SANDIA REPORT
SAND2022-14164
Printed October 2022

Sandia National Laboratories

Compressed Natural Gas Component Leak Frequency Estimation

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ABSTRACT

The frequency of unintended releases in a compressed natural gas system is an important aspect of the system quantitative risk assessment. The frequencies for possible release scenarios, along with engineering models, are utilized to quantify the risks for compressed natural gas facilities. This report documents component leakage frequencies representative of compressed natural gas components that were estimated as a function of the normalized leak size. A Bayesian statistical method was used which results in leak frequency distributions for each component which represent variation and uncertainty in the leak frequency. The analysis shows that there is high uncertainty in the estimated leak frequencies due to sparsity in compressed natural gas data. These leak frequencies may still be useful in compressed natural gas system risk assessments, as long as this high uncertainty is acknowledged and considered appropriately.

ACKNOWLEDGEMENTS

This research was supported by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office, as part of the Technology Integration program and Technical Assistance sub-program under the supervision of Mark Smith and Michael Laughlin.

The authors would like to thank YeongAe Heo and Myra Blaylock for their careful reviews and suggestions for improving this report.

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ACRONYMS AND TERMS

Acronym/Term	Definition
CNG	compressed natural gas
MCMC	Markov chain Monte Carlo
QRA	quantitative risk assessment

1. INTRODUCTION

The frequency of unintended releases in a compressed natural gas (CNG) system is an important aspect of the system quantitative risk assessment (QRA). The frequencies for possible release scenarios, along with engineering models, are utilized to quantify the risks for compressed natural gas facilities. Generally, a QRA is used to quantify the risk associated with unintended releases of CNG, identify significant risk contributors for a given type of facility, and inform prevention and mitigation strategies for stakeholders. However, not all 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. Establishing more realistic leak frequencies can improve these QRAs by removing some of this conservatism.

This report documents estimation of component leak frequencies representative of CNG components as a function of the normalized leak area. The goal of the analysis was to assess the current state-of-knowledge on CNG component leak frequencies and derive up-to-date leak frequency estimates for use in QRA. A literature review was conducted to identify applicable leak frequencies, which are listed in Appendix A. The most comprehensive references from this review are more than 20 years out of date [1, 2] but more recent references were available for some components [3, 4, 5, 6]. Hence, both are used, and the estimates documented here summarize the cumulative state-of-knowledge on CNG leak frequencies, which may be conservative if leak frequencies have decreased over time.

Additionally, uncertainty may be underestimated because the compressed gas data is so sparse. It is possible that the published frequencies only represent a subset of compressed gas systems and do not represent the full range of frequencies that can be expected between compressed gas systems. For these reasons, the leak frequencies estimated in this report should be treated cautiously, with the understanding that the frequencies and their uncertainty could change significantly with the addition of more data.

The data collected in the literature review are discussed in Chapter 2. A Bayesian statistical model was fit with the data from the literature review to estimate leak frequency distributions as in previous analyses for hydrogen [7, 8, 9] and liquid natural gas [10]. This model is discussed in Section 3; Section 3.1 describes the model and its mathematical definition and Section 3.2 discusses how the model is fit.

The estimated leak frequencies are presented in Section 4.

2. DATA

A literature review was performed to find leak frequency data for compressed gas systems, as well as other source fuels. Data from other source fuels were included in the review because analyses for other source fuels have shown that this more generic data can be useful for reducing uncertainty [10]. All data had to provide enough information to be binned by component type (compressor, filter, flange, heat exchanger, hose, instrument, joint, jumper, valve, or vessel) and either qualitatively or quantitatively into a fractional leak area bin of 0.01%, 0.1%, 1%, 10%, or 100% (see Section 3). The level of detail that can be found within data determines the component and leak area bins. For example, if published data do not provide sufficient detail for different types and sizes of valves, then all valve data is combined to predict valve frequencies which would be applied to every size and type of valve in a QRA. In the absence, therefore, of more detailed data, data were binned independently of component size and type.

Qualitative descriptions were mapped to bins with "rupture" mapping to 100%, "major" mapping to 10%, "medium" mapping to 1%, "minor" mapping to 0.1%, and "very small" mapping to 0.01%. When enough information was provided to estimate the cross-sectional area of the component and the cross-sectional area of the leak (assuming circular areas for both), the ratio of these areas was calculated [10] to bin the data. The component categories reflect the specificity of data from the literature review; there are not enough specific data points to describe leak frequencies for different types and sizes of valves, for example, so all valve data points are combined into a single category. The binned data from this literature review are listed in Appendix A with their corresponding references.

Ideally, CNG component leak frequencies would be based solely on CNG component leak data. However, there is an insufficient quantity of publicly available data to accomplish highly accurate and/or precise frequencies. Additionally, data may be published based on different categories of components, component specificity, component sizes, leak sizes or leak size bins, operational conditions, etc. or may be biased due to reporting requirements that apply only to larger leaks. Some sources include accidental releases due to operator actions as leaks, whereas other sources only include accidental releases due to mechanical failure. These factors can prevent data from different sets from being combined.

To mitigate these challenges, this analysis includes generic leak frequencies. However, these generic frequencies are used differently than in similar analyses for hydrogen [7, 8, 9] and liquid natural gas [10]. Generic frequencies are derived from, or are applicable to, a broader range of energy technologies than CNG. The benefit of using generic data is that it enables estimates for components with no CNG data. In previous analyses, these generic data were also useful for reducing uncertainty in estimates for components with some fuel-specific data [7, 8, 9, 10, 11]. There are downsides to this approach. First, the estimates may be biased if true CNG leak frequencies differ substantially from generic data. Secondly, the uncertainty in the estimates may be poorly estimated. For example, this can happen because there is more variation in the generic data due to diversity in the different types of systems included, resulting in overestimation of uncertainty.

Comparison of compressed gas data with generic data shows that, on average, compressed gas leak frequencies are higher than generic leak frequencies. This can be seen in Figure 2-1 through Figure 2-9, which show the compressed gas data points collected for each component in this analysis compared to generic data. Plots for components with no compressed gas data are shown in Figure 2-10 and Figure 2-11. This trend of higher leak frequencies for compressed gas systems may indicate that they are more prone to leakage than other systems. Alternatively, there is also not as much

compressed gas data and much of it is out-of-date, so it could be the case that the data reflects higher leak frequencies than is currently typical for CNG systems. However, in the absence of more information, it is prudent to conclude that compressed gas systems (like CNG) are expected to leak more than other systems. Because of this, generic data was only included in leak frequencies when no CNG data was available (instruments and joints). The leak frequencies for compressors, filters, flanges/gaskets, heat exchangers, hoses, jumpers, pipes, valves, and vessels are derived solely from published compressed gas frequencies. This is a departure from previous uses of the model [7, 8, 9, 10, 11], which were able to combine different types of data for improved estimates.

The data considered for this analysis are listed in Appendix A and summarized in Table 2-1.

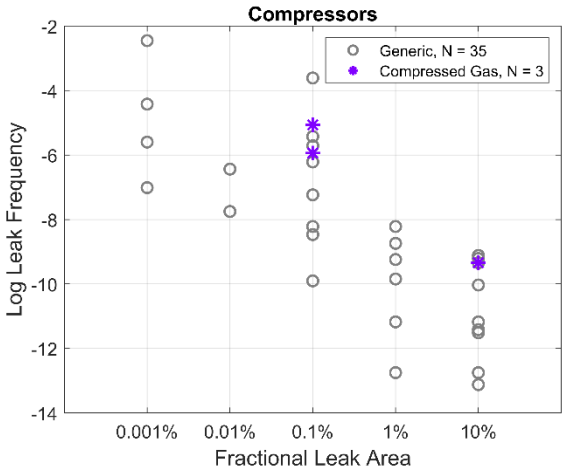


Figure 2-1 Scatterplot of binned data for compressors

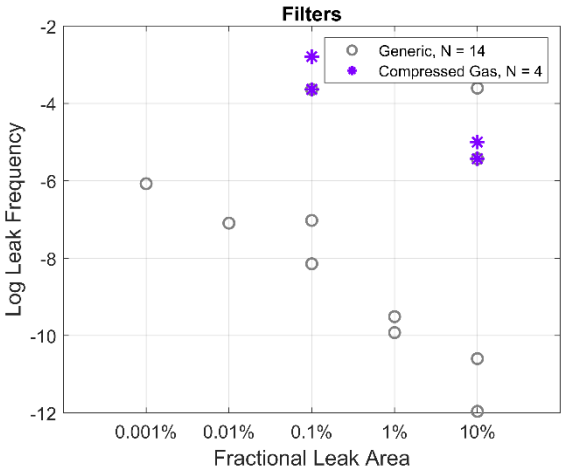


Figure 2-2 Scatterplot of binned data for filters

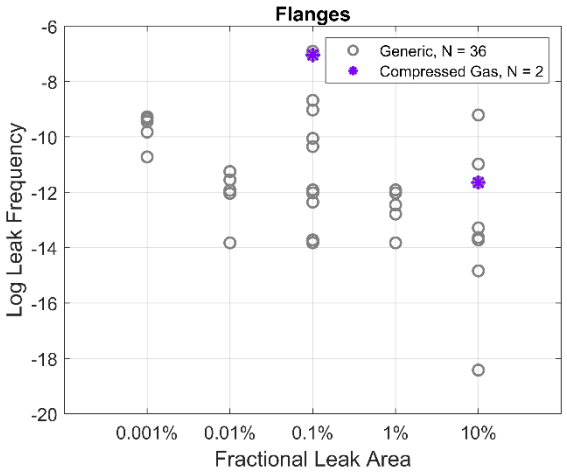


Figure 2-3 Scatterplot of binned data for flanges

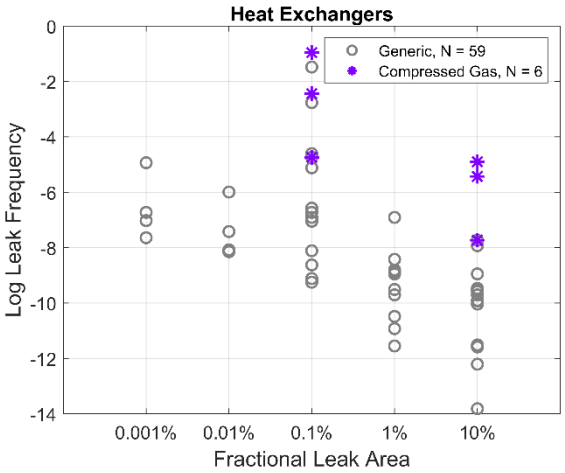


Figure 2-4 Scatterplot of binned data for heat exchangers

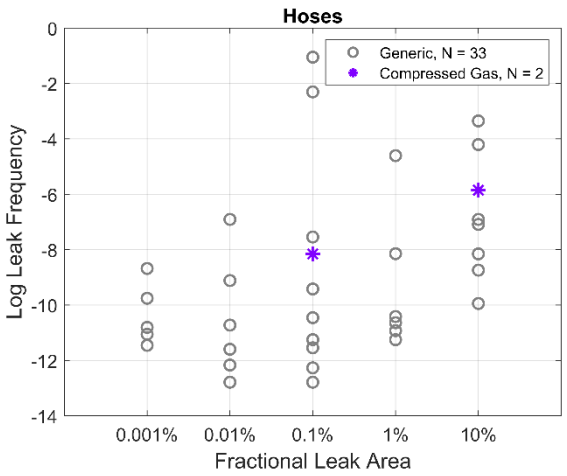


Figure 2-5 Scatterplot of binned data for hoses

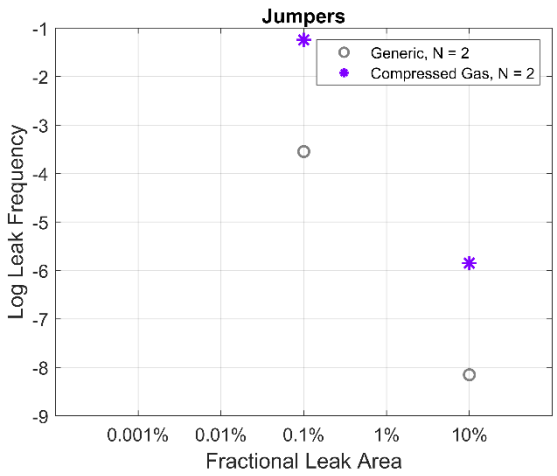


Figure 2-6 Scatterplot of binned data for jumpers

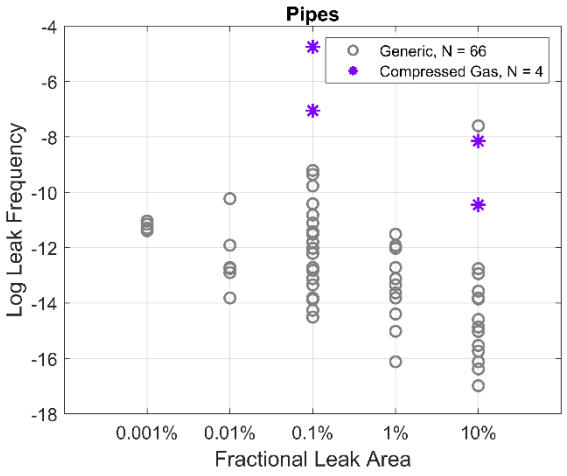


Figure 2-7 Scatterplot of binned data for pipes

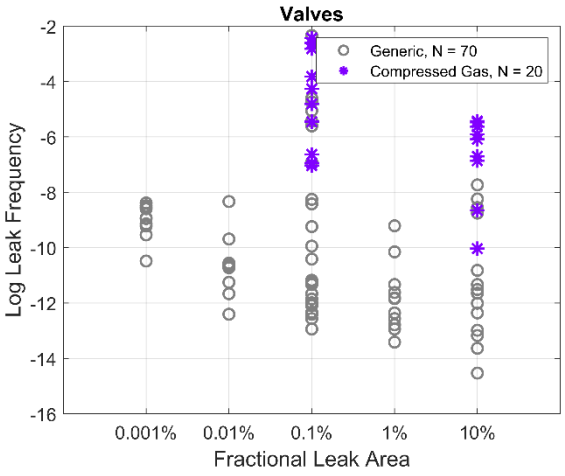


Figure 2-8 Scatterplot of binned data for valves

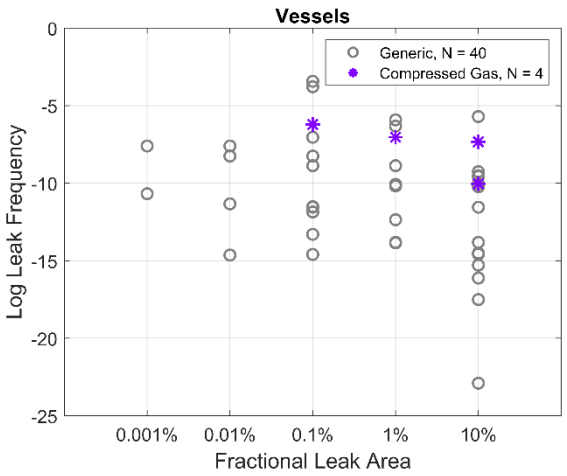


Figure 2-9 Scatterplot of binned data for vessels

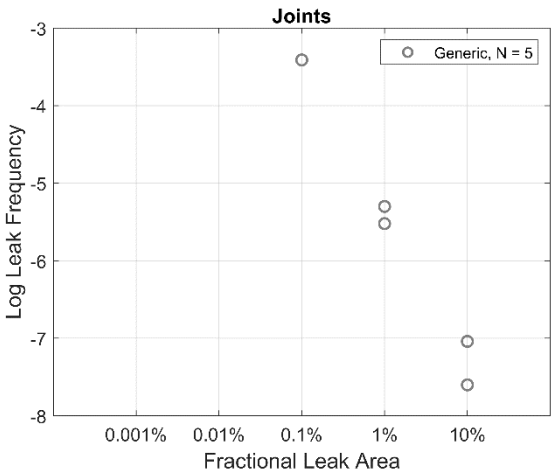


Figure 2-10 Scatterplot of binned data for joints

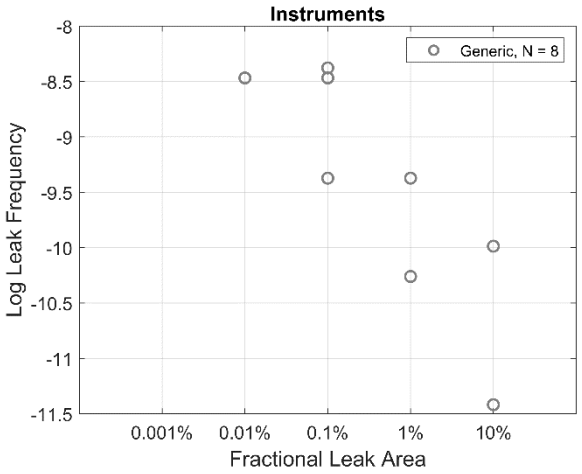


Figure 2-11 Scatterplot of binned data for instruments

Table 2-1 Data point counts for the compressed natural gas analysis

Component	Generic Data	Compressed Gas Data
Compressors	35	**3**
Filters	14	**4**
Flanges/Gaskets	36	**2**
Heat Exchangers	59	**6**
Hoses	33	**2**
Instruments	**8**	0
Joints	**5**	0
Jumpers	2	2
Pipes	66	**4**

Component	Generic Data	Compressed Gas Data
Valves	70	**20**
Vessels	40	**4**

Bold and underlined indicates data that were used in the final analysis

3. CNG LEAK FREQUENCY MODEL

This chapter describes the Bayesian model used to derive CNG leak frequencies; models of the same form have previously been applied [7, 8, 9, 10, 11] to hydrogen and liquid natural gas systems. The Bayesian model was used because of the limited quantity of data available for some components. The benefit of the Bayesian model is that it makes more efficient use of small data sets than frequentist methods.

The model described in this chapter is structured to related leak frequency to the fractional leak area of the component cross-section. This formulation is what enables leak frequencies for components of potentially different size to be combined. As in previous analyses [7, 8, 9, 10, 11], the fractional leak areas were also binned by order of magnitude of the fractional leak area. The bins are 0.01%, 0.1%, 1%, 10%, or 100% fractional leak areas as compared to the cross-sectional flow area of interconnecting piping. Because of this binning, the model predicts leak frequencies for each of the five fractional leak area bins, rather than for any fractional leak area between the bins. Median log leak frequencies for fractional leak areas between bins (e.g., 2% fractional leak area) may be estimated by interpolating between bins, but uncertainty should not be interpolated between bins.

The model is described in this section as it pertains to one component; the process is simply repeated for each component. Section 3.1 describes and mathematically defines of the model form and Section 3.2 discusses how the model is fit with the data from Section 2.

3.1. Definition of the Leak Frequency Model

The model described in this section is designed to accomplish two goals for each component: 1) characterize the expected leak frequency within each specific leak area bin, and 2) model the relationship between the leak area bins. The description of the model in this section is a revised version of the description in [5].

Conceptually, there should be a separate leak frequency distribution for each leak area bin, but the different leak area bins should be mathematically related to each other. For example, larger leaks are typically more likely to result in dangerous situations, so people are more likely to design systems that prevent larger leaks from occurring for most components.

The leak frequency model is Bayesian. Its structure consists of a line which models the log leak frequency as a function of the leak area bin. The slope and intercept of this line are random variables. Normal distributions on the log leak frequency are centered around this line and the precisions of the distributions for each leak area bin are also random variables. When the model is fit, it is fully defined by probability distributions on the line parameters and normal distribution precisions. When propagated through the mathematical structure of the model, random samples of the line parameters and precisions result in a distribution of log leak frequency predictions for each leak area bin.

To define the model mathematically, first denote the leak area bins by $j \in \{1,2,\ldots,5\}$, with each bin corresponding to an order of magnitude increase in fractional leak area. Also denote the fractional leak area for the j^{th} bin by LA_j, and the mean of the underlying normal distribution on the log leak frequency by $\mu_{LF,j}$. To accomplish our first goal, we define the probabilistic model in Equation 1. This describes a normally distributed log leak frequency for the j^{th} leak area bin centered around $\mu_{LF,j}$ with precision τ_j; the normal distribution is denoted by $N(\cdot,\ \cdot)$. As discussed above, the parameters of our probabilistic model are treated as random variables, so Equation 2 describes uncertainty in the precision of our model (τ_j) using a gamma distribution with shape and rate

hyperparameters s_j and r_j. The gamma distribution was chosen for τ_j, as is common in Bayesian analysis, because this distribution restricts the precision to only positive values, which is necessary for the distribution in Equation 1 to be defined.

Our second goal is to functionally relate the leak area bins to each other. This is accomplished with Equation 3, which assumes a linear relationship between the logs of the means, $\log(\mu_{LF})$, of the underlying normal distributions on log leak. As with the probabilistic portion of the model, we characterize uncertainty describing the intercept, α_1, and slope, α_2, of this linear relationship as random variables according to the normal distributions in Equations 4 and 5, respectively. Normal distributions were selected for α_1 and α_2 so that the sign of these parameters could be determined by data; in particular, the slope may be positive or negative depending on the component. α_{11} and α_{12} are the mean and precision hyperparameters for the intercept α_1. Likewise, α_{21} and α_{22} are the mean and precision hyperparameters for the slope α_2.

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

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

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

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

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

The model is fit by using the data (Section 2) to calculate values for the hyperparameters $s_j, r_j, \alpha_{11}, \alpha_{12}, \alpha_{21}, \alpha_{22}$, as described in Section 3.2.

A notional version of the model is plotted in Figure 3-1, where the normal distributions of leak frequencies are represented with violin plots (symmetrical densities) when fixed values are used for α_1, α_2, and τ_j. This can be thought of as a single realization of the model. The model is defined by specific values for $s_j, r_j, \alpha_{11}, \alpha_{12}, \alpha_{21}, \alpha_{22}$ and includes all possible lines and distributions that can be defined by drawing new samples from the resulting distributions on τ_j, α_1, and α_2. The linear relationship is a strong assumption in the model, but it allows data from one leak size bin to affect the values of s_j and r_j for another bin even if the other bin has no data.

The spread in the distributions changes between each bin in Figure 3-1 because the precision of the normal distribution changes between each bin. The precision for each bin reflects the quantity of data and variation within the data for each bin. This may reflect state-of-knowledge uncertainty; if one bin contains more data than the other bins, then the state-of-knowledge for that bin is higher and the precision may be higher as a result. However, the precision may also reflect another type of uncertainty, which is inherent variability within the population. One bin may contain more data than the others but there may be higher variation within that data. This would result in a lower precision for that bin despite the higher state-of-knowledge.

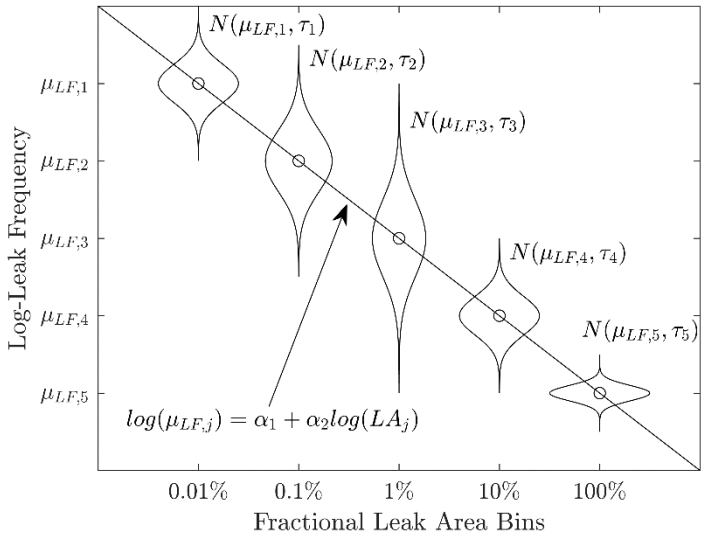


Figure 3-1 Notional illustration of a single realization of the leak frequency model from [11] for fixed values of α_1, α_2, and τ_j.

3.2. Bayesian Update

To describe the Bayesian updating procedure, we first present a very brief review of basic Bayesian concepts and terminology. Bayesian statistics are governed by Bayes Theorem, one form of which is shown in Equation 6, where θ is a vector of parameters and x is observed data from the probability distribution with parameters θ.

$$p(\theta|x) \propto p(x|\theta)p(\theta) \tag{6}$$

In Equation 6, $p(x|\theta)$ is called the likelihood, which is the joint probability distribution of data for fixed values of θ. The function $p(\theta)$ is called the prior, and this function is used within a Bayesian analysis to represent prior knowledge or analyst belief about the parameters θ. $p(\theta|x)$ is called the posterior and this is what we are trying to estimate in our analysis. It is the uncertainty distribution on our parameters given our data and initial knowledge, which we calculate by convolving the likelihood and the prior.

For the leak frequency model described in Section 3.1, the same concept from Equation 6 applies; the underlying model is just more complicated than a single probability distribution. Equations 2, 4, and 5 are the priors in the leak frequency model and are defined by setting initial values for s_j, r_j, α_{11}, α_{12}, α_{21}, and α_{22}. The Bayesian update is performed to adjust these initial values based on known leak frequencies from the data (Section 2) and the relationships specified in Equations 1 and 3. The new values for s_j, r_j, α_{11}, α_{12}, α_{21}, and α_{22} define the posterior distributions on τ_j, α_1, and α_2. Heuristically, we specify initial values for s_j, r_j, α_{11}, α_{12}, α_{21}, and α_{22}. Then the Bayesian procedure compares the leak frequencies predicted from these values to the leak frequencies in our data set, and outputs new values of s_j, r_j, α_{11}, α_{12}, α_{21}, and α_{22} based on this comparison. The posterior distributions are propagated through Equation 1 to generate the predictive posterior (i.e. the uncertainty distribution on leak frequency). This process is illustrated in Figure 3-2.

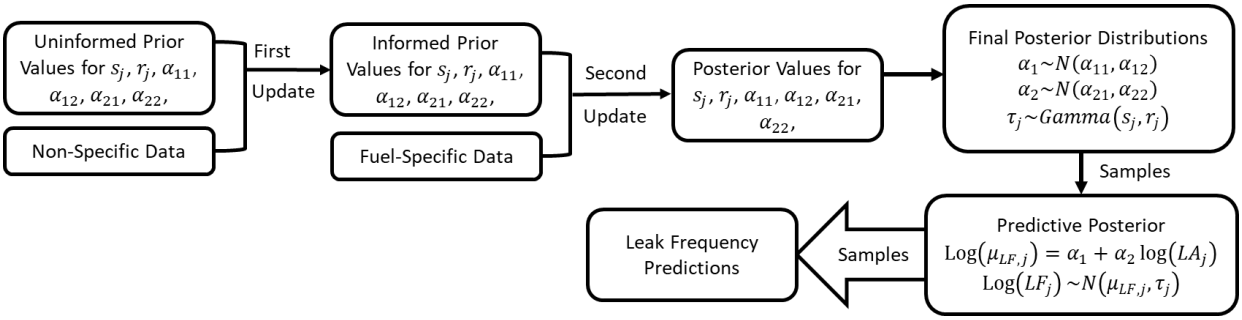


Figure 3-2 Diagram showing the flow of information to perform a Bayesian update of a leak frequency model for any specific fuel [11]

This process was modified based on analysis of the available data (Section 2) to avoid fitting a non-conservative model. Unlike with previous fuel types [7, 8, 9, 10, 11], the non-specific (or generic) data were not consistent with the fuel-specific (compressed gas) data. Based on the available generic and compressed gas data, compressed gas leak frequencies are on average higher than frequencies for other fuel types. If the lower generic leak frequencies are included in the model update, they will bias the model fit towards lower leak frequencies. This would be non-conservative because lower leak frequencies in the QRA would suggest the system leaks less and is thus safer than suggested by the CNG data.

Hence, the approach described in Figure 3-2 was modified to exclude the generic data when possible. The model is only updated once with either generic data (when no compressed gas data are available) or with compressed gas data (when available), never both. The consequences of this change are that: 1) for components without compressed gas data, the leak frequencies may be non-conservative, and 2) for components with compressed gas data, the leak frequencies may be conservative and the variability in leak frequencies may be underestimated. The modified approach is diagramed in Figure 3-3

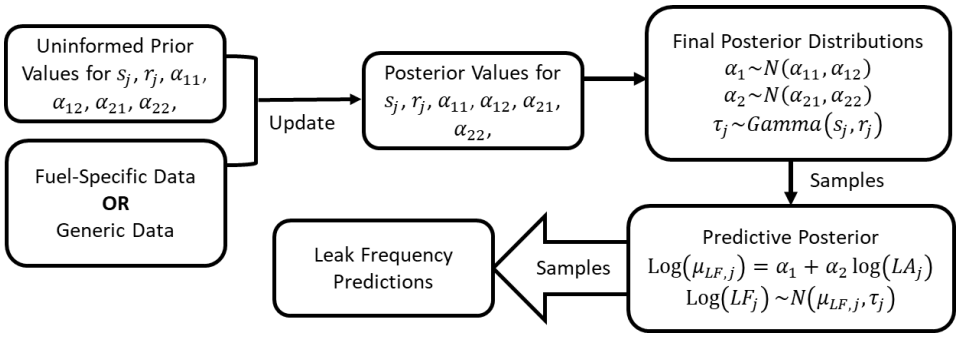


Figure 3-3 Diagram showing the flow of information within the Bayesian analysis that produces the leak frequency prediction model

The specification of initial values for s_j, r_j, α_{11}, α_{12}, α_{21}, and α_{22} is a significant subjective choice which affects the final model results. The priors selected for α_1 and α_2 were:

$$\alpha_1 \sim N(0, 0.001) \tag{7}$$

$$\alpha_2 \sim N(0, 0.001) \tag{8}$$

The initial values were selected to center the linear assumption around a horizontal line at 0 with low precision; this allows even a small amount of data to significantly change the slope and location of the line. The priors selected for τ_j were:

$$\tau_j \sim Gamma(1,5) \tag{9}$$

The gamma distribution with shape and scale parameters both equal to 1 is a common uninformed prior for precision parameters in Bayesian analysis. It defines a distribution concentrated around low precision values, representing an assumption that state of knowledge is low. However, it was shown in [8] and [10] that sparse leak frequency data is often not sufficient to fit a leak frequency model with a finite mean when such a low initial state of knowledge of assumed. Those analyses also showed that the scale parameter could be incremented to spread the precision distribution out, representing an initial assumption that the state of knowledge could be very low (compared to assuming it is low). The effects of this adjustment to the gamma distribution are shown in Figure 3-4. Based on the analysis for liquified natural gas in [10], the scale parameter for the CNG leak frequency model was chosen to be 5. This value did not need to be further incremented, since the mean leak frequency predictions for each component were finite when this value was used.

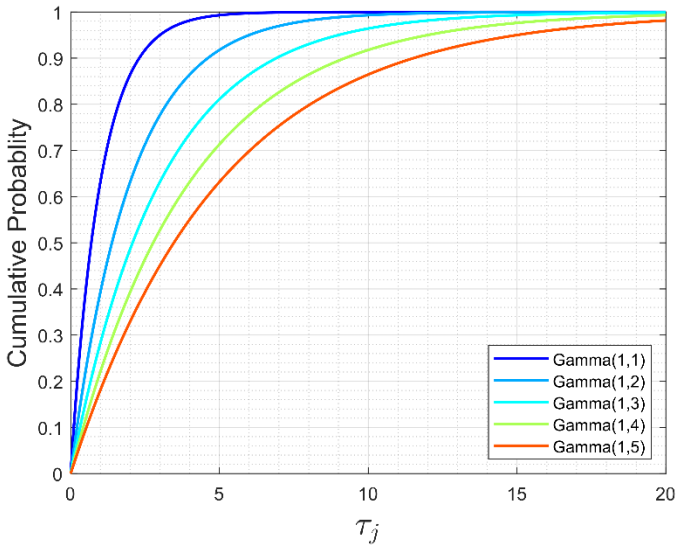


Figure 3-4 Demonstration of the effects that incrementing the scale parameter has on the gamma distribution

With respect to implementation, the leak frequency model was updated using standard Bayesian analysis tools. We used the open source software JAGS [12], which we called using the rjags package in R [13, 14] as demonstrated by Kruschke [15]. Hence, the Bayesian updating procedure is standard with respect to how Markov chain Monte Carlo (MCMC) sampling is applied to estimate the posterior distributions of the model parameters and, ultimately, sample leak frequency predictions. Our analyses for compressed natural gas discussed in the next section used five chains for MCMC sampling. The model was built using 10^6 samples for each chain, each chain was updated using 10^6 samples, and 5×10^5 samples were taken from the final model to estimate leak frequency

distributions. These sample sizes were shown to be far in excess of those required for convergence of the leak frequency distributions estimated by Mulcahy et al. [10].

Leak frequencies were estimated for compressors, filters, flanges/gaskets, heat exchangers, hoses, instruments, joints, jumpers, pipes, valves, and vessels. Data are required to fit the model and compressed gas data were available for compressors, filters, flanges/gaskets, heat exchangers, hoses, jumpers, pipes, valves, and vessels. Only generic data were available for joints and instruments, so generic data were used in lieu of compressed gas data for these components.

Plots of the estimated leak frequency distributions are provided in Section 4. These plots were generated in Matlab [16] using the 5×10^5 leak frequency predictions output from the Bayesian update for each leak area bin. The smooth distributions in the plots were generated using the following basic procedure:

1. Apply the log function to the leak frequency predictions to get the log leak frequency predictions; call these predictions y_{pred}
2. Fit a normal distribution, f, to these log leak frequencies using the **fitdist** function:
   $f = fitdist(y_{pred})$
   This step is performed because it is efficient for plotting; the samples are from a normal distribution by definition (Section 3.1) so this step does not introduce fitting error to the plots.
3. Calculate the minimum and the maximum log leak frequency. Create a vector of evenly spaced numbers from this minimum to the maximum. This defines the domain of the distribution in log space. Call this vector x.
4. Apply the fitted normal distributions to the vector defined in the previous step using the **pdf** function. This gives the pdf values to be plotted verses x. Call these:
   $y = pdf(f, x)$
5. Scale the pdf values for plotting by dividing y by the maximum of y
6. Duplicate y and multiple by -1 to get the mirror image of the distribution
7. Plot for each leak area bin using $\mathbf{plot}(y, x)$

4. RESULTS AND CONCLUSION

The estimated uncertainty distributions on the log leak frequencies for compressed gas components are plotted in Figure 4-1 through Figure 4-11. None of the compressed gas data in the literature review covered leaks within the 0.01% and 0.1% bins, so the compressed gas frequencies in these bins are extrapolated for all components. The distributions are only plotted from the lowest sampled frequency to the highest sampled frequency from the final 500,000 samples in the Bayesian analysis (see Section 3.2). Because the underlying model consists of normal distributions, the domains of the distributions in the figures are $[-\infty, \infty]$, but when these distributions are used, they should be truncated to physically possible values. Some percentiles are provided in the results (Table 4-1) and distribution parameters are provided in the appendices (Appendix B) to enable different truncation options.

In previous analyses with sparse fuel specific data [7, 8, 9, 10, 11], the inclusion of generic data was essential to arrive at reasonable leak frequency estimates. In those analyses, fuel-specific and generic data were combined to fit the leak frequency models for each component; all generic data were not excluded when fuel-specific data were available. In comparison, the generic data were not clearly applicable for compressed gas, so the compressed gas model does not include generic data unless compressed gas data are unavailable. This means that the compressed gas model does not benefit from the same reduction in uncertainty as the models in [7, 8, 9, 10, 11] did with their inclusion of generic data. As a result, the uncertainty ranges for compressed gas components can range from unreasonably small to unreasonably large; this full range of uncertainty would not be a reasonable input the QRA because it covers a range of values that is not physically reasonable. However, the median leak frequencies may be reasonable inputs for QRA until these estimates can be further refined with CNG data.

In general, there are few data points for most components, and the uncertainty appears to be underestimated due to the lack of data for some components; valves had the most compressed gas data, yet the results for valves (Figure 4-10) have higher variation in the leak frequencies than for other components. For example, the spread in the distributions for compressors (Figure 4-1) is low compared to valves, even for bins that have no data. This is because the valve data is of sufficient size to reflect the inherent variation between all types and sizes of valves for compressed gas systems. For the other components, the size of the data set is too small to sufficiently cover the range of variation that could be expected in the true population of compressors. For this reason, the uncertainty distributions should be used cautiously as they may underestimate uncertainty.

The geometric mean (median) leak frequencies for each component are listed in Table 4-1. These are the values recommended for use in QRA. However, due to the sparsity of data, these are the current best estimates and may change in the future if more data are published. As discussed in Section 2, the compressed gas data used in this analysis appears conservative relative to generic system data. It is assumed that it reflects a higher tendency for CNG systems to leak though a bias imposed by the sparsity of CNG data might be involved.

Caution is particularly advised when using the point estimates and uncertainty for instruments (Figure 4-6) and joints (Figure 4-7). No compressed gas data were available for these components, so the leak frequencies are based exclusively on generic data, which may result in non-conservative estimates.

Though this analysis was limited by sparsity in publicly available data, the method proved applicable, and the foundation is established for easily updating the leak frequency estimates with additional data in the future.

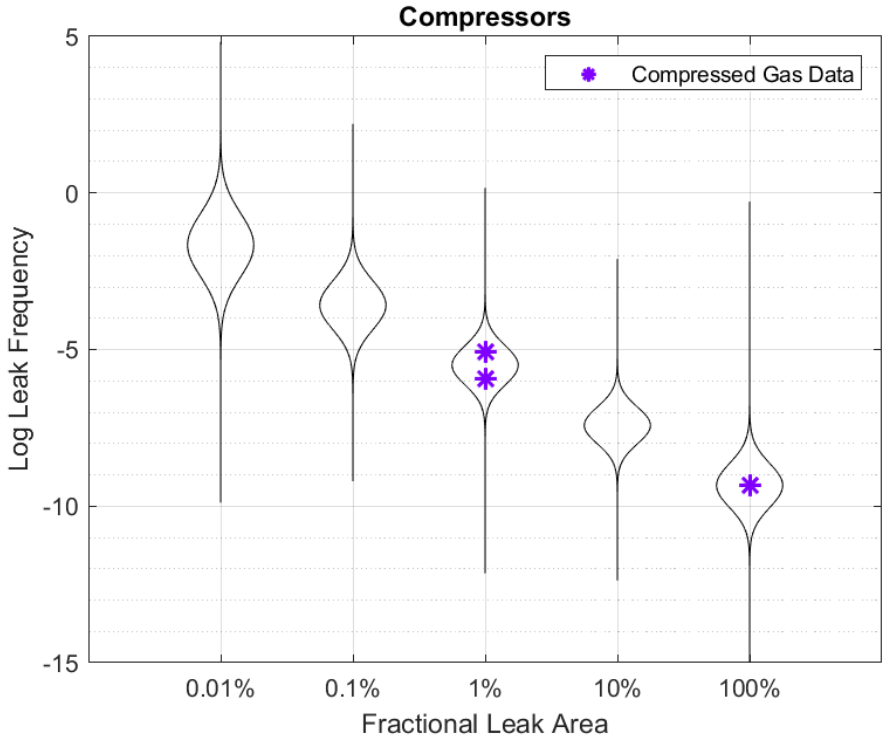


Figure 4-1 Log leak frequency distributions for compressors

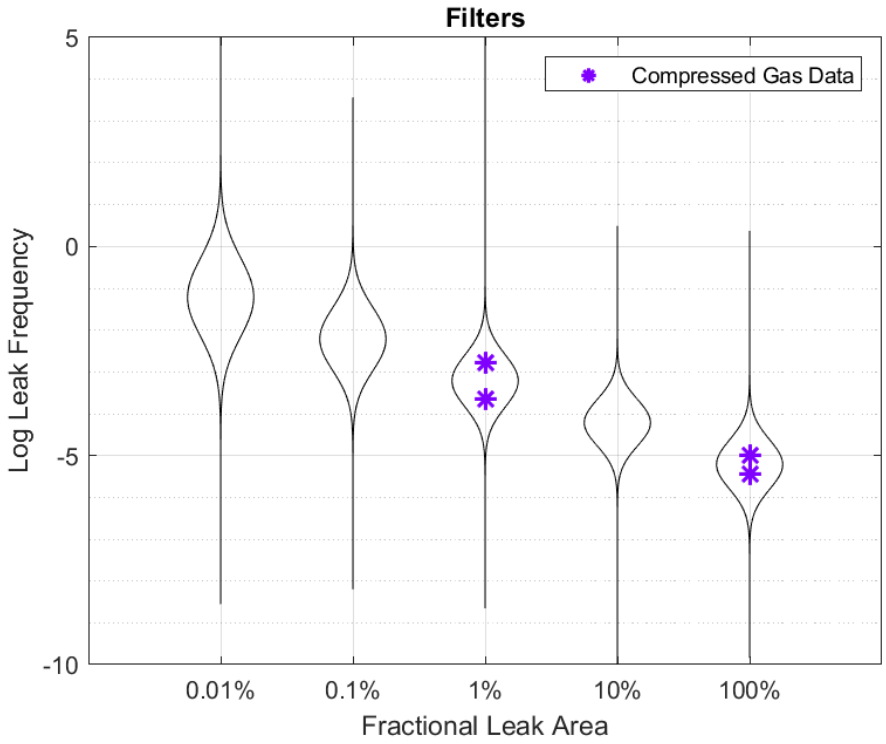


Figure 4-2 Log leak frequency distributions for filters

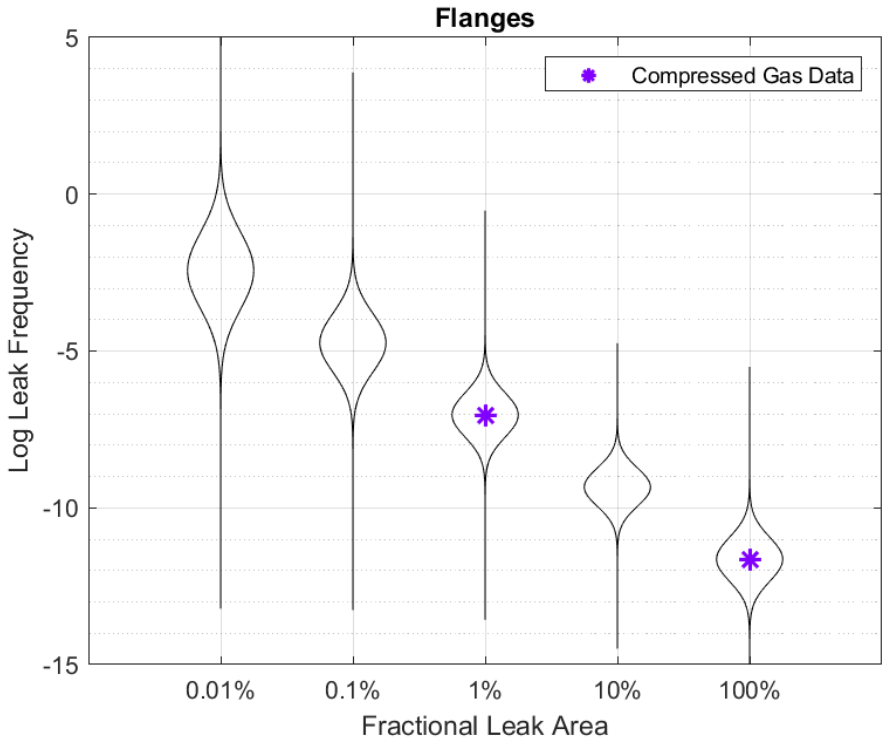


Figure 4-3 Log leak frequency distributions for flanges

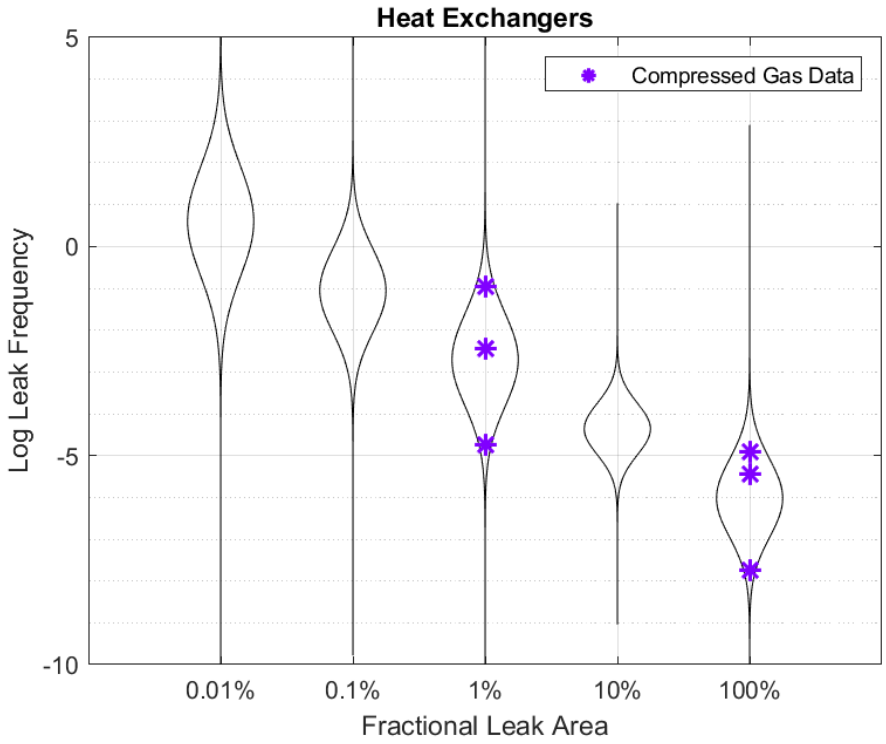


Figure 4-4 Log leak frequency distributions for heat exchangers

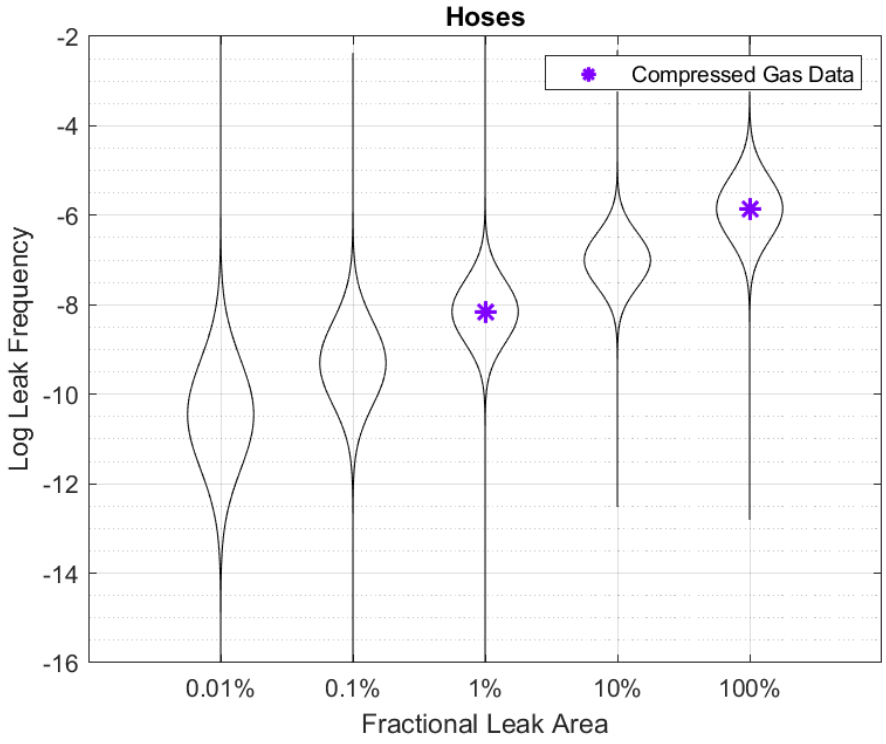


Figure 4-5 Log leak frequency distributions for hoses

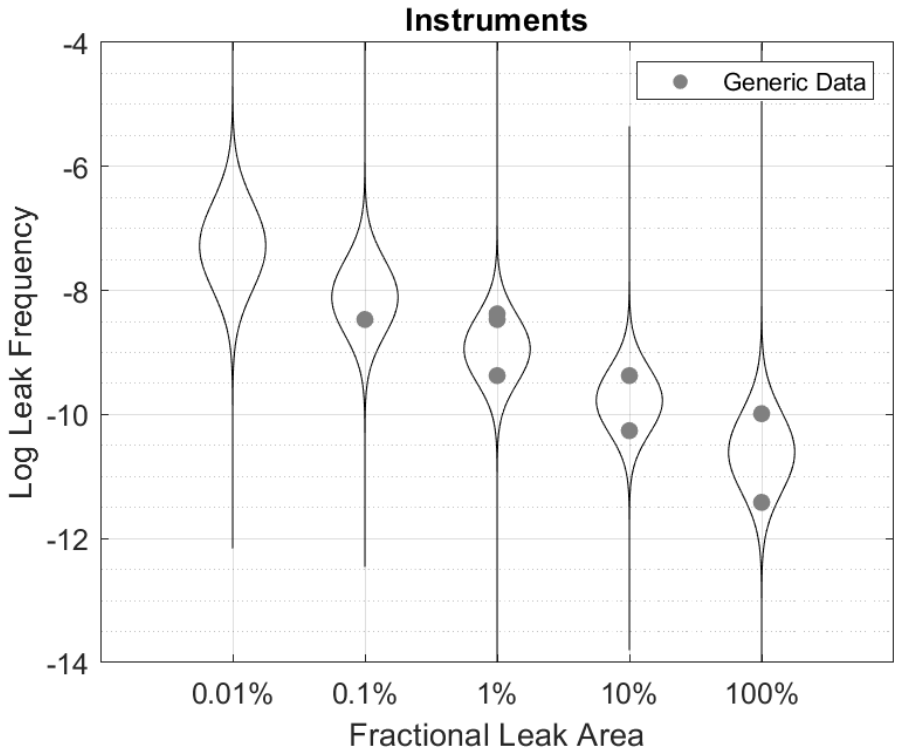


Figure 4-6 Log leak frequency distributions for instruments; no compressed gas data were available for this analysis

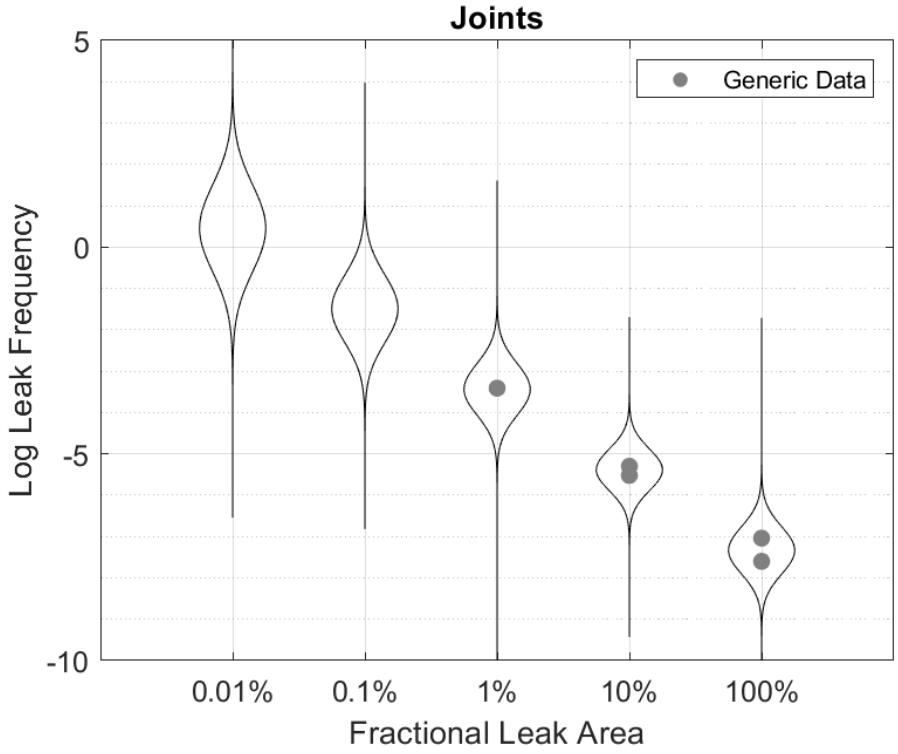


Figure 4-7 Log leak frequency distributions for joints

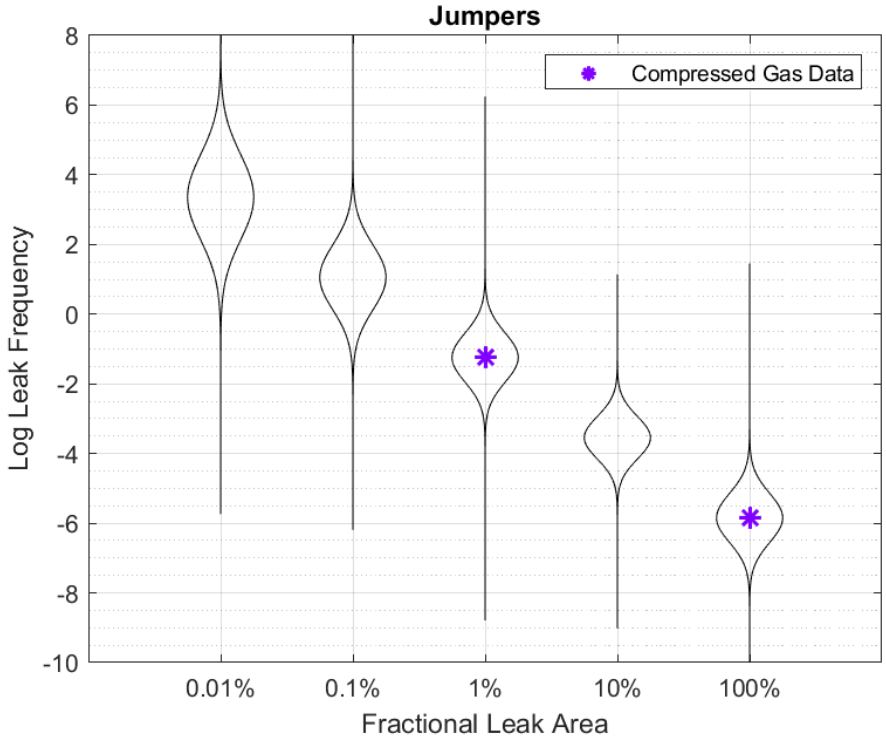


Figure 4-8 Log leak frequency distributions for jumpers

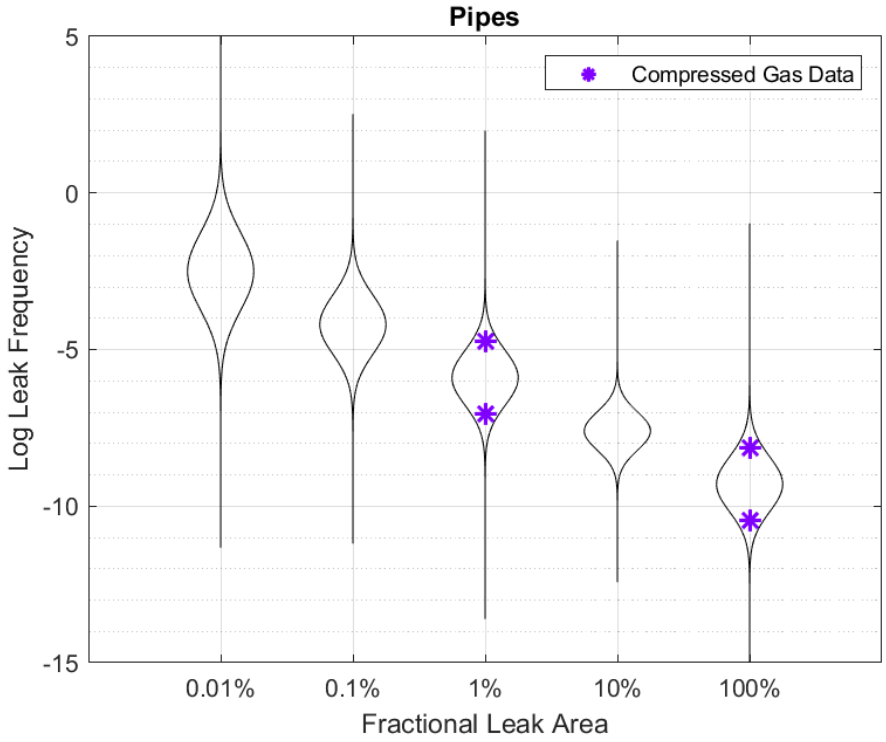


Figure 4-9 Log leak frequency distributions for pipes

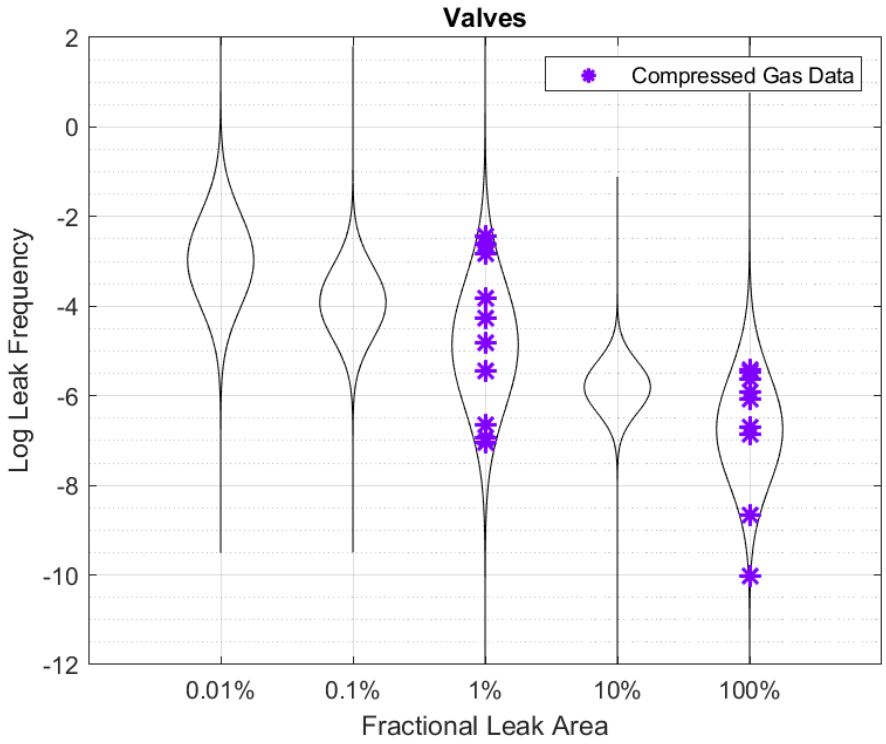


Figure 4-10 Log leak frequency distributions for valves

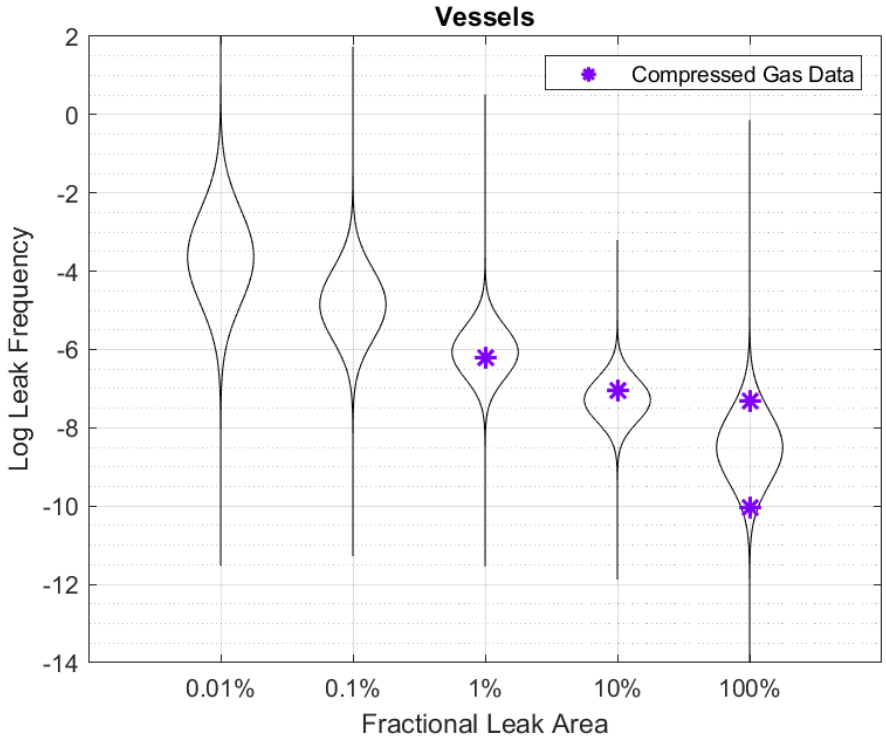


Figure 4-11 Log leak frequency distributions for vessels

Table 4-1 Recommended point estimates for the annual CNG leak frequencies

Component	Leak Bin	5th Percentile	Median	95th Percentile	Component	Leak Bin	5th Percentile	Median	95th Percentile
Compressor	0.01	3.60E-02	1.89E-01	9.95E-01	Instrument*	0.01	2.15E-04	6.85E-04	2.23E-03
	0.1	7.74E-03	2.78E-02	9.98E-02		0.1	1.14E-04	2.96E-04	8.21E-04
	1	1.46E-03	4.07E-03	1.13E-02		1	5.25E-05	1.31E-04	3.16E-04
	10	2.29E-04	5.97E-04	1.56E-03		10	2.38E-05	5.67E-05	1.36E-04
	100	2.79E-05	8.77E-05	2.76E-04		100	8.61E-06	2.46E-05	7.24E-05
Filter	0.01	6.35E-02	2.97E-01	1.39E+00	Joint*	0.01	2.82E-01	1.58E+00	8.79E+00
	0.1	3.17E-02	1.09E-01	3.76E-01		0.1	5.86E-02	2.25E-01	8.61E-01
	1	1.45E-02	4.02E-02	1.11E-01		1	1.15E-02	3.21E-02	8.90E-02
	10	5.96E-03	1.48E-02	3.67E-02		10	2.01E-03	4.57E-03	1.05E-02
	100	2.08E-03	5.44E-03	1.42E-02		100	2.56E-04	6.54E-04	1.66E-03
Flange	0.01	1.18E-02	8.76E-02	6.47E-01	Jumper	0.01	3.91E+00	2.88E+01	2.12E+02
	0.1	1.90E-03	8.76E-03	4.04E-02		0.1	6.26E-01	2.88E+00	1.32E+01
	1	2.79E-04	8.77E-04	2.76E-03		1	9.16E-02	2.88E-01	9.05E-01
	10	3.23E-05	8.78E-05	2.39E-04		10	1.06E-02	2.88E-02	7.83E-02
	100	2.80E-06	8.78E-06	2.76E-05		100	9.19E-04	2.88E-03	9.07E-03
Heat Exchanger	0.01	2.16E-01	1.82E+00	1.54E+01	Pipe	0.01	1.07E-02	8.17E-02	6.21E-01
	0.1	6.79E-02	3.49E-01	1.79E+00		0.1	3.18E-03	1.49E-02	7.01E-02
	1	1.09E-02	6.64E-02	4.06E-01		1	6.53E-04	2.73E-03	1.14E-02
	10	4.64E-03	1.27E-02	3.48E-02		10	1.83E-04	4.99E-04	1.37E-03
	100	5.32E-04	2.43E-03	1.11E-02		100	2.18E-05	9.12E-05	3.82E-04
Hose	0.01	3.91E-06	2.88E-05	2.12E-04	Valve	0.01	9.19E-03	5.13E-02	2.85E-01
	0.1	1.98E-05	9.10E-05	4.19E-04		0.1	5.17E-03	1.99E-02	7.68E-02
	1	9.16E-05	2.88E-04	9.07E-04		1	7.30E-04	7.73E-03	8.18E-02
	10	3.36E-04	9.11E-04	2.47E-03		10	1.18E-03	3.01E-03	7.68E-03
	100	9.17E-04	2.88E-03	9.08E-03		100	1.53E-04	1.17E-03	8.93E-03
					Vessel	0.01	3.64E-03	2.61E-02	1.98E-01
						0.1	1.77E-03	7.74E-03	3.54E-02

	1	7.94E-04	2.29E-03	6.98E-03
	10	2.68E-04	6.88E-04	1.71E-03
	100	4.56E-05	2.00E-04	9.29E-04

*Indicates frequencies that were estimated using only generic data; these frequencies may be non-conservative (lower than would be estimated with compressed gas data)

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APPENDIX A. LEAK FREQUENCY DATA

All of the data and references considered for our analysis of CNG leak frequencies are listed in this appendix. The majority of these data were not included in the final CNG leak frequency estimates because the available compressed gas data suggested that CNG systems are more prone to leakage than other systems, so including the generic data would be non-conservative. If future published compressed gas data suggests otherwise, this generic data may be considered for inclusion in future CNG leak frequency estimates.

Table A-1 Compressor leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
1	2.90E-06	Generic	[17]	2017	No
0.1	2.90E-06	Generic	[17]	2017	No
0.01	2.70E-04	Generic	[17]	2017	No
0.0001	1.20E-02	Generic	[17]	2017	No
1	1.40E-05	Generic	[17]	2017	No
0.1	1.40E-05	Generic	[17]	2017	No
0.01	3.30E-03	Generic	[17]	2017	No
0.0001	8.60E-02	Generic	[17]	2017	No
1	8.76E-05	Generic	[18]	1982	No
1	1.00E-05	Generic	[19]	2009	No
0.01	5.00E-05	Generic	[19]	2009	No
1	1.00E-04	Generic	[19]	2009	No
0.01	4.40E-03	Generic	[19]	2009	No
0.0001	3.70E-03	Hydrocarbons	[20]	2019	No
0.001	1.60E-03	Hydrocarbons	[20]	2019	No
0.01	7.20E-04	Hydrocarbons	[20]	2019	No
0.1	2.70E-04	Hydrocarbons	[20]	2019	No
0.0001	3.70E-03	Hydrocarbons	[20]	2019	No
0.001	1.60E-03	Hydrocarbons	[20]	2019	No
0.01	7.20E-04	Hydrocarbons	[20]	2019	No
0.1	1.60E-04	Hydrocarbons	[20]	2019	No
1	1.10E-04	Hydrocarbons	[20]	2019	No
0.0001	9.00E-04	Hydrocarbons	[20]	2019	No
0.001	4.30E-04	Hydrocarbons	[20]	2019	No
0.01	2.10E-04	Hydrocarbons	[20]	2019	No
0.1	9.70E-05	Hydrocarbons	[20]	2019	No
0.0001	9.00E-04	Hydrocarbons	[20]	2019	No
0.001	4.30E-04	Hydrocarbons	[20]	2019	No
0.01	2.10E-04	Hydrocarbons	[20]	2019	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.1	5.30E-05	Hydrocarbons	[20]	2019	No
1	4.40E-05	Hydrocarbons	[20]	2019	No
0.01	2.00E-03	Process Equipment	[21]	2005	No
0.01	2.70E-02	Process Equipment	[21]	2005	No
1	2.00E-06	Process Equipment	[21]	2005	No
1	1.10E-05	Process Equipment	[21]	2005	No
1	8.76E-05	Compressed Gas	[1]	1995	Yes
0.01	2.63E-03	Compressed Gas	[1]	1995	Yes
0.01	6.31E-03	Compressed Gas	[22]	1998	Yes

Table A-2 Filter leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	2.63E-02	Chemical Process	[1]	1995	No
1	4.38E-03	Chemical Process	[1]	1995	No
1	2.72E-02	Generic	[23]	2005	No
0.0001	2.30E-03	Hydrocarbons	[20]	2019	No
0.001	8.30E-04	Hydrocarbons	[20]	2019	No
0.01	2.90E-04	Hydrocarbons	[20]	2019	No
0.1	7.40E-05	Hydrocarbons	[20]	2019	No
0.0001	2.30E-03	Hydrocarbons	[20]	2019	No
0.001	8.30E-04	Hydrocarbons	[20]	2019	No
0.01	2.90E-04	Hydrocarbons	[20]	2019	No
0.1	4.90E-05	Hydrocarbons	[20]	2019	No
1	2.50E-05	Hydrocarbons	[20]	2019	No
0.01	8.90E-04	Process Equipment	[21]	2005	No
1	6.40E-06	Process Equipment	[21]	2005	No
0.01	6.13E-02	Chemical Process	[22]	1998	No
1	6.75E-03	Chemical Process	[22]	1998	No
0.01	2.63E-02	Compressed Gas	[1]	1995	Yes
1	4.38E-03	Compressed Gas	[1]	1995	Yes

Table A-3 Flange leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	1.00E-03	Chemical Process	[7]	2009	No
1	1.00E-04	Chemical Process	[7]	2009	No
0.01	1.70E-04	Chemical Process	[6]	2021	No
1	1.70E-05	Chemical Process	[6]	2021	No
0.01	8.76E-04	Chemical Process	[1]	1995	No
1	8.76E-06	Chemical Process	[1]	1995	No
1	8.76E-05	Generic	[18]	1982	No
0.001	1.30E-05	Hydrocarbons	[20]	2019	No
0.01	6.00E-06	Hydrocarbons	[20]	2019	No
0.1	2.80E-06	Hydrocarbons	[20]	2019	No
1	1.20E-06	Hydrocarbons	[20]	2019	No
0.0001	2.20E-05	Hydrocarbons	[20]	2019	No
0.001	9.60E-06	Hydrocarbons	[20]	2019	No
0.01	4.30E-06	Hydrocarbons	[20]	2019	No
0.1	9.90E-07	Hydrocarbons	[20]	2019	No
1	1.70E-06	Hydrocarbons	[20]	2019	No
0.0001	5.40E-05	Hydrocarbons	[20]	2019	No
0.001	5.90E-06	Hydrocarbons	[20]	2019	No
0.01	1.10E-06	Hydrocarbons	[20]	2019	No
0.1	3.90E-06	Hydrocarbons	[20]	2019	No
0.0001	7.90E-05	Hydrocarbons	[20]	2019	No
0.001	6.60E-06	Hydrocarbons	[20]	2019	No
0.01	1.00E-06	Hydrocarbons	[20]	2019	No
0.1	6.00E-06	Hydrocarbons	[20]	2019	No
0.0001	8.70E-05	Hydrocarbons	[20]	2019	No
0.001	6.60E-06	Hydrocarbons	[20]	2019	No
0.01	9.90E-07	Hydrocarbons	[20]	2019	No
0.1	6.70E-06	Hydrocarbons	[20]	2019	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.0001	9.36E-05	Hydrocarbons	[20]	2019	No
0.001	9.90E-07	Hydrocarbons	[20]	2019	No
0.01	6.70E-06	Hydrocarbons	[20]	2019	No
0.01	3.20E-05	Process Equipment	[21]	2005	No
0.01	4.30E-05	Process Equipment	[21]	2005	No
0.01	1.20E-04	Process Equipment	[21]	2005	No
1	3.60E-07	Process Equipment	[21]	2005	No
1	1.10E-06	Process Equipment	[21]	2005	No
0.01	8.76E-04	Compressed Gas	[1]	1995	Yes
1	8.76E-06	Compressed Gas	[1]	1995	Yes

Table A-4 Heat exchanger leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	8.76E-04	Chemical Process	[1]	1995	No
1	4.38E-05	Chemical Process	[1]	1995	No
0.01	8.76E-03	Chemical Process	[1]	1995	No
1	4.38E-04	Chemical Process	[1]	1995	No
1	5.00E-05	Generic	[24]	2005	No
0.01	1.00E-03	Generic	[24]	2005	No
1	1.00E-06	Generic	[24]	2005	No
1	1.00E-05	Generic	[24]	2005	No
0.1	1.00E-03	Generic	[24]	2005	No
0.01	1.00E-02	Generic	[24]	2005	No
0.1	9.64E-06	Generic	[23]	2005	No
0.01	9.64E-05	Generic	[23]	2005	No
1	4.99E-06	Generic	[23]	2005	No
0.0001	1.20E-03	Hydrocarbons	[20]	2019	No
0.001	6.00E-04	Hydrocarbons	[20]	2019	No
0.01	3.00E-04	Hydrocarbons	[20]	2019	No
0.1	1.30E-04	Hydrocarbons	[20]	2019	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.0001	1.20E-03	Hydrocarbons	[20]	2019	No
0.001	6.00E-04	Hydrocarbons	[20]	2019	No
0.01	3.00E-04	Hydrocarbons	[20]	2019	No
0.1	7.40E-05	Hydrocarbons	[20]	2019	No
1	6.10E-05	Hydrocarbons	[20]	2019	No
0.0001	4.80E-04	Hydrocarbons	[20]	2019	No
0.001	2.90E-04	Hydrocarbons	[20]	2019	No
0.01	1.80E-04	Hydrocarbons	[20]	2019	No
0.1	1.40E-04	Hydrocarbons	[20]	2019	No
0.0001	4.80E-04	Hydrocarbons	[20]	2019	No
0.001	2.90E-04	Hydrocarbons	[20]	2019	No
0.01	1.80E-04	Hydrocarbons	[20]	2019	No
0.1	6.10E-05	Hydrocarbons	[20]	2019	No
1	7.70E-05	Hydrocarbons	[20]	2019	No
0.0001	7.20E-03	Hydrocarbons	[20]	2019	No
0.001	2.50E-03	Hydrocarbons	[20]	2019	No
0.01	8.70E-04	Hydrocarbons	[20]	2019	No
0.1	2.20E-04	Hydrocarbons	[20]	2019	No
0.0001	7.20E-03	Hydrocarbons	[20]	2019	No
0.001	2.50E-03	Hydrocarbons	[20]	2019	No
0.01	8.70E-04	Hydrocarbons	[20]	2019	No
0.1	1.50E-04	Hydrocarbons	[20]	2019	No
1	7.40E-05	Hydrocarbons	[20]	2019	No
0.0001	8.90E-04	Hydrocarbons	[20]	2019	No
0.001	3.10E-04	Hydrocarbons	[20]	2019	No
0.01	1.10E-04	Hydrocarbons	[20]	2019	No
0.1	2.80E-05	Hydrocarbons	[20]	2019	No
0.0001	8.90E-04	Hydrocarbons	[20]	2019	No
0.001	3.10E-04	Hydrocarbons	[20]	2019	No
0.01	1.10E-04	Hydrocarbons	[20]	2019	No
0.1	1.80E-05	Hydrocarbons	[20]	2019	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
1	9.30E-06	Hydrocarbons	[20]	2019	No
0.01	1.40E-03	Process Equipment	[21]	2005	No
1	1.30E-04	Process Equipment	[21]	2005	No
0.01	1.00E-03	Process Equipment	[21]	2005	No
1	4.90E-05	Process Equipment	[21]	2005	No
0.01	6.00E-03	Process Equipment	[21]	2005	No
1	3.60E-04	Process Equipment	[21]	2005	No
0.01	1.20E-03	Process Equipment	[21]	2005	No
1	6.90E-05	Process Equipment	[21]	2005	No
0.01	2.28E-01	Chemical Process	[22]	1998	No
0.01	6.31E-02	Chemical Process	[22]	1998	No
0.01	8.76E-02	Compressed Gas	[1]	1995	Yes
1	4.38E-03	Compressed Gas	[1]	1995	Yes
0.01	8.76E-03	Compressed Gas	[1]	1995	Yes
1	4.38E-04	Compressed Gas	[1]	1995	Yes
0.01	3.85E-01	Compressed Gas	[22]	1998	Yes
1	7.45E-03	Compressed Gas	[22]	1998	Yes

Table A-5 Hose leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
1	2.88E-04	Chemical Process	[1]	1995	No
0.01	2.88E-05	Chemical Process	[1]	1995	No
1	8.34E-04	Chemical Process	[22]	1998	No
1	1.49E-02	Generic	[18]	1982	No
1	3.50E-02	Generic	[24]	2005	No
0.01	3.50E-01	Generic	[24]	2005	No
0.001	1.00E-03	Hydrocarbons	[20]	2019	No
0.01	5.30E-04	Hydrocarbons	[20]	2019	No
0.1	2.90E-04	Hydrocarbons	[20]	2019	No
1	1.60E-04	Hydrocarbons	[20]	2019	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.0001	1.70E-04	Hydrocarbons	[20]	2019	No
0.001	1.10E-04	Hydrocarbons	[20]	2019	No
0.01	8.10E-05	Hydrocarbons	[20]	2019	No
0.1	3.00E-05	Hydrocarbons	[20]	2019	No
1	4.80E-05	Hydrocarbons	[20]	2019	No
0.0001	5.80E-05	Hydrocarbons	[20]	2019	No
0.001	2.20E-05	Hydrocarbons	[20]	2019	No
0.01	9.70E-06	Hydrocarbons	[20]	2019	No
0.1	2.40E-05	Hydrocarbons	[20]	2019	No
0.0001	2.03E-05	Hydrocarbons	[20]	2019	No
0.001	9.20E-06	Hydrocarbons	[20]	2019	No
0.01	4.70E-06	Hydrocarbons	[20]	2019	No
0.1	1.80E-05	Hydrocarbons	[20]	2019	No
0.0001	1.06E-05	Hydrocarbons	[20]	2019	No
0.001	5.20E-06	Hydrocarbons	[20]	2019	No
0.01	2.80E-06	Hydrocarbons	[20]	2019	No
0.1	1.30E-05	Hydrocarbons	[20]	2019	No
0.0001	1.58E-05	Hydrocarbons	[20]	2019	No
0.001	2.80E-06	Hydrocarbons	[20]	2019	No
0.01	1.30E-05	Hydrocarbons	[20]	2019	No
0.1	1.00E-02	Hydrogen Fueling Process	[6]	2021	No
1	1.00E-03	Hydrogen Fueling Process	[6]	2021	No
0.01	1.00E-01	Hydrogen Fueling Process	[6]	2021	No
1	2.88E-03	Compressed Gas	[1]	1995	Yes
0.01	2.88E-04	Compressed Gas	[1]	1995	Yes

Table A-6 Instruments leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	2.10E-04	Hydrocarbons	[20]	2019	Yes
0.1	8.50E-05	Hydrocarbons	[20]	2019	Yes
1	4.60E-05	Hydrocarbons	[20]	2019	Yes
0.001	2.10E-04	Hydrocarbons	[20]	2019	Yes
0.01	8.50E-05	Hydrocarbons	[20]	2019	Yes
0.1	3.50E-05	Hydrocarbons	[20]	2019	Yes
1	1.10E-05	Hydrocarbons	[20]	2019	Yes
0.01	2.30E-04	Process Equipment	[21]	2005	Yes

Table A-7 Joints leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.1	4.99E-03	Process Equipment	[2]	1981	Yes
0.01	3.30E-02	Hydrogen Fueling Process	[6]	2021	Yes
0.1	4.00E-03	Hydrogen Fueling Process	[6]	2021	Yes
1	5.00E-04	Hydrogen Fueling Process	[6]	2021	Yes
1	8.76E-04	Generic	[18]	1982	Yes

Table A-8 Jumper leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	2.88E-02	Chemical Process	[1]	1995	No
1	2.88E-04	Chemical Process	[1]	1995	No
1	2.88E-03	Compressed Gas	[1]	1995	Yes
0.01	2.88E-01	Compressed Gas	[1]	1995	Yes

Table A-9 Pipe leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	3.00E-06	Chemical Process	[25]	1982	No
0.01	6.00E-06	Chemical Process	[25]	1982	No
0.01	1.00E-05	Chemical Process	[25]	1982	No
0.1	1.00E-07	Chemical Process	[25]	1982	No
0.1	3.00E-07	Chemical Process	[25]	1982	No
0.1	1.00E-06	Chemical Process	[25]	1982	No
0.01	1.00E-05	Chemical Process	[7]	2009	No
0.01	3.00E-05	Chemical Process	[7]	2009	No
0.01	1.00E-04	Chemical Process	[7]	2009	No
0.01	1.00E-04	Chemical Process	[7]	2009	No
0.1	3.00E-06	Chemical Process	[7]	2009	No
0.1	6.00E-06	Chemical Process	[7]	2009	No
0.1	1.00E-05	Chemical Process	[7]	2009	No
0.1	1.00E-05	Chemical Process	[7]	2009	No
1	1.00E-07	Chemical Process	[7]	2009	No
1	3.00E-07	Chemical Process	[7]	2009	No
1	1.00E-06	Chemical Process	[7]	2009	No
1	1.00E-06	Chemical Process	[7]	2009	No
1	5.00E-04	Chemical Process	[7]	2009	No
0.01	8.63E-05	Chemical Process	[1]	1995	No
1	2.88E-06	Chemical Process	[1]	1995	No
0.01	5.00E-07	Generic	[24]	2005	No
0.01	2.00E-06	Generic	[24]	2005	No
0.01	5.00E-06	Generic	[24]	2005	No
1	1.00E-07	Generic	[24]	2005	No
1	3.00E-07	Generic	[24]	2005	No
1	1.00E-06	Generic	[24]	2005	No
0.01	4.99E-06	Generic	[23]	2005	No
1	9.64E-07	Generic	[23]	2005	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	2.01E-06	Generic	[23]	2005	No
1	2.98E-07	Generic	[23]	2005	No
0.001	3.60E-05	Hydrocarbons	[20]	2019	No
0.01	1.50E-05	Hydrocarbons	[20]	2019	No
0.1	6.60E-06	Hydrocarbons	[20]	2019	No
1	2.40E-06	Hydrocarbons	[20]	2019	No
0.0001	1.60E-05	Hydrocarbons	[20]	2019	No
0.001	6.70E-06	Hydrocarbons	[20]	2019	No
0.01	2.70E-06	Hydrocarbons	[20]	2019	No
0.1	5.60E-07	Hydrocarbons	[20]	2019	No
1	3.50E-07	Hydrocarbons	[20]	2019	No
0.0001	1.61E-05	Hydrocarbons	[20]	2019	No
0.001	2.50E-06	Hydrocarbons	[20]	2019	No
0.01	6.40E-07	Hydrocarbons	[20]	2019	No
0.1	5.60E-07	Hydrocarbons	[20]	2019	No
0.0001	1.24E-05	Hydrocarbons	[20]	2019	No
0.001	2.90E-06	Hydrocarbons	[20]	2019	No
0.01	9.40E-07	Hydrocarbons	[20]	2019	No
0.1	1.20E-06	Hydrocarbons	[20]	2019	No
0.0001	1.13E-05	Hydrocarbons	[20]	2019	No
0.001	3.00E-06	Hydrocarbons	[20]	2019	No
0.01	1.00E-06	Hydrocarbons	[20]	2019	No
0.1	1.60E-06	Hydrocarbons	[20]	2019	No
0.0001	1.43E-05	Hydrocarbons	[20]	2019	No
0.001	1.00E-06	Hydrocarbons	[20]	2019	No
0.01	1.60E-06	Hydrocarbons	[20]	2019	No
1	4.60E-07	Hydrogen Fueling Process	[6]	2021	No
0.01	7.50E-06	Hydrogen Fueling Process	[6]	2021	No
0.1	2.00E-06	Hydrogen Fueling Process	[6]	2021	No
0.01	1.10E-05	Process Equipment	[21]	2005	No
0.01	2.00E-05	Process Equipment	[21]	2005	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	5.70E-05	Process Equipment	[21]	2005	No
1	4.20E-08	Process Equipment	[21]	2005	No
1	7.70E-08	Process Equipment	[21]	2005	No
1	1.28E-06	Unspecified	[5]	2012	No
1	1.80E-07	Unspecified	[5]	2012	No
1	1.46E-07	Process Equipment	[2]	1989	No
1	2.88E-05	Compressed Gas	[1]	1995	Yes
0.01	8.63E-04	Compressed Gas	[1]	1995	Yes
0.01	8.63E-03	Compressed Gas	[1]	1995	Yes
1	2.88E-04	Compressed Gas	[1]	1995	Yes

Table A-10 Valve leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	8.76E-03	Chemical Process	[1]	1995	No
1	4.38E-04	Chemical Process	[1]	1995	No
0.01	4.38E-03	Chemical Process	[1]	1995	No
1	2.63E-04	Chemical Process	[1]	1995	No
0.01	1.00E-03	Chemical Process	[7]	2009	No
0.1	1.00E-04	Chemical Process	[7]	2009	No
1	1.00E-05	Chemical Process	[7]	2009	No
1	8.76E-06	Generic	[18]	1982	No
1	2.00E-05	Generic	[24]	2005	No
0.001	2.40E-05	Hydrocarbons	[20]	2019	No
0.01	1.30E-05	Hydrocarbons	[20]	2019	No
0.1	7.40E-06	Hydrocarbons	[20]	2019	No
1	4.30E-06	Hydrocarbons	[20]	2019	No
0.0001	2.80E-05	Hydrocarbons	[20]	2019	No
0.001	1.30E-05	Hydrocarbons	[20]	2019	No
0.01	6.20E-06	Hydrocarbons	[20]	2019	No
0.1	1.50E-06	Hydrocarbons	[20]	2019	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
1	1.20E-06	Hydrocarbons	[20]	2019	No
0.0001	7.20E-05	Hydrocarbons	[20]	2019	No
0.001	1.30E-05	Hydrocarbons	[20]	2019	No
0.01	3.50E-06	Hydrocarbons	[20]	2019	No
0.1	3.50E-06	Hydrocarbons	[20]	2019	No
0.0001	9.90E-05	Hydrocarbons	[20]	2019	No
0.001	2.30E-05	Hydrocarbons	[20]	2019	No
0.01	7.10E-06	Hydrocarbons	[20]	2019	No
0.1	9.00E-06	Hydrocarbons	[20]	2019	No
0.0001	1.07E-04	Hydrocarbons	[20]	2019	No
0.001	2.60E-05	Hydrocarbons	[20]	2019	No
0.01	8.60E-06	Hydrocarbons	[20]	2019	No
0.1	1.20E-05	Hydrocarbons	[20]	2019	No
0.0001	1.33E-04	Hydrocarbons	[20]	2019	No
0.001	8.60E-06	Hydrocarbons	[20]	2019	No
0.01	1.20E-05	Hydrocarbons	[20]	2019	No
0.001	2.40E-04	Hydrocarbons	[20]	2019	No
0.01	9.70E-05	Hydrocarbons	[20]	2019	No
0.1	3.90E-05	Hydrocarbons	[20]	2019	No
1	1.20E-05	Hydrocarbons	[20]	2019	No
0.0001	1.30E-04	Hydrocarbons	[20]	2019	No
0.001	6.20E-05	Hydrocarbons	[20]	2019	No
0.01	3.00E-05	Hydrocarbons	[20]	2019	No
0.1	7.20E-06	Hydrocarbons	[20]	2019	No
1	6.10E-06	Hydrocarbons	[20]	2019	No
0.0001	1.85E-04	Hydrocarbons	[20]	2019	No
0.001	2.50E-05	Hydrocarbons	[20]	2019	No
0.01	5.60E-06	Hydrocarbons	[20]	2019	No
0.1	4.30E-06	Hydrocarbons	[20]	2019	No
0.0001	1.96E-04	Hydrocarbons	[20]	2019	No
0.001	2.20E-05	Hydrocarbons	[20]	2019	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	4.40E-06	Hydrocarbons	[20]	2019	No
0.1	2.80E-06	Hydrocarbons	[20]	2019	No
0.0001	2.06E-04	Hydrocarbons	[20]	2019	No
0.001	2.20E-05	Hydrocarbons	[20]	2019	No
0.01	4.10E-06	Hydrocarbons	[20]	2019	No
0.1	2.40E-06	Hydrocarbons	[20]	2019	No
0.0001	2.28E-04	Hydrocarbons	[20]	2019	No
0.001	4.10E-06	Hydrocarbons	[20]	2019	No
0.01	2.40E-06	Hydrocarbons	[20]	2019	No
0.01	1.00E-02	Hydrogen Fueling Process	[6]	2021	No
1	4.90E-07	Process Equipment	[21]	2005	No
1	1.90E-06	Process Equipment	[21]	2005	No
1	2.30E-06	Process Equipment	[21]	2005	No
0.01	1.40E-05	Process Equipment	[21]	2005	No
0.01	4.80E-05	Process Equipment	[21]	2005	No
0.01	2.20E-04	Process Equipment	[21]	2005	No
0.01	2.60E-04	Process Equipment	[21]	2005	No
0.01	9.64E-02	Chemical Process	[22]	1998	No
0.01	6.39E-03	Chemical Process	[22]	1998	No
1	1.93E-04	Chemical Process	[22]	1998	No
0.01	3.68E-03	Chemical Process	[22]	1998	No
1	1.58E-04	Chemical Process	[22]	1998	No
1	4.38E-03	Compressed Gas	[1]	1995	Yes
0.01	8.76E-02	Compressed Gas	[1]	1995	Yes
1	4.38E-05	Compressed Gas	[1]	1995	Yes
0.01	8.76E-04	Compressed Gas	[1]	1995	Yes
0.01	4.29E-03	Compressed Gas	[21]	2005	Yes
1	1.23E-03	Compressed Gas	[21]	2005	Yes
0.01	8.15E-03	Compressed Gas	[21]	2005	Yes
1	1.05E-03	Compressed Gas	[21]	2005	Yes
0.01	5.96E-02	Compressed Gas	[21]	2005	Yes

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
1	2.28E-03	Compressed Gas	[21]	2005	Yes
0.01	2.19E-02	Compressed Gas	[21]	2005	Yes
1	3.59E-03	Compressed Gas	[21]	2005	Yes
0.01	1.40E-02	Compressed Gas	[21]	2005	Yes
1	1.75E-04	Compressed Gas	[21]	2005	Yes
0.01	1.31E-03	Compressed Gas	[21]	2005	Yes
0.01	1.31E-03	Compressed Gas	[21]	2005	Yes
0.01	7.36E-02	Compressed Gas	[21]	2005	Yes
1	2.72E-03	Compressed Gas	[21]	2005	Yes
1	4.20E-03	Compressed Gas	[21]	2005	Yes
0.01	9.64E-04	Compressed Gas	[21]	2005	Yes

Table A-11 Vessel leak frequency data

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	2.28E-02	Chemical Process	[21]	2005	No
1	9.64E-06	Generic	[23]	2005	No
1	9.55E-05	Generic	[2]	1989	No
0.01	8.76E-04	Chemical Process	[1]	1995	No
1	4.38E-05	Chemical Process	[1]	1995	No
0.001	5.00E-04	Hydrocarbons	[20]	2019	No
0.01	2.60E-04	Hydrocarbons	[20]	2019	No
0.1	1.40E-04	Hydrocarbons	[20]	2019	No
1	7.40E-05	Hydrocarbons	[20]	2019	No
0.0001	5.00E-04	Hydrocarbons	[20]	2019	No
0.001	2.60E-04	Hydrocarbons	[20]	2019	No
0.01	1.40E-04	Hydrocarbons	[20]	2019	No
0.1	3.80E-05	Hydrocarbons	[20]	2019	No
1	3.60E-05	Hydrocarbons	[20]	2019	No
0.0001	2.30E-05	Hydrocarbons	[20]	2010	No
0.001	1.20E-05	Hydrocarbons	[20]	2010	No

Leak Bin	Leak Frequency	Applicability	Reference	Published	Used in model?
0.01	7.10E-06	Hydrocarbons	[20]	2010	No
0.1	4.30E-06	Hydrocarbons	[20]	2010	No
1	4.70E-07	Hydrocarbons	[20]	2010	No
0.001	4.40E-07	Hydrocarbons	[20]	2010	No
0.01	4.60E-07	Hydrocarbons	[20]	2010	No
1	1.00E-07	Hydrocarbons	[20]	2010	No
1	2.30E-07	Ammonia	[25]	1982	No
1	2.50E-08	Propylene	[25]	1982	No
1	7.00E-05	Generic	[5]	2012	No
0.1	4.00E-05	Generic	[5]	2012	No
0.1	4.20E-05	Generic	[5]	2012	No
0.1	1.00E-06	Generic	[5]	2012	No
0.1	2.70E-03	Olefins	[5]	2012	No
0.1	1.80E-03	Olefins	[5]	2012	No
0.01	1.68E-06	Generic	[4]	2014	No
1	1.14E-10	Generic	[4]	2014	No
1	1.00E-06	Generic	[24]	2005	No
1	5.00E-07	Generic	[24]	2005	No
0.01	1.00E-05	Generic	[24]	2005	No
0.1	9.64E-07	Generic	[23]	2005	No
1	4.99E-07	Generic	[23]	2005	No
0.01	9.64E-06	Generic	[23]	2005	No
1	3.33E-03	Chemical Process	[22]	1998	No
0.01	3.24E-02	Chemical Process	[22]	1998	No
0.1	8.76E-04	Compressed Gas	[1]	1995	Yes
1	4.38E-05	Compressed Gas	[1]	1995	Yes
1	6.57E-04	Compressed Gas	[22]	1998	Yes
0.01	2.01E-03	Compressed Gas	[22]	1998	Yes

APPENDIX B. LEAK FREQUENCY DISTRIBUTION STATISTICS AND DISTRIBUTIONS

This appendix provides additional statistics for the estimated leak frequency distributions in this analysis. The arithmetic mean of the leak frequencies is included; this is not the center of the leak frequency distribution because the leak frequency distribution is normal in natural log-frequency space. As such, this mean is in the upper tail of the leak frequency distribution. The center of the distribution is best characterized by the median. The mean (μ) and standard deviation (σ) and of the normal distributions in log space are also provided; these are the normal distributions on the log-leak frequency. To obtain leak frequency samples from these distributions, sample from the normal distribution defined by (μ, σ) and exponentiate the samples.

Component	Leak Size	Mean	5th	Median	95th	μ	σ
Compressors	0.0001	3.22E-01	3.60E-02	1.89E-01	9.95E-01	-1.66E+00	1.01E+00
	0.001	3.79E-02	7.74E-03	2.78E-02	9.98E-02	-3.58E+00	7.81E-01
	0.01	5.00E-03	1.46E-03	4.07E-03	1.13E-02	-5.50E+00	6.30E-01
	0.1	7.12E-04	2.29E-04	5.97E-04	1.56E-03	-7.42E+00	5.88E-01
	1	1.14E-04	2.79E-05	8.77E-05	2.76E-04	-9.34E+00	7.07E-01
Filters	0.0001	4.70E-01	6.35E-02	2.97E-01	1.39E+00	-1.21E+00	9.44E-01
	0.001	1.46E-01	3.17E-02	1.09E-01	3.76E-01	-2.22E+00	7.58E-01
	0.01	4.92E-02	1.45E-02	4.02E-02	1.11E-01	-3.21E+00	6.27E-01
	0.1	1.73E-02	5.96E-03	1.48E-02	3.67E-02	-4.21E+00	5.59E-01
	1	6.50E-03	2.08E-03	5.44E-03	1.42E-02	-5.21E+00	5.91E-01
Flanges	0.0001	2.04E-01	1.18E-02	8.76E-02	6.47E-01	-2.44E+00	1.23E+00
	0.001	1.38E-02	1.90E-03	8.76E-03	4.04E-02	-4.74E+00	9.36E-01
	0.01	1.14E-03	2.79E-04	8.77E-04	2.76E-03	-7.04E+00	7.08E-01
	0.1	1.06E-04	3.23E-05	8.78E-05	2.39E-04	-9.34E+00	6.13E-01
	1	1.14E-05	2.80E-06	8.78E-06	2.76E-05	-1.16E+01	7.06E-01
Heat Exchangers	0.0001	4.70E+00	2.16E-01	1.82E+00	1.54E+01	6.01E-01	1.31E+00
	0.001	5.88E-01	6.79E-02	3.49E-01	1.79E+00	-1.05E+00	1.00E+00
	0.01	1.35E-01	1.09E-02	6.64E-02	4.06E-01	-2.71E+00	1.11E+00
	0.1	1.54E-02	4.64E-03	1.27E-02	3.48E-02	-4.36E+00	6.18E-01
	1	3.87E-03	5.32E-04	2.43E-03	1.11E-02	-6.02E+00	9.33E-01
Hoses	0.0001	6.49E-05	3.91E-06	2.88E-05	2.12E-04	-1.05E+01	1.22E+00
	0.001	1.44E-04	1.98E-05	9.10E-05	4.19E-04	-9.30E+00	9.35E-01
	0.01	3.75E-04	9.16E-05	2.88E-04	9.07E-04	-8.15E+00	7.08E-01
	0.1	1.10E-03	3.36E-04	9.11E-04	2.47E-03	-7.00E+00	6.12E-01
	1	3.75E-03	9.17E-04	2.88E-03	9.08E-03	-5.85E+00	7.07E-01

Component	Leak Size	Mean	5th	Median	95th	μ	σ
Instruments	0.0001	8.92E-04	2.15E-04	6.85E-04	2.23E-03	-7.28E+00	7.15E-01
	0.001	3.63E-04	1.14E-04	2.96E-04	8.21E-04	-8.11E+00	6.05E-01
	0.01	1.52E-04	5.25E-05	1.31E-04	3.16E-04	-8.94E+00	5.51E-01
	0.1	6.56E-05	2.38E-05	5.67E-05	1.36E-04	-9.78E+00	5.34E-01
	1	3.09E-05	8.61E-06	2.46E-05	7.24E-05	-1.06E+01	6.53E-01
Joints	0.0001	2.77E+00	2.82E-01	1.58E+00	8.79E+00	4.56E-01	1.05E+00
	0.001	3.16E-01	5.86E-02	2.25E-01	8.61E-01	-1.49E+00	8.19E-01
	0.01	3.92E-02	1.15E-02	3.21E-02	8.90E-02	-3.44E+00	6.27E-01
	0.1	5.21E-03	2.01E-03	4.57E-03	1.05E-02	-5.39E+00	5.06E-01
	1	7.72E-04	2.56E-04	6.54E-04	1.66E-03	-7.33E+00	5.74E-01
Jumpers	0.0001	6.54E+01	3.91E+00	2.88E+01	2.12E+02	3.36E+00	1.22E+00
	0.001	4.55E+00	6.26E-01	2.88E+00	1.32E+01	1.06E+00	9.35E-01
	0.01	3.75E-01	9.16E-02	2.88E-01	9.05E-01	-1.24E+00	7.07E-01
	0.1	3.49E-02	1.06E-02	2.88E-02	7.83E-02	-3.55E+00	6.12E-01
	1	3.75E-03	9.19E-04	2.88E-03	9.07E-03	-5.85E+00	7.06E-01
Pipes	0.0001	1.87E-01	1.07E-02	8.17E-02	6.21E-01	-2.51E+00	1.24E+00
	0.001	2.38E-02	3.18E-03	1.49E-02	7.01E-02	-4.20E+00	9.46E-01
	0.01	4.12E-03	6.53E-04	2.73E-03	1.14E-02	-5.90E+00	8.79E-01
	0.1	6.06E-04	1.83E-04	4.99E-04	1.37E-03	-7.60E+00	6.16E-01
	1	1.38E-04	2.18E-05	9.12E-05	3.82E-04	-9.30E+00	8.81E-01
Valves	0.0001	8.96E-02	9.19E-03	5.13E-02	2.85E-01	-2.97E+00	1.05E+00
	0.001	2.81E-02	5.17E-03	1.99E-02	7.68E-02	-3.92E+00	8.23E-01
	0.01	2.39E-02	7.30E-04	7.73E-03	8.18E-02	-4.86E+00	1.44E+00
	0.1	3.56E-03	1.18E-03	3.01E-03	7.68E-03	-5.81E+00	5.76E-01
	1	2.66E-03	1.53E-04	1.17E-03	8.93E-03	-6.75E+00	1.24E+00
Vessels	0.0001	5.85E-02	3.64E-03	2.61E-02	1.98E-01	-3.64E+00	1.22E+00
	0.001	1.21E-02	1.77E-03	7.74E-03	3.54E-02	-4.85E+00	9.14E-01
	0.01	2.93E-03	7.94E-04	2.29E-03	6.98E-03	-6.07E+00	6.68E-01
	0.1	8.04E-04	2.68E-04	6.88E-04	1.71E-03	-7.29E+00	5.68E-01
	1	3.23E-04	4.56E-05	2.00E-04	9.29E-04	-8.51E+00	9.26E-01

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