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Updated Filter Leak Frequencies for Use in Risk Assessments

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ABSTRACT

Quantitative risk assessment (QRA) is highly dependent on data, leading to more robust models as new and updated data is acquired. The Hydrogen Plus Other Alternative Fuels Risk Assessment (HyRAM+) QRA capabilities include calculations of individual risk from leaks in a gaseous hydrogen facility due to the potential effects of jet fires and explosions. Leak frequencies are acquired through statistical analysis of published data from a variety of sources and industries. The filter leak frequencies in previous versions of the HyRAM+ software are substantially greater than the leak frequencies of other components, leading to QRA results for gaseous hydrogen in which filters consistently dominate the overall risk. Data that were previously used to derive the filter leak frequencies were reevaluated for applicability and additional data points were added to update the filter leak frequencies. The new frequencies are more comparable to leak frequencies for other components.

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ACRONYMS AND TERMS

Acronym/Term	Definition
CCPS	Center for Chemical Process Safety
CNG	compressed natural gas
EPRI	Electric Power Research Institute
HSE	Health and Safety Executive
HyRAM+	Hydrogen Plus Other Alternative Fuels Risk Assessment Models
IEEE	Institute of Electrical and Electronics Engineers
LPG	liquefied petroleum gas
QRA	quantitative risk assessment
UK	United Kingdom

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1. INTRODUCTION

Quantitative risk assessment (QRA) is highly dependent on data, leading to more robust models as new and updated data is acquired. The Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) software [1] QRA capabilities include calculations of individual risk from leaks in a gaseous hydrogen system due to the potential effects of jet fires and explosions. The calculation requires leak frequency inputs for each of the systems components and dispenser failure types. These inputs are acquired through statistical analysis of published data from a variety of sources and industries. The different amount and quality of information available in each data source necessitates leak size binning (see Section 2.1); leak frequencies in HyRAM+ are specified for 0.01%, 0.1%, 1%, 10%, and 100% of the cross-sectional area of the component connection pipe size.
The default filter leak frequencies in version 5.1 (and previous versions) of the HyRAM+ software are substantially greater than the leak frequencies of other components, with the differences being especially pronounced for larger (10% and 100%) leaks. These frequencies lead to QRA results for gaseous hydrogen in which filters consistently dominate the overall risk. There is little sensitivity to the presence of other components in comparison. The median annual leak frequencies for each leak size bin for gaseous hydrogen are shown in Table 1-1 for several components in HyRAM+ for comparison; these frequencies are also plotted in Figure 1-1.

Table 1-1. Default median annual leak frequencies by leak size for possible gaseous hydrogen system components in HyRAM+ v5.1

Component	Leaks per Year				
	0.01%	0.1%	1%	10%	100%
Compressor	9.97E-2	1.70E-2	4.57E-3	1.52E-4	1.46E-5
Filter	5.33E-3	5.08E-3	4.84E-3	4.61E-3	4.39E-3
Flange	2.00E-2	2.20E-3	2.42E-4	2.67E-5	2.94E-6
Hose	5.79E-4	2.03E-4	1.65E-4	1.51E-4	6.17E-5
Instrument	6.24E-4	1.95E-4	1.12E-4	1.00E-4	3.68E-5
Joint	3.50E-5	4.69E-6	7.53E-6	7.53E-6	6.40E-6
Pipe	8.02E-6	3.70E-6	9.56E-7	4.61E-7	1.47E-7
Valve	2.87E-3	5.86E-4	5.44E-5	2.47E-5	4.82E-6
Vessel	1.40E-6	1.19E-6	7.90E-7	4.50E-7	2.33E-7

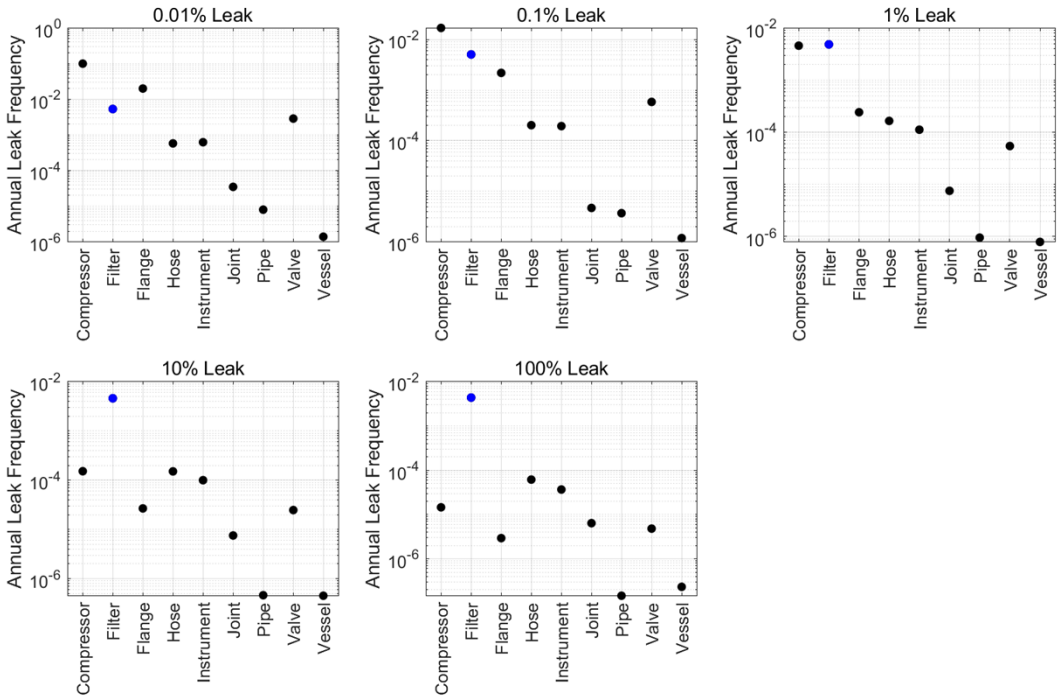


Figure 1-1. Default median annual leak frequencies for gaseous hydrogen components showing dominance of filters for 10% and 100% sized leaks.

As discussed in Section 2.2, similar data sets were used to derive leak frequencies in HyRAM+ for compressed natural gas (CNG) and liquefied petroleum gas (LPG). Default median annual leak frequencies for CNG and LPG are shown in Appendix A. For CNG systems, the filter leak frequencies are relatively high compared to some components, but are similar to other components (e.g., heat exchangers, jumpers, hoses). For LPG systems, the filter leak frequencies are not a leading risk contributor for larger leaks.

This work examines the source data for filter leak frequencies for gaseous hydrogen to determine why the leak frequencies are so much higher than for other components. Revisions to this source data are considered, and new suggested default leak frequencies are determined.

2. METHODS

Section 2.1 summarizes the statistical model that was used to derive the filter leak frequencies. Section 2.2 discusses the data input to that model.

2.1. Determination of Leak Frequencies

Leak frequencies for HyRAM+ are derived using a Bayesian hierarchical model that predicts the log-leak frequency for each of five leak size bins, in which the leak sizes are based on flow area of interconnecting pipe. The bins arose out of necessity to pool data from different sources with different levels of detail for statistical analysis [2], [3]. Leak data points are binned into sizes based either on qualitative descriptions of leak severity or, when it can be estimated, the ratio between the cross-sectional area of the leak and the cross-sectional area of the component connection flow area. The mapping between the qualitative descriptions and quantitative fractions of pipe flow area is as follows:

- 0.01% - Very Small
- 0.1% - Minor
- 1% - Medium
- 10% - Major
- 100% - Rupture

The Bayesian model functions as a linear regression between the leak size bins with bin-dependent variability in each bin. This is illustrated in Figure 2-1. A normal distribution (in natural log frequency space) is fit for each leak area bin, but this is done so that the centers of the normal distributions are all on the same line. This is described by the equation:

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

where $\mu_{LF,j}$ is the median leak frequency for the jth leak area bin, τ_j is the precision of the normal distribution for that bin, α_1 is the intercept of the line connecting all $j = 1, 2, 3, 4, 5$ bins, α_2 is the slope of the line connecting all of the bins, and LA_j is the leak area for the jth bin.

This construction allows the model to predict leak frequencies for bins for which there are no data points; if there are two or more bins with data, the linear relationship can be fit and used to predict leak frequencies for the other bins. The spread of the normal distribution in each bin is determined by the data points in that bin.

The model fitting procedure assumes uninformed prior distributions on α_1, α_2, and τ_j for $j \in \{1, 2, 3, 4, 5\}$, which are then updated using generic leak frequency data (not specific to the fuel type) and, when available, fuel-specific data. The posterior distributions for these parameters determine the final distributions for each leak size bin. This process is described for gaseous hydrogen in [3], for CNG in [4], and for LPG in [5].

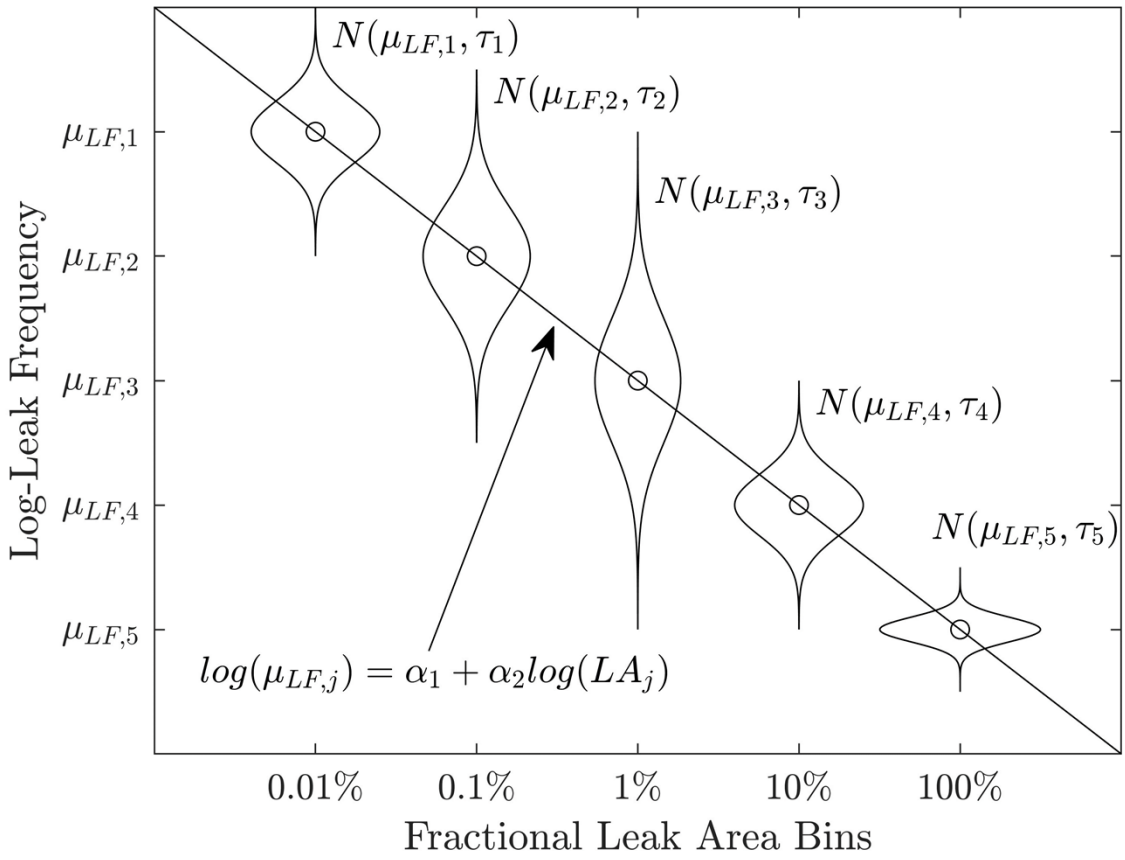


Figure 2-1. Conceptual illustration of the leak frequency model [6].

The relatively high filter frequencies for gaseous hydrogen are not a consequence of any error in this model structure, so it remains unchanged. It is fit using the data alternatives discussed in Section 2.2 to predict filter frequencies that may be more realistic. The new filter frequencies are presented and discussed in Section 0.

2.2. Data Selection

The 2023 release of HyRAM+ (v5.1[1]) used two sources of data to determine annual filter leak frequencies for each leak size. The data are summarized in the table below. Some of these data may not be appropriate for hydrogen systems and additional data are now available. This section discusses potential alternative data sets that may provide more appropriate leak frequencies.

[1] And prior versions

Table 2-1. Sources and filter leak frequency data used for gaseous hydrogen in the version 5.1 release of HyRAM+

Author	System Description	Leak Description	Annual Filter Leak Frequency	Leak Size Bin in HyRAM+
Savannah River [7]	Compressed gas system	Filter "internal rupture"	4.38E-03	100%
		Filter "internal leakage"	2.63E-02	1%
Spouge [8]	Offshore process plants	Full leaks (at normal operating pressure, controlled by emergency shutdown and blowdown) with ≥ 1 mm diameter	8.90E-04	1%

The data in Table 2-1 were compiled in a 2009 Sandia report [2] and were included in the first release of HyRAM+ in 2015 [9]. The Savannah River leak frequencies, published in 1993, were recommended values for compressed gas systems [7]. The original data were classified into Category 2 and Category 3 data. Category 2 data were described as failure data with some uncertainty for a variety of reasons, including less comprehensive data searches, approximate methods for component populations and exposure durations, and an ambiguous breakdown of failures into the failure modes that the authors of the Savannah River report were attempting to characterize. The Category 2 data were taken from Idaho National Engineering Laboratory databases published in 1990 [10] and 1991 [11] and a database from the Reliability Analysis Center [12]. The Category 3 data were comprised of failure rate estimates from sources including the U.S. Nuclear Regulatory Commission (NRC) [13], the Center for Chemical Process Safety (CCPS) [14], The Institute of Electrical and Electronics Engineers (IEEE) [15], the Electric Power Research Institute (EPRI) [16], and a paper by Lemmerse and Bosman [17]. While the many sources and considerations for the Savannah River data set lend credibility to its robustness, the failure mechanisms described for filters may not align with the physical failure modes in HyRAM+ QRA. The Savannah River data describe filter frequencies for "internal" events such as ruptures and leakages. In both cases, the filter would cease to function correctly, but neither would necessarily result in an external release of fuel, which is the failure mechanism modeled in HyRAM+. Therefore, it is worth exploring removing this data from the overall dataset used to determine leak frequencies in favor of more applicable data.

The second source used for the filter leak frequencies in versions 1.0-5.1 of HyRAM+ was a 2005 paper by Spouge [8]. The leak frequencies included in the paper were derived from a hydrocarbon release dataset for offshore industries in the UK Sector from 1992 through 2002; the dataset was compiled by the U.K. Health and Safety Executive (HSE). The filter frequencies provided were 8.9E-4 per year for leaks with a diameter of at least 1 mm and 6.4E-6 per year for leaks with a diameter of at least 50 mm. The paper does not specify whether the 8.9E-4 per year number refers to all leaks greater than or equal to 1 mm in diameter, or if it excludes the leaks greater than 50 mm in diameter. The 2009 Sandia report [2] only included the smaller leak frequency, classifying it as a 1% leak by pipe area. This leak size bin choice was not initially explained, but it would be based on a minimum pipe diameter of around 10 mm. The omission of the leak frequency for leaks greater than or equal to 50 mm in diameter was also not explained in the Sandia report but may be due to pipe sizes of at least 50 mm not being considered for hydrogen systems.

If the Savannah River data were removed from the filter leak frequency predictions, there would only be one data point remaining in the model (the 1% leak size from the Spouge paper). Although the original rationale in the 2009 Sandia report for omitting the Spouge frequency of a large filter

leak (≥50 mm in diameter) is unknown, this point should be considered as part of the dataset as a leak frequency for a 100% release.

To increase accuracy and credibility of the model, a dataset published in 2019 by the International Association of Oil & Gas Producers (IOGP) can also be added [18]. These data were gathered by the HSE from offshore hydrocarbon installations; the data were "intended to be applied to process equipment on the topsides of offshore installations and on onshore facilities handling hydrocarbons" without being restricted to hydrocarbon release applications. The IOGP recommends that the frequencies in this dataset only be used for equipment with a diameter range of 40 to 400 mm; the report discourages use of the dataset for equipment outside of the 40 to 400 mm diameter range, or recommends that the leak frequencies be subject to sensitivity testing if used over a larger range. This limitation should be considered when using the leak frequencies generated in this report. However, a lack of other industry data for equipment sizes outside of the provided range may warrant using these values anyway, with the acknowledgement that there is high uncertainty and the accuracy for equipment sizes outside the range is unknown.

The IOGP report contains two data sets: one based on leaks from 2006-2015 and one based on leaks from 1992-2015. The rationale for IOGP including both options is that the more recent time period reflects reduced leak frequencies. This is attributed to improvements in system design and maintenance. Using the more recent data sets would be appropriate when conservatism is not needed, and the data are being applied to a system likely to be more consistent with that time period. Using the data set based on leaks from 1992-2015, however, is more appropriate when conservatism is desired, or the data are being applied to a population of systems that includes earlier designs. HyRAM+ is designed to be applicable to many different systems, so it is appropriate to use the full 1992-2015 IOGP data set to inform leak frequencies. Because both the Spouge and IOGP data sets are based on HSE data, the 1992-2015 IOGP data set should be used without the Spouge data to avoid double counting the HSE data from 1992-2002. The IOGP data set as well as the chosen bin for each point is shown in the table below.

Table 2-2. Selected IOGP filter leak frequency data and bin sizes

Orifice Diameter (mm)	Annual Leak Frequency	Bin Size Selected
Inlets 50 to 150 mm in Diameter		
1 to 3	2.3E-03	0.01%
3 to 10	8.3E-04	1%
10 to 50	2.9E-04	10%
50 to 150	7.4E-05	100%
Inlets >150 mm in Diameter		
1 to 3	2.3E-03	0.01%
3 to 10	8.3E-04	0.1%
10 to 50	2.9E-04	1%
50 to 150	4.9E-05	10%
>150	2.5E-05	100%

Multiple analyses were performed based on these data insights to model updated filter leak frequencies. These analyses included:

- removing the Savannah River data set,
- adding the previously excluded Spouge rupture frequency, and
- replacing the Spouge data with the new data from IOGP.

To support evaluation of each of these choices, the steps were performed sequentially, and results are presented for each step in Section 0. The naming convention in Table 2-3 is used to refer to the different subsets of data.

Table 2-3. Different tested combinations of filter leak frequency data points for generating leak frequency distributions

Data Point Combination	Leak Frequency	Leak Size Bin	Reference	Description
Alt0	4.39E-03	100%	Savannah River	Original data set in [2], [3]
	2.63E-02	1%	Savannah River	
	8.90E-04	1%	Spouge	
Alt1	8.90E-04	1%	Spouge	Alt0 without the Savannah River data
Alt2	8.90E-04	1%	Spouge	Alt1 with the Spouge rupture point added
	6.40E-06	100%	Spouge	
Alt3	2.30E-03	0.01%	IOGP	Only use the IOGP data set
	8.30E-04	1%	IOGP	
	2.90E-04	10%	IOGP	
	7.40E-05	100%	IOGP	
	2.30E-03	0.01%	IOGP	
	8.30E-04	0.1%	IOGP	
	2.90E-04	1%	IOGP	
	4.90E-05	10%	IOGP	
	2.50E-05	100%	IOGP	

Hydrogen is not the only fuel type in HyRAM+ for which leak frequencies were derived from generic and sparse data. The failure mode for the Savannah River site also does not apply for CNG and LPG systems and Savannah River data was also used in those previous analyses. Though the filter leak frequencies for these fuels were not unreasonably high compared to other components, the frequencies for CNG and LPG were also updated. Removing the Savannah River data leaves only generic data for CNG and LPG filters, which means that the same generic filter frequencies apply for gaseous hydrogen, CNG, and LPG; the final recommended values for these frequencies are based solely on the IOGP data. This more substantially changes the CNG leak frequencies for filters because the original CNG leak frequency model did not include the IOGP data. The effect on

the LPG leak frequencies for filters is minor because the original LPG leak frequency model already included the IOGP data.

3. RESULTS

Results from the original gaseous hydrogen leak frequency analysis for filters are plotted in Figure 3-1.

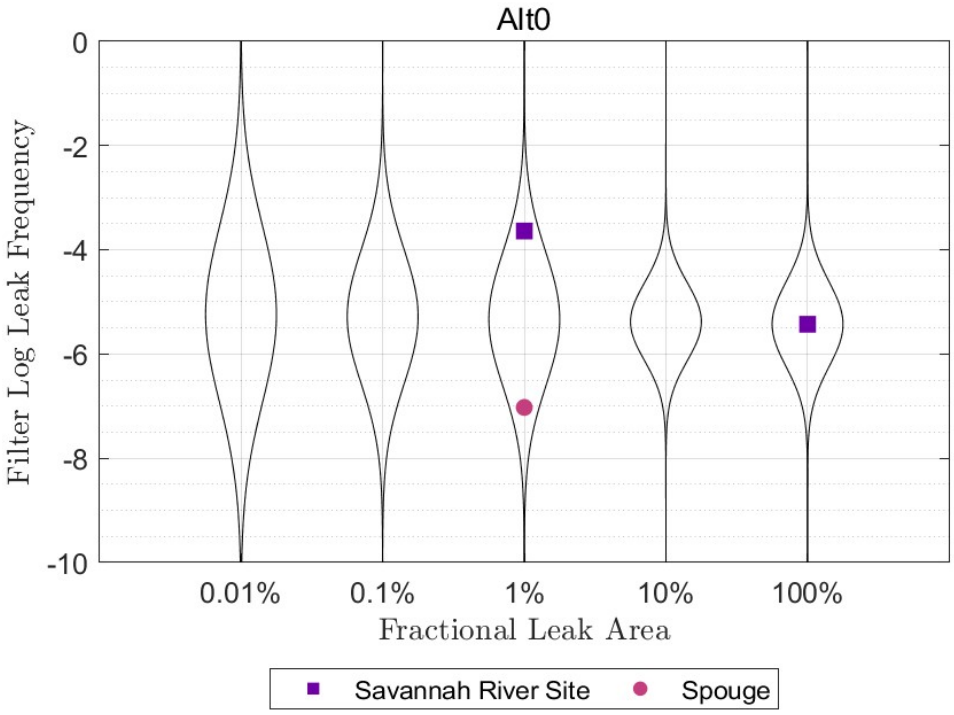


Figure 3-1. The original gaseous hydrogen filter leak frequency model based on Savannah River data and one Spouge data point.

The leak frequency model that arises from excluding the Savannah River site data is plotted in Figure 3-2. This demonstrates the challenge with sparse data sets; while the data point included in this model is believed to be more applicable than the Savannah River data, the model cannot converge without at least another data point.

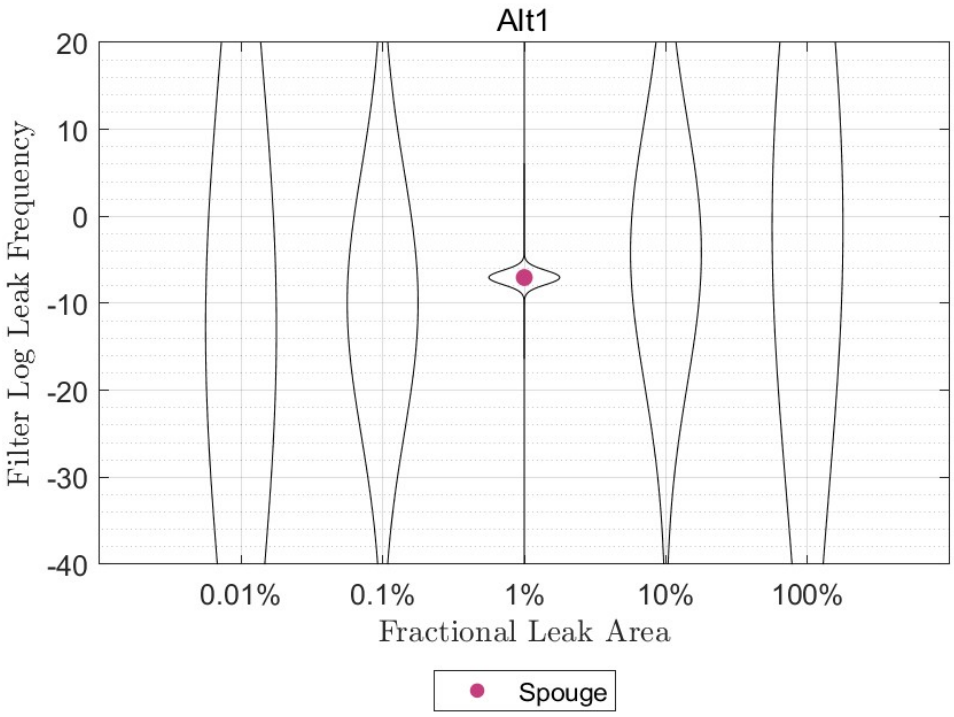


Figure 3-2. The gaseous hydrogen filter leak frequency model after removing the Savannah River data points, showing a non-converged model due to insufficient data points.

Simply adding the Spouge rupture point to the filter leak frequency model allows for a converged result, as shown in Figure 3-3. The point in the rupture bin is sufficient to fit the linear trend between the leak size bins. However, the IOGP data set contains more data and covers a longer period of time but, to avoid double counting, should not be combined with the Spouge data. The next option is to exclude both the Savannah River Site and Spouge data and fit the model to the IOGP data.

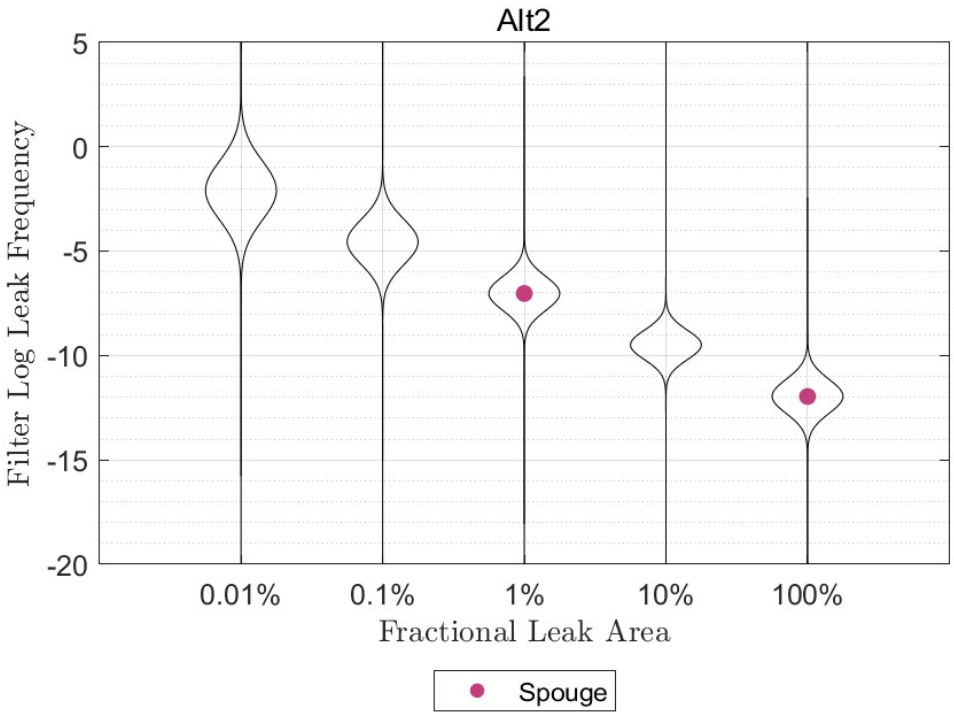


Figure 3-3. The gaseous hydrogen filter leak frequency model after removing Savannah River Site data and adding the Spouge rupture point, which allows for a converged model consistent with experience that ruptures are generally less common than small leaks.

The final model, which only includes the IOGP data, is plotted in **Error! Reference source not found.**. This model maintains the trend of decreasing leak frequency for larger leaks as seen in Figure 3-3, with some changes in variation within bins. This model still has relatively high uncertainty, which is consistent with the low state of knowledge about gaseous hydrogen filter leaks; filters are not expected to dominate risk, but the precise leak frequencies for filters in gaseous hydrogen systems are not quantified in the current research. A probabilistic model with a wider range of predictions is appropriate. The variation in the smallest leak size bins is reduced in this model because there are more data points in the larger leak area bins and those data points are relatively close together. In the absence of data for the smallest bins, the model extrapolates the distributions for these bins based on both the means and variances in the leak size bins with data. This extrapolation is more pronounced in this model than in the previous options because of the increased number of data points.

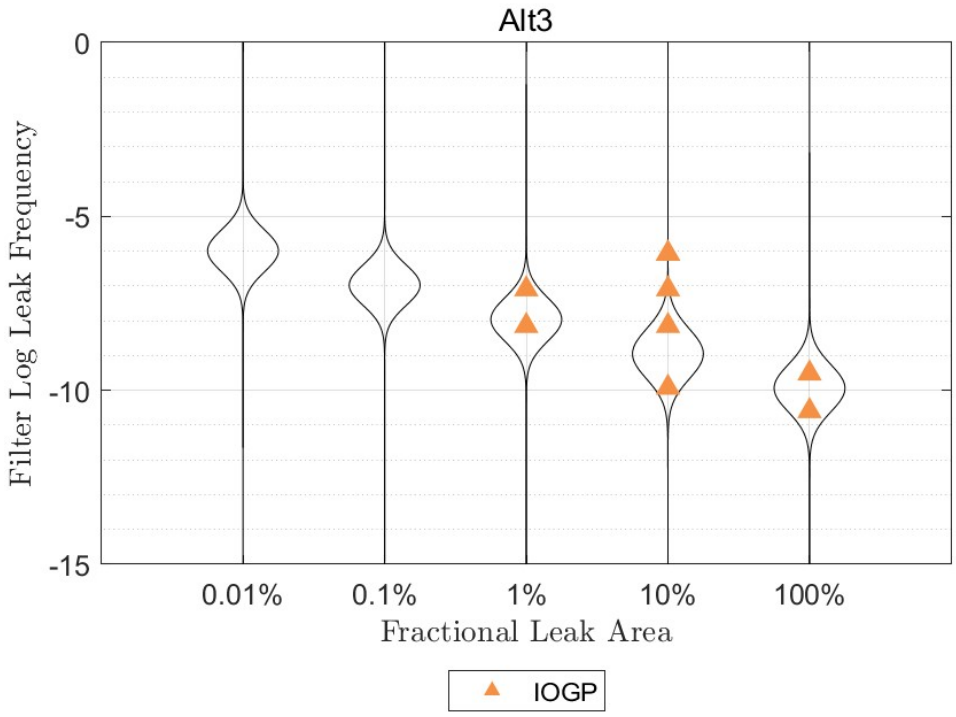


Figure 3-4. The gaseous hydrogen filter leak frequency model based solely on the IOGP data, which results in decreased median leak frequency predictions and reduced variation in some bins.

The new median filter frequencies for each leak size bin are plotted against the median leak frequencies for other components for gaseous hydrogen in Figure 3-5, for CNG in Figure 3-6 [4], and for LPG in Figure 3-7 [5]. The hydrogen results show a significant reduction in frequency of large leaks and ruptures, which lowers gaseous hydrogen leak frequencies for filters, so they are closer to the leak frequencies for other components. Filters are still among the top contributors of leaks to an overall system, but no longer dominate the risk by over an order of magnitude. For CNG, filter frequencies are substantially decreased with the new model; filters would not be expected to dominate risk results for CNG. The LPG leak frequencies are similar with the new model because the IOGP data were already included in the original LPG leak frequencies and, being the largest data set, dominated the behavior of the previous LPG leak frequency model.

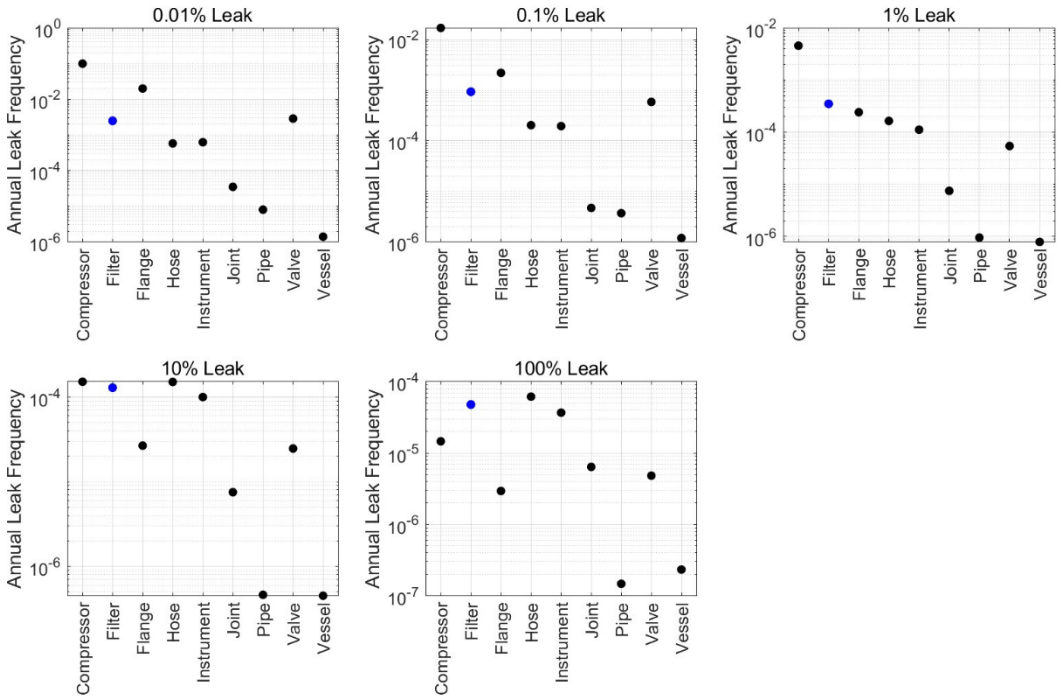


Figure 3-5. The median from the new gaseous hydrogen filter leak frequency model compared to other components, showing that filter leak frequencies for larger leaks are still among the top contributors to risk, but are no longer an order of magnitude higher than for other components.

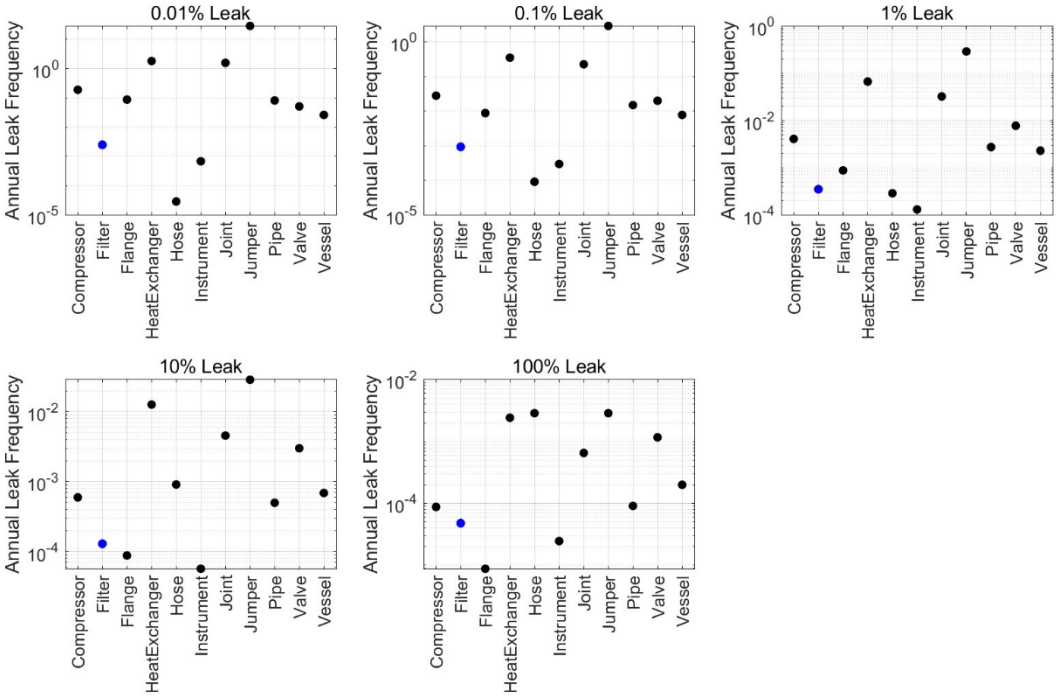


Figure 3-6. The median from the new CNG leak frequency model compared to other components, showing that filter leak frequencies are not primary contributors to risk.

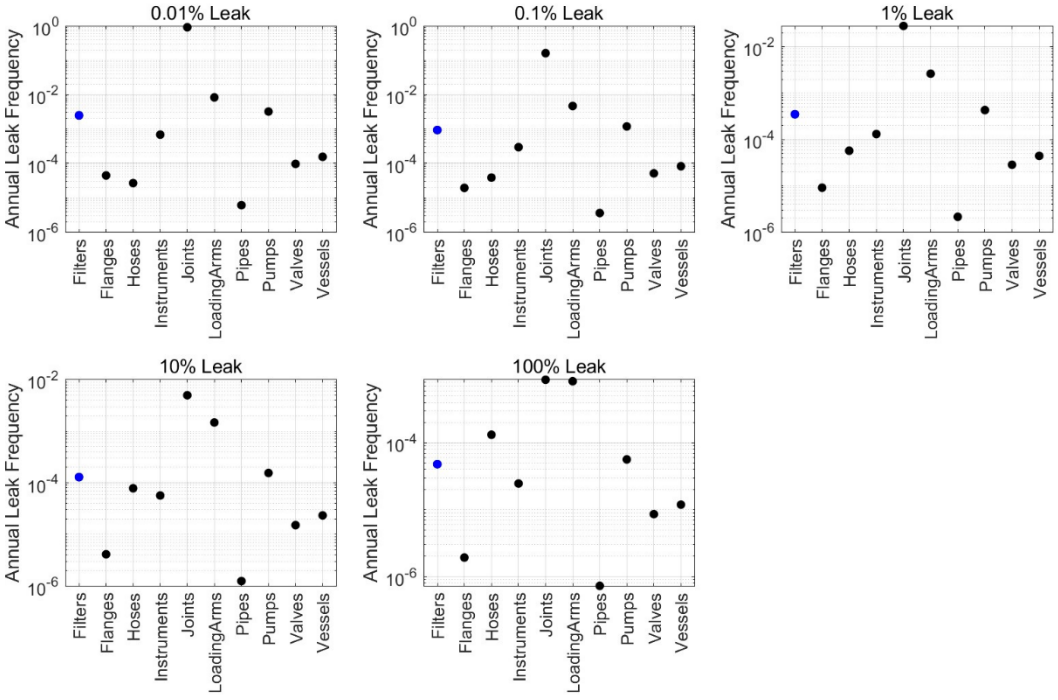


Figure 3-7. The median from the new LPG leak frequency model, which are similar to the original predictions in [5] with a slight but noticeable decrease in rupture frequency.

4. CONCLUSIONS

The data set used to derive filter leak frequencies for gaseous hydrogen systems in HyRAM+ versions 1.0-5.1 was reevaluated for applicability and additional data were assessed for inclusion to resolve unreasonable dominance of filters in QRA. The Savannah River site data for filter leak frequencies was judged to reflect a failure mode that is not relevant for the filter leaks modeled in HyRAM+. An additional data point from Spouge was also evaluated since it was not included in the original filter leak frequency derivation. This point was judged to be applicable, however, the Spouge data were excluded, and a larger IOGP data set (which includes rupture) was used instead. The Spouge data had to be excluded to incorporate the IOGP data set because the data that was used to derive the Spouge frequencies was also used to derive the IOGP frequencies. Removing the Spouge data avoided double counting this data. The larger data set from IOGP, which had been incorporated as generic data for LPG leak frequencies earlier in 2023 [5], was judged to be applicable and more comprehensive than Spouge.

Savannah River data had previously also been applied in the filter leak frequencies for CNG and LPG but reflects an incorrect failure mode for these fuels as well. The Savannah River data was similarly removed for these fuels. The Spouge data was also removed because of the overlap between the Spouge and IOGP data. As a result, the filter leak frequencies for gaseous hydrogen, CNG, and LPG are the same; the only available data for these fuels are generic leak frequencies from IOGP that apply to all three fuels.

The resulting larger data set for filter leak frequencies was applied with the same statistical framework as used for the other HyRAM+ default leak frequencies. The new gaseous hydrogen filter leak frequencies still suggest filters are one of the top contributing components to risk, but the frequencies are now comparable to other components, rather than being over an order of magnitude higher.

Uncertainty distributions are provided (Table 3-1) in the form of means and standard deviations for the normal distributions on log leak frequency. These distributions can be used for uncertainty quantification by sampling in log (base e) leak frequency and exponentiating the samples. The distributions should be truncated at physically reasonable values if used for uncertainty quantification.

Table 4-1. Default leak frequency recommendations for gaseous hydrogen, CNG, or LPG systems

Leak Size	Mean	5th Perc.	Median	95th Perc.	μ	σ
0.01%	3.04E-03	9.47E-04	2.49E-03	6.78E-03	-5.99E+00	6.06E-01
0.1%	1.12E-03	3.63E-04	9.31E-04	2.43E-03	-6.98E+00	5.85E-01
1%	4.25E-04	1.24E-04	3.51E-04	9.50E-04	-7.96E+00	6.26E-01
10%	1.70E-04	4.05E-05	1.29E-04	4.17E-04	-8.95E+00	7.18E-01
100%	6.14E-05	1.63E-05	4.79E-05	1.46E-04	-9.94E+00	6.74E-01

The new leak frequencies for filters resolve some of the dominance of filters in gaseous hydrogen QRAs, but still reflect high uncertainty due to the lack of fuel-specific data. The frequencies may be updated in the future if more hydrogen, CNG, or LPG data become publicly available; it is also appropriate for HyRAM+ individual users to replace or update these leak frequency estimates should they have more applicable data.

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APPENDIX A. DEFAULT LEAK FREQUENCIES FOR OTHER FUELS

A.1. Compressed Natural Gas

Table A-2. Previous default median annual leak frequencies by leak size for different CNG system components in HyRAM+ V5.1

Component	Leaks per Year				
	0.01%	0.1%	1%	10%	100%
Compressor	1.89E-1	2.78E-2	4.07E-3	5.97E-4	8.77E-5
Filter	2.97E-1	1.09E-1	4.02E-2	1.48E-2	5.44E-3
Flange	8.76E-2	8.76E-3	8.77E-4	8.78E-5	8.78E-6
Heat Exchanger	1.82E+0	3.49E-1	6.64E-2	1.27E-2	2.43E-3
Hose	2.88E-5	9.10E-5	2.88E-4	9.11E-4	2.88E-3
Instrument	6.85E-4	2.96E-4	1.31E-4	5.67E-5	2.46E-5
Joint	1.58E+0	2.25E-1	3.21E-2	4.57E-3	6.54E-4
Jumper	2.88E+1	2.88E+0	2.88E-1	2.88E-2	2.88E-3
Pipe	8.17E-2	1.49E-2	2.73E-3	4.99E-4	9.12E-5
Valve	5.13E-2	1.99E-2	7.73E-3	3.01E-3	1.17E-3
Vessel	2.61E-2	7.74E-3	2.29E-3	6.88E-4	2.00E-4

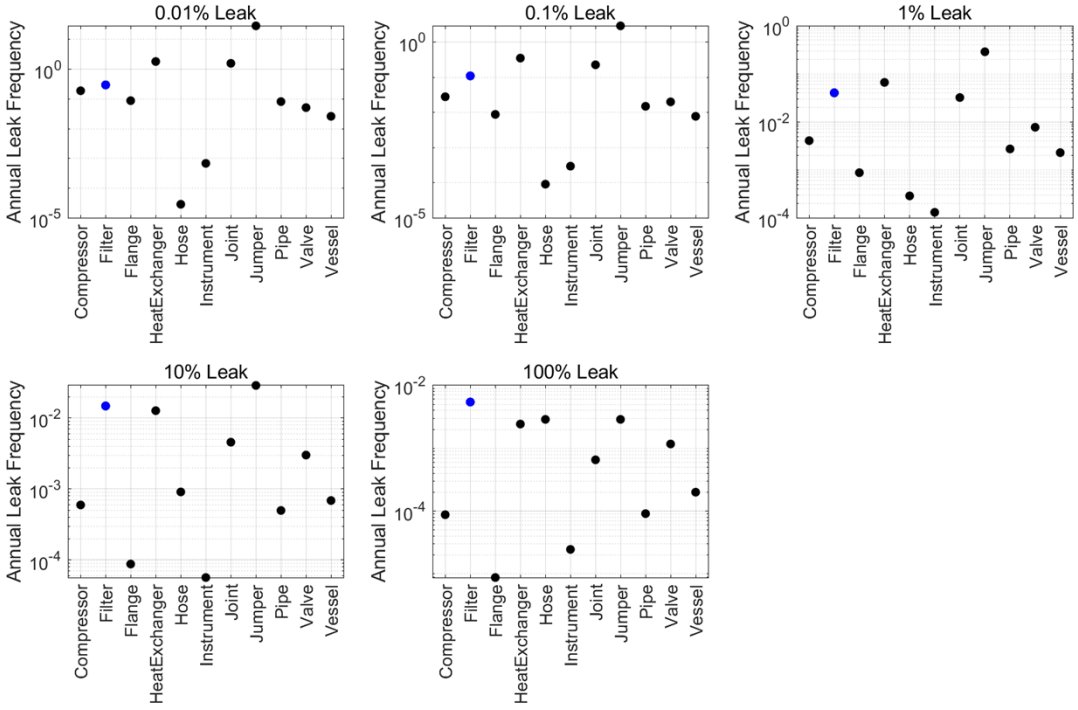


Figure A-1. Previous default median annual leak frequencies for CNG systems showing that filter leak frequencies for larger leaks were relatively high but did not dominate over all other components for CNG systems.

A.2. Liquefied Petroleum Gas

Table A-3. Previous default median annual leak frequencies by leak size for different LPG system components.

Component	Leaks per Year				
	0.01%	0.1%	1%	10%	100%
Filters	2.28E-3	8.79E-4	3.49E-4	1.21E-4	5.39E-5
Flanges	4.45E-5	1.93E-5	9.08E-6	4.11E-6	1.92E-6
Hoses	2.67E-5	3.85E-5	5.71E-5	7.83E-5	1.32E-4
Instruments	6.86E-4	2.96E-4	1.31E-4	5.67E-5	2.46E-5
Joints	9.15E-1	1.61E-1	2.83E-2	4.99E-3	8.78E-4
Loading Arms	8.32E-3	4.68E-3	2.63E-3	1.48E-3	8.33E-4
Pipes	6.07E-6	3.59E-6	2.14E-6	1.24E-6	7.24E-7
Pumps	3.22E-3	1.19E-3	4.31E-4	1.55E-4	5.64E-5
Valves	9.63E-5	5.12E-5	2.84E-5	1.51E-5	8.57E-6
Vessels	1.55E-4	8.24E-5	4.42E-5	2.33E-5	1.19E-5

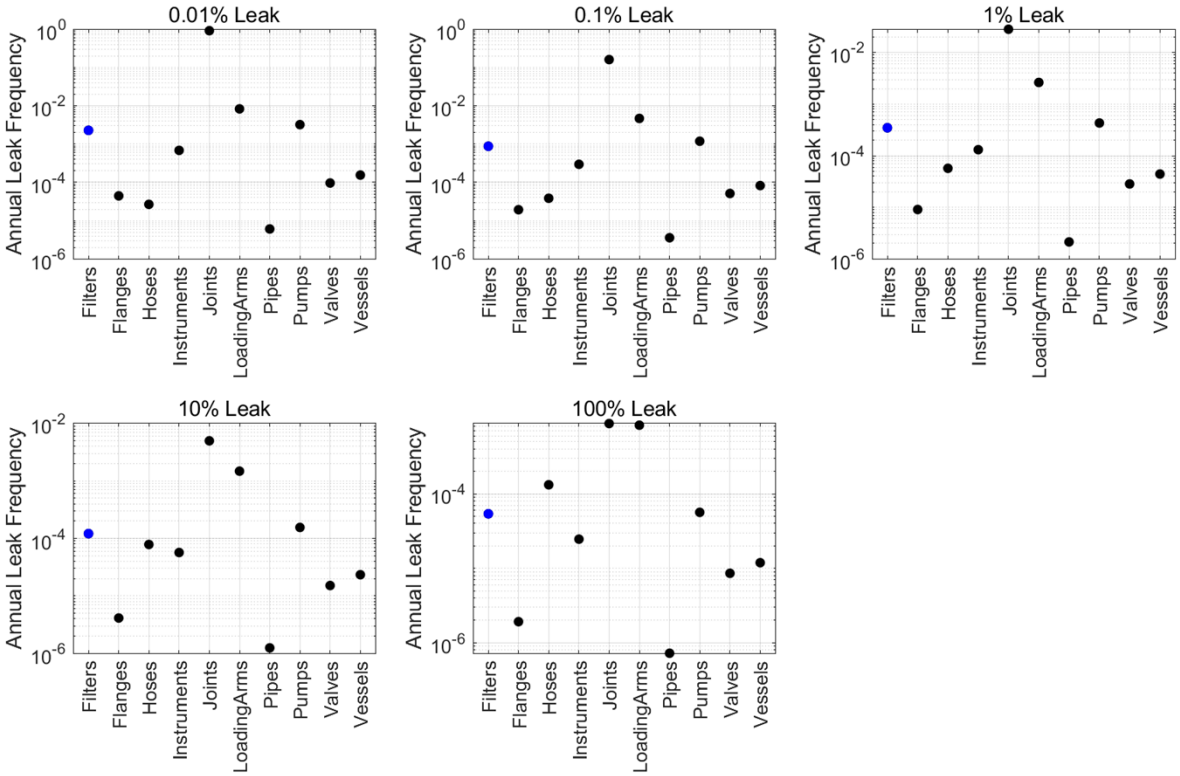


Figure A-2. Previous default median annual leak frequencies for LPG systems showing that filter leak frequencies for larger leaks were not higher than for other components.

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