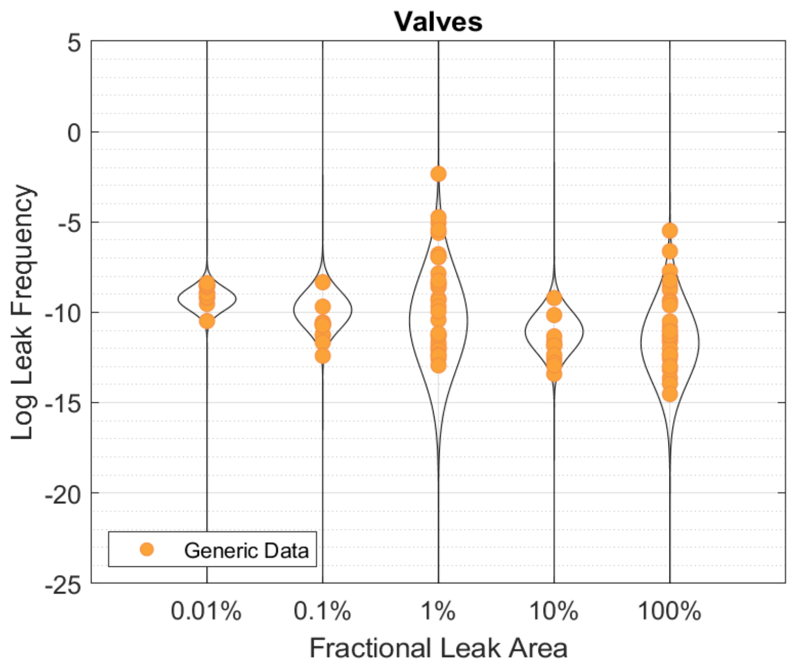

Figure 3-11 Log leak frequency distributions for valves from generic data

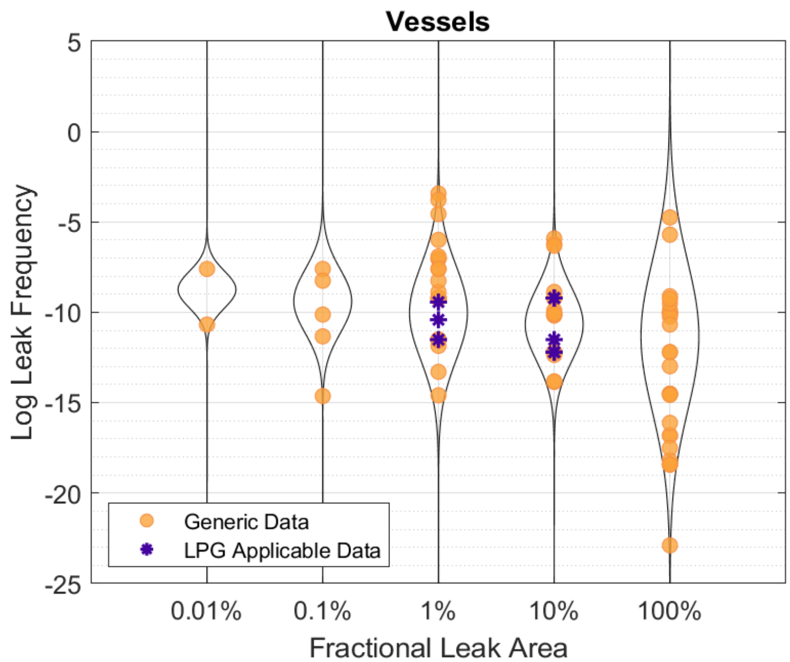

Figure 3-12 Log leak frequency distributions for vessels from generic data and LPG applicable data

Table 3-1 Recommended point estimates for LPG leak frequencies

Component	Leak Bin (%)	5th Perc.	Median	95th Perc.	Component	Leak Bin (%)	5thPerc.	Median	95th Perc.
Filters	0.01	9.48E-04	2.28E-03	5.48E-03	Loading Arms (Annual)	0.01	1.12E-03	8.32E-03	6.17E-02
	0.1	3.90E-04	8.79E-04	2.02E-03		0.1	1.01E-03	4.68E-03	2.16E-02
	1	1.32E-05	3.49E-04	8.29E-03		1	8.36E-04	2.63E-03	8.27E-03
	10	4.20E-05	1.21E-04	5.63E-04		10	5.44E-04	1.48E-03	4.04E-03
	100	5.08E-07	5.39E-05	4.21E-03		100	1.99E-04	8.33E-04	3.49E-03
Flanges	0.01	1.41E-05	4.45E-05	1.18E-04	Loading Arms (Per Transfer)	0.01	1.88E-06	3.04E-05	4.25E-04
	0.1	3.49E-06	1.93E-05	1.20E-04		0.1	1.48E-06	1.10E-05	6.39E-05
	1	2.62E-07	9.08E-06	3.08E-04		1	9.55E-07	3.94E-06	1.20E-05
	10	1.47E-06	4.11E-06	1.21E-05		10	3.79E-07	1.27E-06	5.36E-06
	100	1.26E-07	1.92E-06	2.77E-05		100	3.28E-08	5.24E-07	4.67E-06
Hoses (Annual)	0.01	6.60E-06	2.67E-05	1.01E-04	Pipes	0.01	1.02E-06	6.07E-06	3.85E-05
	0.1	3.83E-06	3.85E-05	3.97E-04		0.1	6.67E-07	3.59E-06	1.97E-05
	1	4.67E-07	5.71E-05	6.82E-03		1	1.11E-07	2.14E-06	3.97E-05
	10	1.54E-05	7.83E-05	5.64E-04		10	1.47E-07	1.24E-06	1.06E-05
	100	3.01E-06	1.32E-04	3.89E-03		100	4.26E-08	7.24E-07	1.27E-05

Component	Leak Bin (%)	5^{th} Perc.	Median	95^{th} Perc.	Component	Leak Bin (%)	5^{th}Perc.	Median	95^{th} Perc.
Hoses (Per Transfer)	0.01	7.02E-06	9.76E-05	1.43E-03	Pumps	0.01	9.97E-04	3.22E-03	1.13E-02
	0.1	4.69E-06	2.45E-05	1.28E-04		0.1	3.67E-04	1.19E-03	3.77E-03
	1	2.18E-06	6.27E-06	1.56E-05		1	3.26E-05	4.31E-04	5.64E-03
	10	3.67E-07	1.30E-06	1.04E-05		10	4.70E-05	1.55E-04	5.22E-04
	100	4.72E-09	4.90E-07	1.27E-05		100	2.65E-06	5.64E-05	1.22E-03
Instruments	0.01	2.15E-04	6.86E-04	2.22E-03	Valves	0.01	3.29E-05	9.63E-05	2.62E-04
	0.1	1.14E-04	2.96E-04	8.19E-04		0.1	9.36E-06	5.12E-05	2.99E-04
	1	5.25E-05	1.31E-04	3.16E-04		1	3.18E-07	2.84E-05	2.49E-03
	10	2.38E-05	5.67E-05	1.36E-04		10	2.41E-06	1.51E-05	1.07E-04
	100	8.61E-06	2.46E-05	7.24E-05		100	2.21E-07	8.57E-06	3.02E-04
Joints	0.01	1.43E-02	9.15E-01	5.87E+01	Vessels	0.01	3.17E-05	1.55E-04	8.75E-04
	0.1	7.63E-03	1.61E-01	3.41E+00		0.1	4.81E-06	8.24E-05	1.54E-03
	1	3.84E-03	2.83E-02	2.09E-01		1	5.79E-07	4.42E-05	3.24E-03
	10	1.59E-03	4.99E-03	1.57E-02		10	8.18E-07	2.33E-05	6.38E-04
	100	2.79E-04	8.78E-04	2.76E-03		100	1.31E-08	1.19E-05	1.21E-02

4. SENSITIVITY STUDY

Three sensitivity studies were performed to interrogate the effects of analyst decisions on the leak frequency estimates. The first analysis, in Section 4.1, examined options for filtering the vessel data based on whether the source fuel system was pressurized or atmospheric. The second analysis, in Section 4.2, examined the effect of excluding the data points that were applicable to LNG, CNG, or LOX systems. The third analysis, in Section 4.3, examined the influence of generic hydrocarbon data.

4.1. Vessel Pressure Study

Vessels were the only component for which there were data that are applicable to LPG. Because of the large amount of generic data available for vessels, there was some consideration of options for reducing the generic data set to the subset of generic data that would be most applicable to LPG systems. The generic data span many source fuels with systems that operate at a wide range of pressures, so it was considered whether using only generic vessel data from pressurized systems or only generic vessel data from atmospheric systems would be appropriate; there was insufficient information on specific system pressure levels to further select only data from low pressure systems, which would be most similar to the expected operating pressure for LPG systems. LPG vessels operate at fairly low pressure, so they may be expected to leak similarly to other low-pressure systems and some atmospheric systems. System pressure information was typically not available for data from other components, so the effect of system pressure on component leak frequency was only studied for vessels.

The leak frequency model (Section 2.2) for vessels was fit using the data applicable to LPG as well as either the generic data from pressurized systems or the generic data from atmospheric systems. These models are plotted with the LPG-applicable data in Figure 4-1, along with the model used to generate the results in Section 3, which used both pressurized and atmospheric generic data. For the 10% fractional leak area bin, the models are quite similar and match the LPG-applicable data well. For the 1% leak area bin, the model fit with only pressurized system data seems slightly more appropriate for the LPG-applicable data, but the data is still consistent with the model fit to atmospheric data.

This sensitivity study showed that there are significant differences between the generic vessel data from pressurized systems and the generic vessel data from atmospheric systems, particularly for the smaller leak area bins. The data from atmospheric systems dominates the combined model, so the combined model is similar to the model fit with only generic data from the atmospheric systems. Had only the generic data from atmospheric systems been used, the estimated leak frequencies for the 0.01%, 0.1%, and 1% fractional leak area bins would have been higher, and the estimated leak frequency for the 100% fractional leak area bin would have been lower. The physical reason for this difference is not clear; it could be due to the fact that near-atmospheric pressure systems are not designed or leak-tested in the same way, leading to more frequency smaller leaks.

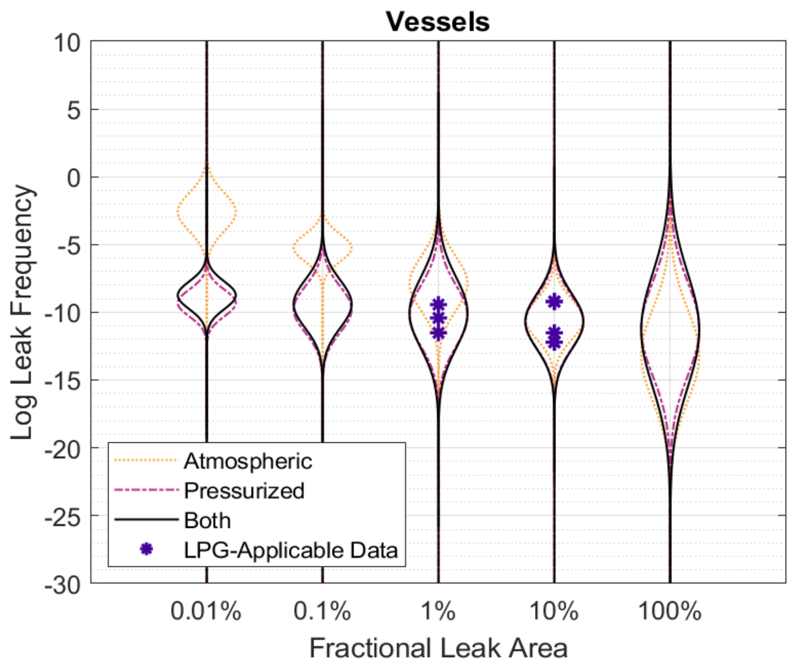

Figure 4-1 Comparison of leak frequency models based on use of either atmospheric or pressurized generic data for vessels

The statistics and distribution parameters for the model fit using only generic data from pressurized systems are provided in Table 4-1 as a potential alternative to the recommended leak frequency estimates for vessels from Section 3. The mean, 5th percentile, median, and 95th percentile values are provided for leak frequencies, whereas μ and σ are the parameters for the normal distribution on the log-leak frequencies (see Appendix B).

Table 4-1 Leak frequency statistics and log-leak frequency normal distribution parameters for the vessel leak frequency model obtained using only pressurized generic data

Leak Bin (%)	Mean	5th Perc.	Median	95th Perc.	μ	σ
0.01	1.50E-04	1.78E-05	9.11E-05	4.44E-04	-9.31E+00	9.86E-01
0.1	3.91E-04	3.61E-06	5.56E-05	9.01E-04	-9.79E+00	1.69E+00
1	8.09E-04	8.52E-07	3.49E-05	1.40E-03	-1.03E+01	2.26E+00
10	1.75E-04	8.96E-07	2.17E-05	5.17E-04	-1.07E+01	1.94E+00
100	2.98E-01	4.79E-08	1.33E-05	3.78E-03	-1.12E+01	3.45E+00

4.2. LNG, CNG, or LOX Data Study

As discussed in Section 2.1, generic data that was derived from or published as applicable to LNG, CNG, or LOX was excluded when estimating leak frequencies for LPG based on engineering judgement that these systems are substantially different in design and operation from LPG systems.

Because this decision was based on engineering judgement and there was insufficient LPG data to verify the assumption, the analysis was repeated with the LNG, CNG, and LOX data included. The goal of this sensitivity study is to show how significant this assumption is to the results of the analysis.

Figure 4-2 through Figure 4-9 show the estimated log leak frequency distributions from Section 3 (solid black) compared to the estimated log leak frequency distributions obtained when including LNG, CNG, or LOX data in the generic data set (pink dashed). Plots are only shown for components for which LNG, CNG, or LOX data exist. For some components (hoses, loading arms, valves), including the LNG, CNG, or LOX data would have increased some of the leak frequency estimates. For pipes, including the LNG, CNG, or LOX data would have decreased the leak frequency estimates Figure 4-7. The median leak frequencies for joints would have remained the same, however, including the LNG, CNG, or LOX data would have decreased the variation, particularly for the smaller leak size bins.

Overall, this sensitivity study showed that the LNG, CNG, or LOX data do not systematically bias the leak frequencies for all component types in the same direction. Therefore, these data were not included in the recommended distributions (Section 3) because they may introduce non-conservatisms for some components and leak sizes.

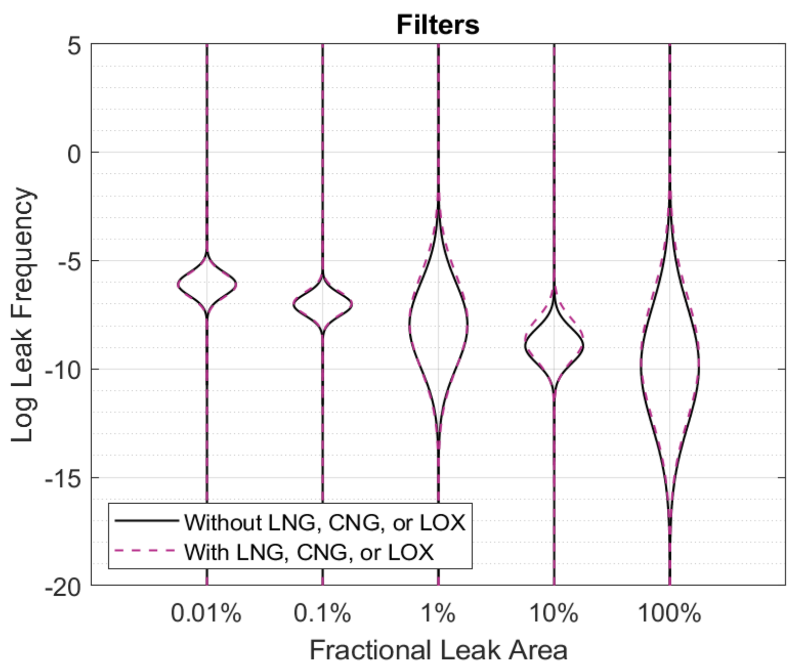

Figure 4-2 Comparison of log leak frequency distributions for filters using only generic data versus using generic data with data that are applicable to LNG, CNG, or LOX

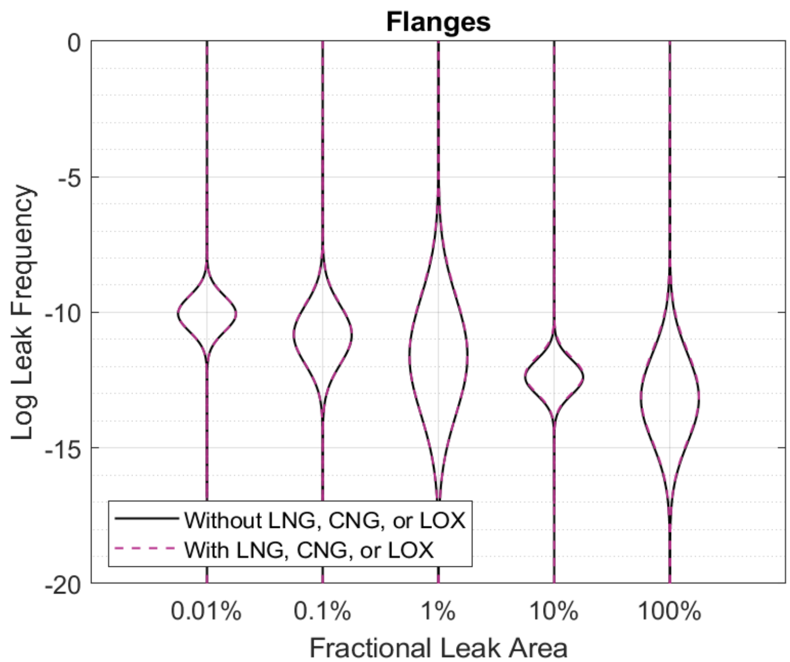

Figure 4-3 Comparison of log leak frequency distributions for flanges using only generic data versus using generic data with data that are applicable to LNG, CNG, or LOX

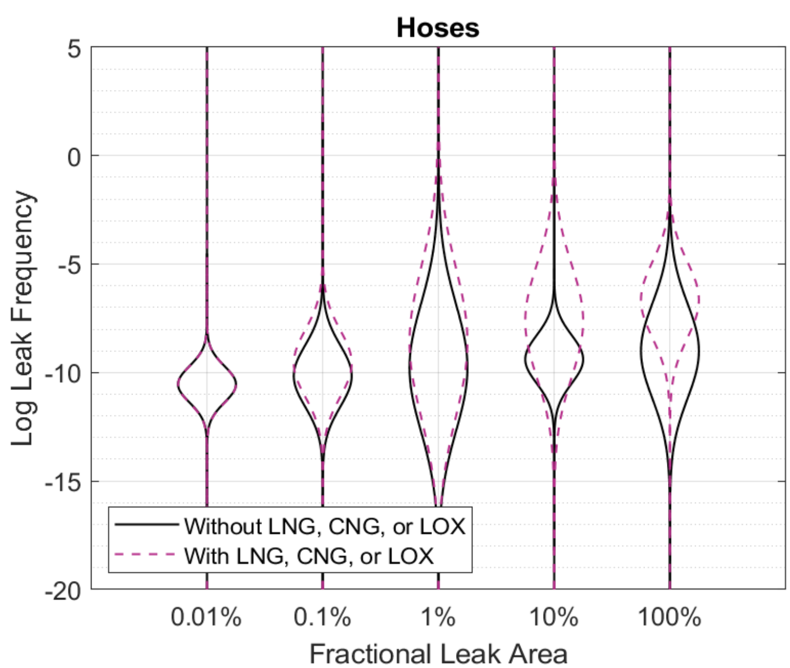

Figure 4-4 Comparison of log leak frequency distributions for hoses using only generic data versus using generic data with data that are applicable to LNG, CNG, or LOX

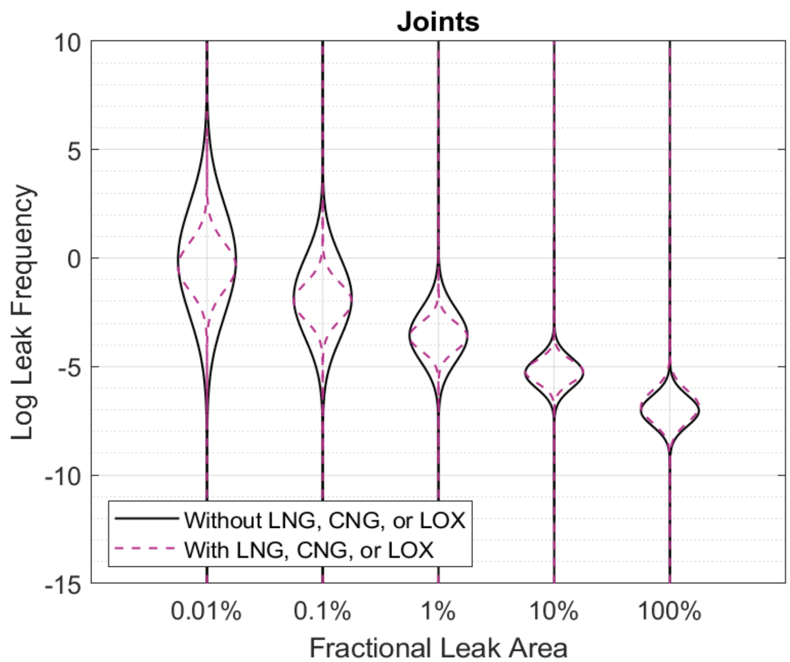

Figure 4-5 Comparison of log leak frequency distributions for joints using only generic data versus using generic data with data that are applicable to LNG, CNG, or LOX

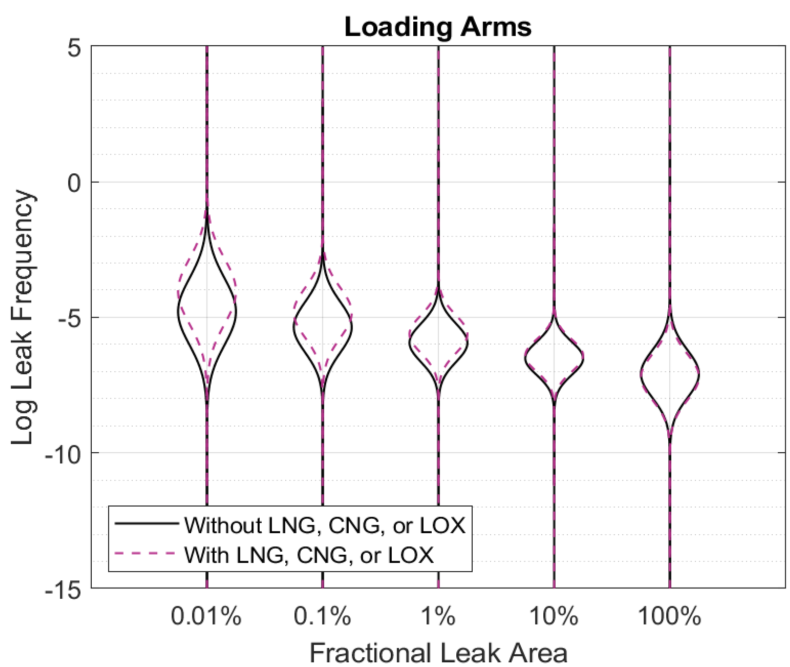

Figure 4-6 Comparison of log leak frequency distributions for loading arms using only generic data versus using generic data with data that are applicable to LNG, CNG, or LOX

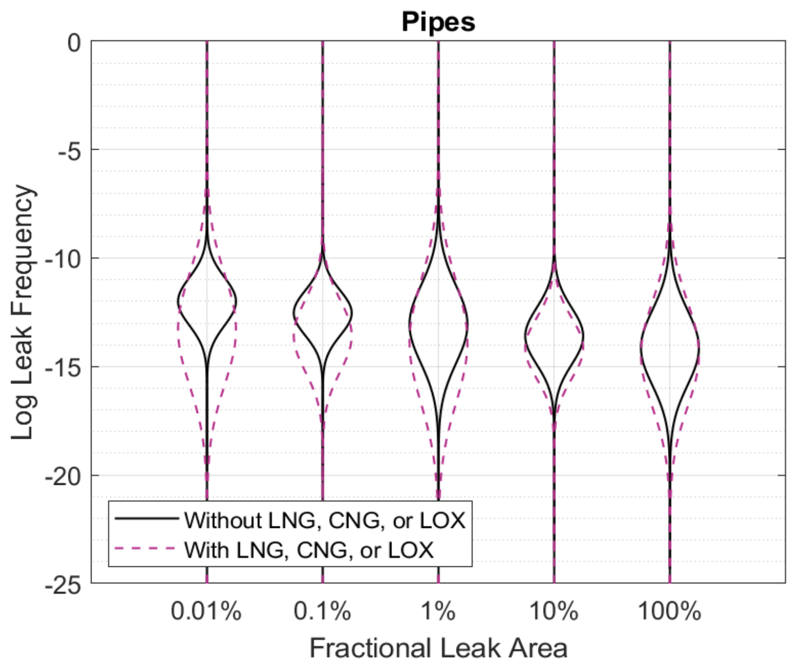

Figure 4-7 Comparison of log leak frequency distributions for pipes using only generic data versus using generic data with data that are applicable to LNG, CNG, or LOX

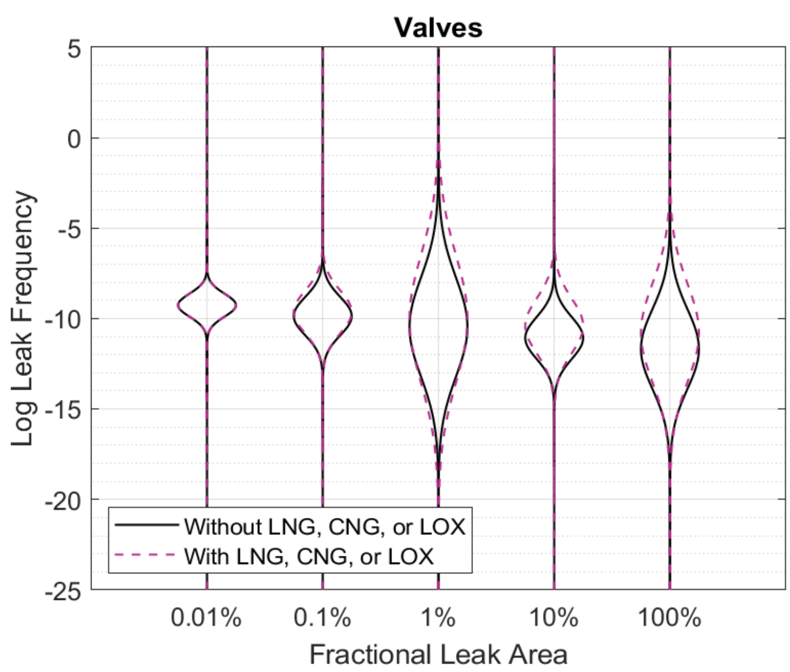

Figure 4-8 Comparison of log leak frequency distributions for valves using only generic data versus using generic data with data that are applicable to LNG, CNG, or LOX

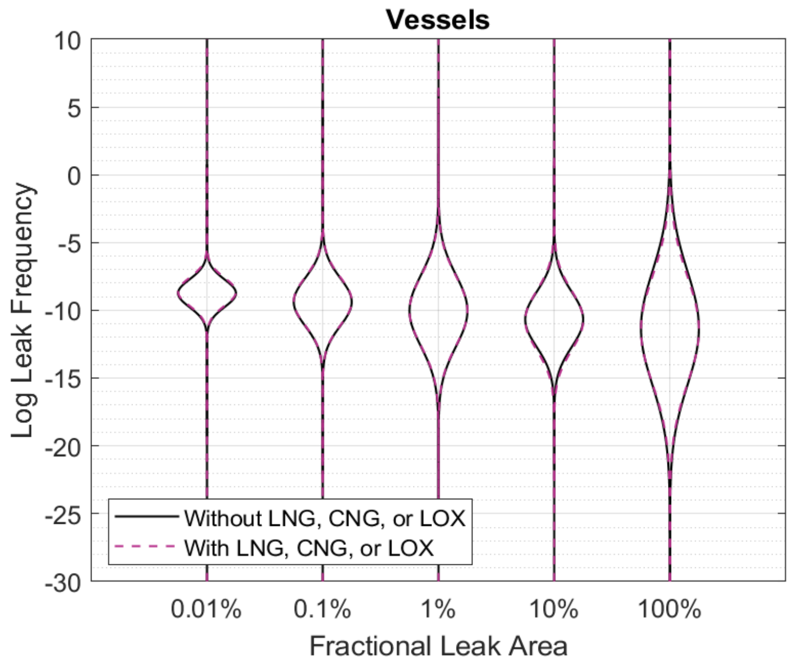

Figure 4-9 Comparison of log leak frequency distributions for vessels using only generic data versus using generic data with data that are applicable to LNG, CNG, or LOX

4.3. Hydrocarbon Data Study

The generic data discussed in Section 2.1 include data from multiple industries. Some of the frequencies, which come from [7, 8], were derived from onshore and offshore hydrocarbon systems. This may include systems for liquid hydrocarbons, liquified gas hydrocarbons, and gaseous hydrocarbons. The ratio of these different hydrocarbon types determines whether the data are applicable to LPG systems, but this information is not included in the data. It was assumed that the data are applicable since they were derived from such a broad data set, however this assumption could not be verified. A sensitivity study was performed to investigate the impact of including the generic hydrocarbon data in the leak frequency estimates.

Figure 4-10 through Figure 4-16 show the estimated log leak frequency distributions from Section 3 (solid black) compared to the estimated log leak frequency distributions obtained when excluding generic hydrocarbon data (pink dashed). The comparison was performed for filters, flanges, hoses, pipes, pumps, and valves because the data sets for these components contained enough non-hydrocarbon generic data and hydrocarbon generic data to fit both models for comparison. Instruments, joints, and loading arms were not included because there was insufficient data after removing the hydrocarbon data to fit the leak frequency model.

For filters (Figure 4-10), flanges (Figure 4-11), hoses (Figure 4-12), and valves (Figure 4-15), the model fit without hydrocarbon data would be conservative. For the other components, the conservative model differed between bins. This sensitivity study showed that there are some significant effects from including the hydrocarbon data set because it comprises significant portion of the generic data set. However, this effect is not consistent across all components and bins.

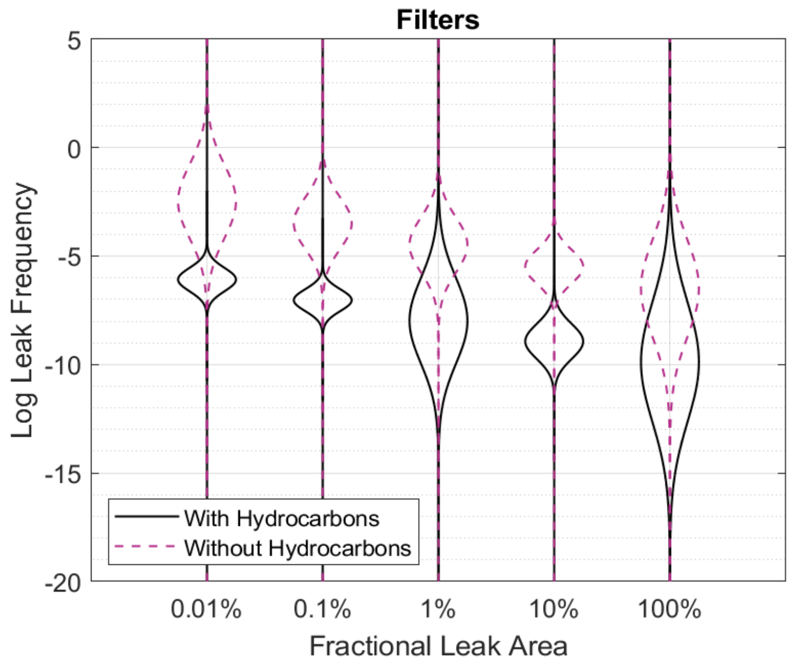

Figure 4-10 Comparison of log leak frequency distributions for filters using generic data that either includes or excludes hydrocarbon data

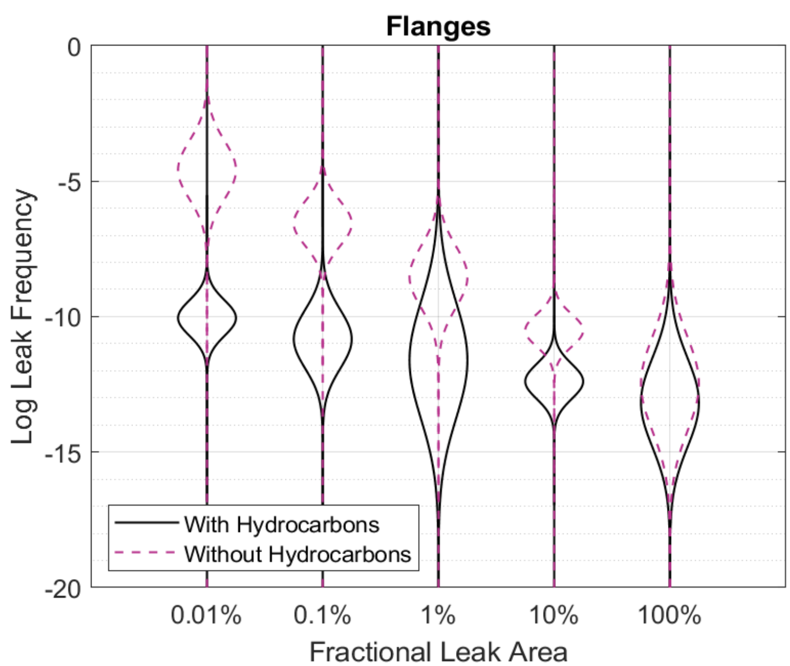

Figure 4-11 Comparison of log leak frequency distributions for flanges using generic data that either includes or excludes hydrocarbon data

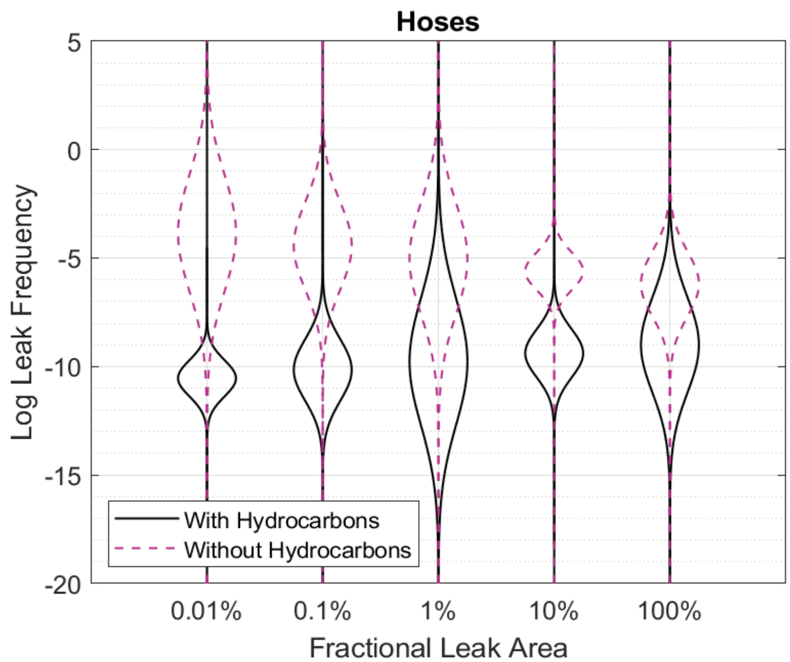

Figure 4-12 Comparison of log leak frequency distributions for hoses using generic data that either includes or excludes hydrocarbon data

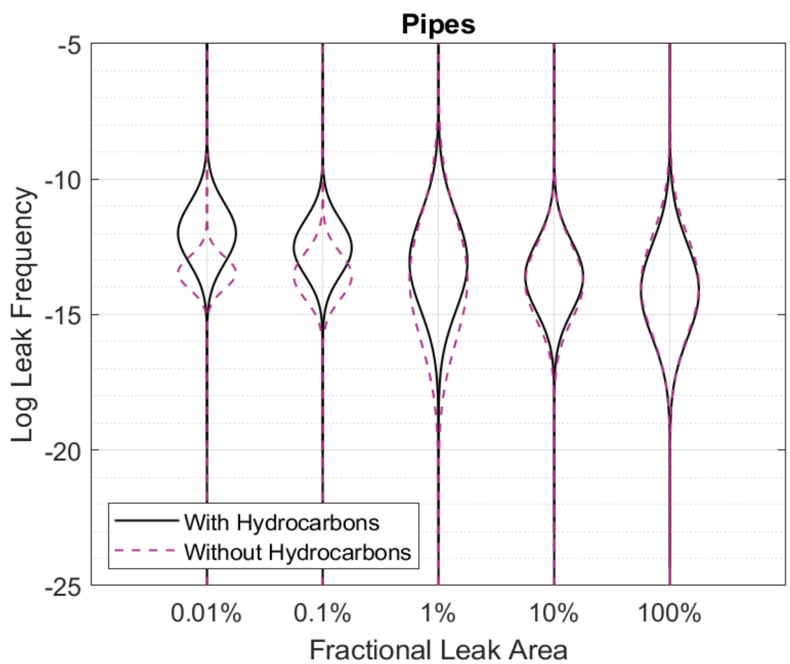

Figure 4-13 Comparison of log leak frequency distributions for pipes using generic data that either includes or excludes hydrocarbon data

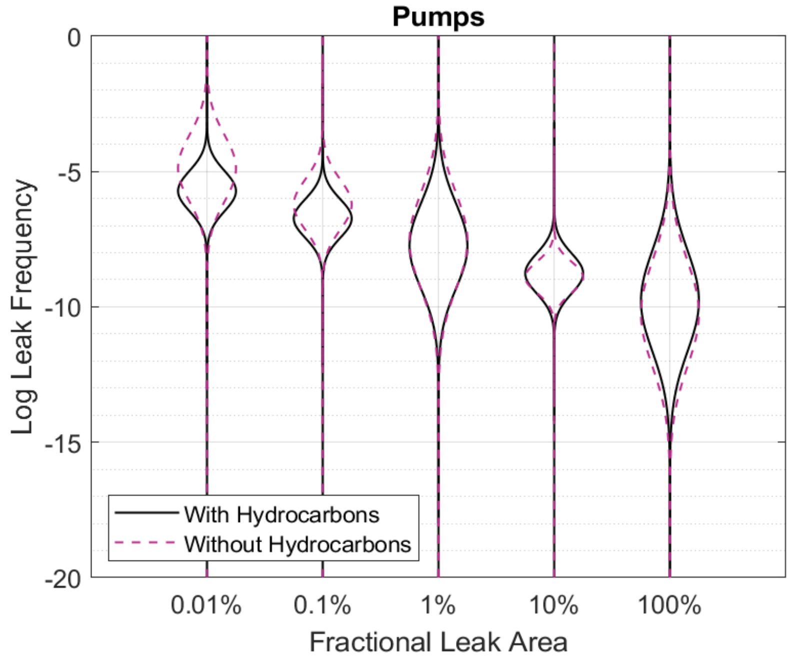

Figure 4-14 Comparison of log leak frequency distributions for pumps using generic data that either includes or excludes hydrocarbon data

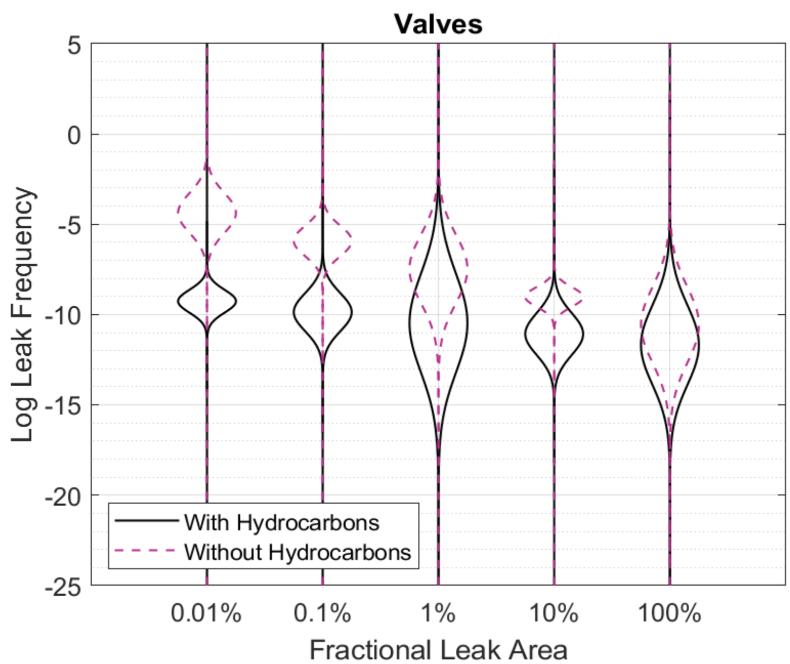

Figure 4-15 Comparison of log leak frequency distributions for valves using generic data that either includes or excludes hydrocarbon data

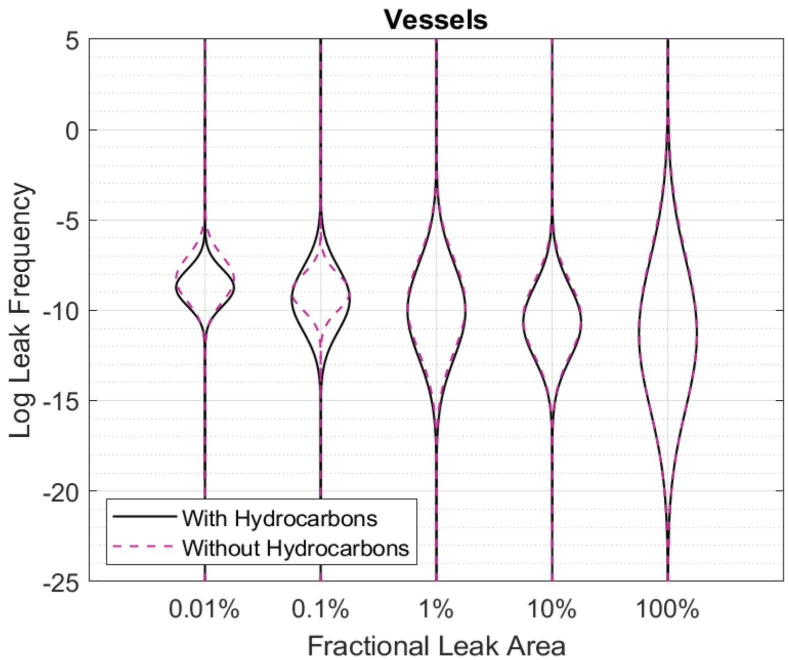

Figure 4-16 Comparison of log leak frequency distributions for vessels using generic data that either includes or excludes hydrocarbon data

5. CONCLUSIONS

The estimated leak frequency distributions for LPG are shown in Figure 3-1 through Figure 3-12 and the median values with percentiles are shown in Table B-1. As discussed in Section 2.1, data obtained from LPG were only available for vessels; for all other components, only generic data were available. This means that the estimated leak frequencies should be used with caution in the context of LPG risk assessment, since it is not known whether the median values are conservative or non-conservative for LPG.

Some of the generic data considered in the analysis had been derived from sources which included CNG, LNG, or LOX. These systems tend to operate at much higher pressures (for CNG) or cryogenic temperatures (for LNG or LOX), meaning that the components are designed in very different ways. This can include thicker walls for higher-pressure components and insulation for cryogenic components. Our engineering judgement was that, because of these differences, it makes sense to exclude the CNG, LNG, or LOX-based generic data. However, this may also bias results because detailed information on source fuels was not available for all generic data. This makes it impossible to definitively categorize the generic data based on similarity of the source fuel systems to LPG.

A sensitivity study was performed (Section 4.1) investigating the effects of filtering the generic data included in the model based on whether the source fuel system was pressurized or atmospheric. This study showed that there are some significant differences between the two types of generic data and that data from atmospheric systems typically leads to lower frequency estimates for small leaks and slightly higher frequency estimates for ruptures than data from pressurized systems. The model used for the recommended frequencies (Section 3, Appendix B) uses both types of data but is dominated by the data from atmospheric systems. Whether this is conservative or non-conservative will depend on the system being modeled and the consequences for small leaks versus large leaks. The leak frequencies from the model fit using only generic data from pressurized systems may be used in analysis as an alternative option if judged to be conservative or more realistic for the specific system being analyzed (Section 4.1, Table 4-1).

A second sensitivity study was performed (Section 4.2), which compared estimated log-leak frequency distributions derived with and without including the CNG, LNG, or LOX-based generic data. The comparison showed that the inclusion of CNG, LNG, or LOX-based generic data would not have systematically biased the estimated leak frequencies in a consistent direction for all component types. Rather, including this data for some components (hoses, loading arms, valves) would have increased leak frequency estimates, whereas for pipes, including this data would have decreased leak frequency estimates. For joints, including the data would have decreased variation, while not significantly changing the median.

A final sensitivity study was performed (Section 4.3) comparing the estimated log-leak frequency distributions derived either including or excluding generic hydrocarbon data. This study showed that the analyst choice to include hydrocarbon data is significant to the results, but the effect of this choice on leak frequency estimates is inconsistent between components and bins. Excluding the generic hydrocarbon data would lead to substantially higher median leak frequency predictions for some, but not all, of the components.

This analysis established a baseline of generic leak frequencies that may be used, with caution, for LPG risk assessments. If additional leak data for LPG systems are published in the literature in the future, the analysis should be repeated to update the leak frequency estimates to incorporate this new information.

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APPENDIX A. LEAK FREQUENCY DATA

This appendix contains the data from the literature review discussed in Section 2.1. Data that are applicable to CNG, LNG, or LOX are also included. These data were not used to generate the final leak frequency leak estimates (Section 3) but were used for the sensitivity study (Section 4.2).

Table A-1 Filter leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
1	6.13E-02	Chemical Process	[14]	1998	Yes
100	6.75E-03	Chemical Process	[14]	1998	Yes
1	2.63E-02	Chemical Process	[15]	1995	Yes
100	4.38E-03	Chemical Process	[15]	1995	Yes
100	2.72E-02	Generic	[16]	2005	Yes
0.01	2.30E-03	Hydrocarbons	[8]	2019	Yes
0.1	8.30E-04	Hydrocarbons	[8]	2019	Yes
1	2.90E-04	Hydrocarbons	[8]	2019	Yes
10	7.40E-05	Hydrocarbons	[8]	2019	Yes
0.01	2.30E-03	Hydrocarbons	[8]	2019	Yes
0.1	8.30E-04	Hydrocarbons	[8]	2019	Yes
1	2.90E-04	Hydrocarbons	[8]	2019	Yes
10	4.90E-05	Hydrocarbons	[8]	2019	Yes
100	2.50E-05	Hydrocarbons	[8]	2019	Yes
1	8.90E-04	Process Equipment	[17]	2005	Yes
100	6.40E-06	Process Equipment	[17]	2005	Yes
1	2.63E-02	Compressed Gas	[15]	1995	No
100	4.38E-03	Compressed Gas	[15]	1995	No

Table A-2 Flange leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
1	1.00E-03	Chemical Process	[2]	2009	Yes
100	1.00E-04	Chemical Process	[2]	2009	Yes
1	8.76E-04	Chemical Process	[15]	1995	Yes
100	8.76E-06	Chemical Process	[15]	1995	Yes
100	5.00E-06	Chlorine, LPG, petrochemical, steam/water, nuclear, other	[18]	2017	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	1.00E-07	Chlorine, LPG, petrochemical, steam/water, nuclear, other	[18]	2017	Yes
100	5.00E-06	Chlorine, LPG, petrochemical, steam/water, nuclear, other	[18]	2017	Yes
1	8.76E-04	Compressed Gas	[15]	1995	Yes
100	8.76E-06	Compressed Gas	[15]	1995	Yes
100	8.76E-05	Generic, Nuclear	[19]	1982	Yes
0.1	1.30E-05	Hydrocarbons	[8]	2019	Yes
1	6.00E-06	Hydrocarbons	[8]	2019	Yes
10	2.80E-06	Hydrocarbons	[8]	2019	Yes
100	1.20E-06	Hydrocarbons	[8]	2019	Yes
0.01	2.20E-05	Hydrocarbons	[8]	2019	Yes
0.1	9.60E-06	Hydrocarbons	[8]	2019	Yes
1	4.30E-06	Hydrocarbons	[8]	2019	Yes
10	9.90E-07	Hydrocarbons	[8]	2019	Yes
100	1.70E-06	Hydrocarbons	[8]	2019	Yes
0.01	5.40E-05	Hydrocarbons	[8]	2019	Yes
0.1	5.90E-06	Hydrocarbons	[8]	2019	Yes
1	1.10E-06	Hydrocarbons	[8]	2019	Yes
10	3.90E-06	Hydrocarbons	[8]	2019	Yes
0.01	7.90E-05	Hydrocarbons	[8]	2019	Yes
0.1	6.60E-06	Hydrocarbons	[8]	2019	Yes
1	1.00E-06	Hydrocarbons	[8]	2019	Yes
10	6.00E-06	Hydrocarbons	[8]	2019	Yes
0.01	8.70E-05	Hydrocarbons	[8]	2019	Yes
0.1	6.60E-06	Hydrocarbons	[8]	2019	Yes
1	9.90E-07	Hydrocarbons	[8]	2019	Yes
10	6.70E-06	Hydrocarbons	[8]	2019	Yes
0.01	9.36E-05	Hydrocarbons	[8]	2019	Yes
0.1	9.90E-07	Hydrocarbons	[8]	2019	Yes
1	6.70E-06	Hydrocarbons	[8]	2019	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
1	8.76E-05	Nuclear	[20]	1991	Yes
100	8.76E-07	Nuclear	[20]	1991	Yes
1	3.20E-05	Process Equipment	[17]	2005	Yes
1	4.30E-05	Process Equipment	[17]	2005	Yes
1	1.20E-04	Process Equipment	[17]	2005	Yes
100	3.60E-07	Process Equipment	[17]	2005	Yes
100	1.10E-06	Process Equipment	[17]	2005	Yes
1	1.70E-04	LOX	[21]	2021	No
100	1.70E-05	LOX	[21]	2021	No

Table A-3 Hose annual leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	8.34E-04	Chemical Process	[14]	1998	Yes
100	2.88E-04	Chemical Process	[15]	1995	Yes
1	2.88E-05	Chemical Process	[15]	1995	Yes
1	2.88E-02	Chemical Process	[15]	1995	Yes
100	2.88E-04	Chemical Process	[15]	1995	Yes
100	1.49E-02	Generic	[19]	1982	Yes
100	3.50E-02	Generic	[22]	2005	Yes
1	3.50E-01	Generic	[22]	2005	Yes
0.1	1.00E-03	Hydrocarbons	[8]	2019	Yes
1	5.30E-04	Hydrocarbons	[8]	2019	Yes
10	2.90E-04	Hydrocarbons	[8]	2019	Yes
100	1.60E-04	Hydrocarbons	[8]	2019	Yes
0.01	1.70E-04	Hydrocarbons	[8]	2019	Yes
0.1	1.10E-04	Hydrocarbons	[8]	2019	Yes
1	8.10E-05	Hydrocarbons	[8]	2019	Yes
10	3.00E-05	Hydrocarbons	[8]	2019	Yes
100	4.80E-05	Hydrocarbons	[8]	2019	Yes
0.01	5.80E-05	Hydrocarbons	[8]	2019	Yes
0.1	2.20E-05	Hydrocarbons	[8]	2019	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
1	9.70E-06	Hydrocarbons	[8]	2019	Yes
10	2.40E-05	Hydrocarbons	[8]	2019	Yes
0.01	2.03E-05	Hydrocarbons	[8]	2019	Yes
0.1	9.20E-06	Hydrocarbons	[8]	2019	Yes
1	4.70E-06	Hydrocarbons	[8]	2019	Yes
10	1.80E-05	Hydrocarbons	[8]	2019	Yes
0.01	1.06E-05	Hydrocarbons	[8]	2019	Yes
0.1	5.20E-06	Hydrocarbons	[8]	2019	Yes
1	2.80E-06	Hydrocarbons	[8]	2019	Yes
10	1.30E-05	Hydrocarbons	[8]	2019	Yes
0.01	1.58E-05	Hydrocarbons	[8]	2019	Yes
0.1	2.80E-06	Hydrocarbons	[8]	2019	Yes
1	1.30E-05	Hydrocarbons	[8]	2019	Yes
100	2.88E-03	Compressed Gas	[15]	1995	No
1	2.88E-01	Compressed Gas	[15]	1995	No
100	2.88E-03	Compressed Gas	[15]	1995	No
1	2.88E-04	Compressed Gas	[15]	1995	No
100	4.00E-02	LNG Applicable	[23]	2019	No
10	4.00E-01	LNG Applicable	[23]	2019	No
10	1.00E-02	LOX (H_2 applicable)	[21]	2021	No
100	1.00E-03	LOX (H_2 applicable)	[21]	2021	No
1	1.00E-01	LOX (H_2 applicable)	[21]	2021	No

Table A-4 Hose per-transfer leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	4.00E-05	Chlorine	[18]	2017	Yes
10	1.00E-06	Chlorine	[18]	2017	Yes
1	1.30E-05	Chlorine	[18]	2017	Yes
100	4.00E-06	Chlorine	[18]	2017	Yes
10	4.00E-07	Chlorine	[18]	2017	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
1	6.00E-06	Chlorine	[18]	2017	Yes
100	2.00E-07	Chlorine	[18]	2017	Yes
10	4.00E-07	Chlorine	[18]	2017	Yes
1	6.00E-06	Chlorine	[18]	2017	Yes
100	1.60E-05	Generic	[24]	2017	Yes

Table A-5 Instrument leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
1	2.10E-04	Hydrocarbons	[8]	2019	Yes
10	8.50E-05	Hydrocarbons	[8]	2019	Yes
100	4.60E-05	Hydrocarbons	[8]	2019	Yes
0.1	2.10E-04	Hydrocarbons	[8]	2019	Yes
1	8.50E-05	Hydrocarbons	[8]	2019	Yes
10	3.50E-05	Hydrocarbons	[8]	2019	Yes
100	1.10E-05	Hydrocarbons	[8]	2019	Yes
1	2.30E-04	Process Equipment	[17]	2005	Yes

Table A-6 Joint leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
10	4.99E-03	Process Equipment	[25]	1989	Yes
100	8.76E-04	Generic, Nuclear	[19]	1982	Yes
1	3.30E-02	LOX, H_2 applicable	[21]	2021	No
10	4.00E-03	LOX, H_2 applicable	[21]	2021	No
100	5.00E-04	LOX, H_2 applicable	[21]	2021	No
100	4.00E-03	LNG Applicable	[23]	2019	No

Table A-7 Loading arm annual leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	2.63E-03	Generic	[19]	1982	Yes
100	2.63E-04	Generic	[22]	2005	Yes
1	2.63E-03	Generic	[22]	2005	Yes
100	3.00E-04	LNG Applicable	[23]	2019	No
10	3.00E-03	LNG Applicable	[23]	2019	No

Table A-8 Loading arm per-transfer leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	2.00E-07	Generic	[18]	2017	Yes
10	4.00E-07	Generic	[18]	2017	Yes
1	6.00E-06	Generic	[18]	2017	Yes
100	1.20E-05	Generic	[24]	2017	Yes
100	2.60E-05	LNG	[24]	2017	No

Table A-9 Pipe leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
1	3.00E-06	Chemical Process	[2]	2009	Yes
1	6.00E-06	Chemical Process	[2]	2009	Yes
1	1.00E-05	Chemical Process	[2]	2009	Yes
10	1.00E-07	Chemical Process	[2]	2009	Yes
10	3.00E-07	Chemical Process	[2]	2009	Yes
10	1.00E-06	Chemical Process	[2]	2009	Yes
1	1.00E-05	Chemical Process	[2]	2009	Yes
1	3.00E-05	Chemical Process	[2]	2009	Yes
1	1.00E-04	Chemical Process	[2]	2009	Yes
1	1.00E-04	Chemical Process	[2]	2009	Yes
10	3.00E-06	Chemical Process	[2]	2009	Yes
10	6.00E-06	Chemical Process	[2]	2009	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
10	1.00E-05	Chemical Process	[2]	2009	Yes
10	1.00E-05	Chemical Process	[2]	2009	Yes
100	1.00E-07	Chemical Process	[2]	2009	Yes
100	3.00E-07	Chemical Process	[2]	2009	Yes
100	1.00E-06	Chemical Process	[2]	2009	Yes
100	1.00E-06	Chemical Process	[2]	2009	Yes
100	5.00E-04	Chemical Process	[2]	2009	Yes
1	8.63E-05	Chemical Process	[15]	1995	Yes
100	2.88E-06	Chemical Process	[15]	1995	Yes
0.1	1.00E-05	Chlorine	[18]	2017	Yes
10	5.00E-06	Chlorine	[18]	2017	Yes
100	1.00E-06	Chlorine	[18]	2017	Yes
0.01	2.00E-06	Chlorine	[18]	2017	Yes
1	1.00E-06	Chlorine	[18]	2017	Yes
100	5.00E-07	Chlorine	[18]	2017	Yes
0.01	1.00E-06	Chlorine	[18]	2017	Yes
0.1	7.00E-07	Chlorine	[18]	2017	Yes
10	4.00E-07	Chlorine	[18]	2017	Yes
100	2.00E-07	Chlorine	[18]	2017	Yes
0.01	8.00E-07	Chlorine	[18]	2017	Yes
0.1	5.00E-07	Chlorine	[18]	2017	Yes
10	2.00E-07	Chlorine	[18]	2017	Yes
100	7.00E-08	Chlorine	[18]	2017	Yes
0.01	7.00E-07	Chlorine	[18]	2017	Yes
1	4.00E-07	Chlorine	[18]	2017	Yes
10	1.00E-07	Chlorine	[18]	2017	Yes
100	4.00E-08	Chlorine	[18]	2017	Yes
1	5.00E-07	Generic	[22]	2005	Yes
1	2.00E-06	Generic	[22]	2005	Yes
1	5.00E-06	Generic	[22]	2005	Yes
100	1.00E-07	Generic	[22]	2005	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	3.00E-07	Generic	[22]	2005	Yes
100	1.00E-06	Generic	[22]	2005	Yes
1	4.99E-06	Generic	[16]	2005	Yes
100	9.64E-07	Generic	[16]	2005	Yes
1	2.01E-06	Generic	[16]	2005	Yes
100	2.98E-07	Generic	[16]	2005	Yes
0.1	3.60E-05	Hydrocarbons	[8]	2019	Yes
1	1.50E-05	Hydrocarbons	[8]	2019	Yes
10	6.60E-06	Hydrocarbons	[8]	2019	Yes
100	2.40E-06	Hydrocarbons	[8]	2019	Yes
0.01	1.60E-05	Hydrocarbons	[8]	2019	Yes
0.1	6.70E-06	Hydrocarbons	[8]	2019	Yes
1	2.70E-06	Hydrocarbons	[8]	2019	Yes
10	5.60E-07	Hydrocarbons	[8]	2019	Yes
100	3.50E-07	Hydrocarbons	[8]	2019	Yes
0.01	1.61E-05	Hydrocarbons	[8]	2019	Yes
0.1	2.50E-06	Hydrocarbons	[8]	2019	Yes
1	6.40E-07	Hydrocarbons	[8]	2019	Yes
10	5.60E-07	Hydrocarbons	[8]	2019	Yes
0.01	1.24E-05	Hydrocarbons	[8]	2019	Yes
0.1	2.90E-06	Hydrocarbons	[8]	2019	Yes
1	9.40E-07	Hydrocarbons	[8]	2019	Yes
10	1.20E-06	Hydrocarbons	[8]	2019	Yes
0.01	1.13E-05	Hydrocarbons	[8]	2019	Yes
0.1	3.00E-06	Hydrocarbons	[8]	2019	Yes
1	1.00E-06	Hydrocarbons	[8]	2019	Yes
10	1.60E-06	Hydrocarbons	[8]	2019	Yes
0.01	1.43E-05	Hydrocarbons	[8]	2019	Yes
0.1	1.00E-06	Hydrocarbons	[8]	2019	Yes
1	1.60E-06	Hydrocarbons	[8]	2019	Yes
100	8.63E-07	Nuclear	[20]	1991	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	3.45E-06	Nuclear	[20]	1991	Yes
1	8.63E-05	Nuclear	[20]	1991	Yes
1	1.10E-05	Process Equipment	[17]	2005	Yes
1	2.00E-05	Process Equipment	[17]	2005	Yes
1	5.70E-05	Process Equipment	[17]	2005	Yes
100	4.20E-08	Process Equipment	[17]	2005	Yes
100	7.70E-08	Process Equipment	[17]	2005	Yes
100	1.28E-06	Generic	[26]	2012	Yes
100	1.80E-07	Generic	[26]	2012	Yes
100	1.46E-07	Generic	[25]	1989	Yes
100	2.88E-05	Compressed Gas	[15]	1995	No
1	8.63E-04	Compressed Gas	[15]	1995	No
1	8.63E-03	Compressed Gas	[15]	1995	No
100	2.88E-04	Compressed Gas	[15]	1995	No
1	3.33E-07	LNG	[27]	2018	No
10	1.22E-07	LNG	[27]	2018	No
100	7.40E-08	LNG	[27]	2018	No
0.1	1.38E-07	LNG	[27]	2018	No
1	8.00E-08	LNG	[27]	2018	No
100	2.70E-08	LNG	[27]	2018	No
0.1	5.50E-08	LNG	[27]	2018	No
1	4.00E-08	LNG	[27]	2018	No
100	1.70E-08	LNG	[27]	2018	No
0.1	4.80E-08	LNG	[27]	2018	No
1	2.60E-08	LNG	[27]	2018	No
100	1.10E-08	LNG	[27]	2018	No
0.1	6.60E-08	LNG	[27]	2018	No
1	2.00E-08	LNG	[27]	2018	No
100	1.20E-08	LNG	[27]	2018	No
0.01	1.30E-08	LNG	[27]	2018	No
100	6.00E-09	LNG	[27]	2018	No

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
0.01	8.00E-09	LNG	[27]	2018	No
100	4.00E-09	LNG	[27]	2018	No
0.01	1.00E-08	LNG	[27]	2018	No
0.01	6.00E-09	LNG	[27]	2018	No
100	6.00E-09	LNG	[27]	2018	No
100	1.00E-06	LNG Applicable	[23]	2019	No
10	5.00E-06	LNG Applicable	[23]	2019	No
100	5.00E-07	LNG Applicable	[23]	2019	No
1	2.00E-06	LNG Applicable	[23]	2019	No
100	2.00E-07	LNG Applicable	[23]	2019	No
0.1	7.00E-07	LNG Applicable	[23]	2019	No
10	4.00E-07	LNG Applicable	[23]	2019	No
100	7.00E-08	LNG Applicable	[23]	2019	No
0.1	5.00E-07	LNG Applicable	[23]	2019	No
10	2.00E-07	LNG Applicable	[23]	2019	No
1	4.00E-07	LNG Applicable	[23]	2019	No
100	2.00E-08	LNG Applicable	[23]	2019	No
0.01	4.00E-07	LNG Applicable	[23]	2019	No
10	1.00E-07	LNG Applicable	[23]	2019	No
1	2.00E-07	LNG Applicable	[23]	2019	No
100	4.60E-07	LOX, H_2 applicable	[21]	2021	No
1	7.50E-06	LOX, H_2 applicable	[21]	2021	No
10	2.00E-06	LOX, H_2 applicable	[21]	2021	No

Table A-10 Pump leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	5.20E-08	Applicable to chemical process	[14]	1998	Yes
1	9.20E-06	Applicable to chemical process	[14]	1998	Yes
1	3.00E-03	Chemical Process	[2]	2009	Yes
10	1.00E-04	Chemical Process	[2]	2009	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	1.00E-05	Chemical Process	[2]	2009	Yes
1	8.76E-03	Chemical Process	[15]	1995	Yes
100	4.38E-04	Chemical Process	[15]	1995	Yes
100	8.76E-05	Generic	[19]	1982	Yes
100	1.00E-05	Generic	[28]	2009	Yes
1	5.00E-05	Generic	[28]	2009	Yes
100	1.00E-04	Generic	[28]	2009	Yes
1	4.40E-03	Generic	[28]	2009	Yes
100	1.00E-05	Generic	[22]	2005	Yes
1	5.00E-05	Generic	[22]	2005	Yes
100	1.00E-04	Generic	[22]	2005	Yes
1	5.00E-04	Generic	[22]	2005	Yes
100	5.00E-05	Generic	[22]	2005	Yes
1	2.50E-04	Generic	[22]	2005	Yes
100	5.00E-04	Generic, LPG, petrochemical, steam/water, nuclear, other	[18]	2017	Yes
100	5.00E-05	Generic, LPG, petrochemical, steam/water, nuclear, other	[18]	2017	Yes
0.1	5.90E-03	Hydrocarbons	[8]	2019	Yes
1	1.40E-03	Hydrocarbons	[8]	2019	Yes
10	3.00E-04	Hydrocarbons	[8]	2019	Yes
100	3.90E-05	Hydrocarbons	[8]	2019	Yes
0.01	5.90E-03	Hydrocarbons	[8]	2019	Yes
0.1	1.40E-03	Hydrocarbons	[8]	2019	Yes
1	3.00E-04	Hydrocarbons	[8]	2019	Yes
10	3.00E-05	Hydrocarbons	[8]	2019	Yes
100	8.90E-06	Hydrocarbons	[8]	2019	Yes
0.1	8.10E-04	Hydrocarbons	[8]	2019	Yes
1	5.50E-04	Hydrocarbons	[8]	2019	Yes
10	4.20E-04	Hydrocarbons	[8]	2019	Yes
100	4.40E-04	Hydrocarbons	[8]	2019	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
0.01	8.10E-04	Hydrocarbons	[8]	2019	Yes
0.1	5.50E-04	Hydrocarbons	[8]	2019	Yes
1	4.20E-04	Hydrocarbons	[8]	2019	Yes
10	1.60E-04	Hydrocarbons	[8]	2019	Yes
100	2.80E-04	Hydrocarbons	[8]	2019	Yes
1	2.45E-03	Nuclear	[29]	2015	Yes
100	1.72E-04	Nuclear	[29]	2015	Yes
1	1.80E-03	Process Equipment	[17]	2005	Yes
1	3.70E-03	Process Equipment	[17]	2005	Yes
100	2.40E-05	Process Equipment	[17]	2005	Yes
100	5.20E-04	Process Equipment	[17]	2005	Yes

Table A-11 Valve leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
1	9.64E-02	Applicable to chemical process	[14]	1998	Yes
1	6.39E-03	Applicable to chemical process	[14]	1998	Yes
100	1.93E-04	Applicable to chemical process	[14]	1998	Yes
100	1.58E-04	Applicable to chemical process	[14]	1998	Yes
1	3.68E-03	Applicable to chemical process	[14]	1998	Yes
1	8.76E-03	Chemical Process	[15]	1995	Yes
100	4.38E-04	Chemical Process	[15]	1995	Yes
1	4.38E-03	Chemical Process	[15]	1995	Yes
100	2.63E-04	Chemical Process	[15]	1995	Yes
1	1.00E-03	Chemical Process	[2]	2009	Yes
10	1.00E-04	Chemical Process	[2]	2009	Yes
100	1.00E-05	Chemical Process	[2]	2009	Yes
100	8.76E-06	Generic	[19]	1982	Yes
100	2.00E-05	Generic	[22]	2005	Yes
0.1	2.40E-05	Hydrocarbons	[8]	2019	Yes
1	1.30E-05	Hydrocarbons	[8]	2019	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
10	7.40E-06	Hydrocarbons	[8]	2019	Yes
100	4.30E-06	Hydrocarbons	[8]	2019	Yes
0.01	2.80E-05	Hydrocarbons	[8]	2019	Yes
0.1	1.30E-05	Hydrocarbons	[8]	2019	Yes
1	6.20E-06	Hydrocarbons	[8]	2019	Yes
10	1.50E-06	Hydrocarbons	[8]	2019	Yes
100	1.20E-06	Hydrocarbons	[8]	2019	Yes
0.01	7.20E-05	Hydrocarbons	[8]	2019	Yes
0.1	1.30E-05	Hydrocarbons	[8]	2019	Yes
1	3.50E-06	Hydrocarbons	[8]	2019	Yes
10	3.50E-06	Hydrocarbons	[8]	2019	Yes
0.01	9.90E-05	Hydrocarbons	[8]	2019	Yes
0.1	2.30E-05	Hydrocarbons	[8]	2019	Yes
1	7.10E-06	Hydrocarbons	[8]	2019	Yes
10	9.00E-06	Hydrocarbons	[8]	2019	Yes
0.01	1.07E-04	Hydrocarbons	[8]	2019	Yes
0.1	2.60E-05	Hydrocarbons	[8]	2019	Yes
1	8.60E-06	Hydrocarbons	[8]	2019	Yes
10	1.20E-05	Hydrocarbons	[8]	2019	Yes
0.01	1.33E-04	Hydrocarbons	[8]	2019	Yes
0.1	8.60E-06	Hydrocarbons	[8]	2019	Yes
1	1.20E-05	Hydrocarbons	[8]	2019	Yes
0.1	2.40E-04	Hydrocarbons	[8]	2019	Yes
1	9.70E-05	Hydrocarbons	[8]	2019	Yes
10	3.90E-05	Hydrocarbons	[8]	2019	Yes
100	1.20E-05	Hydrocarbons	[8]	2019	Yes
0.01	1.30E-04	Hydrocarbons	[8]	2019	Yes
0.1	6.20E-05	Hydrocarbons	[8]	2019	Yes
1	3.00E-05	Hydrocarbons	[8]	2019	Yes
10	7.20E-06	Hydrocarbons	[8]	2019	Yes
100	6.10E-06	Hydrocarbons	[8]	2019	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
0.01	1.85E-04	Hydrocarbons	[8]	2019	Yes
0.1	2.50E-05	Hydrocarbons	[8]	2019	Yes
1	5.60E-06	Hydrocarbons	[8]	2019	Yes
10	4.30E-06	Hydrocarbons	[8]	2019	Yes
0.01	1.96E-04	Hydrocarbons	[8]	2019	Yes
0.1	2.20E-05	Hydrocarbons	[8]	2019	Yes
1	4.40E-06	Hydrocarbons	[8]	2019	Yes
10	2.80E-06	Hydrocarbons	[8]	2019	Yes
0.01	2.06E-04	Hydrocarbons	[8]	2019	Yes
0.1	2.20E-05	Hydrocarbons	[8]	2019	Yes
1	4.10E-06	Hydrocarbons	[8]	2019	Yes
10	2.40E-06	Hydrocarbons	[8]	2019	Yes
0.01	2.28E-04	Hydrocarbons	[8]	2019	Yes
0.1	4.10E-06	Hydrocarbons	[8]	2019	Yes
1	2.40E-06	Hydrocarbons	[8]	2019	Yes
100	1.33E-03	Nuclear	[25]	1989	Yes
1	8.76E-05	Nuclear	[20]	1991	Yes
100	8.76E-07	Nuclear	[20]	1991	Yes
100	3.50E-06	Nuclear	[20]	1991	Yes
100	8.76E-05	Nuclear	[26]	2012	Yes
1	1.83E-04	Nuclear	[29]	2015	Yes
1	3.90E-04	Nuclear	[29]	2015	Yes
1	2.25E-04	Nuclear	[29]	2015	Yes
1	1.13E-03	Nuclear	[29]	2015	Yes
1	6.27E-05	Nuclear	[29]	2015	Yes
1	9.56E-04	Nuclear	[29]	2015	Yes
100	1.28E-05	Nuclear	[29]	2015	Yes
100	2.73E-05	Nuclear	[29]	2015	Yes
100	1.58E-05	Nuclear	[29]	2015	Yes
100	7.91E-05	Nuclear	[29]	2015	Yes
100	4.39E-06	Nuclear	[29]	2015	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	6.69E-05	Nuclear	[29]	2015	Yes
100	4.15E-03	Nuclear	[29]	2015	Yes
100	4.90E-07	Process Equipment	[17]	2005	Yes
100	1.90E-06	Process Equipment	[17]	2005	Yes
100	2.30E-06	Process Equipment	[17]	2005	Yes
1	1.40E-05	Process Equipment	[17]	2005	Yes
1	4.80E-05	Process Equipment	[17]	2005	Yes
1	2.20E-04	Process Equipment	[17]	2005	Yes
1	2.60E-04	Process Equipment	[17]	2005	Yes
1	8.15E-03	Compressed Gas	[14]	1998	No
100	1.05E-03	Compressed Gas	[14]	1998	No
1	5.96E-02	Compressed Gas	[14]	1998	No
100	2.28E-03	Compressed Gas	[14]	1998	No
1	7.36E-02	Compressed Gas	[14]	1998	No
100	2.72E-03	Compressed Gas	[14]	1998	No
1	1.40E-02	Compressed Gas	[14]	1998	No
100	1.75E-04	Compressed Gas	[14]	1998	No
1	9.64E-04	Compressed Gas	[14]	1998	No
1	4.29E-03	Compressed Gas	[14]	1998	No
100	1.23E-03	Compressed Gas	[14]	1998	No
1	2.19E-02	Compressed Gas	[14]	1998	No
100	3.59E-03	Compressed Gas	[14]	1998	No
100	4.20E-03	Compressed Gas	[14]	1998	No
1	1.31E-03	Compressed Gas	[14]	1998	No
100	4.38E-03	Compressed Gas	[15]	1995	No
1	8.76E-02	Compressed Gas	[15]	1995	No
100	4.38E-05	Compressed Gas	[15]	1995	No
1	8.76E-04	Compressed Gas	[15]	1995	No
100	9.00E-06	LNG Applicable	[23]	2019	No
1	1.00E-02	LOX, H_2 applicable	[21]	2021	No

Table A-12 Vessel leak frequency data

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	4.30E-05	Acrylonitrile	[30]	2014	Yes
1	1.05E-02	Applicable to chemical process	[14]	1998	Yes
1	3.24E-02	Applicable to chemical process	[14]	1998	Yes
1	2.28E-02	Chemical Process	[14]	1998	Yes
1	8.76E-04	Chemical Process	[15]	1995	Yes
1	8.76E-04	Chemical Process	[15]	1995	Yes
100	4.38E-05	Chemical Process	[15]	1995	Yes
100	4.38E-05	Chemical Process	[15]	1995	Yes
100	3.33E-03	Chemical Process	[14]	1998	Yes
1	1.00E-05	Chlorine	[18]	2017	Yes
10	5.00E-06	Chlorine	[18]	2017	Yes
10	5.00E-06	Chlorine	[18]	2017	Yes
0.1	4.00E-05	Chlorine	[18]	2017	Yes
10	1.00E-04	Flammable Liquids	[18]	2017	Yes
1	2.50E-03	Flammable Liquids	[18]	2017	Yes
10	2.00E-03	Flammable Liquids	[18]	2017	Yes
10	1.00E-04	Flammable Contents	[18]	2017	Yes
1	1.00E-03	Flammable Contents	[18]	2017	Yes
10	9.64E-07	Generic	[16]	2005	Yes
100	5.00E-08	Generic	[22]	2005	Yes
1	1.00E-04	Generic	[28]	2009	Yes
1	1.00E-04	Generic	[22]	2005	Yes
1	1.00E-04	Generic	[22]	2005	Yes
1	1.00E-04	Generic	[22]	2005	Yes
1	1.00E-05	Generic	[22]	2005	Yes
100	1.00E-08	Generic	[22]	2005	Yes
100	1.00E-08	Generic	[22]	2005	Yes
100	5.00E-06	Generic	[22]	2005	Yes
100	5.00E-07	Generic	[22]	2005	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
100	1.25E-08	Generic	[22]	2005	Yes
100	5.00E-07	Generic	[22]	2005	Yes
100	5.00E-08	Generic	[22]	2005	Yes
100	5.00E-07	Generic	[22]	2005	Yes
100	5.08E-05	Generic	[28]	2009	Yes
1	9.64E-06	Generic	[16]	2005	Yes
100	5.00E-06	Generic	[28]	2009	Yes
100	4.70E-07	Hydrocarbons	[7]	2010	Yes
100	3.60E-05	Hydrocarbons	[8]	2019	Yes
0.1	5.00E-04	Hydrocarbons	[8]	2019	Yes
0.01	5.00E-04	Hydrocarbons	[8]	2019	Yes
0.01	2.30E-05	Hydrocarbons	[7]	2010	Yes
10	1.40E-04	Hydrocarbons	[8]	2019	Yes
1	1.40E-04	Hydrocarbons	[8]	2019	Yes
1	7.10E-06	Hydrocarbons	[7]	2010	Yes
0.1	4.40E-07	Hydrocarbons	[7]	2010	Yes
1	2.60E-04	Hydrocarbons	[8]	2019	Yes
0.1	2.60E-04	Hydrocarbons	[8]	2019	Yes
0.1	1.20E-05	Hydrocarbons	[7]	2010	Yes
1	4.60E-07	Hydrocarbons	[7]	2010	Yes
100	7.40E-05	Hydrocarbons	[8]	2019	Yes
10	3.80E-05	Hydrocarbons	[8]	2019	Yes
10	4.30E-06	Hydrocarbons	[7]	2010	Yes
1	1.00E-05	Hydrocarbons	[7]	2010	Yes
100	2.30E-05	Hydrocarbons	[7]	2010	Yes
100	2.30E-06	Hydrocarbons	[7]	2010	Yes
100	1.00E-07	Hydrocarbons	[7]	2010	Yes
100	2.50E-08	Hydrocarbons	[7]	2010	Yes
100	1.00E-08	Hydrocarbons	[7]	2010	Yes
10	5.00E-05	Non-Flammable Contents	[18]	2017	Yes
1	5.00E-04	Non-Flammable Contents	[18]	2017	Yes

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
10	2.70E-03	Olefins	[26]	2012	Yes
10	1.80E-03	Olefins	[26]	2012	Yes
1	5.00E-04	Process Equipment	[17]	2005	Yes
100	1.10E-04	Process Equipment	[17]	2005	Yes
10	4.00E-05	UNSP	[26]	2012	Yes
10	4.20E-05	UNSP	[26]	2012	Yes
10	1.00E-06	UNSP	[26]	2012	Yes
1	1.68E-06	Unspecified	[31]	2014	Yes
100	8.63E-03	Unspecified	[25]	1989	Yes
100	9.55E-05	Unspecified	[25]	1989	Yes
100	1.14E-10	Unspecified	[31]	2014	Yes
10	1.00E-04	Multiple, Applicable to LPG	[30]	2014	Yes
10	1.00E-04	Ammonia, LPG, LNG	[18]	2017	Yes
10	1.00E-05	Ammonia, LPG, LNG	[18]	2017	Yes
1	8.00E-05	Ammonia, LPG, LNG	[18]	2017	Yes
1	3.00E-05	Ammonia, LPG, LNG	[18]	2017	Yes
1	1.00E-05	Applicable to LPG	[18]	2017	Yes
10	5.00E-06	Applicable to LPG	[18]	2017	Yes
10	5.00E-06	Applicable to LPG	[18]	2017	Yes
1	2.01E-03	Compressed Gas	[14]	1998	No
100	6.57E-04	Compressed Gas	[14]	1998	No
10	8.76E-04	Compressed Gas	[15]	1995	No
100	4.38E-05	Compressed Gas	[15]	1995	No
100	8.76E-06	Generic, LNG	[19]	1982	No
100	8.76E-07	Generic, LNG	[19]	1982	No
100	1.00E-07	LNG	[32]	2003	No
100	3.00E-05	LNG	[32]	2003	No
100	5.00E-07	LNG	[32]	2003	No
10	2.50E-03	LNG Applicable	[23]	2019	No
1	1.00E-04	LNG Applicable	[23]	2019	No
10	6.32E-07	LNG, LNG Applicable	[33]	2006	No

Leak Bin (%)	Leak Frequency	Applicability or Source Fuel	Reference	Published	Used in model?
10	3.47E-06	LNG, LNG Applicable	[33]	2006	No
10	1.63E-06	LNG, LNG Applicable	[33]	2006	No
10	4.47E-06	LNG, LNG Applicable	[33]	2006	No
10	8.05E-06	LNG, LNG Applicable	[33]	2006	No
10	3.27E-05	LNG, LNG Applicable	[33]	2006	No
10	1.08E-04	LNG, LNG Applicable	[33]	2006	No
10	1.33E-04	LNG, LNG Applicable	[33]	2006	No
10	1.00E-06	LNG, LNG Applicable	[18]	2017	No
1	3.00E-06	LNG, LNG Applicable	[18]	2017	No
10	1.00E-04	LOX, LOX Applicable	[18]	2017	No
10	1.00E-05	LOX, LOX Applicable	[18]	2017	No
1	8.00E-05	LOX, LOX Applicable	[18]	2017	No
1	5.00E-05	LOX, LOX Applicable	[18]	2017	No
10	2.00E-04	Multiple, Applicable to LNG	[30]	2014	No
10	6.40E-06	NUC	[26]	2012	No

APPENDIX B. LEAK FREQUENCY DISTRIBUTION STATISTICS AND DISTRIBUTIONS

This appendix provides the arithmetic mean, 5th percentile, median, and 95th percentiles of the estimated LPG leak frequency distributions. The leak frequency distributions are estimated by sampling from the normal distributions on the log leak frequency (Section 3) and exponentiating the samples. The median is the best characterization of the center of the leak frequency distribution because the leak frequency distributions are log-normal, so the arithmetic mean can be in the upper tail of the distribution, making it a highly conservative estimate. The table also includes the means (μ) and standard deviations (σ) of the log-leak frequency distributions. These distributions can be used to sample leak frequencies by sampling log-leak frequencies from the normal distribution, Normal(μ, σ), and exponentiating the samples.

As described in Section 2.2, the model fitting procedure uses the mean (μ) and precision (τ) parameterization of the normal distribution; we present the final result using the mean and standard deviation parameterization since that is more common in non-Bayesian software tools. These results can be converted back to the mean and precision parameterization using $\tau = 1/\sigma^2$ (the mean is unchanged).

Table B-1 Recommended point estimates and statistics for LPG leak frequencies with normal parameters for the log-leak frequency normal distributions

Component	Leak Bin (%)	Mean	5th Perc.	Median	95th Perc.	μ	σ
Filters	0.01	2.64E-03	9.48E-04	2.28E-03	5.48E-03	-6.08E+00	5.38E-01
	0.1	1.01E-03	3.90E-04	8.79E-04	2.02E-03	-7.03E+00	5.05E-01
	1	7.38E-03	1.32E-05	3.49E-04	8.29E-03	-7.98E+00	1.97E+00
	10	2.07E-04	4.20E-05	1.21E-04	5.63E-04	-8.93E+00	8.07E-01
	100	5.48E-02	5.08E-07	5.39E-05	4.21E-03	-9.88E+00	2.76E+00
Flanges	0.01	5.28E-05	1.41E-05	4.45E-05	1.18E-04	-1.01E+01	6.57E-01
	0.1	3.80E-05	3.49E-06	1.93E-05	1.20E-04	-1.08E+01	1.09E+00
	1	1.45E-04	2.62E-07	9.08E-06	3.08E-04	-1.16E+01	2.16E+00
	10	5.15E-06	1.47E-06	4.11E-06	1.21E-05	-1.24E+01	6.45E-01
	100	8.12E-06	1.26E-07	1.92E-06	2.77E-05	-1.32E+01	1.65E+00
Hoses (Annual)	0.01	3.75E-05	6.60E-06	2.67E-05	1.01E-04	-1.05E+01	8.37E-01
	0.1	1.23E-04	3.83E-06	3.85E-05	3.97E-04	-1.02E+01	1.42E+00
	1	4.25E-02	4.67E-07	5.71E-05	6.82E-03	-9.77E+00	2.93E+00
	10	1.92E-04	1.54E-05	7.83E-05	5.64E-04	-9.39E+00	1.11E+00
	100	2.62E-03	3.01E-06	1.32E-04	3.89E-03	-9.01E+00	2.20E+00
Hoses (Per Transfer)	0.01	3.48E-04	7.02E-06	9.76E-05	1.43E-03	-9.23E+00	1.65E+00
	0.1	4.06E-05	4.69E-06	2.45E-05	1.28E-04	-1.06E+01	1.02E+00
	1	7.28E-06	2.18E-06	6.27E-06	1.56E-05	-1.20E+01	6.15E-01

Component	Leak Bin (%)	Mean	5th Perc.	Median	95th Perc.	μ	σ
	10	3.34E-06	3.67E-07	1.30E-06	1.04E-05	-1.34E+01	1.04E+00
	100	6.32E-04	4.72E-09	4.90E-07	1.27E-05	-1.48E+01	2.45E+00
Instruments	0.01	8.91E-04	2.15E-04	6.86E-04	2.22E-03	-7.28E+00	7.14E-01
	0.1	3.63E-04	1.14E-04	2.96E-04	8.19E-04	-8.11E+00	6.05E-01
	1	1.52E-04	5.25E-05	1.31E-04	3.16E-04	-8.94E+00	5.51E-01
	10	6.57E-05	2.38E-05	5.67E-05	1.36E-04	-9.78E+00	5.35E-01
	100	3.09E-05	8.61E-06	2.46E-05	7.24E-05	-1.06E+01	6.53E-01
Joints	0.01	1.58E+02	1.43E-02	9.15E-01	5.87E+01	-8.86E-02	2.55E+00
	0.1	1.50E+00	7.63E-03	1.61E-01	3.41E+00	-1.83E+00	1.87E+00
	1	6.39E-02	3.84E-03	2.83E-02	2.09E-01	-3.56E+00	1.22E+00
	10	6.48E-03	1.59E-03	4.99E-03	1.57E-02	-5.30E+00	7.07E-01
	100	1.15E-03	2.79E-04	8.78E-04	2.76E-03	-7.04E+00	7.07E-01
Loading Arms (Annual)	0.01	1.92E-02	1.12E-03	8.32E-03	6.17E-02	-4.79E+00	1.23E+00
	0.1	7.40E-03	1.01E-03	4.68E-03	2.16E-02	-5.37E+00	9.37E-01
	1	3.42E-03	8.36E-04	2.63E-03	8.27E-03	-5.94E+00	7.07E-01
	10	1.79E-03	5.44E-04	1.48E-03	4.04E-03	-6.51E+00	6.14E-01
	100	1.26E-03	1.99E-04	8.33E-04	3.49E-03	-7.09E+00	8.80E-01
Loading Arms (Per Transfer)	0.01	1.21E-04	1.88E-06	3.04E-05	4.25E-04	-1.04E+01	1.67E+00
	0.1	1.97E-05	1.48E-06	1.10E-05	6.39E-05	-1.15E+01	1.16E+00
	1	4.93E-06	9.55E-07	3.94E-06	1.20E-05	-1.25E+01	7.88E-01
	10	1.93E-06	3.79E-07	1.27E-06	5.36E-06	-1.35E+01	8.14E-01
	100	1.37E-06	3.28E-08	5.24E-07	4.67E-06	-1.46E+01	1.53E+00
Pipes	0.01	1.19E-05	1.02E-06	6.07E-06	3.85E-05	-1.20E+01	1.11E+00
	0.1	6.32E-06	6.67E-07	3.59E-06	1.97E-05	-1.25E+01	1.04E+00
	1	1.15E-05	1.11E-07	2.14E-06	3.97E-05	-1.31E+01	1.79E+00
	10	3.04E-06	1.47E-07	1.24E-06	1.06E-05	-1.36E+01	1.30E+00
	100	3.71E-06	4.26E-08	7.24E-07	1.27E-05	-1.41E+01	1.74E+00
Pumps	0.01	4.40E-03	9.97E-04	3.22E-03	1.13E-02	-5.72E+00	7.44E-01
	0.1	1.54E-03	3.67E-04	1.19E-03	3.77E-03	-6.74E+00	7.14E-01
	1	1.63E-03	3.26E-05	4.31E-04	5.64E-03	-7.75E+00	1.57E+00
	10	2.06E-04	4.70E-05	1.55E-04	5.22E-04	-8.77E+00	7.37E-01
	100	3.83E-04	2.65E-06	5.64E-05	1.22E-03	-9.78E+00	1.87E+00

Component	Leak Bin (%)	Mean	5^{th} Perc.	Median	95^{th} Perc.	μ	σ
Valves	0.01	1.16E-04	3.29E-05	9.63E-05	2.62E-04	-9.26E+00	6.35E-01
	0.1	9.43E-05	9.36E-06	5.12E-05	2.99E-04	-9.87E+00	1.06E+00
	1	2.05E-03	3.18E-07	2.84E-05	2.49E-03	-1.05E+01	2.73E+00
	10	3.30E-05	2.41E-06	1.51E-05	1.07E-04	-1.11E+01	1.16E+00
	100	1.14E-04	2.21E-07	8.57E-06	3.02E-04	-1.17E+01	2.20E+00
Vessels	0.01	2.94E-04	3.17E-05	1.55E-04	8.75E-04	-8.74E+00	1.02E+00
	0.1	8.78E-04	4.81E-06	8.24E-05	1.54E-03	-9.39E+00	1.77E+00
	1	2.34E-03	5.79E-07	4.42E-05	3.24E-03	-1.00E+01	2.63E+00
	10	2.13E-04	8.18E-07	2.33E-05	6.38E-04	-1.07E+01	2.03E+00
	100	3.68E+00	1.31E-08	1.19E-05	1.21E-02	-1.13E+01	4.19E+00

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