Final Report

Quantifying Methane Emissions from Distribution Pipelines in California

ARB Agreement Number: 12-420
GTI Project No. 22504

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September 2019

Disclaimer

Acknowledgement

The information gathered in this report could not have been completed without cooperation and support of several organizations within the state of California. Those companies include Southern California Gas Company, Pacific Gas and Electric, and San Diego Gas and Electric.

We would also like to acknowledge the following project team members who contributed to this project.

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Abstract

This study examined methane emissions from distribution main and service pipelines within the state of California. Natural gas, which is comprised of mostly methane, leaks from various sources along the distribution pipeline. The objective of the project was to develop California-specific emission factors (EFs) for various pipe material types commonly found in natural gas utility distribution systems. These factors can then be used to improve the accuracy of the reporting of total emissions for natural gas local distribution companies (LDCs).

Executive Summary

Methane emissions from natural gas pipelines are of growing interest to federal, state, and local organizations. Accurately quantifying fugitive emissions from natural gas pipeline leaks is essential not just for understanding total greenhouse gas (GHG) emissions to the atmosphere, but also the development of plans and procedures to reduce those emissions in the future. The objective of this project was to quantify fugitive emissions from natural gas distribution pipelines in California. Currently, emissions are calculated and reported using EFs that were developed in 1996 by the Gas Research Institute (GRI) and the Environmental Protection Agency (EPA). That study is outdated, and recent regulations have changed how utilities maintain their systems, including prevention and mitigation of leaks. Additionally, field measurement instruments and utility practices have changed since the completion of that study. Consequently, EFs could be improved upon with the collection and analysis of new field data. The data collection for this study initially focused on non-hazardous leaks from unprotected steel mains and services, as well as plastic mains and services.

To accomplish this task, field visits were conducted with the three largest local distribution companies within the state of California. Those companies are Southern California Gas Company (SoCal Gas), Pacific Gas and Electric (PG&E), and San Diego Gas and Electric (SDG&E). Each company provided a list of open leaks by material type.

The area where methane was leaking into the atmosphere was identified at each site with a combustible gas indicator (CGI). A Hi-Flow sampler was used to measure the flow rate of the leak. This method of collecting leak measurements is described in detail within this report.

The data collected throughout the execution of this project were analyzed using advanced statistical and probabilistic analysis and distribution fitting. The analysis provided a representation, within the State of California, of the average leak rates for underground distribution mains and services (i.e., by facility type), as well as categorization by material, such as plastic, unprotected or protected steel.

As part of the study, 78 leak sites were measured above ground. During the leak repairs by the utilities, about 1-3 years later, it was discovered that the original identifications of leak facility (mains vs. services) or pipe material (plastic vs steel) were incorrectly classified 59% of the time. The facility and the material were misclassified 40% and 31% of the time respectively. A probabilistic analysis was conducted on the misclassifications. A single-sided prediction limit of 90% was set. Based on the analysis, misclassification of non-pipe items as pipe, and non-leakers as leakers were both found to be 5%. The upper prediction limit for classifying the material and/or facility incorrectly was 66%.

The 76 verified pipe leak samples (of the original 78 unverified samples) were analyzed in grouped categories by facility type or material and subjected to a rigorous Monte Carlo analysis of the difference of means between the facility and material categories. There was no statistically significant difference observed in the mean leak rates between the material groups. In fact, the likelihood that the differences observed from the sample sets were greater than 90% in all material cases to be from random variation in the sample alone from the same population itself. The facility type, i.e., mains and services, showed a 40% and 60% likelihood that the observed difference in means could have been produced by random variation in the sample alone from the same population. In addition to the 76 verified pipe leak samples, there were two samples that were outside the scope of this project. One sample was verified as a leak on a *valve* (not a pipe) and the other sample was verified a non-leaker, i.e. it was incorrectly identified as a leaker.

All the CARB sample categories were fit to lognormal distributions with an excellent "goodness of fit." These distributions of leak rates were used to calculate an average for each category, as well as the combined sample set. The average leak rates from the fitted distributions and their confidence intervals correlated well with the bootstrap analysis of the same sample sets which utilized a non-parametric Monte Carlo analysis with 10,000 resamples. This technique allowed prediction of leak rates from smaller sample sets, until larger numbers of random leaking samples can be collected.

A Bayesian probabilistic analysis of the leak rate distributions by facility or material category was completed. More than 50% of the observed samples had leak rates less than or equal to 1 standard cubic foot per hour (scfh) with no samples having a leak rate greater than 30 scfh.

Bayesian inference was used to calculate the most likely and lower and upper confidence limits for proportions of leaks by category. Individual plots for each asset class were generated and the data suggest that most leaks occurring in distribution pipelines in California are relatively small compared to leaks observed in other sectors of the gas industry. The data also suggests that while the average leak rates for each facility or material category are skewed by a few large emitters, the probability of these emitters occurring is relatively small as shown by the conservative upper confidence limits for the leak rate categories greater than 15 scfh.

The average leak rates for underground distribution mains and services from this study can be used to develop state-wide methane emission estimates from distribution pipelines in California. The data collected from this study suggest that the quantification of emissions could be developed based on a reduced set of groups or categories without a detailed breakdown by material and facility type.

Objective

The objective of the project was to quantify fugitive methane emissions from natural gas distribution pipelines in California. The project focused on field measurements to establish the EFs at sites with known leaks from various types of below ground pipe materials used in natural gas distribution systems.

Methane emissions from underground pipeline leaks are a key contributor to total methane emissions for the Local Gas Distribution Companies (LDCs). The current reported estimates of their annual emissions are based on earlier studies performed by GRI and EPA in the early nineties (GRI/EPA 1996 - Vol. 2). Due to the growing interest in obtaining more accurate estimates for the reduction of greenhouse (GHG) emissions, federal and state organizations and LDCs have indicated the need for updated and more accurate emission estimation methodologies.

Background

The GRI-EPA Study

Until recently, the 1996 GRI-EPA study has served as the primary source of information for methane emissions from the natural gas industry. The study provided emission estimates for the natural gas infrastructure from activity data (AD) and emission factors (EFs) as represented by the following equation:

$$Total\ Emissions = \Sigma\,(EFs \times AD) \quad [1]$$

Where,

EFs = the amount of methane released by an emitting entity, and
AD = the total population of the emitting entity.

For belowground distribution main and service pipelines, leak measurements were collected from the participating companies using a standardized testing protocol (GRI/EPA 1996 - Vol. 9). Because the EFs are variable in nature, subsets of the total emissions were defined for the emission and AD based on pipeline parameters.

The parameters that had the most influence on the estimation of the EFs for belowground pipes were the pipe facility type (i.e., main versus service) and pipe material. It's important to note that the GRI-1996 study (GRI/EPA 1996 - Vol. 9) quantified the AD based on these two parameters.

The EFs were determined by isolating a known underground leak. The line was shut off at both sides of the leak without disturbing the soil around the leak source. Gas was supplied to the isolated pipe section, and measurements were taken using laminar flow elements to estimate the gas flow rates (i.e., volume of gas leak per unit time). Figure 1 shows a schematic of the procedure used to estimate the leak rates.

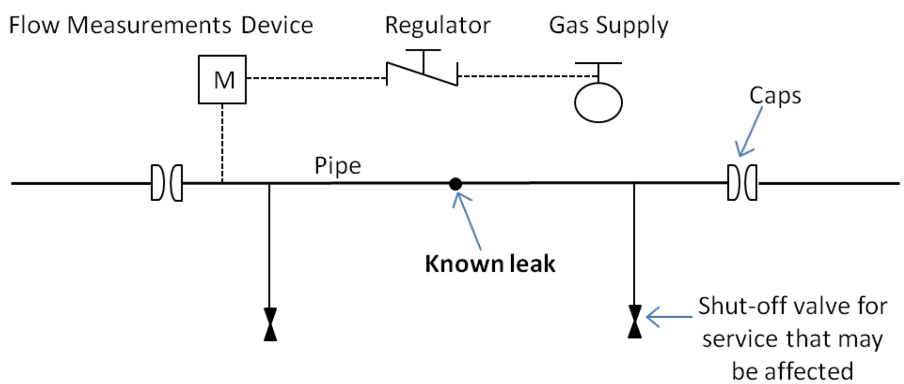


Figure 1 – Schematic of the GRI-EPA testing procedure

(GRI/EPA 1996 - Vol. 9)

The average natural gas leak rates were calculated from these measurements. Table 1 summarizes the EFs by pipe use and material in scf/leak-hour except for the cast iron main pipes which were in scf/mile-hour.

Table 2 shows the calculated annual methane EFs for main and service pipes. For example, the plastic mains natural gas leak rate of 12.45 scf/leak-hour (Table 1) was multiplied by 8,760 hours/year and by the methane content in the gas composition to produce an annual average methane leak rate of 101,897 scf/leak-year.

The methane EFs in Table 2 were calculated after subtracting the amount retained in soil due to oxidation. The soil oxidation rates were estimated from a separate GRI study to account for the oxidation of methane (CH_4) from soil microbes (Washington State University and University of New Hampshire 1996).

Table 1 – Summary of Measurements of Natural Gas Leak Rates

TABLE 7-1. SUMMARY OF THE NORTH AMERICAN LEAK MEASUREMENT DATA

Pipe Use	Pipe Material	Sample Size	Average Leak Rate, (scf/leak-hour)[a]	90% Confidence Interval, (scf/leak-hour)[a,b]
Mains	Cast Iron	21	0.0093[c]	0.0053[c]
	Unprotected Steel	20	6.45	5.61
	Protected Steel	17	2.55	2.01
	Plastic	6	12.45	19.81
Services	Unprotected Steel	13	2.50	2.46
	Protected Steel	24	1.15	0.62
	Plastic	4	0.37	0.51
	Copper	5	0.94	0.62

[a] Leak rate of natural gas (not adjusted for methane content or soil oxidation).
[b] 90% confidence interval around the mean value (upper bound minus the mean).
[c] scf/foot-hour.

TABLE 8-2. METHANE EMISSION FACTORS FOR UNDERGROUND DISTRIBUTION PIPELINES[a]

Pipe Use	Pipe Material	Average Methane Leakage Rate (scf/leak-yr)	Soil Oxidation (%)	Average Emission Factor[a] (scf/leak-yr)	90% Confidence Interval[a,b] (scf/leak-yr)
Mains	Cast Iron	399,867[c]	40.3	238,736[c]	152,059[c]
	Unprotected Steel	52,748	1.8	51,802	48,212
	Protected Steel	20,891	3.0	20,270	17,243
	Plastic	101,897	2.0	99,845	165,617
Services	Unprotected Steel	20,433	1.1	20,204	21,129
	Protected Steel	9,438	2.6	9,196	5,581
	Plastic	3,026	21.2	2,386	3,412
	Copper	7,684	0	7,684	5,559

[a] Adjusted for soil oxidation of methane.
[b] 90% confidence interval around the mean value (upper bound minus the mean).
[c] scf/mile-year.

US EPA Emission Factors for Distribution System

Similar to the GRI study (1996), the US EPA Mandatory Greenhouse Reporting Rule (EPA 2010) requires that natural gas distribution facilities use the appropriate default population EFs (Table 3) to estimate fugitive emissions from distribution pipelines. The methane emission estimates are calculated by multiplying the EFs by the AD.

Table 3 – Default Methane Emission Factors for Distribution Mains and Services (Table W-7) (EPA 2010)

Population Emission Factors - Distribution Mains, Gas Service[2]	
Unprotected Steel	12.58
Protected Steel	0.35
Plastic	1.13
Cast Iron	27.25
Population Emission Factors - Distribution Services, Gas Service[2]	
Unprotected Steel	0.19
Protected Steel	0.02
Plastic	0.001
Copper	0.03

Note: - For Mains, Emission Factor is in scf/mile-hour
- For Services, Emission Factor is in scf/service-hour

Washington State University/Environmental Defense Fund Study (2015)

The Environmental Defense Fund (EDF) commissioned a study that was executed by Washington State University (WSU). The report was published in Environmental Science and Technology (Brian K. Lamb 2015). As part of the project, WSU utilized a similar data collection method as used in this study to quantify fugitive emission from the natural gas distribution system. GTI utilized the data from the WSU study to compare to the data collected in this project. It should be noted that data collected as part of the WSU study were at a national level and not specific to California and as of the time of the writing of this report, the WSU study had not yet reported if the samples were verified. GTI performed statistical analyses to compare the two data sets and the results are presented in this report.

Surface Measurements of Methane Emissions - Methodology

Introduction

In this study, EFs (scf/leak-hour) for distribution pipelines are derived from the surface measurements aboveground of the leak source. These measurements provide an approximation of 'in-air' methane emission rates without the need to excavate the leak source and estimate the amount retained in the soil due to oxidation. In a previous project, GTI established the validity of this approach at utilities testing facilities (Farrag and Wiley 2013). The gas leak rates from the surface measurements were validated in controlled leak tests using the Hi-Flow Sampler device. Figure 2 shows a portable Hi-Flow device that provides real time measurements of gas flow rate and concentration in a captured enclosure.

The testing procedure consisted of introducing leaks in belowground pipes, measuring the surface leak using a cover and a Hi-Flow device (as shown in Figure 3), and correlating the measurements with the applied flow rates.

Figure 2 – View of the Hi Flow Sampler device

Figure 3 – Capturing gas leak area for rate measurements

Field Measurement Procedure

Field tests were performed at utility sites by following the sampling protocols described below::

1. Identify the Leak Area

a) Identify the leak area at the surface from a known leak source by using gas distribution operator leak detection procedures to locate and classify leaks for repair. To identify a leak in a section of pipe, a portable hydrocarbon analyzer or flame ionization detector (FID) was used to screen methane that seeped above the ground while walking along the buried pipeline. Any methane concentrations above the background level (typically about 3-5 ppm) were considered potential indications of a nearby leak.

b) Once the leak was pinpointed, the perimeter of the leak area was mapped using a Combustible Gas Indicator (CGI). The CGI readings, shown in Figure 4, were used to identify the covered area for the Hi-Flow measurements.

Figure 4 – The CGI meter used to identify the leak area

2. Surface Measurements of the Leak Rate

a) The aboveground measurements of the leak rates were performed by enclosing the leak area with a cover and measuring the methane leak rate using the Hi-Flow device. A schematic of the surface measurements is shown in Figure 5. The leak rate was measured three times at each leak site.

b) Various areas of covers were used with an average size of 4 ft wide by 8 ft long. The cover has an opening at the top center to connect to the Hi-Flow device.

c) When the identified leak area was larger than the cover, the area was divided in a grid pattern to avoid overlap of the measurements and the total leak rate was the sum of the individual measurements in each area of the grid.

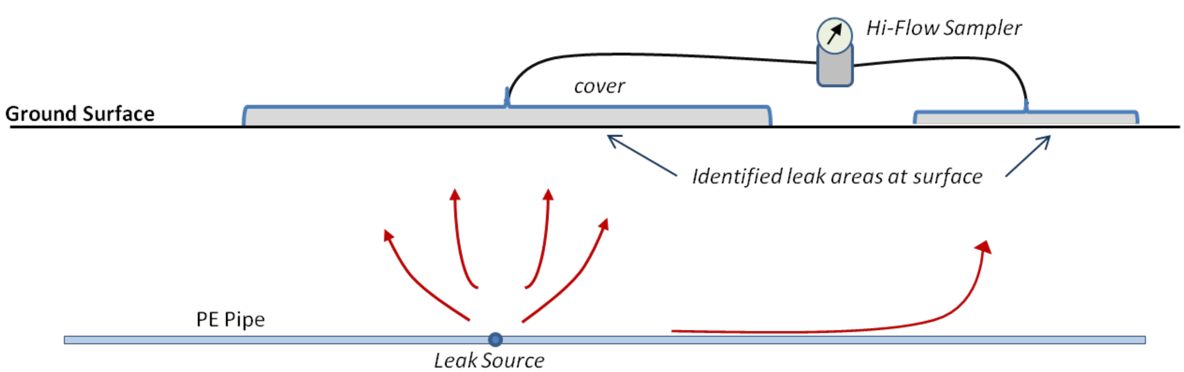


Figure 5 – Schematic of surface measurements with the Hi-Flow device

Improvements Made to the Sensitivity of the Hi-Flow Device

The Hi-Flow device, in its "off the shelf" form, has a sensitivity to detect natural gas at a leak rate of 0.6 scfh. In previous studies, GTI had utilized that as the minimum detection limit for the device. To improve the sensitivity of the device, GTI added a combustible gas indicator to the inlet of the device to directly measure the concentration of gas flowing into the machine. This modification improved the sensitivity, lowering the detection limit to 0.012 scfh.

Summary of Field Tests

Site Selection

GTI worked with the three largest LCDs in California to perform field testing on unprotected steel main and service pipes and plastic main and service pipes: SoCal Gas, PG&E and SDG&E. The service territories of these three companies are depicted in Figure 6 below. In total, GTI made eight field trips to the three service territories to collect leak measurements on underground pipelines.

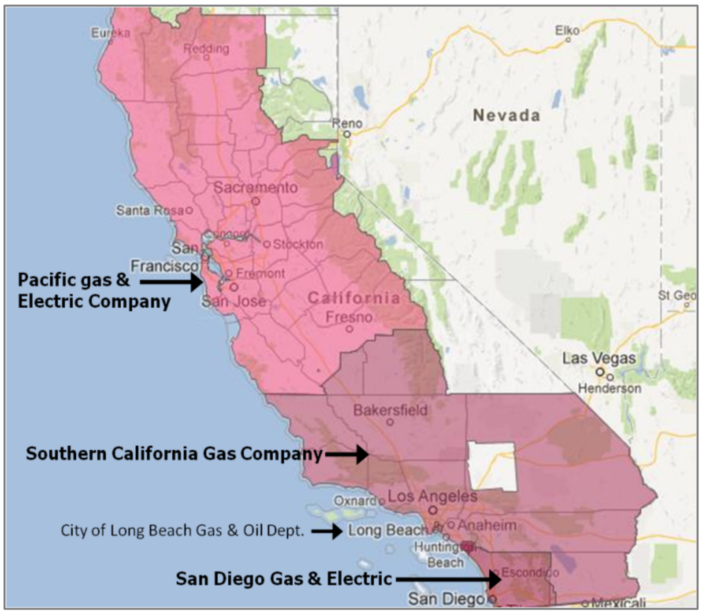


Figure 6 – CA Gas Utilities - Service Territories

The selection of sites was based on the type of pipeline material in the distribution system. This study targeted plastic and steel pipes for its field campaign. Plastic accounts for about 57% of the distribution pipelines in CA and steel (protected and unprotected) accounts for the remaining 43% as shown in Table 4. The other pipe materials (e.g., cast iron, copper) account for a negligible 0.03% of the pipelines in CA so these were not included in the field campaign. (Note: cast iron pipe has been phased out of California's pipeline network).

The utility sites were selected as randomly as possible given project constraints. There was not sufficient time or budget to perform a truly random sampling of leaks in CA. A truly random sample set would include conducting a leak survey of randomly selected sites (rather than relying on leaks already identified by utilities).

In this study, test sites were randomly selected from non-hazardous leaks (i.e., Grade 2 and Grade 3 leaks) based on utility records without consideration of planned repair or replacement. The classification of these grades varies according to utilities but mostly follow the Gas Piping Technology Committee (GPTC) guide for leak classification.

Table 4 – Miles of Natural Gas Distribution Pipeline in California by Material Type[1]

		MAIN		SERVICES	
Pipe Material	Calendar Year	Total Miles	% of Miles	Total Miles	% of Miles
STEEL	2014	52,330.2	49.62	33,983.6	35.85
	2013	52,399.4	49.85	34,164.8	36.32
	2012	52,378.5	50.03	34,327.8	36.79
	2011	52,147.1	49.98	37,650.3	37.02
	2010	52,215.2	50.19	37,674.0	37.15
PLASTIC	2014	53,127.4	50.38	60,755.1	64.08
	2013	52,677.0	50.12	59,855.7	63.62
	2012	52,205.6	49.87	58,891.3	63.12
	2011	52,068.4	49.91	63,837.8	62.78
	2010	51,701.7	49.69	63,454.6	62.57
OTHER MATERIALS	2014	0.8	0.00	13.6	0.01
	2013	0.4	0.00		
	2012	0.4	0.00	0.1	0.00
	2011	0.3	0.00	0.1	0.00
	2010	0.3	0.00	3.6	0.00
IRON	2013	29.0	0.03		
	2012	102.0	0.10		
	2011	115.5	0.11		
	2010	125.4	0.12		
COPPER	2014			51.7	0.05
	2013			57.1	0.06
	2012			88.6	0.09
	2011			201.6	0.20
	2010			284.2	0.28

The leaks at each site were initially mapped using a CGI that measured various natural gas concentrations aboveground, ranging from 5 to 80 percent above the lower explosion limit (LEL). Some sites had higher percent gas measurements when the leak sources were pinpointed with bar holes.

Leak rates were measured using the Hi-Flow device at the surface. As shown in the methodology section of this report, the measurements were performed by measuring leak flow rates of covered areas at the surface, where the CGI measurement identified the leaks.

SoCal Gas Field Trips

The field measurements of methane emissions were performed at the SoCal Gas territory in April 2014 and April 2015. The measurements were performed on unprotected steel and plastic main and service pipes at several locations in southern California. Pipeline leak rate measurements were collected at 37 sites. One leak was verified to be on a valve and not a pipe, so it was excluded from the leak rate analysis.

[1]Data Source: US DOT Pipeline and Hazardous Materials Safety Administration.

SDG&E Field Trips

Three trips were made to SDG&E to collect field measurements. The first took place in November of 2014, the second in January of 2015, and the third in August of 2015. GTI had some difficulty collecting measurements on these trips as SDG&E had relatively few leaks on its system. In total, 13 measurements were recorded at locations in SDG&E's territory.

PG&E Field Trips

Three trips were made to PG&E's service territory to collect field measurements on both unprotected steel and plastic main and service pipes. The first trip took place in August of 2014, the second trip took place in February of 2015, and the third in September of 2015. A total of 28 leak rate measurements were recorded from underground natural gas pipelines. One "leak" had a verified leak rate measurement of zero and was not included in the leak rate analysis.

Figure 7 – Surface measurement

Results

GTI worked directly with the utility companies to coordinate field measurements with targeted non-hazardous leaks (e.g., Grade 2 and 3) and measured 78 underground pipeline leaks. Leak survey and repair data varied per company, and sometimes records were not always immediately updated. As a result, there were times when leak locations identified for field measurement could not be found or the leak had already been repaired. Additional leak information such as type, location and material were based on utility records. Designating between a main and service pipe varied per company and without digging up the leak it was difficult to define the real source of the leak, especially those at the junction between main and service lines.

Verification of Facility and Material Categories

The gas distribution operators participating in this project ultimately excavated and repaired the underground pipeline leaks. They verified the *facility* (main or service) and *material* (plastic, unprotected steel, or protected steel) *categories*. Of the 78 originally reported leaks, one of them turned out to be a steel valve (not part of this study which is focused on pipelines) and one was confirmed as a non-leaker (zero emissions). Of the remaining 76 verified pipeline leaks, there were significant percentages of misclassified facility and/or material categories. The results and findings of the verification digs is shown in Table 5 below. For the 78 unverified leaks, 59% were misclassified, where either the facility *or* the material was misclassified. Facility misclassifications were made on 40% of the leak sites and material misclassifications were made on 31% of the leak sites.

Table 5 – Results of Verification Digs on Original Leak Sample Set

	Unverified	Number and Percent Misclassified Based on Verification Digs				
	Leaks	Non-Pipe	Non-Leaker	Facility Misclassified	Material Misclassified	>= One Misclassification*
Number	78	1	1	31	24	46
Percent		1%	1%	40%	31%	59%

*** The number of 46 includes the valve leak that was misidentified as a pipe.**

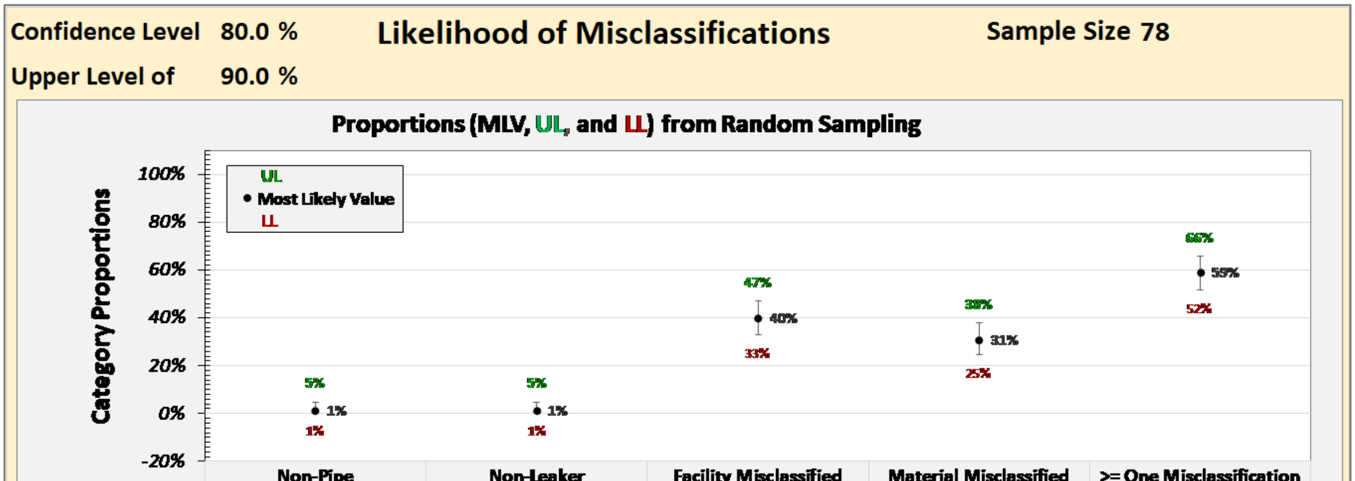
The original 78 aboveground classifications and the verified corrections are presented in **Appendix A.**

Probabilistic Analysis of Category Misclassifications

A probabilistic analysis of the misclassifications was conducted using Bayesian analysis (this technique is explained in detail in a later section and in **Appendix E** of this report). This allowed 90% single-sided upper and lower prediction limits (associated with an 80% double-sided confidence level) to be set around the misclassification percentiles. This analysis incorporated the uncertainty associated with the findings themselves, as well as the sample size of the categories.

The results are presented in Figure 8 below. For example, this figure shows that there is a 90% confidence that the process of classification used by the companies for this study would result in a proportion of no *fewer* than 52% of the sites having either the facility *or* material misclassified and no *more* than 66% of the same categories misclassified.

The figure also shows that one would expect approximately 1% of the classifications to be non-pipe and another 1% of the initially classified leakers to be non-leakers with a 90% confidence that either of those proportions would not be higher than 5%.



	Non-Pipe	Non-Leaker	Facility Misclassified	Material Misclassified	>= One Misclassification
UL	5%	5%	47%	38%	66%
• Most Likely Value	1%	1%	40%	31%	59%
LL	1%	1%	33%	25%	52%

Sample Categories

Figure 8 – Likelihood of misclassifications of unverified facility and/or material categories.

Descriptive Statistics of CARB Verified Sample Set

The verified CARB dataset (76 sample sites) for this report was categorized into six groups or *categories* (with the abbreviations used in all tables and plots in parenthesis):

- All samples (**All**)
- Main Facilities (**Mains**)
- Service Facilities (**Services**)
- Plastic Material (**PL**)
- Unprotected Steel Material (**UPS**)
- Protected Steel Material (**PS**)

If one were to add the number of samples in the *Mains* and *Service* facility categories, they would total to the number of samples in the *All* category. If one were to add the number of samples in the *Plastic*, *Unprotected*

Steel, and *Protected Steel* material categories they would total to the number of samples in the *All* category as well.

Table 6 shows descriptive statistics of the dataset. This table includes the total number of samples in each category as well as the minimum, maximum, and summed values of the samples by category. The mean of each category is presented along with measures of error, variance, and deviation; and the median and the 25th and 75th percentiles.

Through the results and discussion sections of this report, the leak rates are: (a) reported in units of Natural Gas (NG) scfh, and (b) the values reported are typically to two or three decimal places to allow comparison of a wide range of leak rates. When average leak rates are being used to establish EFs, the values should be presented with two significant digits based on the limiting input to such calculations.

Table 6 – Descriptive Statistics of GTI Dataset Natural Gas Leak Rate (scfh)

Category	All	Mains	Services	PL	UPS	PS
N (count)	76	29	47	25	32	19
Min (scfh)	0.007	0.063	0.007	0.007	0.148	0.063
Max (scfh)	20.400	13.985	20.400	20.400	13.985	14.400
Sum (scfh)	188.542	49.689	138.853	64.535	76.441	47.566
Mean (scfh)	**2.481**	**1.713**	**2.954**	**2.581**	**2.389**	**2.503**
Std. error (scfh)	0.448	0.510	0.646	0.938	0.544	0.966
Variance (scfh^2)	15.221	7.535	19.631	22.009	9.474	17.731
Stand. dev (scfh)	3.901	2.745	4.431	4.691	3.078	4.211
Median (scfh)	0.827	0.617	1.000	0.600	1.034	1.000
25 prcntil (scfh)	0.479	0.407	0.600	0.336	0.600	0.462
75 prcntil (scfh)	2.328	2.022	3.900	3.150	2.924	2.154

Verified facility and material categories

Based on a desired 80% double (90% single) sided or tailed confidence level, one prefers 22 or more samples. This is explained in more detail later in this report in the, "Bayesian Inference Analysis of Field Data" section. This is the reason why this study did not further categorize the leak data by another level, such as plastic mains, protected steel services, etc. The probabilistic, as well as the resampling/bootstrap analysis would not have been justified at the 90% single sided confidence level due to the non-significant sample sizes for these sub-categorizations.

Analysis and Discussion

CARB Data Set Calculation of Population Average Leak Rates by Category

The average leak rates and percentiles (e.g., 10% Lower, and 90% Upper Confidence Limit) for the average of each category were calculated using the Bootstrap method (Elfron 1994), (Efron 1979), (Efron 1982), (Lunneborg 2000), and (Good 2006). The non-parametric bootstrap analysis is similar to a Monte Carlo analysis. However, samples drawn to form the population are *re*sampled (10,000 times) with replacement from the actual (physical) sample set. This creates a synthetic population of thousands of samples that can be used to infer the expected value of the population along with the desired confidence limits. The results are summarized in Table 7. The largest mean leak rate is for services and lowest is for mains. The three categories for materials exhibit similar mean leak rates. In addition to the mean, spread, and standard deviation, this table lists eight population percentiles for each of the six categories, plus the 50% median value. These can be used to construct confidence intervals around the mean values.

Table 7 – CARB Mean Leak Rates from Bootstrap Analysis and Leak Rate Percentiles

	Facility and Material Categories					
	All	**Mains**	**Services**	**PL**	**UPS**	**PS**
Parameter	**Population Values for Natural Gas Leak Rate (scfh)**					
Mean	2.478	1.712	2.957	2.575	2.391	2.508
Minimum	1.229	0.510	1.168	0.510	0.794	0.547
Maximum	4.676	4.224	5.998	6.821	4.939	6.456
St. dev.	0.447	0.499	0.639	0.924	0.540	0.937
Percentile	**Average Natural Gas Leak Rate Percentiles (scfh)**					
1%	1.550	0.818	1.633	0.880	1.281	0.822
5%	1.786	0.997	1.974	1.230	1.562	1.075
10%	1.920	1.109	2.174	1.454	1.718	1.332
25%	2.161	1.346	2.510	1.908	2.018	1.806
50%	2.458	1.659	2.916	2.482	2.356	2.440
75%	2.763	2.024	3.366	3.154	2.728	3.124
90%	3.067	2.372	3.807	3.807	3.097	3.772
95%	3.256	2.608	4.086	4.267	3.342	4.182
99%	3.619	3.091	4.563	5.025	3.812	5.024

The variability in the leak rates is also shown in Figure 9 and Figure 10. These figures show that the distributions for the categories are not normally distributed but are skewed with longer right tails. As shown in the cumulative probability and box plots, the data for plastic and protected steel categories has a larger spread compared to the other categories for facilities and materials.

The cumulative plot in Figure 9 shows the cumulative probability of the synthetic population for each sample category. The 50% median values are also noted on the plot. The box plot in Figure 10 shows the same data but plotted in a concise manner showing the inner quartile regions with the mean, as well as the 90% single-sided confidence limits. The outliers are plotted as individual points beyond the plot whiskers.

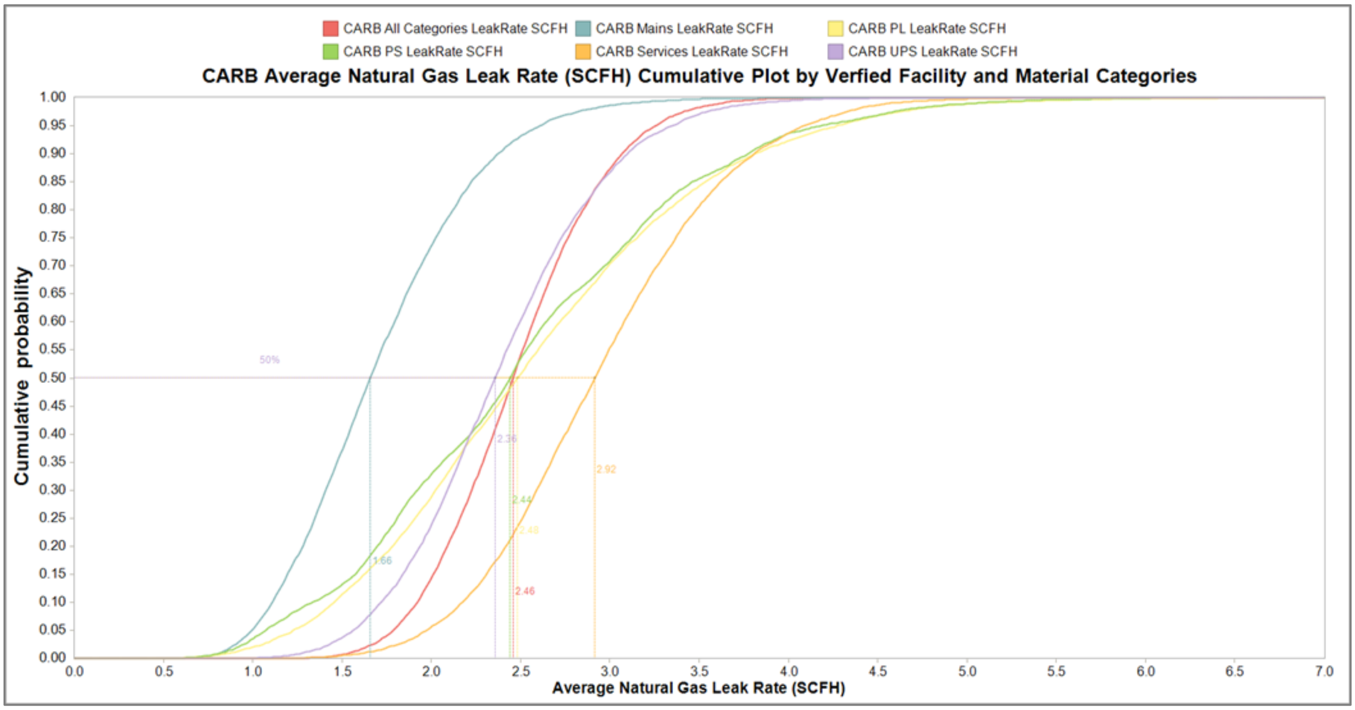


Figure 9 – CARB Ave. Leak Rate Cumulative Plot by Facility and Material Category

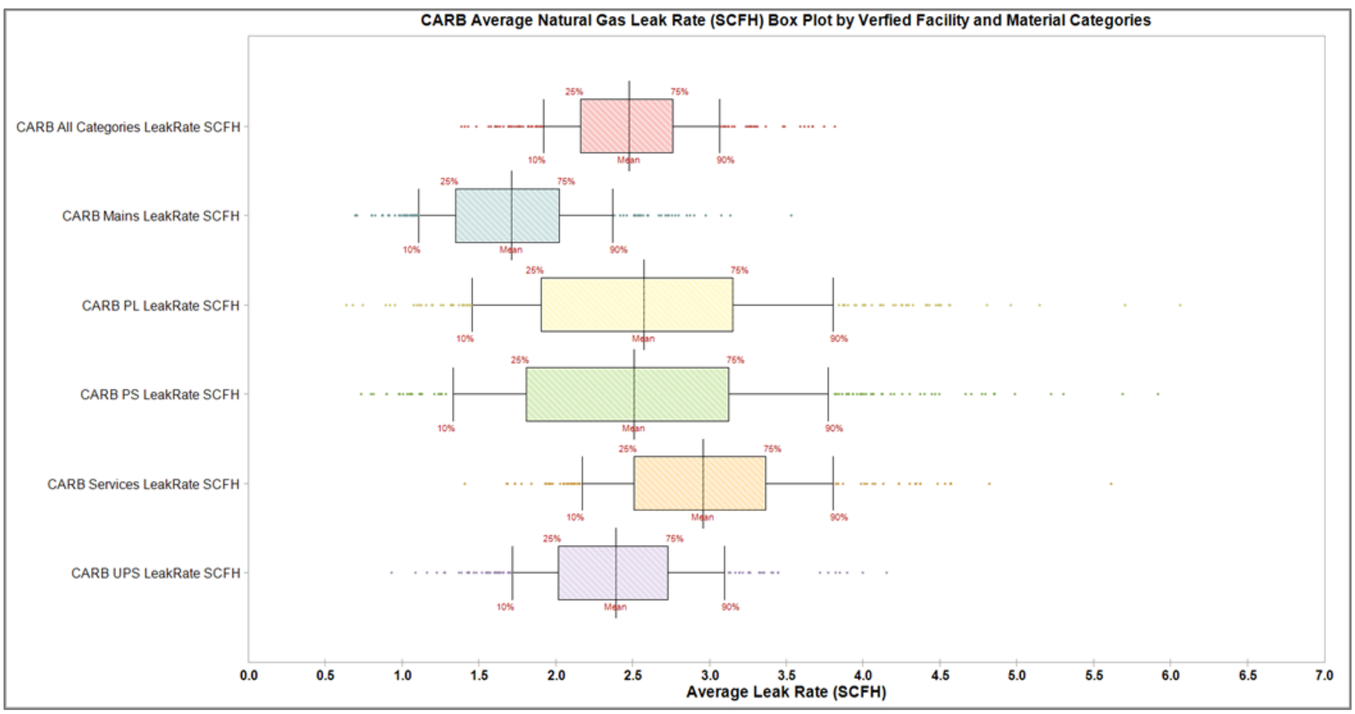
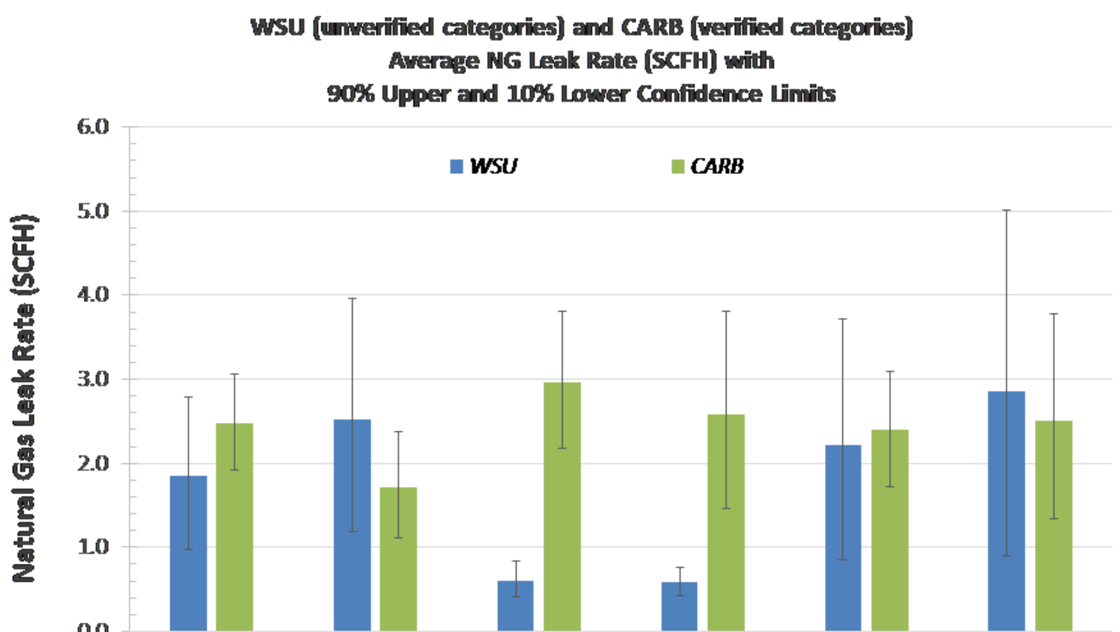


Figure 10 – CARB Average Leak Rate Box Plot

WSU - CARB Comparison

WSU developed EFs for underground main and service pipes by material type (Brian K. Lamb 2015). These factors were used to develop a national methane emission estimate for underground distribution pipelines. A bootstrap analysis was performed on the data (leak rate measurements) from the WSU study, see **Appendix B** for the WSU individual measurements, descriptive statistics, and population analysis using the same bootstrap analysis technique used on the CARB data. The population average NG leak rates from the CARB and WSU studies are presented side-by-side in Figure 11 (below) with 90% single-sided confidence limits.



	All	Mains	Services	PL	UPS	PS
WSU	1.85	2.52	0.61	0.59	2.22	2.86
CARB	2.48	1.71	2.96	2.58	2.39	2.51

Figure 11 – WSU and CARB bootstrapped averages with 10% and 90% confidence limits

As noted earlier, for each study, the Mains plus the Services add up to All category, as well as the Plastic Material + Unprotected Steel Material + Protected Steel Material add up to the All category. From this figure one can see that 90% upper and lower single sided confidence limits for all the categories overlap each other individually *between* studies for *each* category and also across *all* categories for *both* studies except for the WSU services and plastic categories which together do not overlap any other WSU or CARB category.

It is difficult to determine the cause for this trend in the WSU data since the categories of the WSU study were not verified (at the time of this report) and therefore the study might have similar large percentages of misclassifications of facility and/or material categories that the CARB data originally had.

Additionally, the WSU data for services and plastic categories exhibits a much tighter uncertainty band (confidence interval) around the average values as shown in Figure 11 and **Appendix B** Figure 27 (in more detail).

This very tight distribution of leak ranges is not typical of any of the other categories of the CARB, WSU, or numerous other similar studies where underground leaks of similar asset types were analyzed. It is unknown why the distribution of leak values around these two categories in the WSU study is both so low and narrow compared to all the other categories.

Statistical Comparison of Means between Facility and Material Categories

A rigorous Monte Carlo analysis in the form of a Bootstrap with sample replacement was conducted to calculate the likelihood that observed differences between the sample set category means could be accounted for by random variations of samples coming from the same (hypothesized) population. An analysis with 10,000 appropriately sized resamples was conducted.

When the likelihood that the observed difference in category leak rate means (averages) could be from random variation in the sample sets is less than or equal to 5% then one considers the samples taken from different populations. This is analogous to the p-Statistic in classical hypothesis and analysis of variance (ANOVA). However, the non-parametric Monte Carlo analysis makes no assumption in the underlying leak rate population location, shape, or spread and is therefore a more robust analysis than a traditional parametric ANOVA analysis.

To do this the following procedure was used:

1. Calculate the difference between the means of the two observed samples from the field.
2. Consider the two samples as combined as the relevant universe to resample from.
3. Randomly draw hypothetical samples with replacement in the same numbers for each respective study.
4. Compute and record the difference between the means of the two samples.
5. Repeat Steps 3 and 4 a total of 10,000 times.
6. Determine how often the resample difference exceeds the observed difference from Step 1 which will demonstrate whether the two groups are different, so the absolute values are used for the differences, not a single sided difference.
7. Compare the result of Step 6 to a conservative value of 5% (0.05 fraction) to establish if the observed difference is likely to have occurred by chance, or if there is likely a difference between the populations for the sample sets. Values less than 5% are considered not from the same population, i.e., same concept as having a p-Statistic of 0.05 or less.

The above process was completed for the CARB data with the results summarized in Table 8.

Table 8 – Comparison of Means for Five Categories.

Likelihood that the noted categories are from the same population as all other samples					
Category	**Mains**	**Services**	**PL**	**UPS**	**PS**
p-Statistic	40%	60%	91%	92%	98%

Based on the analysis of means, one cannot rule out that chance might be responsible for the observed difference in the CARB data means between any one of the categories and all the remaining samples not within that category.

The very high p-Statistics of 91%, 92%, and 98% for the three material categories present a strong basis that supports the hypothesis that the leak rate variation seen between these three material categories is due to random variation. When compared with the 5% reference value, the leak rate differences among pipe materials can be viewed as not being "statistically significant."

The p-Statistic for the mains and services facility categories are also high at 40% and 60% respectively. As noted, this means that there was a 40% and 60% respective likelihood that the differences in the means between these facility type categories and the rest of the samples was due to random variation.

These p-Statistic values would support a grouped or reduced set of categories, since the analysis supports that the average leak rates are likely from the same population and not sensitive to the specific categories.

Distribution Fits to Leak Data

Fitted distributions can be an excellent resource to model population distributions when smaller or incomplete data sets are only available. Additionally, fitted distributions can be used as “control charts” with credible bounds - to look for upset conditions.

These upset conditions can then be assessed to determine if: (a) they really are an abnormal condition due to a change in the system performance, (b) if they are rather revealing a fatter tail or larger skew of the population parameter, or (c) they are revealing a currently unknown sub-distribution.

For this report, the data sets for leaking samples in each of the five facility and material categories, and the combined (All) group were complete enough to justify using a bootstrap analysis to develop the population distribution as already reported.

Additionally, since this was the first time looking at the particular population of leakers using the procedures of this project/report, it was preferred to use actual data, via the bootstrap, to build up the estimated population distribution in order to calculate the population mean parameter and the associated uncertainty. However, going forward, one could also consider the use of fitted distributions derived from field leak data to supplement the analysis to establish average leak rates by category and their uncertainty limits at a selected confidence level.

To exhibit this, the six groupings of the CARB sample sets were modeled with the lognormal distributions.

As noted earlier in this report, the WSU study is used for comparison with the CARB data set. To be conservative in setting the upper bound of the distribution fit for the CARB study, a value slightly larger than the WSU maximum value of 117 scfh (NG) was used. A bound of 120 was chosen to bound the theoretical distributions when they were fit.

The fitted distributions vs. the respective CARB samples were plotted, as well as the P-P plots to establish the goodness of fit of the lognormal distribution to the categorized data and are presented below.

Lognormal Distribution Fits and Diagnostics of CARB Leak Data

The Lognormal distribution is useful for modeling naturally occurring variables that are the product of several other naturally occurring variables. Lognormal distributions often provide a good representation for a physical quantity that extend from zero to + infinity (a positive number) and are positively skewed. Lognormal distributions are also very useful for representing quantities that are thought of in orders of magnitude, i.e., they have a very large range of values as in the case of leak rate data. An example of a lognormal theoretical cumulative density function and the related distribution equations are shown in **Appendix D**.

The five categories of the CARB leak rate data, as well as the combined category, were fitted to lognormal distributions. The field data values vs. the lognormal distributions and the P-P plots are shown below. An overlay of the *cumulative frequency plots* of the data and the fitted distribution is often used to view the closeness of fit between the data and the fitted distribution. The *P-P plot* is the plot of the cumulative distribution of the fitted curve against the cumulative for all values. The better the fit, the closer this plot resembles a straight line. It can be useful if one is interested in closely matching cumulative percentiles. These plots show excellent fit of the leak rate data to a lognormal distribution.

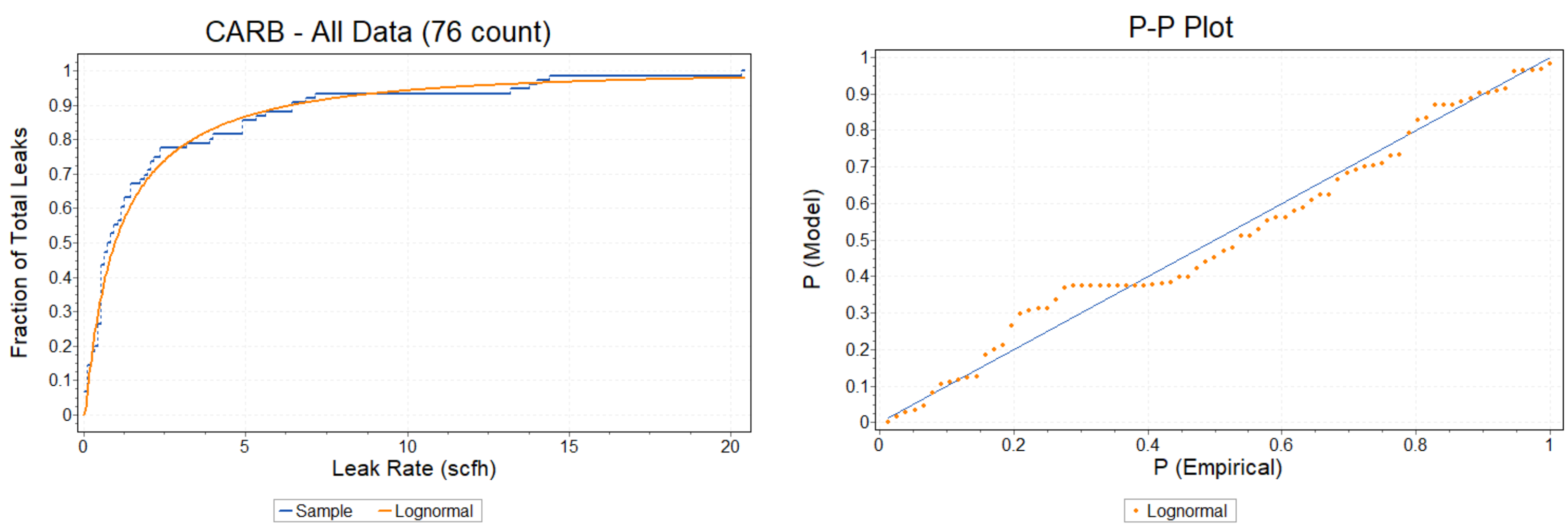


Figure 12 – CARB All Category Field Data vs. Lognormal Distribution Fit

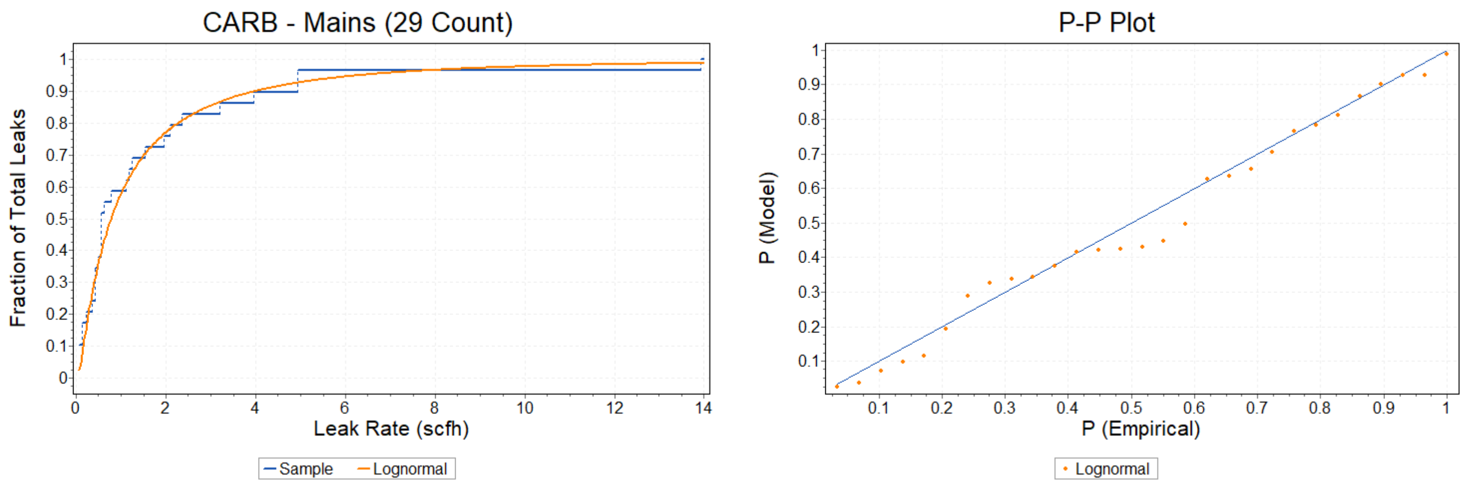


Figure 13 – CARB Mains Category Field Data vs. Lognormal Distribution Fit

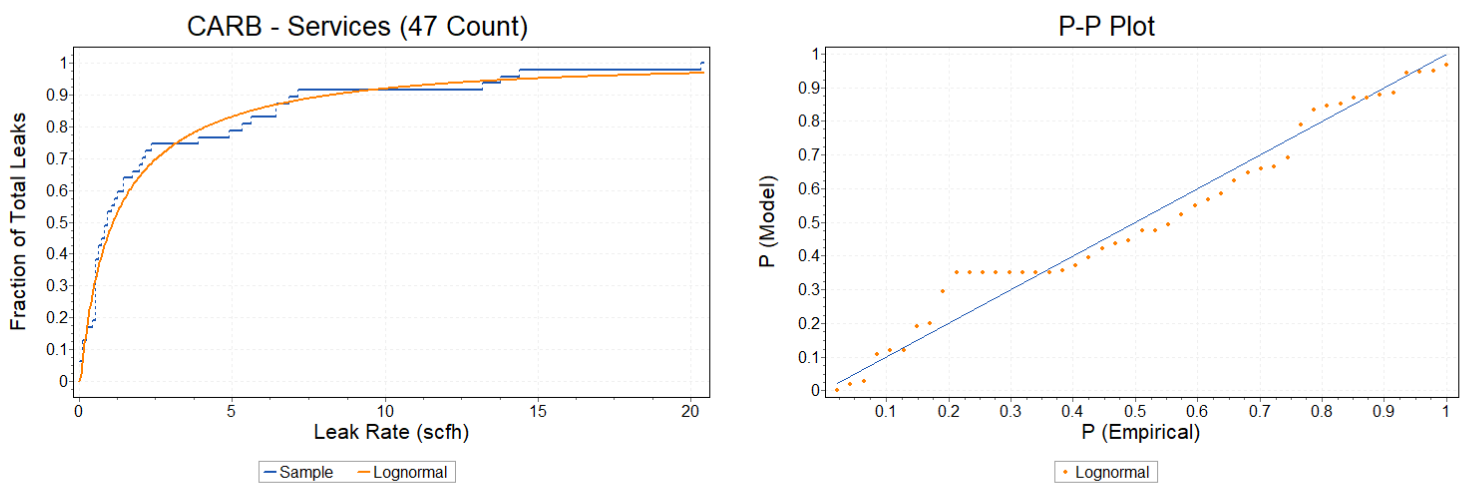


Figure 14 – CARB Services Category Field Data vs. Lognormal Distribution Fit

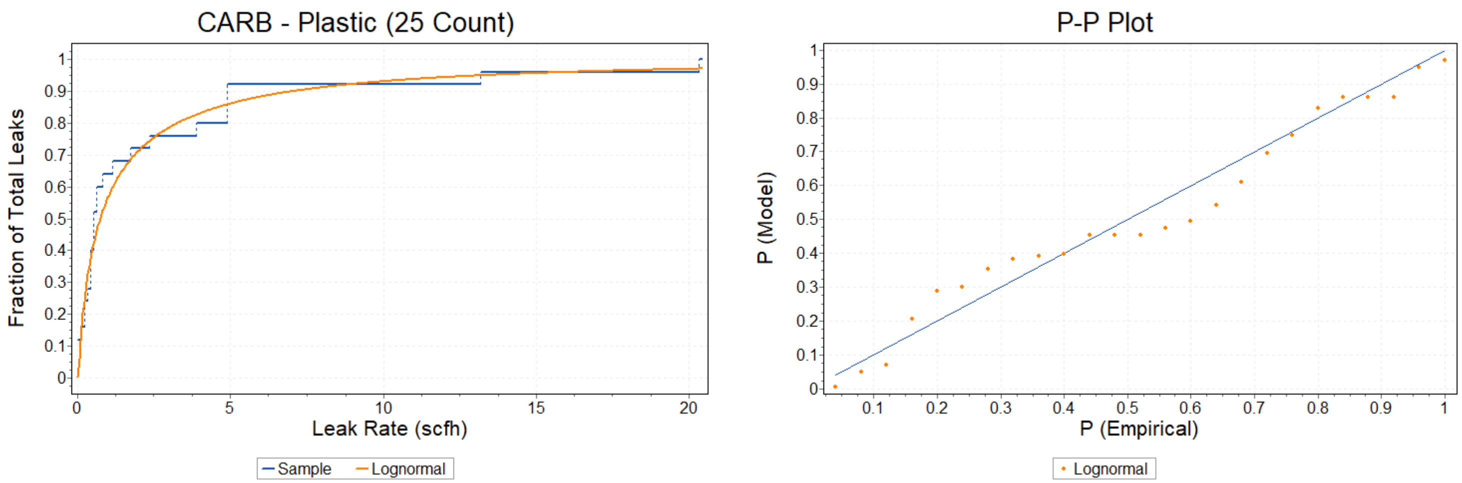


Figure 15 – CARB Plastic Category Field Data vs. Lognormal Distribution Fit

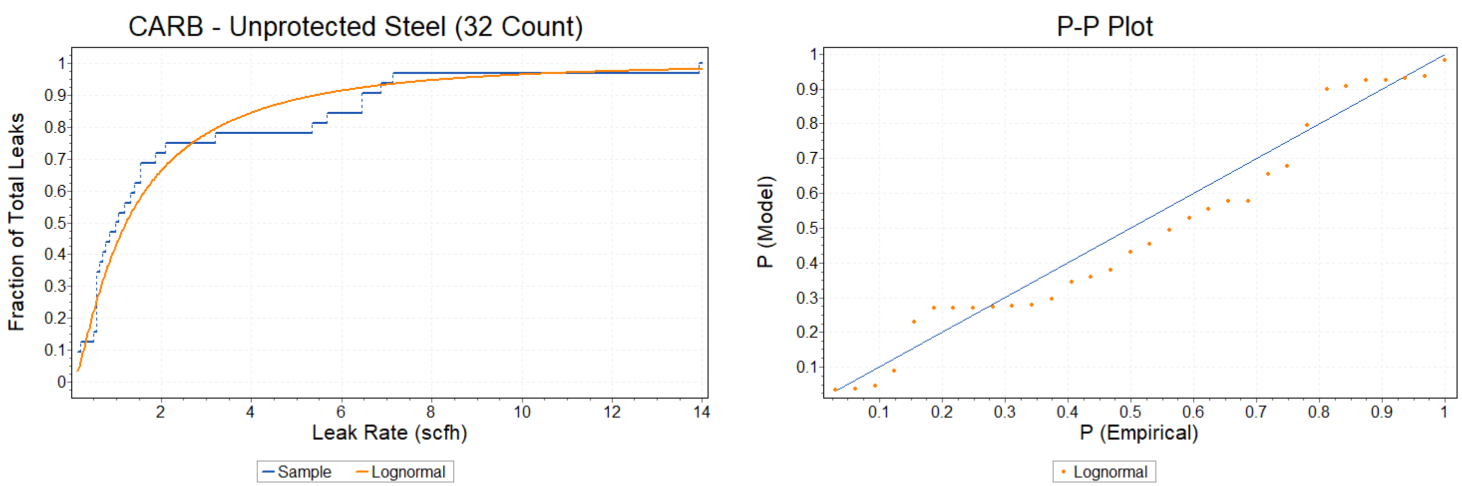


Figure 16 – CARB Unprotected Steel Category Field Data vs. Lognormal Distribution Fit

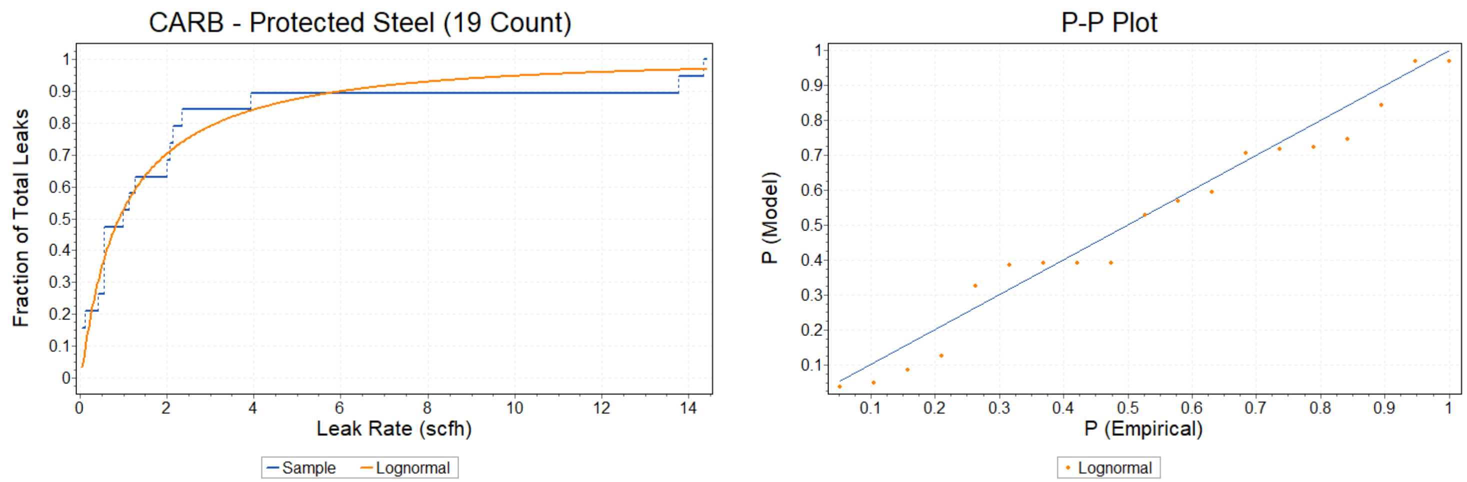


Figure 17 – CARB Protected Steel Category Field Data vs. Lognormal Distribution Fit

As noted above, the lognormal distribution fits to the CARB data were all strong as indicated by multiple goodness of fit parameters and the consistent P-P plot trends between model (fit) and empirical data. The average NG leak rates from lognormal distribution fits are summarized in Table 9 below and compared side-by-side with the average leak rate calculations from the bootstrap analysis of the field data presented earlier in this report. These values are compared to the bootstrap mean values and confidence intervals in the next section.

Table 9 – CARB Average NG Leak Rates from Bootstrap Analysis and Lognormal Distribution Fit

	Average NG Leak Rates (scfh)	
Category	**Lognormal Fit**	**Bootstrap**
All	2.8	2.5
Mains	1.7	1.7
Services	3.5	3.0
PL	3.0	2.6
UPS	2.4	2.4
PS	2.6	2.5

Comparison of Expected Natural Gas Leak Rates from Bootstrap and Distribution Fits

The natural gas average leak rates summarized in Table 9 from the bootstrap analysis and the lognormal distribution fits were overlaid with their respective 90% single-sided upper and lower confidence limits in Figure 18 below.

The correlation between the bootstrap analysis and lognormal distribution fits is very good as shown in the plot. The lognormal uncertainty bands are the same as, or in the case of services and plastic categories, larger than the bootstrap averages on the upper bound. This indicates that if the distributions of the samples follow the lognormal trends – that as additional samples are drawn from the population, one might expect the bootstrap averages to increase towards the lognormal average values over time.

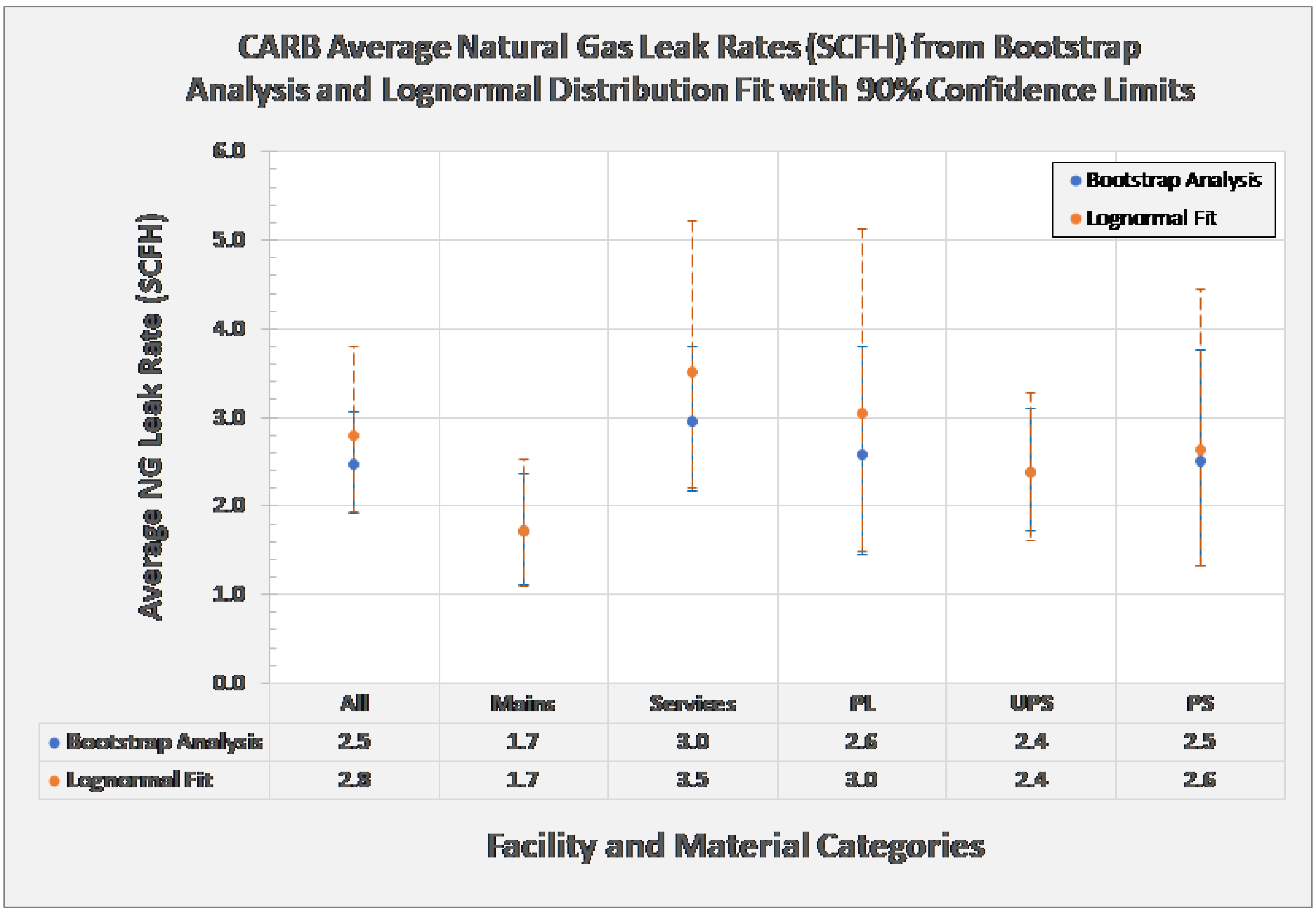


Figure 18 – CARB Average Leak Rates (scfh) from Bootstrap Analysis and Lognormal Distribution Fits

Bayesian Inference Analysis of Field Data

Bayesian inference analysis is ideally suited for this study for several reasons. First, the Bayesian approach does not assume that the underlying form of the population data is normally distributed - this is a non-parametric (non-frequentist) analysis. Second, Bayesian analysis is conservative and if there is no prior information about the leak rate values, one can use a uniform (sometimes termed ignorant) prior assumption. Finally, the Bayesian approach accounts for negative as well as positive findings related to leak rate in any category. This allows an accurate and coherent estimation of the most likely leak rates in the field with lower and upper prediction limits provided. Additional details on the Bayesian analysis method are presented in **Appendix E**.

CARB Probability Predictions (Bayesian Inference for Binomial Proportions)

The total number of verified field samples is 76 leaks. The observed field leak data were sorted by facility and material, and split into five leak categories as shown in Table 10 . More than 50% of the observed samples had leak rates less than or equal to 1 scfh with no samples having a leak rate greater than 30 scfh.

Bayesian inference was used to calculate the likelihood of a leak to fall into each of these categories, as well as its 80% two-sided confidence level with lower and upper confidence at 10% and 90% limits, respectively. Individual plots for each category are presented in Figure 19 to Figure 24.

The data suggest that most leaks occurring in distribution pipelines in California are relatively small compared to leaks observed in other sectors of the gas industry. The data also suggest that while the average leak rates for each facility or material category are skewed by a few large emitters, the probability of these emitters occurring is relatively small as shown by the upper confidence limits for the leak rate categories greater than 15 scfh.

Table 10 – CARB Leak Rates Organized by Leak Category

	Occurrence of Facility and Material Category Type					
Leak Level	**All**	**Mains**	**Services**	**Plastic**	**Unprotected Steel**	**Protected Steel**
< = 1 scfh	42	17	25	16	16	10
> 1 to 15 scfh	33	12	21	8	16	9
> 15 to 30 scfh	1	0	1	1	0	0
> 30 to 45 scfh	0	0	0	0	0	0
> 45 scfh	0	0	0	0	0	0
Totals	76	29	47	25	32	19

Significant Sample Size for Desired Statistical Confidence

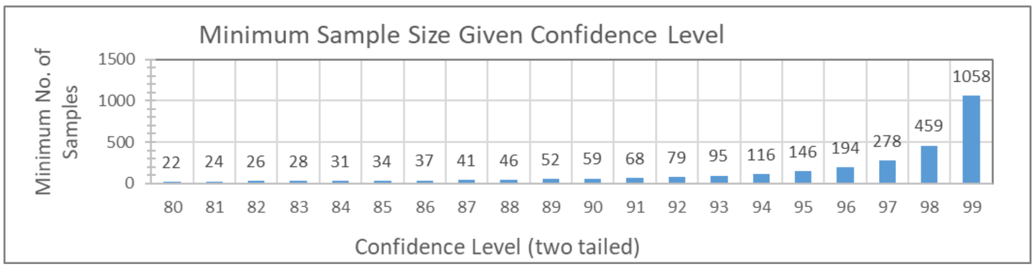
Table 11 below shows the minimum sample size required for a given two-sided (two-tailed) confidence level. This is the sample size for any category of leak rate that will bring the Bayesian analysis Upper Prediction Limit

(UPL) below the specified single sided confidence limits for the analysis when there is no occurrence in that category of a leaking sample.

The table uses a conservative uniform (aka ignorant) prior for the Bayesian analysis to establish this significant sample size. Based on the desired 80% double-sided (two-tailed) confidence level which produces a 90% upper and lower prediction limit, one can see that 22 samples are preferred for such an analysis.

This is the reason why this study did not further categorize the leak data by another level, such as plastic mains, or the like. The probabilistic, as well as the resampling/bootstrap analysis would not have been justified at the 90% single sided confidence level due to the non-significant sample sizes for these sub-categorizations.

Table 11 – Minimum Sample Size Given a Confidence Level.

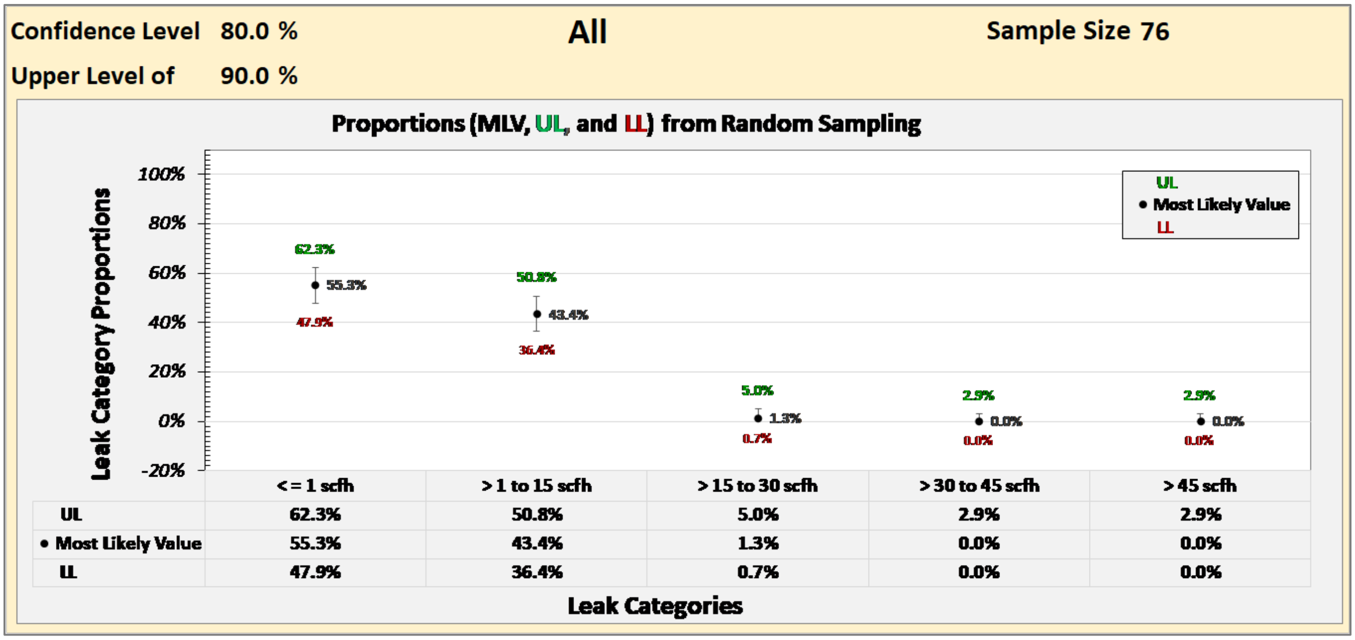


Using Figure 21 as an example, the form of the Bayesian analysis plots will be explained. This figure is related to all the services in the study (regardless of material type) that were leaking, a total of 47 (of the 76) samples in the study. The plot has the five leak categories (in scfh ranges) across the horizontal axis and the proportion of services (from 0% to 100%) along the vertical axis. The black dots are the most likely value (MLV) for the proportion of leaking services that fall into each of the five categories, these values total up to 100%. The 90% single-sided upper and lower limits (UL and LL) are the whiskers around the MLVs.

For example, one can say that for the population of *service* leakers:

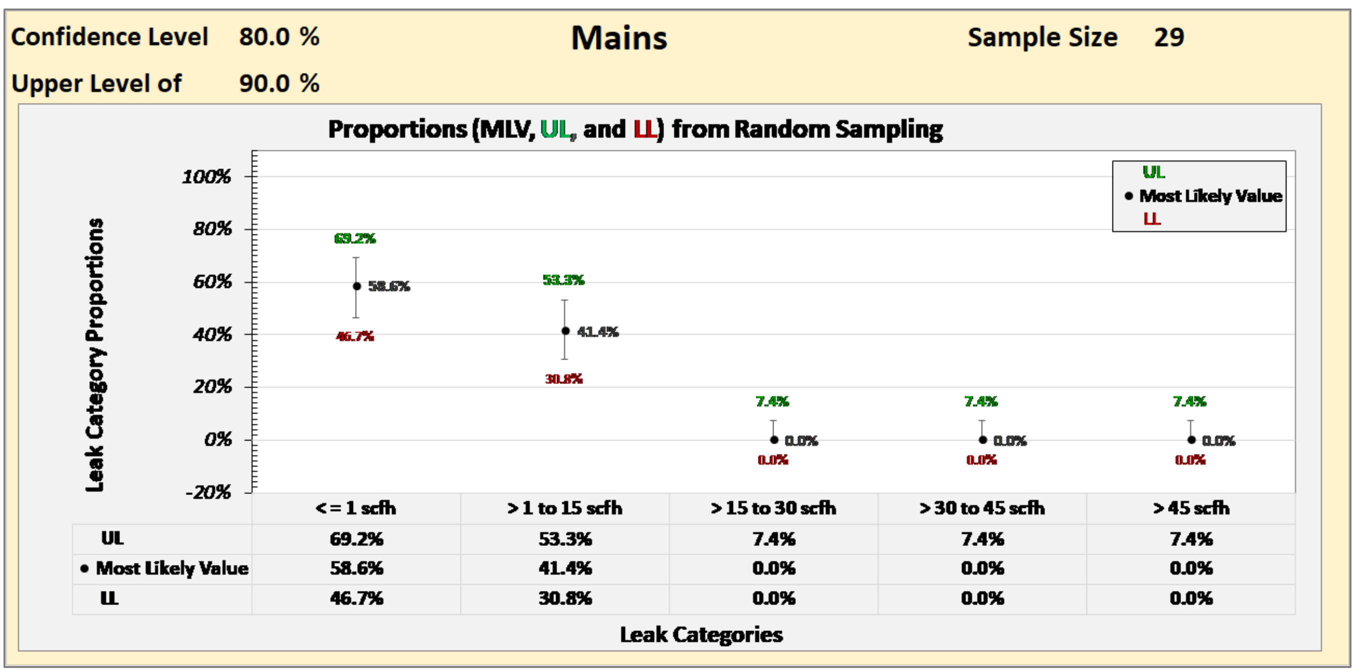
- That 44.7% is the most likely proportion for the 1 to 15 scfh leak rate category
- With a 90% confidence that the proportion in this category would be no *more* than 54.0%
- With a 90% confidence that the proportion in this category would be no *less* than 35.9%
- With an 80% confidence one would expect the proportion to fall *between* 35.9% and 54.0%, and
- Likewise, one could say that one would expect no leakers in the 30 to 45 scfh leak category with a 90% confidence that the actual proportion would be no higher than 4.7%.

As the sample size increases, the confidence limits will tend to shrink and become tighter around the most likely values.



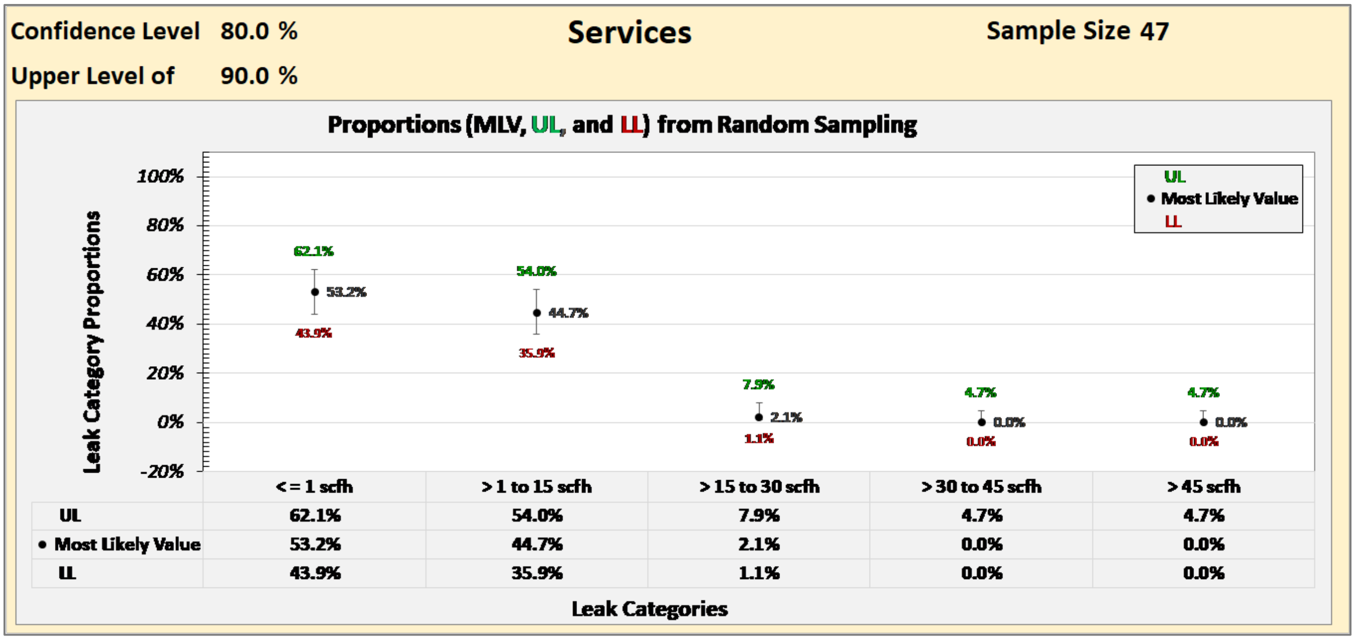
	<= 1 scfh	> 1 to 15 scfh	> 15 to 30 scfh	> 30 to 45 scfh	> 45 scfh
UL	62.3%	50.8%	5.0%	2.9%	2.9%
• Most Likely Value	55.3%	43.4%	1.3%	0.0%	0.0%
LL	47.9%	36.4%	0.7%	0.0%	0.0%

Figure 19 – CARB Leak Proportions for All Categories.



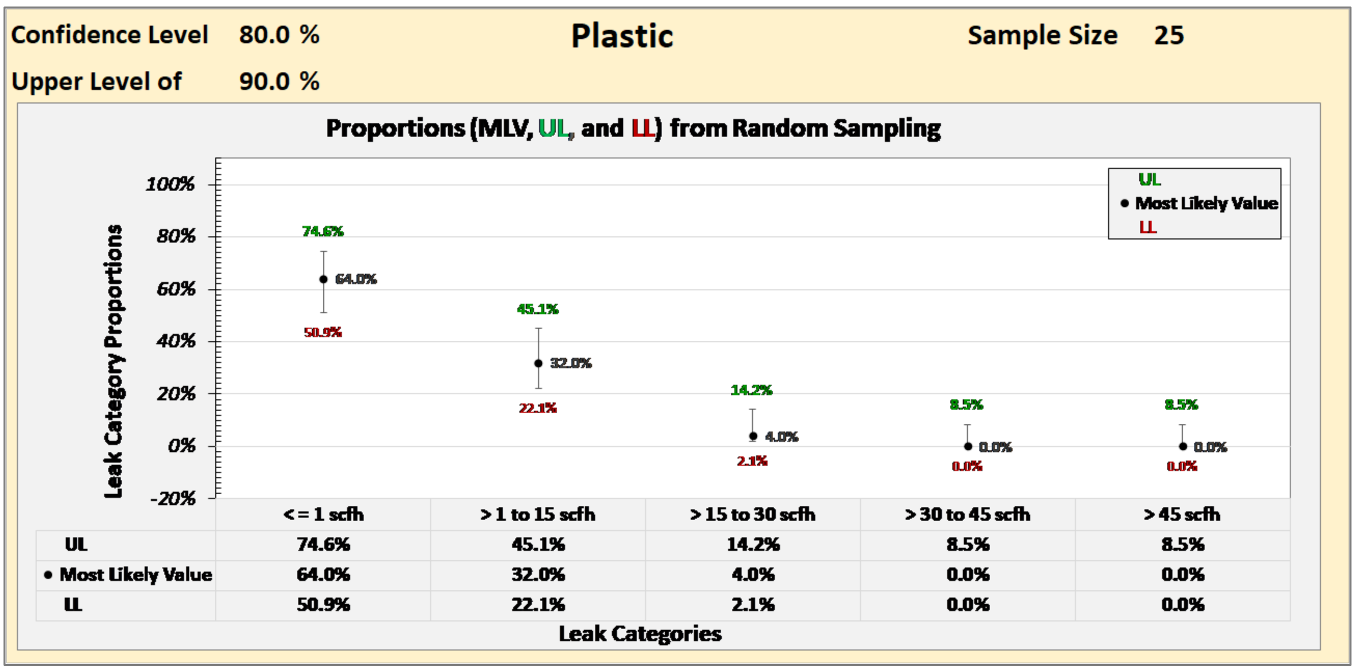
	<= 1 scfh	> 1 to 15 scfh	> 15 to 30 scfh	> 30 to 45 scfh	> 45 scfh
UL	69.2%	53.3%	7.4%	7.4%	7.4%
• Most Likely Value	58.6%	41.4%	0.0%	0.0%	0.0%
LL	46.7%	30.8%	0.0%	0.0%	0.0%

Figure 20 – CARB Leak Proportions for Mains.



	<= 1 scfh	> 1 to 15 scfh	> 15 to 30 scfh	> 30 to 45 scfh	> 45 scfh
UL	62.1%	54.0%	7.9%	4.7%	4.7%
• Most Likely Value	53.2%	44.7%	2.1%	0.0%	0.0%
LL	43.9%	35.9%	1.1%	0.0%	0.0%

Figure 21 – CARB Leak Proportions for Services.



	<= 1 scfh	> 1 to 15 scfh	> 15 to 30 scfh	> 30 to 45 scfh	> 45 scfh
UL	74.6%	45.1%	14.2%	8.5%	8.5%
• Most Likely Value	64.0%	32.0%	4.0%	0.0%	0.0%
LL	50.9%	22.1%	2.1%	0.0%	0.0%

Figure 22 – CARB Leak Proportions for Plastic.

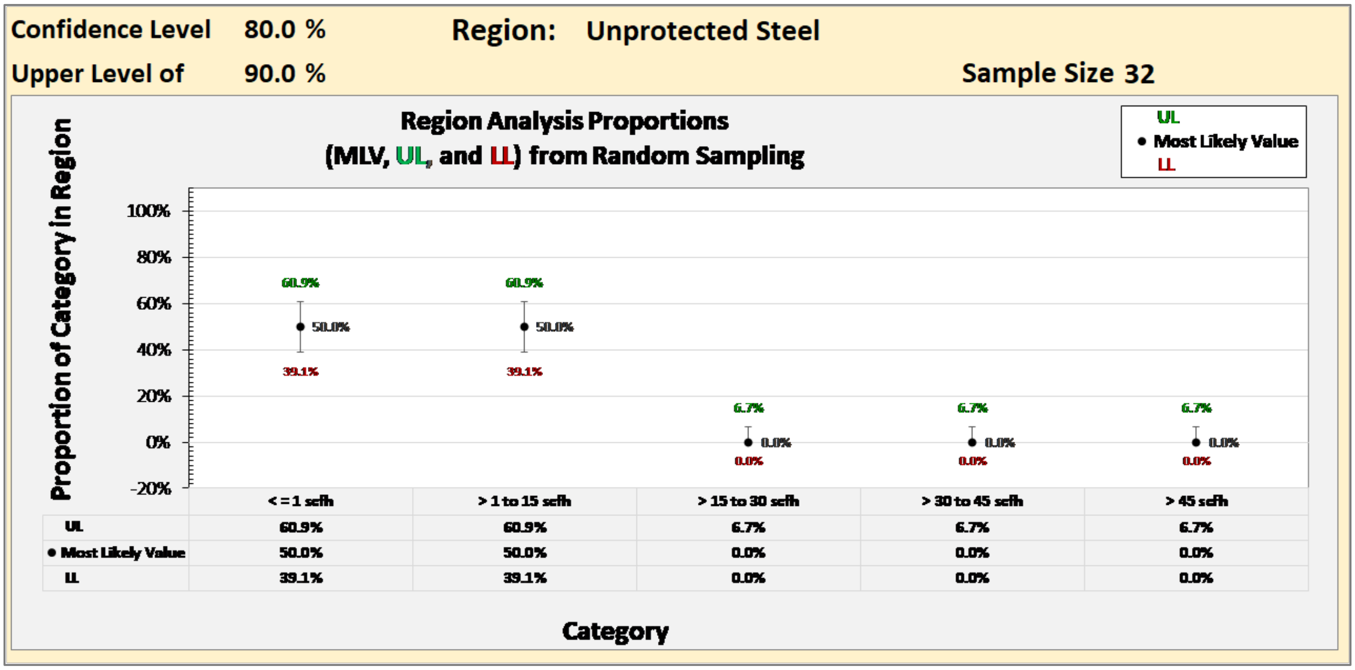


Figure 23 – CARB Leak Proportions for Unprotected Steel.

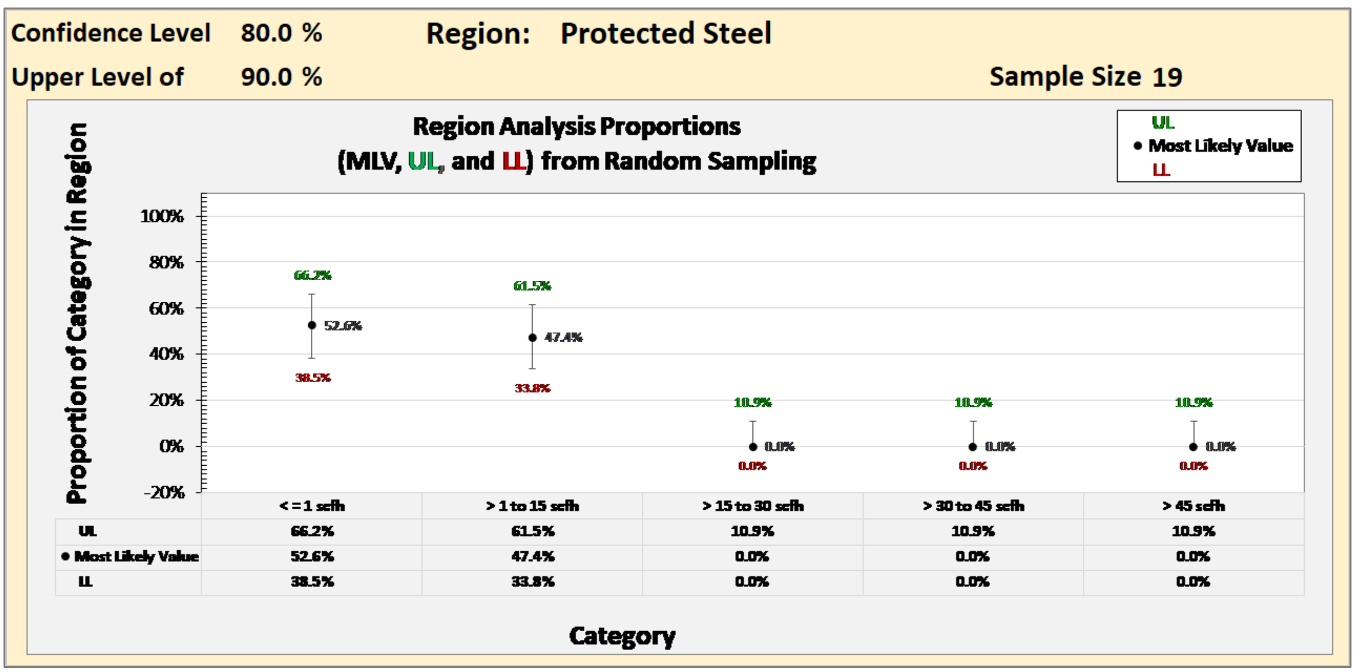


Figure 24 – CARB Leak Proportions for Protected Steel.

Conclusions and Recommendations

The data collected throughout this project were analyzed using advanced statistical and probabilistic analysis, and distribution fitting. The analysis provided a representation, within the State of California, of the average natural gas leak rates for underground distribution main and service pipes, by leak source or pipe material.

As part of the study, 78 originally measured leak sites were verified through direct excavation. During leak repairs, 1-3 years after GTI's field measurements, the utility companies informed CARB that some leak characterizations, either the source, pipe material or both, were different from the information initially given to GTI, approximately 59% of the data were mischaracterized. The facility alone and the material alone were misclassified 40% and 31% of the time respectively. A probabilistic analysis was conducted and the 90% upper prediction limit for misclassifying non-pipe items as pipe and non-leakers as leakers were both 5%. The 90% upper prediction limit for classifying the material and/or facility incorrectly was 66%.

Of the 78 leaks measured, 76 verified pipe leak samples were analyzed in grouped categories by leak source or material and subjected to a rigorous Monte Carlo analysis to compare the NG mean leak rates by leak source or material type of the leaking pipe. It was found that there was no statistically significant difference in the mean leak rates among pipe material. In fact, the likelihood that the differences observed from the sample sets were greater than 90% in all material cases to be from random variation in the sample alone from the same population itself. The facility type, i.e., mains and services, showed a 40% and 60% likelihood that the observed difference in means could have been produced by random variation in the sample drawn from the population.

All data sample were fit to lognormal distributions with excellent goodness of fit. These distributions were used to calculate an average leak rate by leak source and material, as well as the combination of the two. The average leak rates from the fitted distributions and their confidence intervals correlated well with the bootstrap analysis of the same sample sets. This technique will allow inference of the population leak rates from which the sample was drawn in the absence of a larger random sample of NG leaks.

A Bayesian probabilistic analysis of the leak rate distributions by facility or material category was completed. More than 50% of the observed samples had leak rates less than or equal to 1 scfh with no samples having a leak rate greater than 30 scfh.

Bayesian inference was used to calculate the most likely and lower and upper confidence limits for proportions of leak categories by category. Individual plots for each asset class were generated and the data suggest that most leaks occurring in distribution pipelines in California are relatively small compared to leaks observed in other sectors of the gas industry (e.g., production and processing). The data also suggest that while the average leak rates for each facility or material category are skewed by a few large emitters, the probability of these emitters occurring is relatively small as shown by the low upper confidence limits for the leak rate categories greater than 15 scfh.

The average leak rates for underground distribution main and service pipes from this study can be used to develop methane emission estimates from distribution pipelines in California. The data collected from this study suggest that the quantification of methane emissions could be developed based on a reduced set of groups or categories without a detailed breakdown by material and facility type.

Leak characteristics such as spread, concentration, rates and location change over time. Additional work to investigate how leaks change over time accounting for changing environmental conditions can improve our understanding of how this contributes to annual methane emissions.

This study focused on a bottom-up approach utilizing direct measurements of methane emissions from distribution pipelines. Additional work could be performed utilizing alternative measurement techniques (e.g., mobile and remote sensing platforms for methane detection) to conduct a top-down study of emissions.

Appendix A – GTI Data

CARB Field Sample Data

Table 12 – CARB Field NG Leak Data with Unverified and Verified Facilities and Materials

Arbitrary No.	Unverified Facility	Unverified Material(1)	Verified Facility(2)	Verified Material(2)	Natural Gas Leak Rate (scfh)
1	Main	Plastic	Service	Plastic	20.400
2	Main	Plastic	Service	Steel Protected	14.400
3	Main	Steel	Main	Steel Unprotected	13.985
4	Service	Plastic	Service	Steel Protected	13.800
5	Main	Steel	Service	Plastic	13.200
6	Main	Steel	Service	Steel Unprotected	7.200
7	Main	Steel	Service	Steel Unprotected	6.900
8	Main	Steel	Service	Steel Unprotected	6.495
9	Service	Steel	Service	Steel Unprotected	6.475
10	Main	Steel	Service	Steel Unprotected	5.700
11	Service	Steel	Service	Steel Unprotected	5.400
12	Main	Plastic	Main	Plastic	5.000
13	Service	Plastic	Main	Plastic	5.000
14	Main	Plastic	Service	Plastic	3.900
15	Service	Plastic	Main	Steel Unprotected	3.200
16	Service	Plastic	Service	Plastic	2.400
17	Main	Steel	Main	Steel Protected	2.386
18	Service	Steel	Service	Steel Unprotected	2.097
19	Service	Plastic	Service	Steel Protected	2.000
20	Service	Steel	Main	Steel Unprotected	1.944
21	Service	Steel	Service	Steel Unprotected	1.534
22	Main	Steel	Main	Steel Unprotected	1.532
23	Main	Steel	Service	Steel Unprotected	1.436
24	Service	Steel	Service	Steel Unprotected	1.331
25	Main	Plastic	Service	Plastic	1.200
26	Main	Steel	Main	Steel Unprotected	1.200
27	Service	Plastic	Main	Steel Protected	1.168
28	Service	Steel	Service	Steel Unprotected	1.067
29	Main	Steel	Service	Steel Unprotected	1.000
30	Service	Steel	Service	Steel Unprotected	0.853
31	Service	Steel	Service	Steel Unprotected	0.800
32	Main	Steel	Main	Steel Unprotected	0.764
33	Main	Plastic	Service	Plastic	0.719
34	Service	Steel	Main	Steel Unprotected	0.651
35	Main	Steel	Main	Steel Unprotected	0.617
36	Service	Steel	Service	Steel Unprotected	0.613
37	Main	Steel	Main	Steel Unprotected	0.601
38	Main	Plastic	Service	Plastic	0.600

Arbitrary No.	Unverified Facility	Unverified Material[(1)]	Verified Facility[(2)]	Verified Material[(2)]	Natural Gas Leak Rate (scfh)
39	Main	Plastic	Service	Steel Protected	0.600
40	Service	Plastic	Service	Plastic	0.600
41	Main	Steel	Service	Plastic	0.600
42	Main	Steel	Service	Steel Unprotected	0.600
43	Service	Steel	Service	Steel Unprotected	0.600
44	Service	Steel	Service	Steel Unprotected	0.600
45	Main	Plastic	Main	Steel Unprotected	0.515
46	Main	Plastic	Main	Plastic	0.452
47	Service	Plastic	Main	Plastic	0.435
48	Service	Steel	Service	Steel Unprotected	0.172
49	Service	Steel	Service	Steel Unprotected	0.156
50	Main	Plastic	Service	Plastic	5.000
51	Service	Plastic	Main	Steel Protected	4.000
52	Service	Steel	Service	Steel Protected	2.154
53	Service	Plastic	Main	Steel Protected	2.100
54	Service	Plastic	Service	Plastic	1.800
55	Main	Steel	Main	Steel Protected	1.284
56	Service	Plastic	Service	Steel Protected	1.000
57	Service	Plastic	Service	Plastic	0.884
58	Main	Plastic	Service	Plastic	0.654
59	Service	Steel	Main	Steel Protected	0.600
60	Service	Steel	Service	Steel Protected	0.600
61	Service	Plastic	Main	Steel Protected	0.585
62	Service	Plastic	Service	Plastic	0.467
63	Main	Steel	Main	Steel Protected	0.462
64	Service	Plastic	Main	Plastic	0.378
65	Main	Plastic	Service	Plastic	0.293
66	Service	Plastic	Service	Plastic	0.276
67	Main	Steel	Main	Steel Unprotected	0.255
68	Main	Plastic	Service	Plastic	0.174
69	Main	Plastic	Main	Steel Protected	0.166
70	Service	Plastic	Main	Steel Unprotected	0.148
71	Main	Steel	Main	Steel Protected	0.120
72	Main	Steel	Main	Steel Protected	0.078
73	Main	Steel	Main	Steel Protected	0.063
74	Service	Plastic	Service	Plastic	0.055
75	Service	Plastic	Service	Plastic	0.041
76	Service	Plastic	Service	Plastic	0.007
77[(3)]	Main	Steel	**Valve**	Steel	0.855
78[(4)]	Main	Plastic	Main	Plastic	**0.000**

(1) All unverified steel pipes are unprotected.
(2) The corrected classifications for leak source and/or pipe material are highlighted in yellow.
(3) Leak #77 was found to be on a valve and not a pipe so it was dropped from the study.
(4) Leak #78 was verified as a non-leaker and was dropped from the study.

CARB Field Sample Leak Rate Ordinal Plot

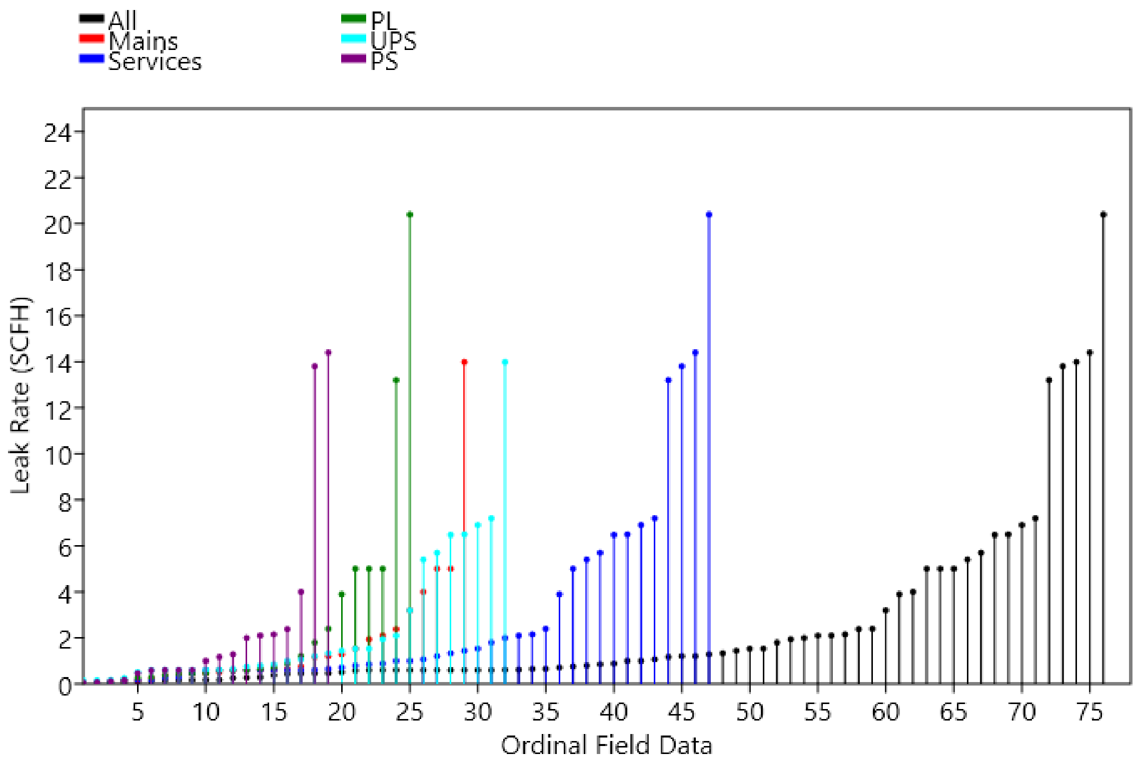


Figure 25 – CARB Field Leak Data Ordinal Ranking Grouped by Verified Facilities and Materials

The figure above plots the ordinal field data with one sample per vertical line ordered from lowest to highest leak rate. The point at the top of the line is the leak rate in scfh of NG. The stem plot is particularly good at showing the shape of the leak distribution and the range of the leak values.

From this plot, one can see there is large range of leakers with the majority of them on the low end with a few high leakers dominating the high end.

As shown earlier in this report, the leak distribution is lognormally distributed and this can be seen from this plot as well by the characteristic shape.

Appendix B – WSU Data

WSU Field Sample Data

All the WSU leak data were converted from methane to natural gas leakage. The molarity of methane is assumed to be approximately93.4 percent, a common assumed value by the industry. This value was used in the published joint annual report on natural gas leaks and emissions by CARB and California Public Utilities Commission (CARB and CPUC 2018). The WSU field samples are nationwide data sets and therefore include non-California data.

The raw data, an ordinal step plot, and the bootstrap population averages are presented below. The data is organized in columns by facility and material, as well as a combined "All" category.

Table 13 – WSU Field NG National Leak Data with Unverified Facilities and Pipe Materials

	All Data	Mains	Services	PL	UPS	PS
Arbitrary No.	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)
1	0.003	0.004	0.003	0.003	0.012	0.009
2	0.004	0.005	0.009	0.004	0.017	0.019
3	0.005	0.007	0.015	0.005	0.025	0.021
4	0.007	0.009	0.023	0.007	0.026	0.023
5	0.009	0.010	0.039	0.009	0.027	0.031
6	0.009	0.012	0.043	0.010	0.027	0.033
7	0.010	0.017	0.049	0.015	0.027	0.044
8	0.012	0.019	0.050	0.025	0.039	0.045
9	0.015	0.021	0.056	0.043	0.040	0.049
10	0.017	0.025	0.057	0.043	0.042	0.061
11	0.019	0.025	0.062	0.043	0.042	0.076
12	0.021	0.026	0.062	0.050	0.044	0.091
13	0.023	0.027	0.076	0.057	0.047	0.091
14	0.025	0.027	0.079	0.062	0.056	0.107
15	0.025	0.027	0.081	0.068	0.062	0.149
16	0.026	0.031	0.091	0.079	0.065	0.165
17	0.027	0.033	0.096	0.086	0.081	0.171
18	0.027	0.040	0.103	0.106	0.085	0.174
19	0.027	0.042	0.106	0.140	0.085	0.179
20	0.031	0.042	0.140	0.142	0.086	0.183
21	0.033	0.043	0.142	0.144	0.088	0.183
22	0.039	0.043	0.144	0.157	0.091	0.184
23	0.040	0.044	0.151	0.174	0.096	0.194
24	0.042	0.044	0.157	0.178	0.101	0.198
25	0.042	0.045	0.166	0.184	0.103	0.226

	All Data	Mains	Services	PL	UPS	PS
Arbitrary No.	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)
26	0.043	0.047	0.171	0.202	0.121	0.260
27	0.043	0.061	0.172	0.204	0.146	0.267
28	0.043	0.065	0.174	0.207	0.151	0.316
29	0.044	0.068	0.178	0.239	0.159	0.318
30	0.044	0.085	0.183	0.242	0.160	0.369
31	0.045	0.085	0.184	0.260	0.160	0.389
32	0.047	0.086	0.184	0.280	0.163	0.403
33	0.049	0.086	0.187	0.305	0.166	0.715
34	0.050	0.088	0.194	0.312	0.169	0.879
35	0.056	0.091	0.202	0.354	0.169	1.552
36	0.057	0.091	0.207	0.363	0.171	1.881
37	0.061	0.101	0.208	0.384	0.172	2.537
38	0.062	0.107	0.239	0.403	0.173	2.859
39	0.062	0.121	0.242	0.406	0.187	2.896
40	0.065	0.146	0.280	0.413	0.193	4.299
41	0.068	0.149	0.293	0.446	0.194	5.088
42	0.076	0.159	0.305	0.466	0.208	8.395
43	0.079	0.160	0.354	0.535	0.213	14.230
44	0.081	0.160	0.363	0.550	0.220	74.625
45	0.085	0.163	0.369	0.632	0.226	
46	0.085	0.165	0.389	0.706	0.230	
47	0.086	0.169	0.403	0.714	0.239	
48	0.086	0.169	0.406	0.855	0.245	
49	0.088	0.171	0.409	0.908	0.260	
50	0.091	0.173	0.446	0.916	0.273	
51	0.091	0.174	0.466	0.951	0.279	
52	0.091	0.179	0.535	1.008	0.282	
53	0.096	0.183	0.550	1.021	0.293	
54	0.101	0.193	0.632	1.053	0.303	
55	0.103	0.194	0.706	1.119	0.305	
56	0.106	0.198	0.855	1.126	0.312	
57	0.107	0.204	0.951	1.559	0.327	
58	0.121	0.213	1.008	2.260	0.332	
59	0.140	0.220	1.021	2.738	0.341	
60	0.142	0.226	1.053	3.175	0.369	
61	0.144	0.226	1.119	6.624	0.403	
62	0.146	0.230	1.190		0.409	
63	0.149	0.239	1.552		0.421	
64	0.151	0.245	1.559		0.544	

	All Data	Mains	Services	PL	UPS	PS
Arbitrary No.	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)
65	0.157	0.260	1.567		0.551	
66	0.159	0.260	1.967		0.602	
67	0.160	0.260	2.310		0.640	
68	0.160	0.267	2.896		0.729	
69	0.163	0.273	11.083		0.792	
70	0.165	0.279			0.819	
71	0.166	0.282			0.972	
72	0.169	0.303			1.118	
73	0.169	0.305			1.119	
74	0.171	0.312			1.168	
75	0.171	0.312			1.190	
76	0.172	0.316			1.514	
77	0.173	0.318			1.527	
78	0.174	0.327			1.567	
79	0.174	0.332			1.737	
80	0.178	0.341			1.967	
81	0.179	0.369			2.177	
82	0.183	0.384			2.188	
83	0.183	0.403			2.310	
84	0.184	0.403			2.953	
85	0.184	0.413			3.087	
86	0.187	0.421			3.450	
87	0.193	0.544			4.866	
88	0.194	0.551			4.915	
89	0.194	0.602			6.321	
90	0.198	0.640			7.344	
91	0.202	0.714			9.609	
92	0.204	0.715			11.083	
93	0.207	0.729			117.208	
94	0.208	0.792				
95	0.213	0.819				
96	0.220	0.879				
97	0.226	0.908				
98	0.226	0.916				
99	0.230	0.972				
100	0.239	1.118				
101	0.239	1.119				

	All Data	Mains	Services	PL	UPS	PS
Arbitrary No.	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)
102	0.242	1.126				
103	0.245	1.168				
104	0.260	1.514				
105	0.260	1.527				
106	0.260	1.737				
107	0.267	1.881				
108	0.273	2.177				
109	0.279	2.188				
110	0.280	2.260				
111	0.282	2.537				
112	0.293	2.738				
113	0.303	2.859				
114	0.305	2.953				
115	0.305	3.087				
116	0.312	3.175				
117	0.312	3.450				
118	0.316	4.299				
119	0.318	4.866				
120	0.327	4.915				
121	0.332	5.088				
122	0.341	6.321				
123	0.354	6.624				
124	0.363	7.344				
125	0.369	8.395				
126	0.369	9.609				
127	0.384	14.230				
128	0.389	74.625				
129	0.403	117.208				
130	0.403					
131	0.403					
132	0.406					
133	0.409					
134	0.413					
135	0.421					
136	0.446					
137	0.466					
138	0.535					
139	0.544					
140	0.550					

	All Data	Mains	Services	PL	UPS	PS
Arbitrary No.	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)
141	0.551					
142	0.602					
143	0.632					
144	0.640					
145	0.706					
146	0.714					
147	0.715					
148	0.729					
149	0.792					
150	0.819					
151	0.855					
152	0.879					
153	0.908					
154	0.916					
155	0.951					
156	0.972					
157	1.008					
158	1.021					
159	1.053					
160	1.118					
161	1.119					
162	1.119					
163	1.126					
164	1.168					
165	1.190					
166	1.514					
167	1.527					
168	1.552					
169	1.559					
170	1.567					
171	1.737					
172	1.881					
173	1.967					
174	2.177					
175	2.188					
176	2.260					
177	2.310					
178	2.537					
179	2.738					

	All Data	Mains	Services	PL	UPS	PS
Arbitrary No.	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)	NG Leak Rate (scfh)
180	2.859					
181	2.896					
182	2.953					
183	3.087					
184	3.175					
185	3.450					
186	4.299					
187	4.866					
188	4.915					
189	5.088					
190	6.321					
191	6.624					
192	7.344					
193	8.395					
194	9.609					
195	11.083					
196	14.230					
197	74.625					
198	117.208					

WSU Field Sample Leak Rate Ordinal Plot and Descriptive Statistics

Figure 26 below plots the ordinal field data with one sample per vertical line ordered from lowest to highest leak rate. The point at the top of the line is the leak rate in scfh of NG. From this plot, one can see a large range of leakers with the majority on the low end and a few high leakers dominating the high end.

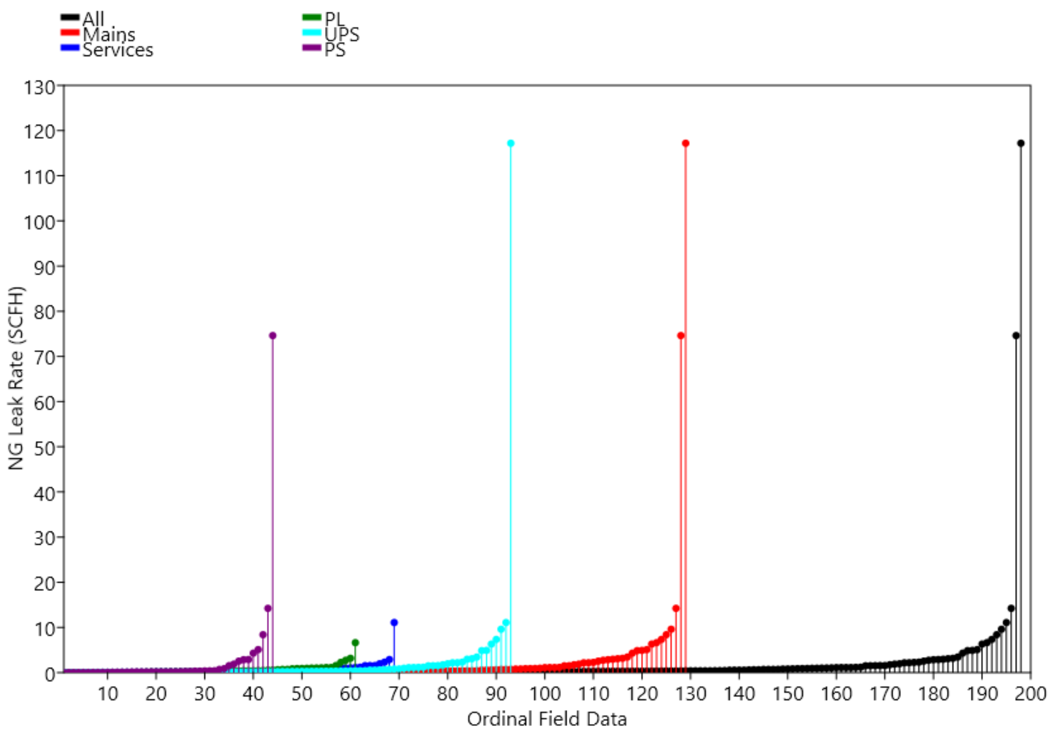


Figure 26 – WSU Field Leak Data Ordinal Ranking Grouped by Unverified Facilities and Materials

Table 14 below includes the total number of samples in each category as well as the minimum, maximum, and summed values of samples by category. The mean of each category is presented along with measures of error, variance, and deviation; as well as the median, 25th and 75th percentiles.

As noted at the top of this section, the leak rate was converted to units of natural gas (scfh), with the values reported to two or three decimal places to allow comparison of a wide range of leak rates. When average leak rates are being used to establish EFs, the values should be presented with the number of significant digits based on the limiting input to such calculations.

Table 14 – WSU Sample Set NG Leak Rate (scfh) Descriptive Statistics

Category	All	Mains	Services	PL	UPS	PS
N (count)	198	129	69	61	93	44
Min (scfh)	0.003	0.004	0.003	0.003	0.012	0.009
Max (scfh)	117.208	117.208	11.083	6.624	117.208	74.625
Sum (scfh)	367.382	325.618	41.764	35.771	206.626	124.985
Mean (scfh)	**1.855**	**2.524**	**0.605**	**0.586**	**2.222**	**2.841**
Std. error (scfh)	0.707	1.078	0.169	0.129	1.266	1.715
Variance (scfh^2)	98.902	149.877	1.969	1.019	148.983	129.365
Stand. dev (scfh)	9.945	12.242	1.403	1.009	12.206	11.374
Median (scfh)	0.235	0.260	0.202	0.260	0.239	0.189
25 prcntil (scfh)	0.090	0.086	0.100	0.074	0.099	0.079
75 prcntil (scfh)	0.799	0.912	0.543	0.710	0.895	0.838

Unverified facility and material categories

WSU Bootstrap Population Average Leak Rate Predictions

The variability in the leak rates for the WSU study is shown in Figure 27. The box plot in this figure shows the inner quartile regions with the mean, as well as the 90% single-sided confidence limits. The outliers are plotted as individual points beyond the box whiskers. This figure shows that the distributions for the categories are not normally distributed but are skewed with longer right tails.

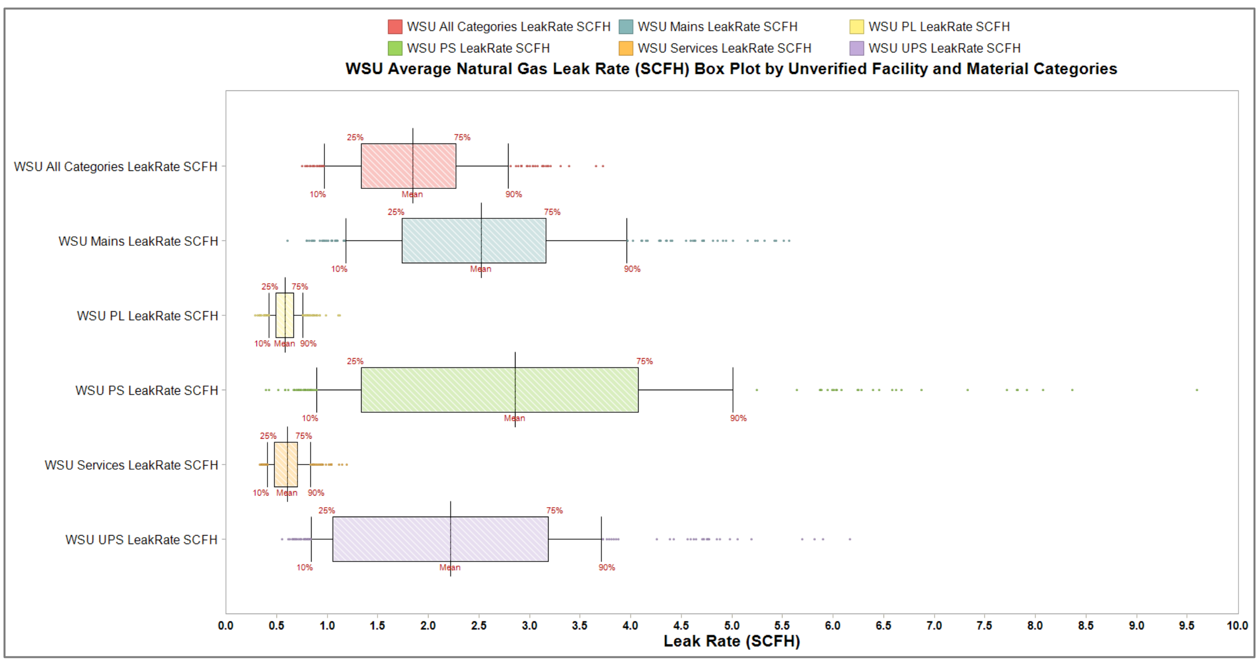


Figure 27 – WSU Average Leak Rate Box Plot

The data for plastic material and service facility categories shows much lower leak rates and a much tighter grouping with very limited spread. This was shown earlier in Figure 11 where the WSU study data was compared across the same categories with the CARB study data. From that figure, one could see that 90% upper and lower single sided confidence limits for all the categories overlap each other individually *between* studies for *each* category and also across *all* categories for *both* studies except for the WSU services and plastic categories which together do not overlap any other WSU or CARB category.

It is difficult to determine the cause for this trend in the WSU data since the categories of the WSU study were not verified (at the time of this report) and therefore might have exhibited large percentages of facility and/or material category misclassifications similar to the CARB data.

The average leak rates and percentiles (e.g., 10% Lower, and 90% Upper Confidence Limit) for the average of each category were calculated for the WSU data using the same Bootstrap method as explained at the beginning of the Analysis and Discussion section of this report for the CARB study data. The results are summarized in Table 15. The largest mean leak rate is for protected steel materials and lowest is for plastic materials. In addition to the mean, spread, and standard deviation, this table list eight population percentiles for each of the six categories, plus the 50% median value. These can be used to construct confidence intervals around the mean values.

Table 15 – WSU Mean Leak Rates from Bootstrap Analysis and Leak Rate Percentiles

	Facility and Material Categories					
	All	**Mains**	**Services**	**PL**	**UPS**	**PS**
Parameter	**Population Values for Natural Gas Leak Rate (scfh)**					
Mean	1.846	2.522	0.608	0.586	2.223	2.863
Minimum	0.527	0.400	0.254	0.241	0.376	0.225
Maximum	5.491	7.782	1.430	1.223	11.963	11.193
St. dev.	0.695	1.066	0.167	0.128	1.260	1.715
Percentile	**Average Natural Gas Leak Rate Percentiles (scfh)**					
1%	0.708	0.811	0.327	0.342	0.628	0.523
5%	0.844	0.990	0.377	0.398	0.760	0.738
10%	0.974	1.184	0.410	0.429	0.847	0.901
25%	1.336	1.745	0.480	0.492	1.058	1.339
50%	1.780	2.402	0.587	0.576	2.145	2.692
75%	2.272	3.161	0.710	0.667	3.187	4.077
90%	2.788	3.961	0.835	0.757	3.710	5.013
95%	3.113	4.488	0.919	0.815	4.690	6.154
99%	3.762	5.443	1.077	0.928	5.955	7.821

Unverified facility and material categories

Appendix C – Belowground Measurement of Pipeline Leaks

A subset of leaks were measured belowground at the pipe using the procedure described below.

Measurements of the Leak Rate in Isolated Pipe Section

(a) At the completion of surface measurements, gas flow rate of belowground leaks were measured in an isolated segment of the pipe. This measurement is similar to the earlier GRI/EPA-1996 procedure which was used to establish EFs.

(b) The pipeline was excavated at two locations at a distance about 15-20 ft at each side of the leak source. The excavations were sufficiently far from the leak source so that the soil condition was not disturbed in the leak area.

(c) The pipe was isolated in each excavated section. Most of the pipes were cut and capped in the test sites. Service lines in the isolated segment were also disconnected.

(d) Gas was introduced in the isolated segment at the same operating pressure of the line. The gas flow rate was monitored using flow meters and Laminar Flow Elements (LFE). A schematic diagram of the flow measurements in the isolated section is in Figure 28.

(e) The measurements of gas flow in the isolated segment represented the flow rate from the leak source. A view of the flow meter and LFE devices used in the measurements are shown in Figure 29.

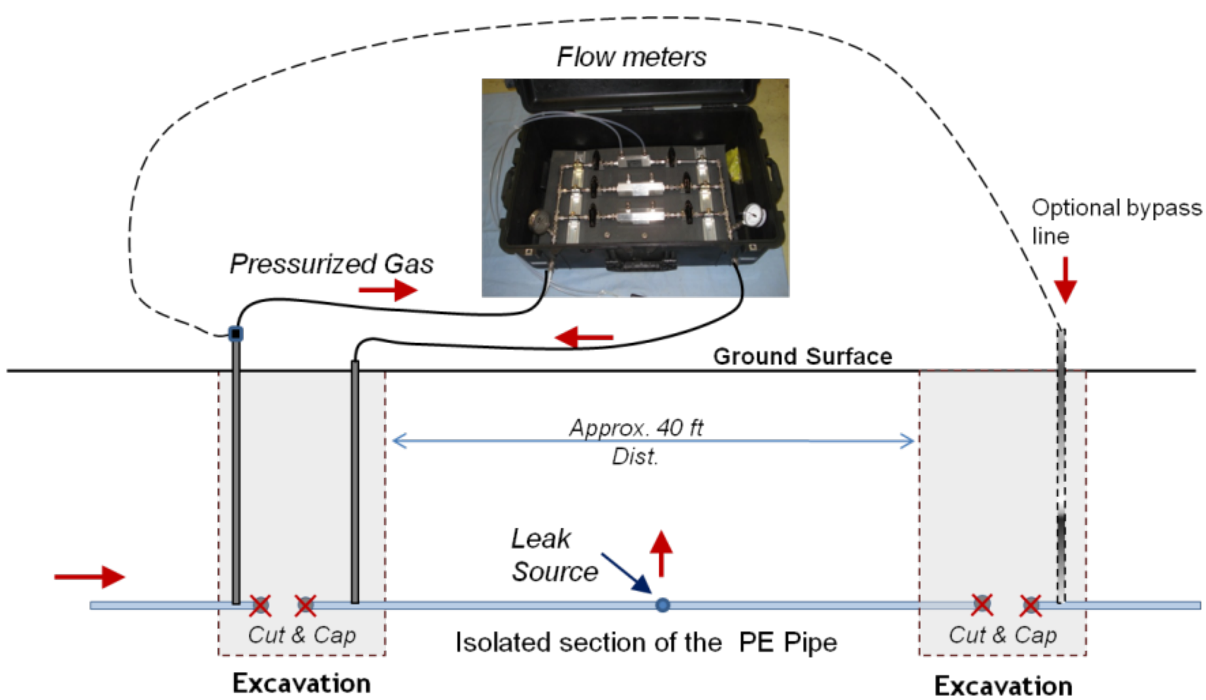


Figure 28 – Measurements belowground leak rates

Figure 29 – View of the LFE and flow meters devices

The leak rate measurements from the isolated belowground pipes were correlated with the Hi-Flow readings to validate the surface measurements results. The Hi-Flow provided a better estimate of leak rates and allowed for performing larger sets of tests at the surface without the need for excavating the pipes, isolating the lines, and disrupting the services.

Belowground Measurement at SoCal Site

Figure 30 shows a belowground measurement performed at one of the leak sites. The measurement was performed by isolating the steel service line at the customer meter and at the joint with the main line in an excavated bell hole.

The gas flow measurements were performed by connecting the gas line to the isolated section and measuring the flow rate using a Laminar Flow Element device.

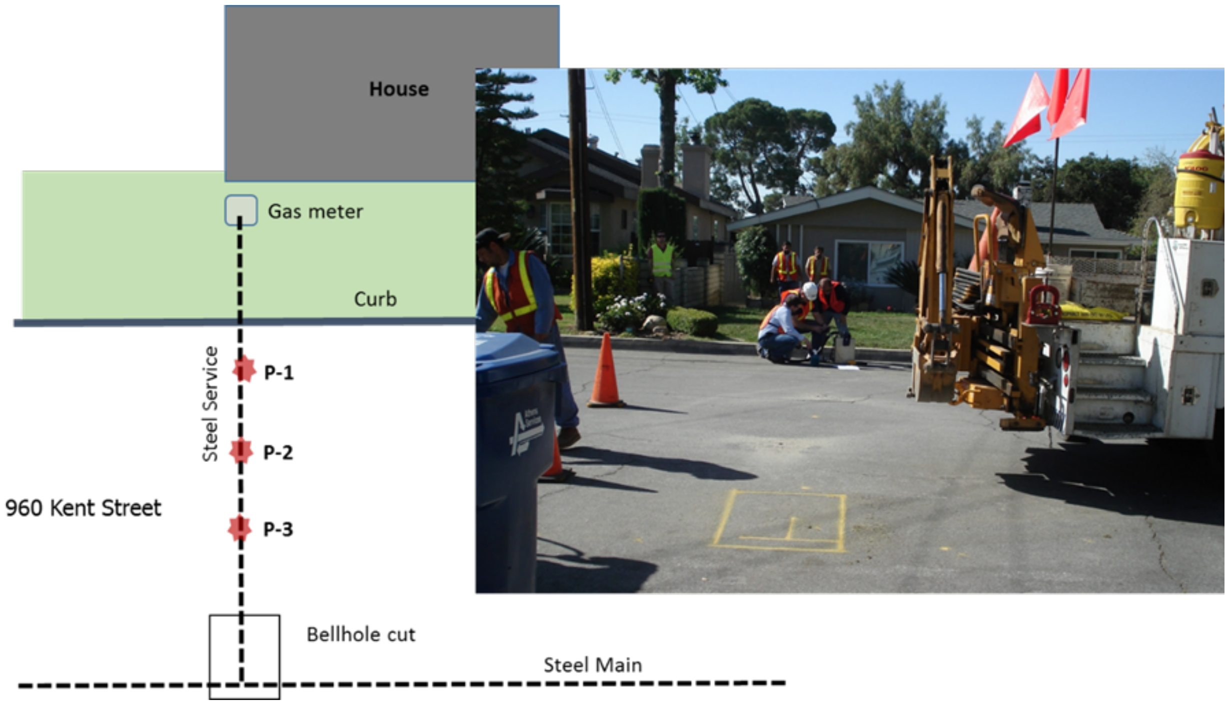


Figure 30 – Below Ground Measurement

Figure 31 – Bell hole excavation for belowground leak measurements

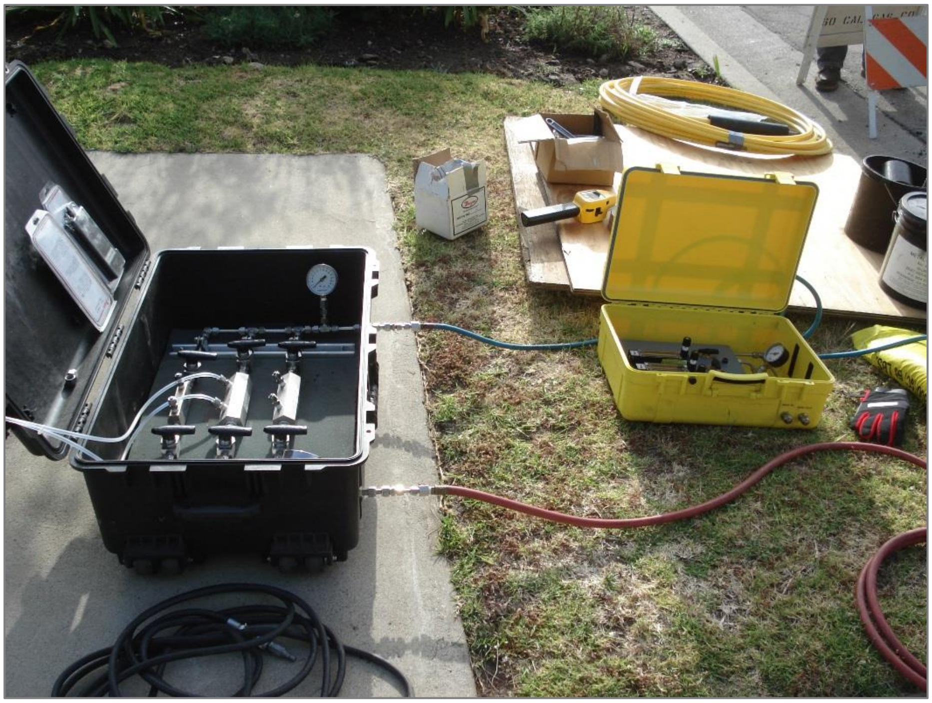


Figure 32 – The Laminar flow and flow meter connections to the serviced line

Validation of Surface Measurements

Belowground measurements using a laminar flow element were taken at several sites throughout the study. This method is designed to directly measure the flow rate of the leak belowground, without disturbing the soil conditions above the leak location. This method is described in the previous section of this report and a depiction of the process can be found in Figure 31 and Figure 32. A previous study performed by GTI validated the use of this surface measurement technique to measure emissions from underground pipelines demonstrating that measurements by the Hi-Flow sampler were repeatable and compared well with the flow rates from the laminar flow element (Farrag and Wiley 2013). The study also evaluated the effect of various parameters that influence leak rates and found that soil type is not a significant factor. However, line pressure and hole size are significant factors that affect the leak rate measured at the surface (Farrag and Wiley 2013). The data collected as part of this report were combined with belowground data that were collected under previous GTI studies to provide the largest sample set for analysis. Figure 33 shows a regression plot of the belowground measurements that were collected. The plot shows that there is good correlation between the belowground measurements and the aboveground or surface measurements.

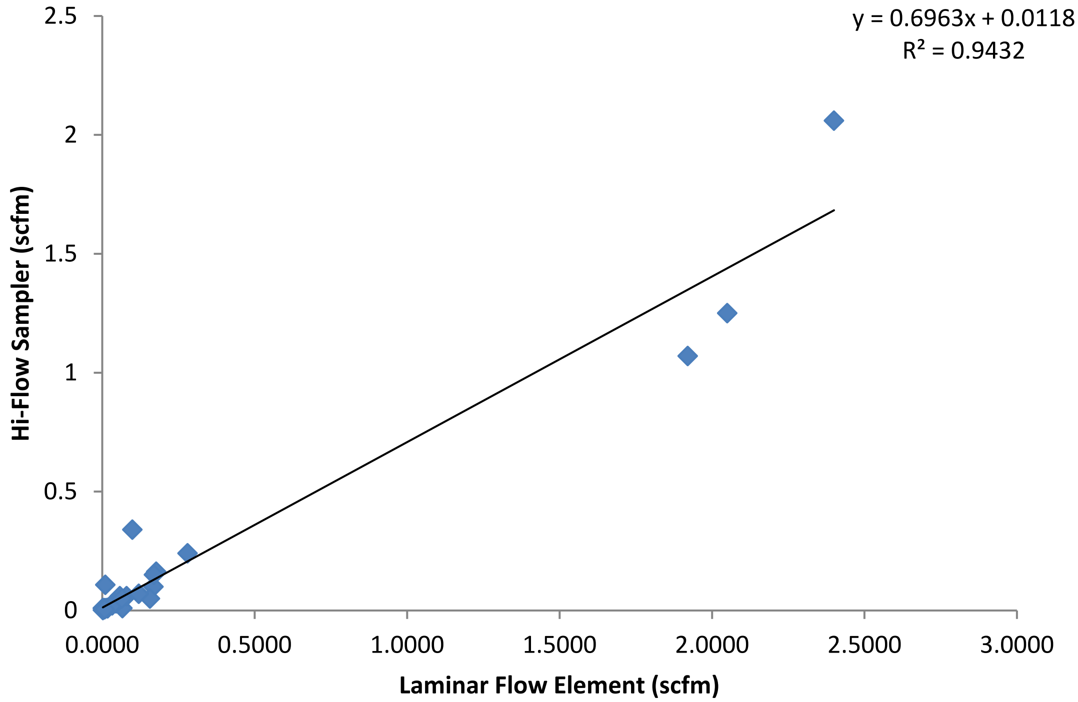


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Figure 33 – Correlation between Belowground Measurements and Surface Measurements

Appendix D – Lognormal Distribution

Lognormal distribution is useful for modeling naturally occurring variables that are the product of several other naturally occurring variables. Lognormal distributions often provide a good representation for a physical quantity that extend from zero to + infinity (a positive number) and are positively skewed. Lognormal distributions are also very useful for representing quantities that are thought of in orders of magnitude, i.e., they have a very large range of values as in the case of leak rate data. An example of a lognormal theoretical cumulative density function and the related distribution equations are shown in Figure 34 and Table 16.

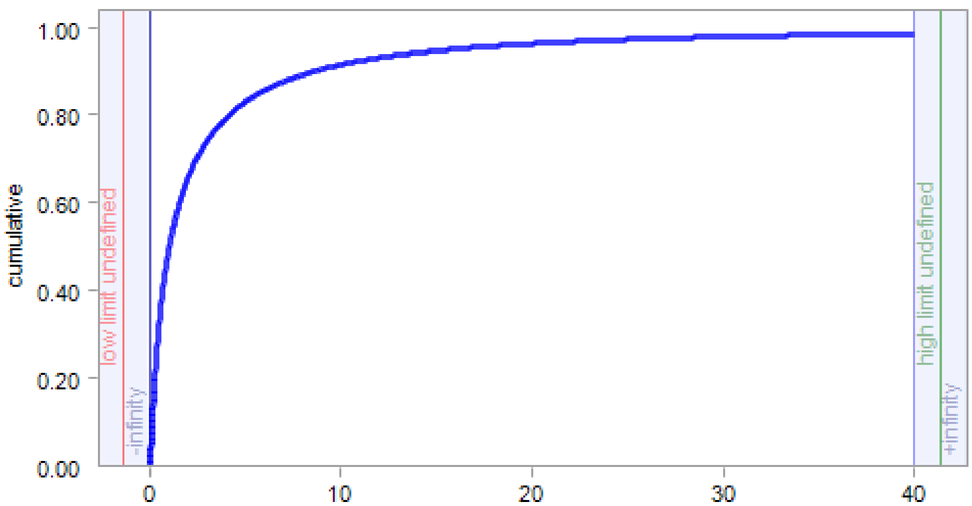

Figure 34 – Example of Theoretical Cumulative Density Function

Table 16 – Distribution Equations for Lognormal Function

Probability density function :	$f(x)=\frac{1}{x\sqrt{2\pi\sigma_1^2}}\exp\left[-\frac{(\ln[x]-\mu_1^2)}{2\sigma_1^2}\right]$ where $\mu_1=\ln\left[\frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}\right]$ and $\sigma_1=\sqrt{\ln\left[\frac{\sigma^2+\mu^2}{\mu^2}\right]}$
Cumulative distribution function :	No closed form
Parameter restriction :	$\sigma>0,\mu>0$
Domain :	$x\geq 0$
Mean :	μ
Mode :	$\exp(\mu_1-\sigma_1^2)$
Variance :	σ^2
Skewness :	$\left(\frac{\sigma}{\mu}\right)^3+3\left(\frac{\sigma}{\mu}\right)$
Kurtosis :	$z^4+2z^3+3z^2-3$ where $z=1+\frac{\sigma}{\mu}$

Appendix E – Bayesian Inference Explanation

GTI has developed a significant body of work that uses Bayesian probabilistic methods to properly calculate expected and limiting values of field-measured attributes (such as latent third-party damage to buried natural gas line, corrosion rates, and methane leak rates). GTI probabilistic models have been developed for emissions analysis, corrosion, leak rupture boundary, damage detection and propagation, and assessment effectiveness. This large body of work and decades of collective experience are used to develop the appropriate Bayesian analysis and predictive model together with their associated conditional probability algorithms.

It is in fact possible to guarantee that decisions are sensible in that they meet the axioms of coherent decision theory by expressing all uncertainties with probabilities and employing the Bayesian approach.

There are two costs of making wrong decisions: the cost of thinking something true when it is not (a false positive) and the cost of thinking something is false when it is true (a false negative). In practical decision making it is important to consider both. One would like to know the probability for both false positives and negatives and balance the significance of both when making decisions. Decision analysis does this and Bayesian methods are integrated at the fundamental level.

The Bayesian approach (Bolstad 2007) (Ferson n.d.), especially when used as part of an updating Bayesian network, elegantly and properly works the prior knowledge into the decision-making process, while at the same time maximizing all empirical data and findings. It does this while keeping all the "bookkeeping" towards a decision coherent, traceable, verifiable, and complete.

For the task of estimating the probability of leak rates, Bayesian statistical analysis is employed on randomly drawn sample sets of field measurements. When a leak is found, this is a positive finding. Equally important are all the times that no leaks would have been found, i.e., a negative finding, which can then be included and accounted for within the analysis.

For this study, only leaks were sampled in the field, so the analysis using Bayesian inference was used to establish the confidence on the leak rate proportions by leak category (bounded and continuous levels of leak rates).

The developed probability distribution weighs the findings (proportions by leak category) and provides an accurate and statistically sound set of most likely leak rates for each leak category and facility or material considered. These will have an upper and lower confidence limit to properly document and carry forward all uncertainty in roll up calculations. This will in turn allow an ordinal ranking with Bayesian credibility levels of the highest to lowest leak categories by category.

List of Acronyms

AD = Activity Data

AGA = American Gas Association

CARB = California Air Resources Board

CI = Cast Iron

CGI = Combustible Gas Indicator / Instrument

CPUC = California Public Utilities Commission

EDF = Environmental Defense Fund

US EPA = United States Environmental Protection Agency

EF = Emission Factor

FID = Flame Ionization Detector

GHG = Greenhouse Gas

GPTC = Gas Piping Technology Committee.

GRI = Gas Research Institute

GTI = Gas Technology Institute (formerly GRI, Gas Research Institute).

GWP = Global Warming Potential (of a particular greenhouse gas for a given time period)

LCL = lower confidence limit

LDC = Local Distribution Company

LEL = Lower Explosive Limit of gas, equals 5 percent methane.

LFE = Laminar Flow Element

LI = Leak Indication

LL = Lower (Prediction) Limit

MLV = Most Likely Value

NG = Natural Gas

OL = Outstanding Leaks (at the beginning of the year)

OTD = Operations Technology Development

PE = Polyethylene

PG&E = Pacific Gas and Electric

ppm = particle per million

psig = Gauge pressure

psia = Absolute pressure (psia = psig + atmospheric pressure)

SDG&E = San Diego Gas and Electric

SoCal = Southern California (Gas)

TEL = Total annual Equivalent Leaks

UCL = Upper Confidence Limit

UDL = Undetected Leaks

UL = Upper (Prediction) Limit

URL = Unreported Leaks

WSU = Washington State University

Gas Volume Units

scf = Standard cubic feet (Standard conditions are at 14.73 psia and 60°F)

scfh = Standard cubic feet per hour

scfm = Standard cubic feet per minute

Mscf = Thousand standard cubic feet (10^3 scf)

MMscf = Million standard cubic feet (10^6 scf)

Bscf = Billion standard cubic feet (10^9 scf)

Gas Weight Units

g = gram

Mg (Megagram) = 10^6 g = 1 metric tonnes

Gg (Gigagram) = 10^9 g

Tg (Teragram) = 10^{12} g

MMT = Million metric tonnes = 1 Tg

MMT of CO_2 eq. = Million metric tonnes, carbon dioxide equivalent.

English to Metric Units Conversions

Volume Units

1 ft^3 = 0.02832 m^3

= 28.32 liters

1 Bscf = 28.32 million cubic meters

1 gallon = 3.785 liters

1 barrel (bbl) = 158.97 liters

1 scf methane = 19.23 g methane

1 Bscf methane = 0.01923 Tg methane

= 19,230. metric tonnes methane

Weight Units

1 lb = 0.4536 kg

1 short ton (2,000 lb) = 907.2 kg

1 long ton (2,400 lb) = 1,016 kg

Pressure units

1 psig = 51.71 mm Hg

1 psi = 6.896 kPa (kN/m^2)

14.5 psi = 1 bar

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