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Classification of Methane Emissions from Industrial Meters, Vintage vs Modern Plastic Pipe, and Plastic-lined Steel and Cast-Iron Pipe

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List of Acronyms

Acronym	Description
AGA	American Gas Association
BQL	Below Quantifiable Limit
CGI	Combustible Gas Indicator
CH_4	Methane
CO_2	Carbon Dioxide
CRDS	Cavity Ring Down Spectroscopy
CSU	Colorado State University
EF	Emission Factor
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GHGI	Greenhouse Gas Inventory
GRI	Gas Research Institute
GTI	Gas Technology Institute
IPCC	Intergovernmental Panel on Climate Change
IQR	Inner Quartile Range
LDC	Local Distribution Company
LEL	Lower Explosive Limit
M&R	Metering and Regulation
MLV	Most Likely Value
NFP	Not for Profit
NG	Natural Gas
OA-ICOS	Off-Axis Integrated Cavity Output Spectroscopy
OTD	Operations Technology Development, Not for Profit
PE	Polyethylene
PHMSA	U.S. Department of Transportation Pipeline Hazardous Materials Safety Administration
RCI	Reconditioned Cast Iron
SCG	Slow Crack Growth
SF_6	Sulfur Hexaflouride
TAP	Technical Advisory Panel
UGGA	Los Gatos Research/ABB Ultraportable Greenhouse Gas Analyzer

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Executive Summary

The project focus was to improve the characterization of methane (CH_4) emissions currently detailed in the U.S. Environmental Protection Agency (EPA) Greenhouse Gas Inventory (GHGI) for categories of assets within the Natural Gas (NG) distribution system to isolate what is driving inflation or deflation behind current, nationwide, aggregated Emission Factors (EFs). These specific categories included industrial/commercial NG customer meters, modern and vintage plastic pipe, along with plastic-lined steel and cast-iron pipe. CH_4 emission rate data was gathered during 25 sampling campaigns at industrial/commercial meter sites, vintage and modern plastic pipe sites, as well as plastic-lined steel and cast-iron sites located within NG distribution networks.

Industrial/Commercial Meters

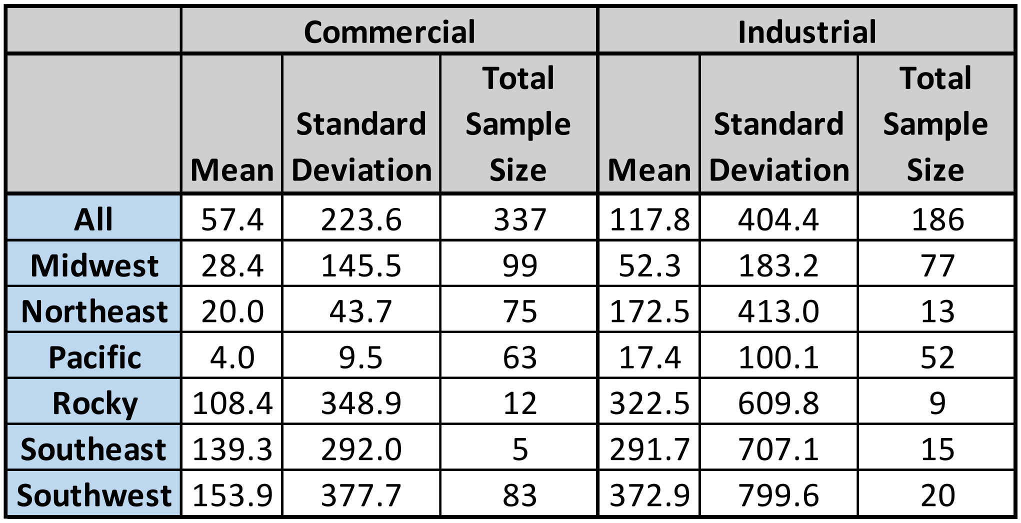
The 13 three-to-five day field sampling campaigns conducted for industrial/commercial meters were performed within six U.S. geographical regions. Sampling sites were selected by pseudo-randomly choosing a starting location for a sampling day then optimizing driving routes to visit the maximum number of meters possible. Upon visiting a meter set, all components were scanned with a combustible gas indicator (CGI) to find all leak indications having a concentration of 100 ppm or above. Depending on the campaign, either all leaks with an indication concentration above 100 ppm were quantified, or leaks with an indication concentration of 22,500 ppm or above were quantified.

A total of 24,670 components were examined across six regions, for six types of industrial/commercial meter sets (Rotary, Turbine, Diaphragm, Orifice, Ultrasonic, and Regulating Equipment), across ten different companies, and at a mix of various types of industrial and commercial facilities within the sector. Of the components scanned, 1,474 components had a leak indication above 100 ppm resulting in emission rate quantifications for 458 individual components nationwide.

Emission rate data distributions for individual components were right-skewed and heavy-tailed, indicating that a small subset of leaks was driving overall emissions from this category. Caps, meters, and regulators had the highest mean EFs for all component types.

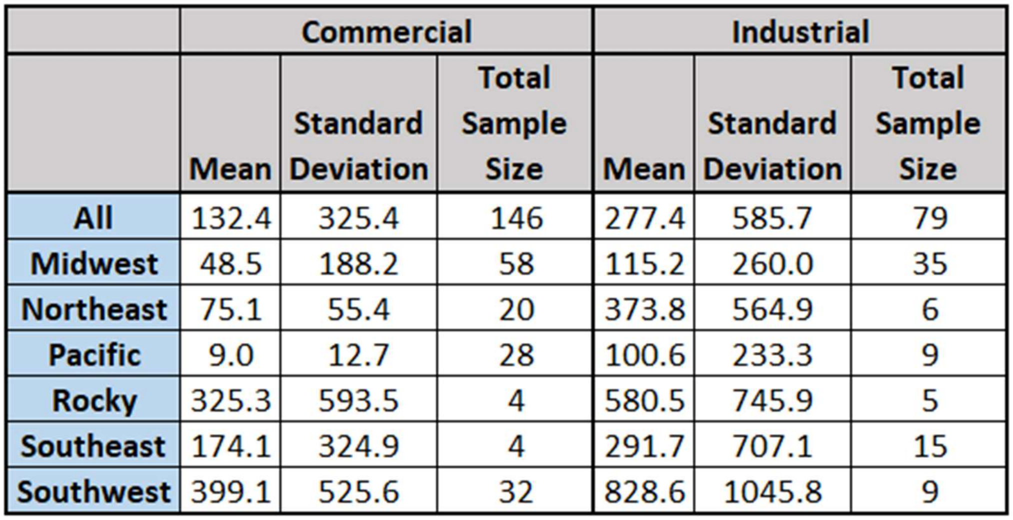
The current factor used in the GHGI for a combined nationwide industrial/commercial meter category is 9.7 kg CH_4 meter^{-1} yr^{-1}. Our data indicate that this nationwide value may be closer to 78.9 kg CH_4 meter^{-1} yr^{-1}. Also, there were differences in EFs calculated for each of the six geographical regions indicating that EFs would be more representative if delineated by region. Turbine meters were emitting larger amounts of CH_4 than rotary and diaphragm meters (indicated by the higher EF), and significant differences were observed in EFs calculated for industrial facilities and commercial facilities. It is therefore recommended that regional EFs be separated by industrial and commercial and then by region and main meter set types (turbine, diaphragm, rotary). Our data allowed for the separation by facility type then region as shown in Tables Table 1 and 2. This would yield more accurate EFs than current aggregated EF estimates in the GHGI.

Table 1. Population EFs for Industrial/Commercial Meters by Region



	Commercial			Industrial		
	Mean	**Standard Deviation**	**Total Sample Size**	**Mean**	**Standard Deviation**	**Total Sample Size**
All	57.4	223.6	337	117.8	404.4	186
Midwest	28.4	145.5	99	52.3	183.2	77
Northeast	20.0	43.7	75	172.5	413.0	13
Pacific	4.0	9.5	63	17.4	100.1	52
Rocky	108.4	348.9	12	322.5	609.8	9
Southeast	139.3	292.0	5	291.7	707.1	15
Southwest	153.9	377.7	83	372.9	799.6	20

Table 2. Leaker-Only EFs for Industrial/Commercial Meters by Region



	Commercial			Industrial		
	Mean	**Standard Deviation**	**Total Sample Size**	**Mean**	**Standard Deviation**	**Total Sample Size**
All	132.4	325.4	146	277.4	585.7	79
Midwest	48.5	188.2	58	115.2	260.0	35
Northeast	75.1	55.4	20	373.8	564.9	6
Pacific	9.0	12.7	28	100.6	233.3	9
Rocky	325.3	593.5	4	580.5	745.9	5
Southeast	174.1	324.9	4	291.7	707.1	15
Southwest	399.1	525.6	32	828.6	1045.8	9

Our data revealed that industrial/commercial meters included heavy-tailed emitters that caused significant impact on emission rates and thus EFs. Addressing these "heavy-tailed" emitters (top 10% of leaks) presents an important opportunity for emission reductions and EF reductions for NG distribution companies.

Modern vs. Vintage Plastic Pipe

Ten, three-to-five day field sampling campaigns were conducted in five of the six geographical regions across the U.S. to study potential differences between CH_4 emissions from buried modern and vintage plastic pipe. Field sampling was conducted using a Hi Flow sampler and surface enclosure, with vintage plastic pipe defined and categorized as being installed prior to 1986, and modern plastic pipe as installed after 1986. We screened 339 potential underground leak sites with emission rates quantified from 186 of the sites. Of these 186 quantified leaks, GTI was able to verify that 103 leaks were located on either modern or vintage plastic pipe with 45 leaks measured on modern plastic pipe and 58 measured on vintage pipe.

Field data was used to develop mean leak rate comparisons for both modern and vintage plastic pipe, delineated by region. After removal of one vintage pipe emission rate outlier, mean emission rates for the two types of pipe were similar with modern plastic having a mean emission rate of 40.9 ± 83.2 g h^{-1} and vintage plastic having a mean emission rate of 48.7 ± 78.4 g h^{-1}. Therefore, this data (although limited), suggests that differences in leak rates between modern and vintage plastic pipe are insignificant. However, the limited sample size and/or removal of one outlier data point for vintage plastic pipe could indicate that either heavy-tailed emissions are more prevalent in vintage plastic pipe, or outliers for the modern plastic pipe were undetected due to the small sample size.

A key finding was that emission rate quantification measurements using surface enclosures may be unreliable for attributing leak rates to specific pipe material without excavation and verification of pipe material type. Of the 83 leaks that were not possible to classify as modern or vintage plastic pipe, 52 were either unknown or unverified (not yet repaired) and 31 were not plastic (eight were steel, 11 were coated steel, nine were bare steel, and three were cast-iron). These differences could be due to several factors including incorrect company records, urban areas with multiple types of pipe located in a small footprint, and/or leaks migrating from one area to another.

Plastic Lined Steel and Cast-Iron Pipe

GTI completed walking surveys of 18 segments of cured-in-place plastic lined steel and cast-iron totaling 3,057.4 m. The randomly selected sites covered roughly 10% of the 33.6 km of the reconditioned cast iron reported by PHMSA in 2016, signified by Re-conditioned Cast Iron (RCI) found in the pipeline database. During the surveys, one leak was found. Upon digging, the utility was able to verify that the "leak" consisted of two smaller leaks - one on the nearby low pressure unlined main and one on an unlined service. Although this verified the validity of the GTI leak survey method, no leaks were found on any of the cured-in-place plastic lined steel or cast-iron segments surveyed. GTI determined that the use of plastic-liners by industry may be limited due to liners being difficult to install in urban areas, as well as the pipe still being classified as a "leak-prone" – even after installation of the liner.

Key Findings and Recommendations

- Leaker factors appear to be a more accurate means of determining emissions than population EFs.
- Industrial/commercial meter sets are likely emitting more CH_4 than currently presented in the GHGI. This is due to significant emission rate differences between industrial and commercial meters, across regions, and among meter set types. Therefore, separate emission factors are recommended for various categories of industrial/commercial meters.
- To further increase the accuracy, separate EFs delineated first by facility type then by region are ultimately recommended to increase the accuracy of the GHGI.
- An alternative suggestion to meter set emission population or leaker-only emission factors would be the Canadian method of disaggregating meter set leaks into component emission calculations. This has the added benefit of reducing uncertainty in EF calculations compared to using nationwide, aggregated meter set EFs. This would require close collaboration between EPA and industry to obtain current and historical records of component counts.
- Future measurements should focus on obtaining high numbers of samples in specific sub-categories to increase understanding of emission rate differences in each subcategory and per region (e.g. commercial rotary meter sets in the Southeast region).
- Addressing "heavy-tailed" emitters (top 10% of leaks) that produce data outliers and cause significant impacts on meter set emission rates and thus EFs is recommended and requires additional study. As such, repairing the top 10% of emitting meter sets would result in a 72.5% reduction in emissions.
- Company policies and leak detection practices appear to also impact meter set leaks. Enabling a streamlined process for company specific EFs may be useful exercises for both NG operators and EPA combined.
- Data collected for vintage and plastic pipe suggested that differences in leak rates between modern and vintage plastic pipes is insignificant. However, the limited sample size created uncertainty around this finding. Additional study is needed to definitively conclude whether heavy-tailed emissions are more prevalent in vintage plastic pipe.
- Plastic-lined pipe typically exists in short, discrete sections within the pipeline network ranging from tens of meters to thousands of meters. Therefore, tracking of total length is significantly challenging.

- Emission rate quantification using surface enclosures may be an unreliable method to determine emission rates of buried plastic pipes if attempting to attribute emissions to a specific pipe material. Excavation and verification of pipe material is needed to alleviate uncertainty caused by such factors as incorrect or incomplete pipeline records, urban areas with multiple types of pipe located in a small footprint and leaks potentially migrating from one subsurface area to another.
- No leaks were observed on any of the cured-in-place plastic lined steel or cast-iron segments surveyed. This may be the result of limited plastic-liner use by industry may be limited due to installation difficulties in urban areas, as well as the pipe maintaining a “leak-prone” classification - even after installation of the liner.

1 Introduction

1.1 Background

Natural gas (NG) combustion leads to lower CO_2 emissions than coal or oil combustion. Due to large domestic reserves, there has been significant investment in the infrastructure and equipment needed to take advantage of this abundant energy source. As a result, electricity generation from NG reached 35.1% in 2018, surpassing coal generation (27.4%, USEIA, 2019c). Unfortunately, some of the climate benefits of lowering CO_2 emissions via NG combustion are offset by releases of CH_4 throughout the value chain. The primary component of NG is CH_4 which has 28 to 87 times more global warming potential than CO_2, depending on the time horizon used (IPCC, 2014).

The importance of NG in the United States energy future has led to an increased necessity of responsibly obtaining and using this resource. Continued increases in NG production and consumption, particularly in the industrial and electric power sector (USEIA, 2019a) have produced an urgent need to understand potential environmental and climatic impacts from the entire NG value chain (e.g., Alvarez et al., 2018; ICF, 2016; Lamb et al., 2015; Moore et al., 2014; Vaughn et al., 2018; Weller et al., 2018). U.S. greenhouse gas emissions are estimated by the EPA through the annual GHGI. The GHGI contains a section on NG systems in which CH_4 emission estimates are broken down by specific stages (production, processing, transmission, and distribution). The stages each contain multiple categories for which EPA makes individual estimates of total emissions. For each category, an estimate of the total activity (e.g., miles, services, stations) is multiplied by an EF, which is a high-level estimate of the typical emissions per unit of activity per year.

Unfortunately, EFs that are used for the individual NG system categories and thus the overall emissions estimates, can be relatively imprecise with an accuracy that is difficult to determine due to the limited data that went into the initial calculations. Many of the EFs are based on a 1990s Gas Research Institute (GRI)/EPA study, that had an objective to develop an overall picture of CH_4 emissions from the NG system, wellhead to burner tip. The goal was not to provide individual EFs for each component, system, and subsystem of the NG industry. The 1996 GRI/EPA study was focused on quantifying CH_4 emissions from U.S. NG operations for the 1992 base year. The study, although over two decades old, and beyond its original intent, is still the foundation for quantifying CH_4 emissions from NG systems. However, EFs from that study may no longer be relevant due to changes in materials, practices or operations utilized within the gas industry. As a result of the limitations of the original GRI/EPA study, several updates to the calculations of CH_4 emissions from NG systems have been made over the years as new information comes available.

Numerous studies from universities, non-government organizations, and regulatory agencies have been initiated over the past few years that focus on CH_4 emissions from the NG industry with estimates for emission rates ranging from 1.1% to 2.3% per unit of production (Alvarez et al., 2018; Littlefield et al., 2017; Peischl et al., 2015; Zavala-Araiza et al., 2017). This wide range demonstrates the need for better estimates of greenhouse gas emissions. More scientific data needs to be collected and EFs developed to identify and quantify major and minor CH_4 leak sources, so that further efforts to reduce CH_4 leakage can be appropriately focused and prioritized. This scientifically validated data is essential for policy makers and regulatory authorities to make well informed decisions relative to the environmental benefits derived from the expanded use of NG in the U.S.

A report recently released by GTI and Operations Technology Development (OTD) showed a 70% reduction in CH_4 leakage for polyethylene (PE) pipes versus the baseline data from the 1992 study. Vintage plastic pipe (such as Aldyl-A) has been shown to experience a phenomenon called slow crack growth (SCG) that occurs as stable growth of a crack with little deformation in the plastic material (e.g., Palermo, 2000). This could indicate that as newer plastic pipe is installed, emissions are reduced. Therefore, a need exists to understand differences in emissions between modern and vintage plastic pipe to better understand the benefits of the modern plastic pipe material.

An OTD report released in 2009 (OTD, 2009) that focused on emissions from various categories of components in NG distribution found potential underestimations of current industrial/commercial customer meters. The results of that study suggested that commercial and industrial NG customer meters were emitting more CH_4 than was being accounted for in the GHGI. Notably, industrial meters were emitting far more CH_4 than commercial meters. Based on these findings, EPA revised the EF for the combined industrial/commercial meter category in the GHGI with the EF for commercial meters from the OTD 2009 study. The population EF currently used for that combined industrial/commercial category is 9.7 kg CH_4 yr^{-1} $meter^{-1}$, which gets applied to an activity of 5.6 million.

Understanding emission rates and EF calculations is crucial to obtaining an accurate estimate of overall greenhouse gas emissions from the NG sector especially since the GHGI estimates are used to drive important environmental policy at the federal level creating impacts to individual natural gas rate payers. By reducing uncertainty and improving the characterization of CH_4 emissions from the natural gas industry, the GHGI can become more resulting in appropriate regulations that minimize costs of compliance.

1.2 Scope

The overall objective of this project was to address uncertainties surrounding current estimates of CH_4 emissions from specific asset categories within U.S. NG distribution systems. More specifically, the research team focused on the following key areas:

1. Improving the characterization of emissions from industrial/commercial NG customer meters in the NG distribution system.
2. Determining whether vintage and modern plastic pipelines exhibited differences in overall CH_4 emissions.
3. Gathering existing data from literature as well as data from field sampling on CH_4 emissions from plastic lined steel and cast-iron pipes within the NG distribution system.
4. Creating emissions estimates that were broken down into the following subsets:
   a. Nationwide component emissions.
   b. Regional meter set emissions disaggregated by meter type, facility type, company, and industrial/commercial sectors.

To address these key focus areas, GTI conducted 25 field sampling campaigns. Each campaign lasted three to five days with field sampling teams focusing on various assets within the NG distribution system. A detailed sampling protocol is discussed later in the report. A high-level outline of field campaign focus areas is summarized below.

- Ten field campaigns focused on plastic pipe.
- Two field campaigns focused on plastic lined steel and cast iron.
- Ten field campaigns focused on industrial/commercial meters.
- Three field campaigns focused on revisiting industrial/commercial meter sites already sampled.

GTI also established a Technical Advisory Panel (TAP) with representatives from eight NG Local Distribution Companies (LDCs), OTD, two consulting firms, the American Gas Association (AGA), the Canadian Energy Partnership for Environmental Innovation, Colorado State University (CSU), and the University of Cincinnati. The TAP was essential for providing site access, data, and critical feedback on data analysis throughout the duration of the project.

2 Project Planning and Protocol Development

2.1 Planning and Industry Engagement

Project completion relied heavily on the participation of NG LDCs who participated as industry partners via the TAP. Extensive field data was needed to evaluate emissions from industrial/commercial meters and underground pipelines, both before deployment of field crews and after the crews had completed their visits. For example, to optimize the number of locations that could be visited during this project, the research team had to work closely with industry partners to determine locations of industrial/commercial meters and of existing underground pipeline leaks that were on specific types of pipe. Collaboration with industry partners through the TAP was therefore crucial to obtaining much of the information needed to complete this project. Additionally, industry partners provided escorts during field campaigns and on-going support throughout the duration of the project to provide feedback regarding company-specific operations.

2.2 Site Selection and Evaluation of Existing Data

2.2.1 Site Selection

Prior to completing any measurements, the U.S. was separated into six geographical regions to focus sampling efforts (Figure 1). GTI used current relationships with industry partners located in those regions to secure sampling locations.

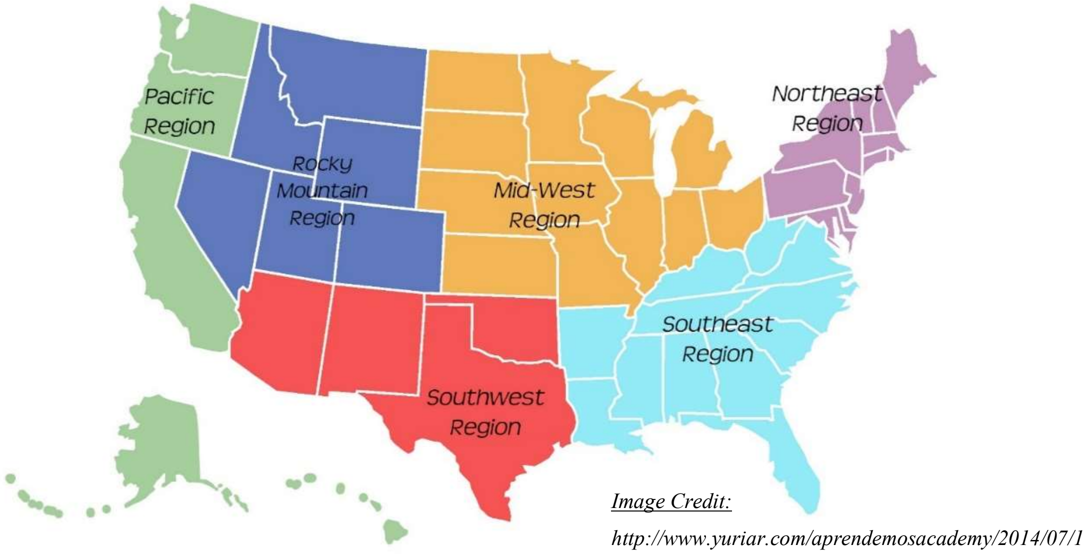


Image Credit:

http://www.yuriar.com/aprendemosacademy/2014/07/1

Figure 1. Study Regions

Location information provided by industry partners was crucial for maximizing the number of sites in a single day. Daily driving routes, sampling protocols, and logistical information (e.g., meeting times and places) were finalized before each field campaign began.

2.2.2 Existing Data - Industrial/Commercial Meters

Several existing sources of data were used to design the industrial/commercial meter portion of the project. These included gathering data from EPA on how industrial/commercial meters were logged in the

GHGI, locating data used by the EPA from The U.S. Energy Information Administration (EIA) on the definitions of industrial and commercial meter, and the numbers of those meters in each state. Specific data was then collected from LDCs on industrial/commercial meters located within their networks.

One important note is that NG customer meters currently fall into two categories - residential or industrial/commercial for the purposes of the GHGI. Initially, the scope of the project was to focus solely on fugitive CH_4 emissions from industrial meters. However, since EPA uses a combined industrial/commercial category, and thus a combined EF for both types of meter, it was decided to also gather information on commercial meters to better align with information currently provided in the GHGI.

The EPA GHGI uses the definitions of industrial and commercial sectors provided by the EIA to define commercial and industrial meters. The use of predefined sectors allows EPA to use both current and historical data collected by EIA on these sectors, which includes numbers of these facilities by state, to estimate the population size of each sector (also called activity in emissions calculations).

EIA defines the industrial sector as –

> “An energy-consuming sector that consists of all facilities and equipment used for producing, processing, or assembling goods. The industrial sector encompasses the following types of activity manufacturing (NAICS codes 31-33); agriculture, forestry, fishing and hunting (NAICS code 11); mining, including oil and gas extraction (NAICS code 21); and construction (NAICS code 23). Overall energy use in this sector is largely for process heat and cooling and powering machinery, with lesser amounts used for facility heating, air conditioning, and lighting. Fossil fuels are also used as raw material inputs to manufactured products.” (USEIA, 2019b)

Likewise, the commercial sector is defined as –

> “An energy-consuming sector that consists of service-providing facilities and equipment of businesses; Federal, State, and local governments; and other private and public organizations, such as religious, social, or fraternal groups. The commercial sector includes institutional living quarters. It also includes sewage treatment facilities. Common uses of energy associated with this sector include space heating, water heating, air conditioning, lighting, refrigeration, cooking, and running a wide variety of other equipment. This sector includes generators that produce electricity and/or useful thermal output primarily to support the activities of the above-mentioned commercial establishments.” (USEIA, 2019b)

On the other hand, LDCs focus on the NG supply needs of customers and match the type of meter for each customer according to those needs. The LDCs collect limited data from customers on the use of the

NG supplied. Therefore, data provided from LDCs had to be combined with information from Google Maps and observations of crews in the field to estimate whether the facilities were commercial or industrial.

It is important to note that fugitive emissions from actual industrial/commercial meters are rare. Emissions are more likely to occur from the additional components that are associated with the meter (e.g., valves, flanges, tees). Due to this distinction, the meter *plus all components associated with that meter* up to the point of transfer of hardware responsibility to the NG customer will be referred to as a "meter set" for the remainder of the report. However, anytime the emission occurred directly from the meter body or connection between the meter body and associated electronics, then that will be referred to as a leak from the "meter" (not meter set).

Prior to starting a sampling campaign, each partner LDC was asked to provide a random subset of their industrial/commercial meter population that included the meter type and service address. All meter set data provided by the LDCs were placed in Google Maps. Each day, a starting meter set was randomly selected, with the remaining meter sets selected to optimize driving routes and maximize the number of sites visited during a single day. This method allowed GTI to maximize the number of sites while still retaining a pseudo-random procedure for sampling.

2.2.3 Existing Data - Modern vs. Vintage Plastic Pipe

Older plastic pipe (particularly Aldyl-A) has been shown to experience slow crack growth, potentially leading to greater emissions. Therefore, Aldyl-A was initially chosen to represent vintage plastic pipe. However, after discussions with NG utility partners, it was determined that different forms of Aldyl-A were produced through 1983 and record keeping for that period did not usually involve tracking production dates of the pipe, but rather installation dates of the pipe. Based on this information, it was decided to label all plastic pipe installed before 1986 as "vintage" and all pipe installed after 1986 as "modern." Additionally, GTI focused on existing Grade 2 and 3 leaks currently in company leak records to optimize the number of leak sites visited. Grade 1 leaks were not included because they are repaired immediately by industry partners when found.

Industry partners were contacted in each of the six regions to locate existing Grade 2 and 3 leaks on vintage plastic pipe (1986 or earlier installation date). Most importantly, GTI requested that the list include leaks that would be fixed prior to the end of the project. This allowed the research team to verify pipe material since the pipe would be excavated to repair the leak. Unfortunately, data on the presence of vintage plastic pipe was limited and was not present in all regions.

Prior to the arrival of field crews and like the method used for industrial/commercial meters, the leak locations were entered into Google Maps prior to the start of each three-to-five day sampling campaign. The first site for each day was randomly selected and the following sites were visited in a fashion to maximize the number of leak sites that could be driven to in a single day.

2.2.4 Existing Data - Plastic Lined Steel and Cast-Iron

The U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) listed the amount of Reconditioned Cast Iron (RCI) pipe as 20.9 miles in 2016. Additionally, RCI was considered to mean plastic-lined steel, however no information was available on plastic-lined steel. Based on that information, GTI contacted LDC partners to first determine if the numbers quoted by PHMSA were accurate, and second whether there were any existing Grade 2 or 3 leaks that could be included in this study. After months of correspondence, it was determined highly likely that PHMSA was correct in their estimate of pipeline miles with liners. An important observation noted from the data received was that plastic-lined pipe typically exists in short, discrete sections within the pipeline network ranging from tens of meters to thousands of meters. Therefore, tracking of total length is significantly challenging.

Furthermore, it was not possible for GTI to locate any open Grade 2 or 3 leaks on plastic-lined pipes owned by industry partners. GTI arranged one field campaign with an industry partner, but upon arrival there were no leaks to be measured. Due to a lack of known leaks, GTI worked with one industry partner to perform second field measurement campaign that would include a special leak survey of a subset of the plastic-lined steel and cast-iron in their system. GTI received a list of plastic-lined segment locations, placed them in Google Maps, randomly selected a starting location for each day of sampling then optimized the rest of the sites to reach as many sites as possible in three days of sampling.

2.3 Industrial/Commercial Meters - Field Sampling Protocol

2.3.1 Component Survey and Leak Identification Procedures

Industrial meters were categorized into six classes – rotary, diaphragm, turbine, orifice, ultrasonic, and regulating-type equipment (Figure 2). The focus of the project was on rotary, diaphragm, and turbine meters as these types make up the majority of both commercial and industrial meters nationwide as determined from existing data obtained from LDC partners. However, during the random sampling, two orifice meters, two ultrasonic meters, and three regulating type meters were encountered and therefore sampled.

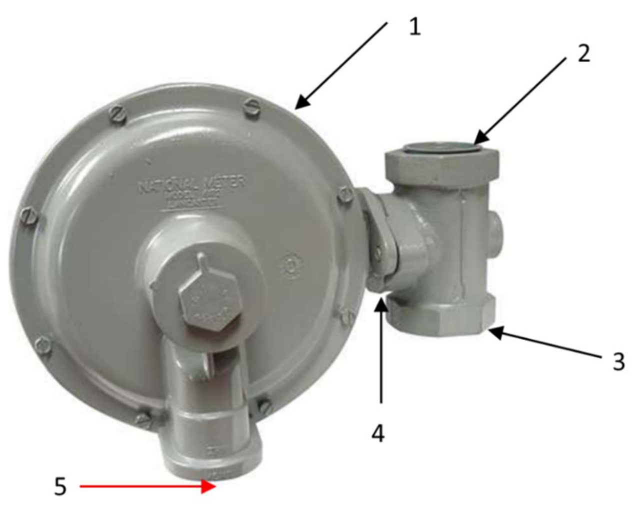
a. Rotary Meter b. Diaphragm Meter c. Turbine Meter

d. Orifice Meter e. Ultrasonic Meter f. Regulating Equipment

Figure 2. Six Classes of Industrial Meters

Ten primary component types were also identified across all meter classes based on existing knowledge of components co-located with industrial/commercial meters. They include Cap, Coupling, Elbow, Flange, Meter, Plug, Pneumatic Device, Regulator, Tee, and Valve. During each campaign, some leaks were identified and quantified on components that were not originally included in the ten main component categories. Since component types used varied from company to company, an additional category titled “Other” was established that included information for leaks identified on components occurring outside the original ten categories. Examples of components that fall into the “Other” category include Strainers, Filters, Pilots, and Compression Fittings.

Only fugitive leaks were within the scope of this study. No vents on regulators or pneumatic devices were included unless they were malfunctioning (e.g., valve stuck open on a pneumatic device or regulator). To clarify, Figure 3 shows an example of an NG regulator that can be found at a typical portion of industrial/commercial meter sets. Positions 1 through 4 show where potential fugitive emissions may be found. Position 1 is the area where two halves of the regulator come together and hold a diaphragm in place, Positions 2 and 3 are threaded connections where the regulator is placed in line with the meter set, and Position 4 is a flange that connects the regulator parts to the pipe connection. Position 5 (red arrow) is the regulator vent. Emissions from Position 5 were not quantified as these are intended or engineered emissions.



https://www.zoro.com/sensus-gas-pressure-regulator-143-80/i/G1748783/

Figure 3. Example NG Regulator.

2.3.2 Measurement Instrumentation – Industrial/Commercial Meters

Hi Flow Sampler: The Hi Flow Sampler (Bacharach, Inc, New Kensington, PA) is a portable, intrinsically safe, battery-powered instrument originally designed to determine the methane leak rates around various components such as pipe fittings, valve packings, and compressor seals. The Hi Flow Sampler measures at a high flow rate to capture all gas from the leaking component along with surrounding air. The gas leak rate is calculated using Equation 1. The instrument compensates for different specific gravity values of air and NG to calculate CH_4 flow rates (Bacharach, 2015).

<u>Equation 1</u>

$$\boldsymbol{E\left(\frac{g}{h}\right) = Q\,(scfm) * \left(C_{gs}(\%\,gas) - C_{bg}(\%\,gas)\right) * 10^{-2} * 19.23\,\frac{g\,CH_4}{scf_{CH_4}} * 60\,\frac{min}{h}}$$

where:

E = rate of gas emission from source

Q = sample flow rate

C_{gs} = concentration of gas from leak source

C_{bg} = background gas concentration

To ensure the instrument is capturing all gas escaping from the component, two measurements are performed at two different flow rates. The first measurement is taken at the highest possible flow rate, followed by a second measurement at a flow rate that is approximately 70–80% of the first. If the two calculated leak rates are within 10% of each other, then it was assumed that all gas was captured during the test (Bacharach, 2015). The manufacturer recommendations were followed for calibration checks at intervals of every 30 days during continuous use.

Hi Flow samplers can measure NG leaks up to 153.8 g CH_4 h^{-1} and down to 11.54 g CH_4 h^{-1} without the need for modification. However, many of the leaks measured during the industrial/commercial meter campaigns were lower than 11.54 g CH_4 h^{-1}, which required the pairing of CH_4 and NG sensors possessing higher sensitivity (discussed in the next two sections). These sensors were positioned at the center of the exhaust flow from the Hi Flow sampler to obtain a more precise CH_4 or NG concentration reading. To calculate the emission rate, the concentration measured at the exhaust was used in Eq. 1 along with the flow rate from the Hi Flow sampler.

Combustible Gas Indicator: A Gold G2 (Sensit Technologies, Valparaiso, IN) combustible gas indicator (CGI) was used to measure combustible gas concentrations near individual components. A CGI like the Gold G2 uses an advanced low power semiconductor sensor to measure combustible gases in the ppm and Lower Explosive Limit (LEL) range and a thermal conductivity style sensor to measure combustible gases in the percent volume range. CGIs are staples of the NG industry and are used extensively to survey for leaks based on increases in CH_4 concentrations. Leaks can be pinpointed by following areas of higher and higher concentrations. The CGI used during sampling was rented from the manufacturer (Sensit Technologies) who performed a calibration before each campaign, ensuring the unit was calibrated within manufacturer specifications.

The Sensit Gold G2 was also placed in the exhaust of the Hi Flow sampler to increase sensitivity. This modification has been shown to reduce the minimum detectable rate to 0.231 g CH_4 h^{-1} (OTD, 2013). Since the CGI measures all combustible gas, a factor of 0.95 was added to the concentration measurement. This number was derived from an EPA pipeline quality NG composition estimate of 95 – 98% methane (USEPA, 2018).

ABB/Los Gatos Research Ultraportable Greenhouse Gas Analyzer (UGGA): A sample line attached to a high sensitivity cavity based UGGA was placed in the exhaust of the Hi Flow sampler to further improve the sensitivity of the emission rate measurement. This was only performed during a subset of campaigns when all leaks with a 100 ppm or greater leak indication were quantified. In particular, the UGGA uses Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS) to obtain parts-per-billion (ppb) precision with a wide dynamic range (0 – 100,000 ppm) and an output every 2 seconds. The UGGA can be used to reliably perform emission rate detections as low as 0.00115 g CH_4 h^{-1}.

2.3.3 Leak Identification and Quantification Methods

All data collected was logged into a data survey created in ArcGIS Survey123 software that was loaded onto an iPad (additional details are provided in Section 8.1 and 8.2 – Appendices on Data Collection Surveys for Industrial Meters and Buried Pipeline). Each component at every meter set visited was scanned with the Sensit Gold G2 by touching areas of a meter possessing the potential for leaks (e.g, areas 1 through 4 in Figure 3). Any component that had an indication of 100 ppm or greater was logged in the data survey. Two leak indication concentration thresholds were used to establish which of the identifications had their emission rates quantified. For eight field campaign weeks, only leaks with indications above 22,500 ppm were selected for emission rate quantification. The remaining five campaigns had all leaks with identification concentrations above 100 ppm bagged and their emission rate quantified. These thresholds will be referred to as "leak quantification thresholds" throughout this report and are discussed in greater detail in Section 2.4.2. These methods were selected to maximize the number of sites visited on each field campaign.

Once a leak was determined to be above the leak quantification threshold for that sampling campaign, that component was wrapped with an anti-static bag to create a small dynamic flux chamber around the component. The bag was attached to the Hi Flow sampler via a 1.5 m hose and hose-quick connection fittings. For quality assurance purposes, each leak was sampled using three or four replicate samples. Two replicate samples were performed at a sample flow rate at or greater than 184 lpm, and one or two replicate samples were performed at a sample flow rate of less than 142 lpm. If the replicate calculated CH_4 emission rates exhibited less than a 10% difference, only three replicates samples were performed rather than four. This helped to minimize time spent on leak quantification and to maximize the number of sites visited overall. The emission rate of each leaking component was calculated as the average of all replicate samples.

According to data collected from other GTI projects, there is often a weak correlation between indication concentration and quantified leak rate. Based on this previous data, GTI decided to use indication concentration as an initial binary indication of whether a leak may be large or small, thus increasing the likelihood of finding the few large leaks likely to be driving the overall emissions for this category. GTI selected 22,500 ppm as the indication concentration, which would allow GTI to find the larger emission rates that may drive the overall emissions from this category. This specific leak indication threshold was chosen because the Hi Flow sampler with a CGI attached was generally not capable of measuring leaks that had an indication concentration below 22,500 ppm (45% LEL). Therefore, to maximize the number of meter sets that that could be visited as well as the likelihood that leaks would be quantifiable, GTI selected this threshold for quantification during eight of the 13 field measurement campaigns. For the five other measurement campaigns, the UGGA was used to extend the range of leaks that could be quantified to any leak with an indication concentration of 100 ppm or larger.

The use of two leak quantification thresholds for different campaigns led to 1,016 leaks that were identified but not quantified and 458 individual component leaks that were identified and quantified. Additional details on the two thresholds are included in Section 8.3 Appendix – Leak Quantification Threshold Discussion. To examine the potential contribution of small leaks that had indication concentrations between 100 ppm and 22,500 ppm to overall emissions, a data set was generated from the 245 leaks that were quantified and had leak indication concentrations between 100 and 22,500 ppm. A bootstrap method was then used to sample from that dataset 10,000 times, thus generating a mean and median for each individual component leak that was not quantified. These modeled leaks were used to create three separate sets of individual component emission rates and included 1) quantified leak rates only, 2) quantified leak rates plus the mean of the bootstrap for each individual leak not quantified, and 3) quantified leak rates plus the median of the bootstrap for each individual leak not quantified.

2.4 Modern vs. Vintage Plastic Pipe – Field Sampling Protocol

2.4.1 Measurement Instrumentation – Modern and Vintage Plastic Pipe

Hi Flow sampler: The Hi Flow sampler used to quantify leak rates from the underground modern and vintage plastic pipe leaks was slightly different than the version used for the industrial/commercial meter measurements. To address limitations with the Bacharach Hi Flow sampler, the Hi Flow sampler used for the underground pipeline leak measurements had a Bascom-Turner Gas Rover built directly into the system. The Gas Rover possesses a sensitivity of 0-100% LEL of gas and 0-40,000 ppm gas concentration. This modification alleviated the need for additional CH_4 concentration instrumentation (as detailed in the industrial/commercial meter sections). This combination system has been used extensively and is described in Lamb et al., (2015), Indaco Air Quality Services (1995), and Howard (2001).

Picarro G2301 Gas Concentration Analyzer: As part of the tracer ratio measurements (discussed below), a high sensitivity CH_4 analyzer was used to monitor for small changes in CH_4 concentrations in correlation with changes in the tracer gas. The Picarro G2301 gas concentration analyzer uses cavity ring down spectroscopy (CRDS) to provide simultaneous measurements of carbon dioxide (CO_2), CH_4, and water vapor at parts-per-billion (ppb) sensitivity. The precision at 5 seconds and at 5 minutes is <70 and <25 ppb for CO_2, and <0.5 and <0.22 ppb for CH_4 respectively.

SF_6 Analyzer: The Sulfur Hexafluoride (SF_6) Analyzer used for tracer measurements was a custom-built unit that consisted of a modified Hewlett Packard 5890 Series II Gas Chromatograph with an electroncapture detector to measure SF_6. The use of this analyzer has been documented elsewhere and was used in Lamb et al., (2015).

3D Ultrasonic Anemometer: A Young Model 81000 3D Ultrasonic Anemometer was used to measure 3-dimensional wind vectors during tracer measurements. The 81000 contains no-moving-parts and has a fast response with high resolution. Measurements can occur at rates from 4 to 32 Hz with a resolution of 0.01 m s^{-1}.

2.4.2 Leak Identification and Quantification Methods

Pipeline leak measurements were made for a series of non-hazardous leaks, previously identified by LDC partners, using a surface enclosure flux technique described in Lamb et al., (2015). Briefly, the technique involved scanning the ground surface above the identified leak with handheld CH_4 sensors to define the surface expression of the leak. The entire surface was then covered in a stepwise fashion with a 1.5 square meter (m^2) dynamic flux enclosure. The gas emission rate from each square was measured using the Hi Flow sampler mentioned earlier in this section. The total emission rate for the leak was obtained by summing the individual emission rates from each enclosure measurement.

The surface enclosure system was very flexible and adaptable since leaks occurred in a wide range of sizes. The general approach followed protocols similar to those used for dynamic chamber flux measurements (used for landfill and other surface flux measurements) where air is flushed through the chamber at a measured rate, the concentrations of CH_4 in the flush air and in the exhaust are measured after steady state conditions are reached and the leak rate is calculated using equation Eq 1 above. The enclosure was made from a plastic membrane laid over a rigid PVC frame. This provided free flow of air into the enclosure via a flexible inlet tube and out through an exhaust port where the CH_4 concentration was measured continuously. Enclosure air flow rates were approximately 170 to 227 slpm (standard liter per minute) resulting in residence times of one to two minutes - such that steady state conditions were reached in approximately five minutes. Once the sample concentrations stabilized, the sample concentrations were recorded along with inlet air concentrations and the velocity readings (Lamb et al., 2015).

2.4.3 Additional Quality Assurance Protocols - Tracer Ratio Methods

To obtain a second independent measurement of a portion of the measured leaks, the research team conducted tracer ratio emission measurements when possible. The tracer ratio method was the primary method used to measure CH_4 leak rates from M&R stations in the GRI/EPA study (Lamb et al., 1995). In this project, the tracer ratio technique was used as a quality assurance tool for the surface enclosure measurements.

In the tracer ratio approach, inert tracer gas (sulfur hexafluoride, SF_6) was released at a steady, measured rate from the leak location where the surface enclosure system was being used. An instrumented van parked a short distance downwind of the release, was used to measure ambient concentrations of CH_4 and the tracer during a 5 to 20-minute period (Figure 4). After accounting for background concentrations of CH_4 and SF6, the CH_4 leak rate was calculated directly from the ratio of ambient CH_4 to tracer concentrations multiplied by the tracer release rate.

Figure 4. Surface Enclosure with Van Parked Downwind

CH_4 and tracer time series data were used to calculate the accumulated sum of concentrations sampled in the field. The accumulated CH_4 sum was regressed and compared to the accumulated tracer sum - where the slope was a measure of the CH_4-to-tracer ratio. The advantage of using this approach was that it minimized issues with exactly matching delay and response times of the two instruments. Additionally, it decreased errors associated with any offset in the location of the tracer release relative to the actual CH_4 source.

Ambient CH_4 concentrations were measured with either a Picarro 2301 CRDS or a UGGA CH_4 analyzer, while tracer gas was measured with the custom built continuous SF_6 analyzer. The SF_6 analyzer used a catalytic oxidation/drier flow system to remove oxygen and water from the sample stream. The typical response time was approximately one second and the detection limit was less than one part per billion volume (ppbv). All data acquired with van-mounted instruments were recorded at 10 Hz on a computer data acquisition system.

Figure 5 below shows the layout of the analyzers in the van. The front of the van was fitted with a sampling mast that held a sampling line, mounted approximately 1 meter above the ground, and the sonic anemometer was mounted approximately 2.5 meters above the ground. The sonic anemometer and GPS unit measured local wind speed, wind direction and location. The SF_6 analyzer was calibrated periodically by filling a syringe from a calibration gas cylinder and then injecting the calibration gas through a tee on the inlet to the analyzer. Diluted standard gas was used to develop a daily multipoint calibration curve.

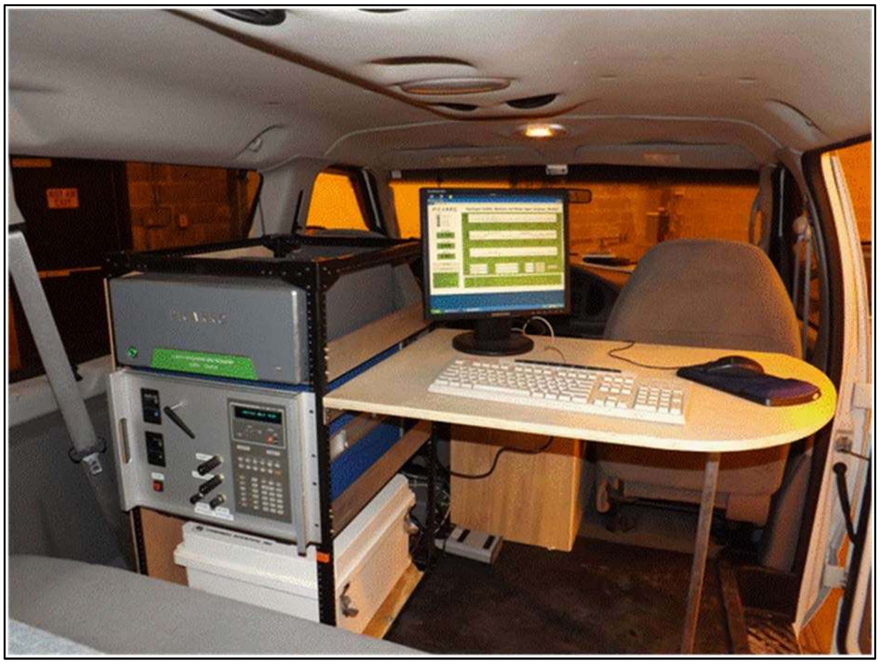


Figure 5. Layout of Instruments for Tracer Flux Measurements

2.5 Data Management Protocol and Statistical Approach

2.5.1 Data Management Protocols

During this project, GTI collected data that included sampling raw emission rates, activity data and metadata gathered during 13 industrial/commercial meter sampling campaigns, ten vintage and modern plastic pipe field campaigns, and 18 walking surveys of cured-in-place plastic lined steel and cast-iron totaling 3,057.4 meters. The sections that follow outline the procedure for how datasets were categorized within each segment studied.

Data Management - Industrial/Commercial Meters

There were 24,670 components examined across six regions, for six types of industrial/commercial meter sets (Rotary, Turbine, Diaphragm, Orifice, Ultrasonic, and Regulating Equipment), across ten different companies, and at a mix of various types of industrial and commercial facilities within the sector. Data was disaggregated into the following categories:

- Nationwide mean leaker emission estimates delineated by main meter components.
- Regional meter set emissions disaggregated by meter type.
- Regional meter set emissions disaggregated by facility type.
- Regional meter set emissions disaggregated by company.

- Regional meter set emissions disaggregated by industrial/commercial sectors.

Data Management - Modern vs. Vintage Plastic Pipe

Vintage plastic pipe was defined and categorized as being installed prior to 1986, and modern plastic pipe as installed after 1986. There were 339 potential underground leak sites screened with emission rates quantified from 186 of sites visited. Of these 186 quantified leaks, GTI was able to verify that 103 leaks were located on either modern or vintage plastic pipe with 45 leaks measured on modern plastic pipe and 58 measured on vintage pipe. Mean leak rates were disaggregated for both modern and vintage plastic pipe and delineated by region.

Data Management - Plastic Lined Steel and Cast-Iron Pipe

GTI completed walking surveys of 18 segments of cured-in-place plastic lined steel and cast-iron totaling 3,057.4 m. No leaks were found on any of the cured-in-place plastic lined steel or cast-iron segments surveyed.

2.5.2 Statistical Approach – Bayesian Methods

Bayesian methods were used for estimating the proportion as well as confidence bounds related to the number of samples falling into individual categorical emission rate bins. Posterior distribution was performed using a combinatory representation of industry information and additional measurements, which was then used as the foundation to predict dataset means and interval bounds specified by the confidence level.

Dirichlet distribution was performed to achieve a multivariate generalization of the beta distribution, which was used to describe the probability distribution of a particular categorical event falling into a particular category. In this case, the "event" was the likelihood that visiting a meter set would result in a leak rate that falls within one of the categorical bins. The form of distribution was parameterized by a K dimensional vector $\boldsymbol{\alpha} = (\alpha_1, \ldots, \alpha_k)$ (Eq. 2)

<u>Equation 2</u>

$$\boldsymbol{f(x_1, \ldots, x_k; \alpha_1, \ldots, \alpha_k) = \frac{1}{B(\alpha)} \prod_{i=1}^{K} x_i^{\alpha_i - 1}}$$

Where $x_1, \ldots, x_k$ were the probabilities in K categories (random variables) and $B(\boldsymbol{\alpha})$ was the normalization constant. Given the above probability distribution function, the marginalized distribution for random variable X_i was considered the Beta distribution (Eq. 3).

Equation 3

$$\boldsymbol{X_i \sim Beta(\alpha_i, \alpha_0 - \alpha_i)}$$

Where $\alpha_0 = \sum_i^K \alpha_i$. Therefore, the mean and variance of random variable X_i could be obtained using Eq.4 and Eq. 5.

Equation 4 and Equation 5

$$\boldsymbol{E(X_i) = \frac{\alpha_i}{\alpha_0}}$$

$$Var(X_i) = \frac{\alpha_i(\alpha_0 - \alpha_i)}{\alpha_0^2(\alpha_0 + 1)}$$

Where $E(X_i)$ is the mean probability estimation for category $\boldsymbol{i}$ and $V\boldsymbol{ar(X_i)}$ is the corresponding variance.

For the purposes of this project, the Bayesian distribution statistics were primarily computed using Equations 4 and 5 above. However, Dirichlet distribution is a conjugate prior of multinomial distribution. This means that the Dirichlet prior distribution can be updated using the data from a multinomial distribution to generate a Dirichlet posterior distribution.

As such, if we assume the multinomial distribution is expressed as Eq. 6,

Equation 6

$$\boldsymbol{f(N_1, \dots, N_k; x_1, \dots, x_k; n) = \frac{n!}{\prod_{i=1}^K N_i!} x_i^{N_i}}$$

Where $N_1, \dots, N_k$ mean the number of occurrences for events in category 1,…,K and $n = \sum_i^K N_i$, then the posterior distribution would be a Dirichlet distribution parameterized as below (Eq. 7).

Equation 7

$$\boldsymbol{f(x_1, \dots, x_k; \alpha_1 + N_1, \dots, \alpha_k + N_k) = \frac{1}{B(\alpha + N)} \prod_{i=1}^{K} x_i^{\alpha_i + N_i - 1}}$$

Therefore, the marginalized distribution of a random variable X_i could be expressed as shown in Eq. 8:

Equation 8

$$\boldsymbol{X_i \sim Beta(\alpha_i + N_i, \alpha_0 - \alpha_i + n - N_i)}$$

Different from calculating the probability directly from collected data, using the Bayesian method achieves a balance between the prior belief and additional measures (such as a new dataset from field sampling). This method helps to minimize uncertainty that can occur by imposing too much confidence on the collected field data. Confidence bounds created using the above Bayesian approach provides more information than a single mean value and is intrinsically included in the posterior distribution.

3 Industrial/Commercial Meter Emissions Analysis and Results

3.1 Nationwide Component Emissions

Of the 25 field campaigns performed for this project, 13 were focused on industrial/commercial meters with sampling locations spanning all six U.S. regions – each of which were three-to-five days in duration. Ten of these 13 campaigns were at original sites, while three campaigns involved re-visiting sampling sites at three host LDCs. The analysis in this section will focus on individual emissions quantified on an individual component basis, while all later sections will focus on *meter set* emissions, where all the individual component fugitive emissions at each meter set were summed to obtain a single leak rate for that meter set (see section 2.2.2 for meter set definitions).

During this project, GTI quantified 458 individual component emissions across specific component classes nationwide - with one category (Other) that detailed any components not included in the component count yet exhibited a quantifiable leak (Table 3).

Table 3. Individual Component Types Scanned within Main Component Categories

Component Name	Component Count	Leak Indications	Quantifications	Percentage Leaking
Cap	424	22	6	5.19%
Coupling	3,030	131	43	4.32%
Elbow	3,261	160	50	4.91%
Flange	5,588	298	58	5.33%
Meter	612	25	11	4.08%
Other		205	75	
Plug	3,458	132	35	3.82%
Pneumatic Device	3	1	1	33.33%
Regulator	1,199	104	42	8.67%
Tee	1,310	71	7	5.42%
Valve	5,785	325	130	5.62%
Total	24,670	1,474	458	

Approximately 5.1% of all components within the ten main, nationwide component categories were found to have a leak indication (calculated as [(1,474-205)/24,670]x100). Table 3 shows that percentages of scanned components with leak indications ranged from 3.82% for plugs to 5.62% for valves nationwide.

3.1.1 Nationwide Component Leaker Emission Rates

Nationwide component leaker emission rates were calculated based on quantified emissions exclusively from individual leaking components - not the entire component population. This means that the analysis in this section does not include components that were not found to be leaking.

The mean leaker emission rate for components with fugitive emissions was 10.29 ± 32.5 g CH_4 h^{-1}, as indicated by the red line in Figure 6 below. The median leaker rate (indicated by the purple line) was 0.593 g CH_4 h^{-1} and the mode (indicated by the blue line) was 0.0046 g CH_4 h^{-1}. Note that leaker emission rates were “heavy-tailed” as detailed in Brandt et al., (2016), and heavily right-skewed with the mean far larger than (or to the right of) the medians and modes of the data. This was due to the influence imposed from a relative few, yet large leaks.

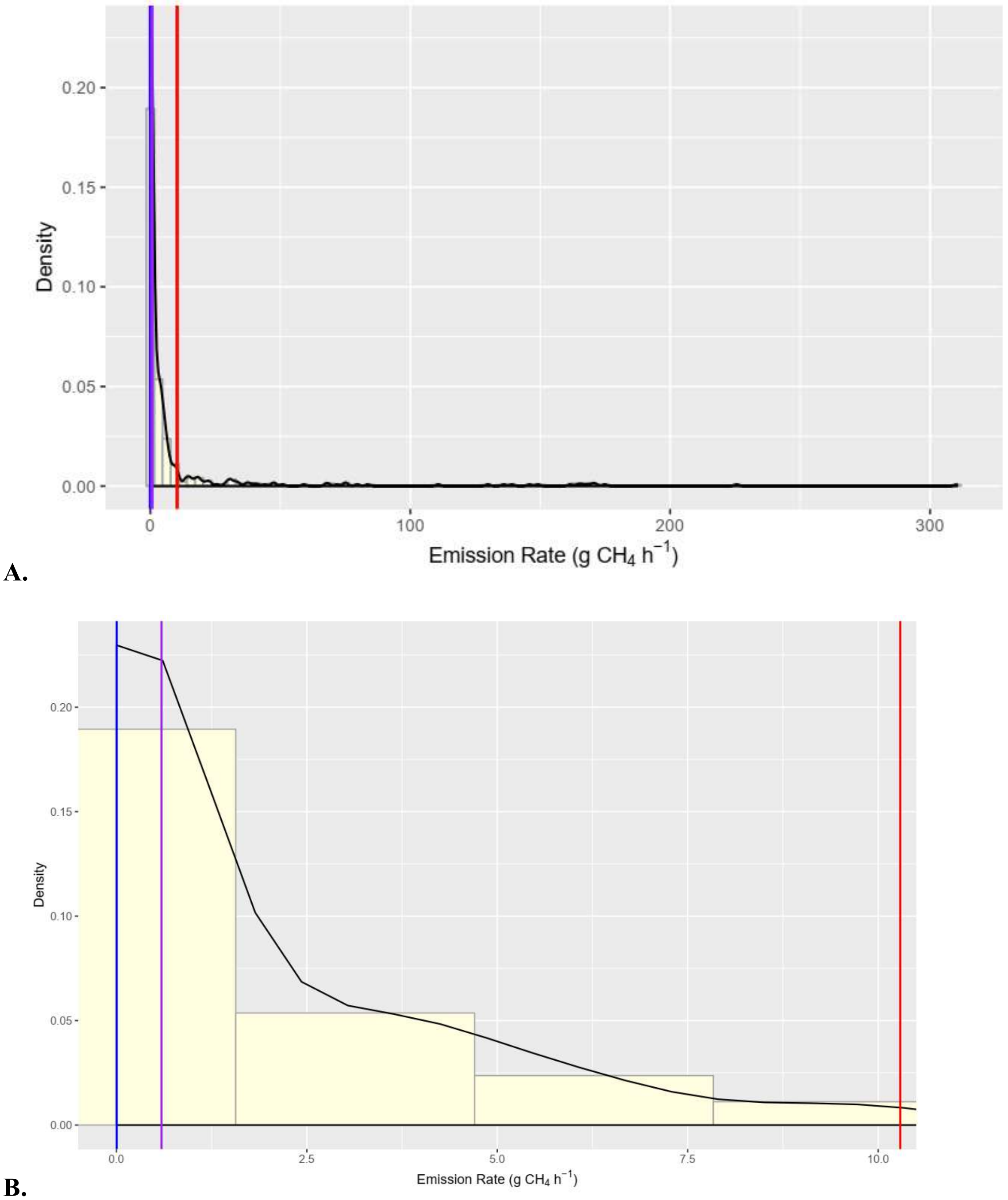


Figure 6. Histogram and Density Plot of Leaker Emission Rates from all Quantified Leaks.

Figure 6A shows the entire dataset and Figure 6B shows the histogram zoomed to between 0 and 10 g CH_4 h^{-1}.

To further demonstrate the "heavy-tailed" nature of the distribution, we examined the cumulative distribution of the quantified leaker rate emissions data in Figure 7. The blue line in Figure 7 shows the percentage of measured leaking components that contributed to the overall total emissions. The red line is a marker to indicate the area of the graph below which 80% of emissions occurred. The point where the red and blue lines cross shows the percentage of total quantified leaks (9% of the leaker population) that contributed 80% of the total emissions for this data set. More specifically, 80% of emissions came from 42 of 458 quantified leaks. This skewed "heavy-tailed" distribution was detailed in Brandt et al., (2016) and is often referred to as a "fat-tailed" distribution or "super-emitters" (Figure 8).

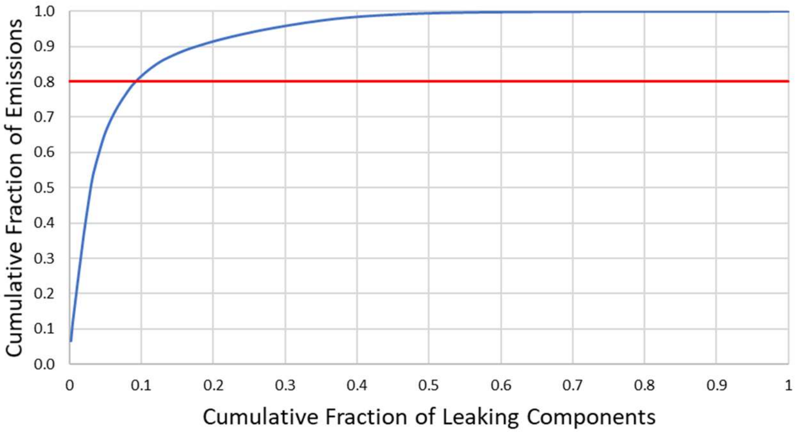


Figure 7. Cumulative Distribution of Measured Leak Rates

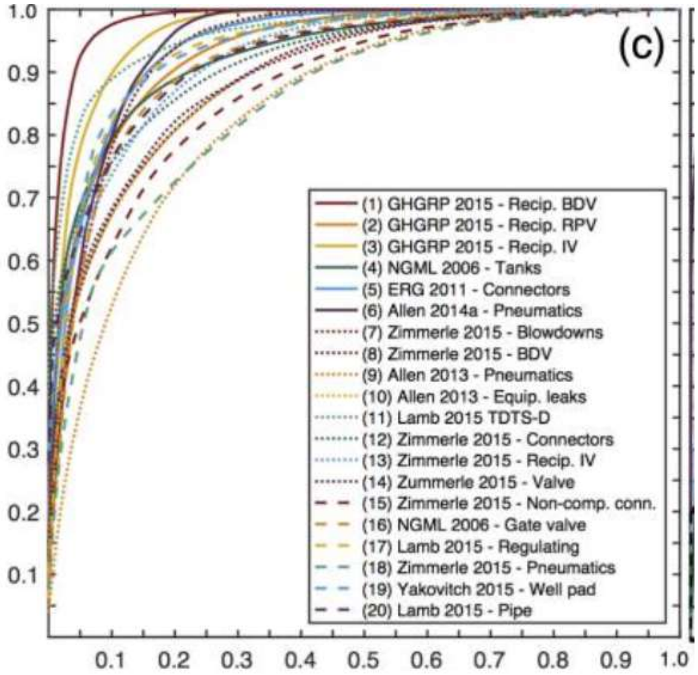


Figure 8. Heavy-Tailed Distributions from 20 NG Emission Studies from Brandt et al. (2016).

The spread of the quantified emission rates for each component type can be observed (Figure 9). The box and whisker plot shows the measured emission rates for each component type as black dots above the component name. The median emission rate for each component is the black horizontal line within the light blue boxes, and the upper and lower edges of the blue boxes indicate first and third quartiles (or the inner quartile range, IQR). The "whiskers" represent data that fell within 1.5 times the IQR and the data points plotted beyond the end of the whiskers were considered outliers. Although the data is quite skewed, only one data point for caps, three for couplings and four for elbows were considered true individual component emission outliers.

Several particularly high individual component emission rates can be seen on the $\log_{10}$ y-axis of Figure 9. The highest emission rate for the entire data set is 310.3 g CH_4 h^{-1} on a flange. This flange was located in the southeast region on a turbine meter at an industrial facility along with five other small leaks at the meter set. This leak was therefore likely influencing the mean emissions for those categories. Field crews did not mention anything extraordinary about this particular leak or meter set that may indicate why this component was leaking more than any other. The next highest emission rate (226.1 g CH_4 h^{-1}) was on a component in the "other" category in the Southwest region on a diaphragm meter. This was a unique leak as a small pinhole had formed directly on the piping where the pipe came out of the ground. Overall, four of the five largest individual component emission rates were on turbine meters and three of the five largest emission rates occurred in the Southwest region.

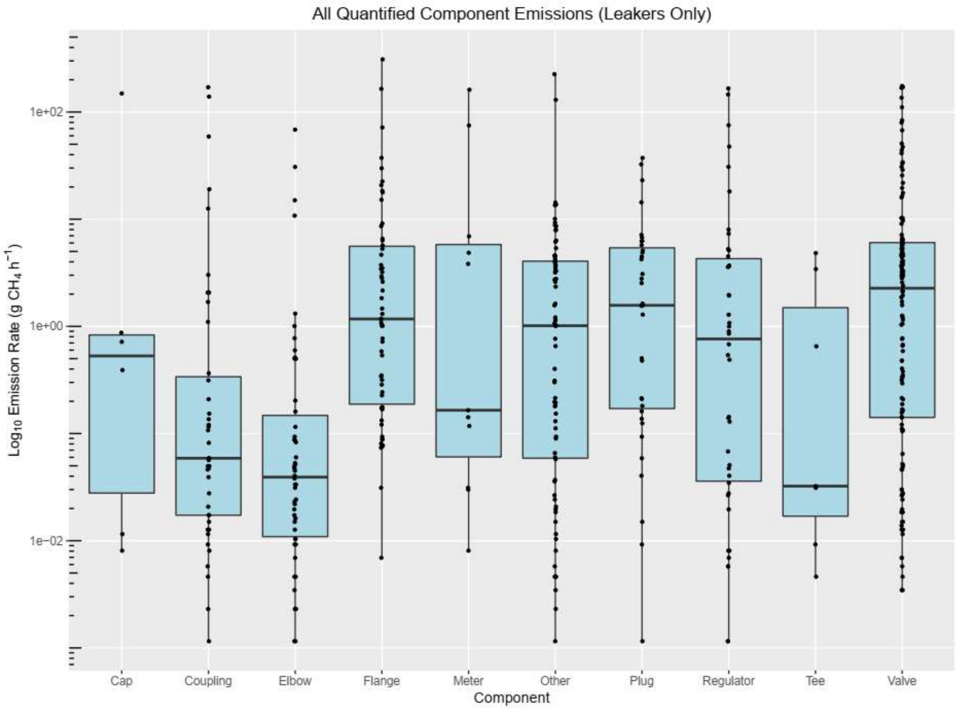


Figure 9. Box and Whisker Plot of Individual Component Emission Rates (Leakers-Only)

Figure 10 below highlights the impact that the extreme spread in the data had on calculated means and standard deviations. For example, an obvious upward pull of the mean emission rate was imposed by a single high emitting outlier observed on the “Cap” component. This impacted the mean data and moved the mean emission rate size of Caps to larger than mean emission rate for Flanges, which had more, higher emitters than Caps.

Figure 10 also shows a comparison of mean emission rates for quantified and modeled data by component type. The mean leaker-only emission rates are shown in bold. The error bar represents one standard deviation above the mean. As discussed in Section 2.3.3, the modeled leaks were for leak indications that were not quantified and were based on the small leaks that were measured with leak indications between 100 ppm and 22,500 ppm. Because of the small nature of the modeled leaks coupled with the larger sample size, leaker emission rates calculated using the modeled leaks were notably lower than the leaker emission rates calculated using only the larger “Quantified Only” leaks. Detailed statistical summary tables can be viewed in Section 8.4 Appendix – Component-Based Data Statistical Summary Tables. The standard deviations of the data are often three to five times higher than the mean emission rate.

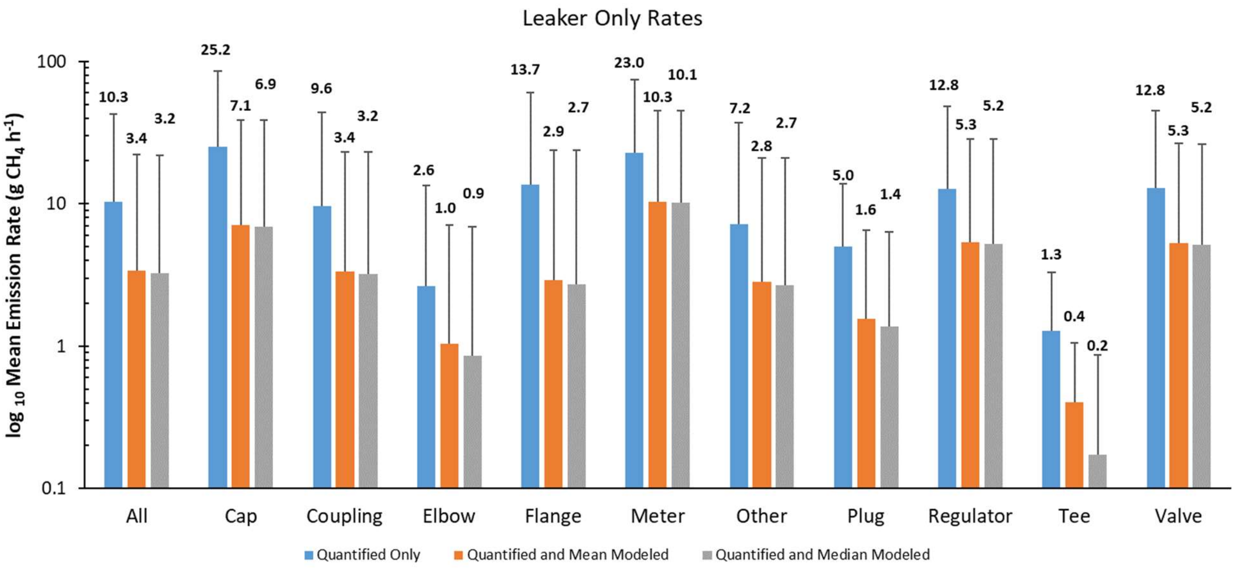


Figure 10. Mean Component-Based Leaker Rates (log$_{10}$ y axis)

3.1.2 Nationwide Emissions for All Components

Figure 11 shows the mean emission rate if calculated for the entire population of components sampled. This method of calculation assumes that all components without a leak indication had an effective leak rate of zero (e.g., when calculating means, the total emissions are divided by the total number of components scanned). For example, the "Quantified Only" bar, includes the total emissions from only leaks that were quantified divided by the total number of components scanned. When calculated in this fashion, the small impact of the non-quantified leaks on the overall population emission rate and factor calculations becomes clear. When small leaks were included by using modeled mean or median data there was very little difference in the overall emission rate per component as can be seen in Figure 11. Detailed statistics can be viewed in Section 8.4 Appendix – Component-Based Data Statistical Summary Tables.

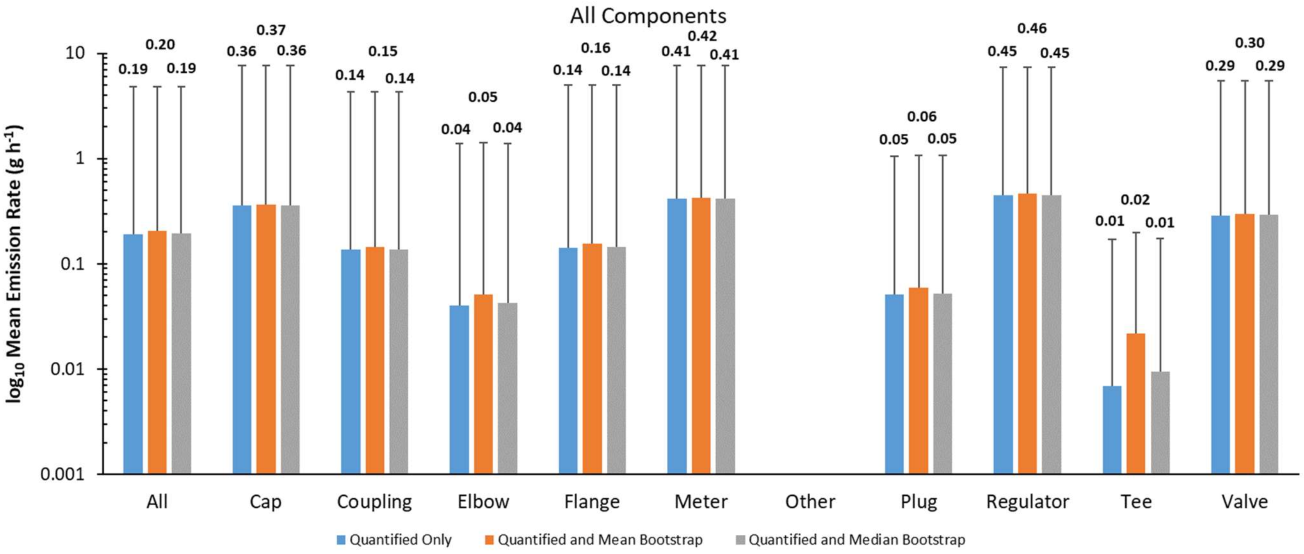


Figure 11. Mean Emission Rates for all Components within the Population

Both Figure 10 and Figure 11 highlight the differences in emission rates by components. The population mean emission rates for Tees were lowest for all component types, due to smaller mean emission rates averaged over 1,310 components scanned. The highest mean population emission rates were found to be from the meter bodies themselves due to a few larger leaks quantified on a small population (612). It is important to note, however, that the "heavy-tailed" nature of the overall distribution of the data and the data distributions within component categories creates a limitation in our ability to find statistically significant differences between components.

In Canada, component EFs are used to calculate national emissions. Companies are required to report components rather than meter set number. To put these measurements into perspective with what is used in Canada, Figure 12 shows the per component population and leaker-only EFs. Annual EFs were calculated by scaling up the mean emission rates to annual estimates per component. This is a method that GTI recommends for future estimates in the GHGI. Use of a component level EFs would greatly improve the accuracy of the GHGI estimates and allow for more in-depth weighting of leaks.

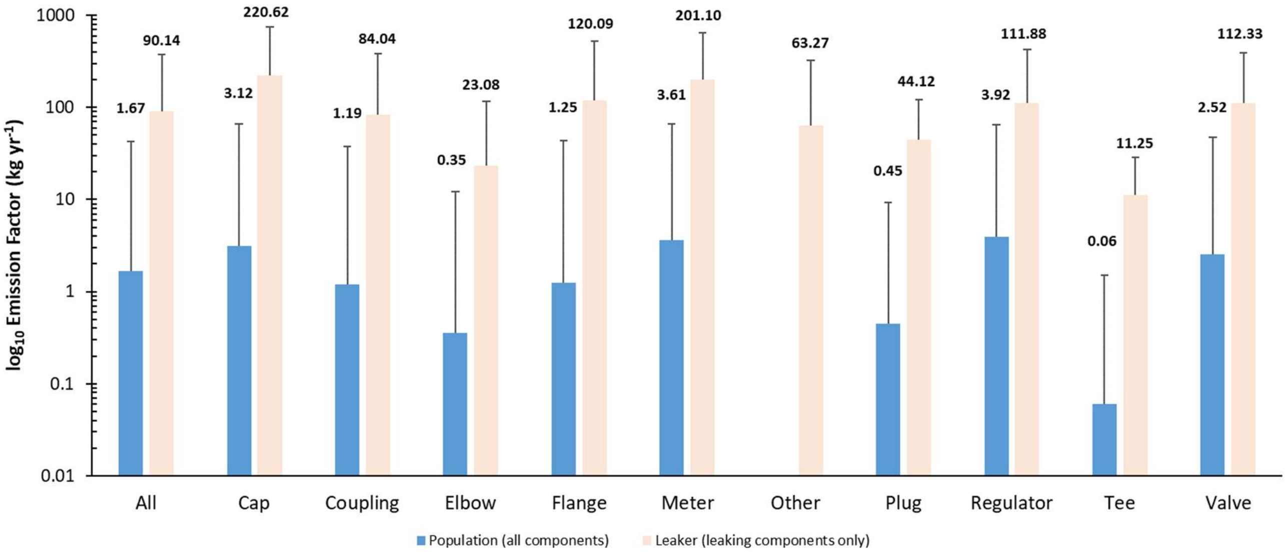


Figure 12. Component Population Annual EFs

3.2 Regional Meter Set Emissions

3.2.1 Meter Set Counts

The primary purpose of this project was to examine CH_4 emissions from entire meter sets. Therefore, the focus will stay on meter set emissions for the remainder of the report. As described in Section 2.2, the U.S. was divided into six regions and sampled based on the percentage of industrial customers located within each of those regions. Regional sampling for both commercial and industrial meters was weighted according to 2015 EIA data on industrial customers by region (Table 4).

Table 4. Total Number of Meter Sets Scanned by Region Compared to Regional EIA Data

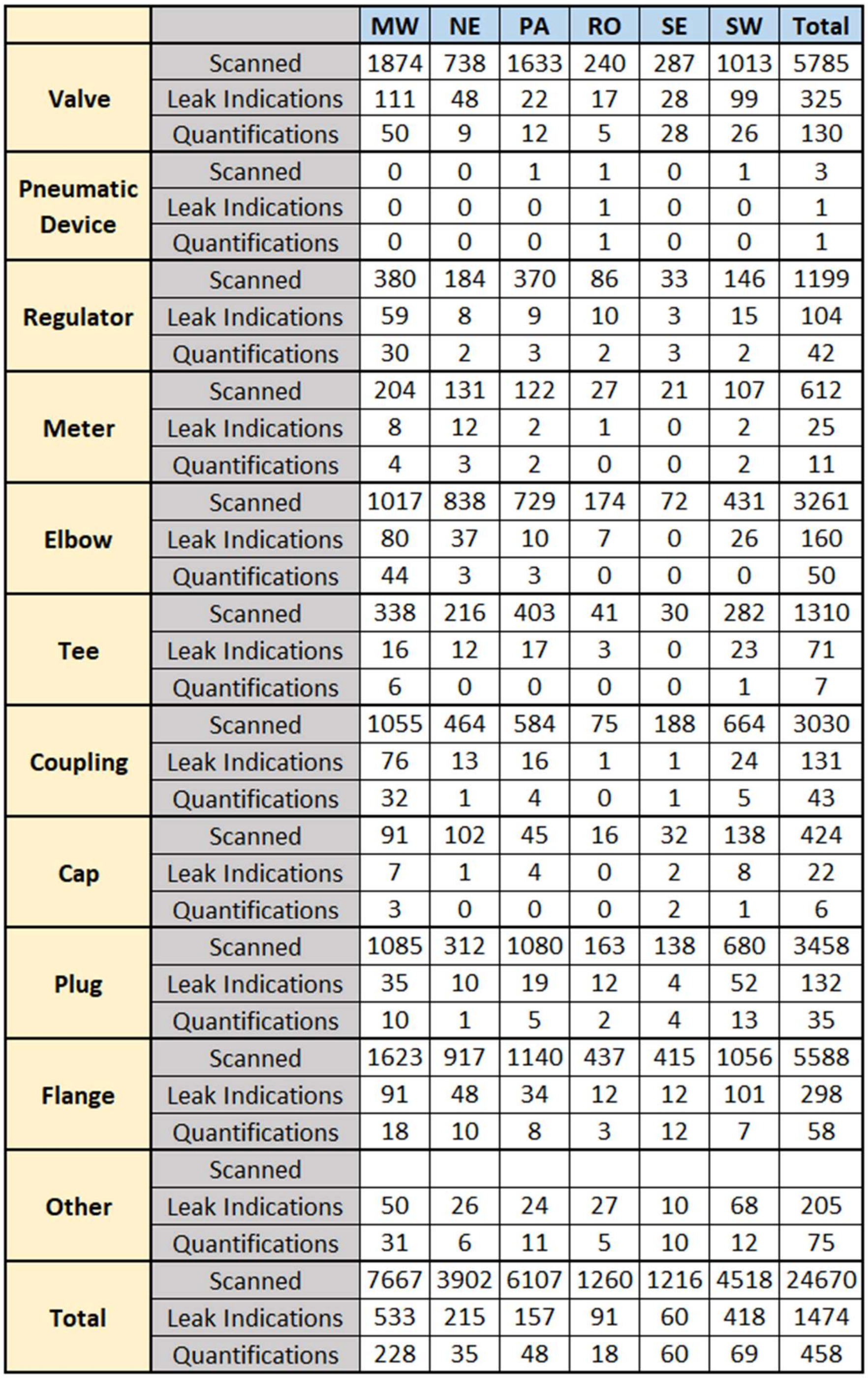
Region	Meter Sets Sampled	Meter Sets With a Leak Indication	Meter Sets with a Quantifiable Leak	Percent of Industrial Customers by Region (EIA 2015)	Percent of Samples by Region (this study)
Midwest (MW)	176	148	93	39.0%	33.7%
Northeast (NE)	88	74	26	18.6%	16.8%
Pacific (PA)	115	85	37	22.0%	22.0%
Rocky (RO)	21	20	9	4.9%	4.0%
Southeast (SE)	20	19	19	10.1%	3.8%
Southwest (SW)	103	93	41	5.4%	19.7%
Total	523	439	225	100.0%	100.0%

The Midwest region had the highest number of meter sets sampled, followed by the Pacific and Southwest regions. Also shown in Table 4, are the number of meter sets with leak indications and the number with a quantifiable leak. A total of 84% of meter sets visited had small leak indications, which was any leak indication above 100 ppm. As discussed in Section 3.1.2, not all leaks with an indication concentration above 100 ppm received an emission rate quantification. A quantifiable leak, which was a leak large enough to quantify depending on the threshold being used, was found on 43% of meter sets screened.

Table 5 shows the number of components scanned in each region for the ten main component types. The total number of components scanned were the highest in the Midwest and Pacific regions which corresponded to those regions having the greatest number of meter sets sampled. Out of all components scanned, the number of leak indications greater than 100 ppm varied from region to region with the Midwest and Southwest regions having the most leak indications, corresponding with those regions having the largest number of samples. The Pacific region, however, had the second highest number meter sets sampled but only the fourth highest number of leak indications. This was consistent with the Pacific region having the lowest number of leak indications per meter set of 1.36, followed by the Northeast (2.44 indications per meter set), Southeast (3.00), Midwest (3.03), Southwest (4.05), and Rocky (4.33).

Table 5 also shows the number of leaks quantified in each region by component type. By far, the largest number of meter set emission rates were quantified in the Midwest region, consistent with the highest number of components scanned and leak indications. The 228 leaks quantified in the Midwest region meant that 42% of leak indications were quantified, this was due to several measurement campaigns being conducted in the Midwest, with some campaigns using the 100 ppm threshold and some using the 22,500 ppm threshold. In contrast, the Southeast region had 100% of leak indications quantified due to only one campaign in that region, which used the 100 ppm leak indication threshold, thus quantifying all leak indications in that region.

Table 5. Components Scanned, Leak Indications, and Leak Rates Quantified by Region



		MW	NE	PA	RO	SE	SW	Total
Valve	Scanned	1874	738	1633	240	287	1013	5785
	Leak Indications	111	48	22	17	28	99	325
	Quantifications	50	9	12	5	28	26	130
Pneumatic Device	Scanned	0	0	1	1	0	1	3
	Leak Indications	0	0	0	1	0	0	1
	Quantifications	0	0	0	1	0	0	1
Regulator	Scanned	380	184	370	86	33	146	1199
	Leak Indications	59	8	9	10	3	15	104
	Quantifications	30	2	3	2	3	2	42
Meter	Scanned	204	131	122	27	21	107	612
	Leak Indications	8	12	2	1	0	2	25
	Quantifications	4	3	2	0	0	2	11
Elbow	Scanned	1017	838	729	174	72	431	3261
	Leak Indications	80	37	10	7	0	26	160
	Quantifications	44	3	3	0	0	0	50
Tee	Scanned	338	216	403	41	30	282	1310
	Leak Indications	16	12	17	3	0	23	71
	Quantifications	6	0	0	0	0	1	7
Coupling	Scanned	1055	464	584	75	188	664	3030
	Leak Indications	76	13	16	1	1	24	131
	Quantifications	32	1	4	0	1	5	43
Cap	Scanned	91	102	45	16	32	138	424
	Leak Indications	7	1	4	0	2	8	22
	Quantifications	3	0	0	0	2	1	6
Plug	Scanned	1085	312	1080	163	138	680	3458
	Leak Indications	35	10	19	12	4	52	132
	Quantifications	10	1	5	2	4	13	35
Flange	Scanned	1623	917	1140	437	415	1056	5588
	Leak Indications	91	48	34	12	12	101	298
	Quantifications	18	10	8	3	12	7	58
Other	Scanned							
	Leak Indications	50	26	24	27	10	68	205
	Quantifications	31	6	11	5	10	12	75
Total	Scanned	7667	3902	6107	1260	1216	4518	24670
	Leak Indications	533	215	157	91	60	418	1474
	Quantifications	228	35	48	18	60	69	458

3.2.2 Meter Set Emission Rates and EFs by Region

Individual meter set emission rates were calculated by summing all measured emission rates from each individual leaking component at a particular meter set to determine a total emission rate that meter set. Then, emissions from each meter set were summed to determine meter set emissions by region. When combined to obtain a regional meter set emission rate, the largest meter set leaks have the potential to significantly impact overall emission rates. As shown in Figure 13, mean meter set emission rates, like individual component meter set emission rates, were right-skewed and heavy tailed, with a few large emission rates heavily influencing mean emission rates.

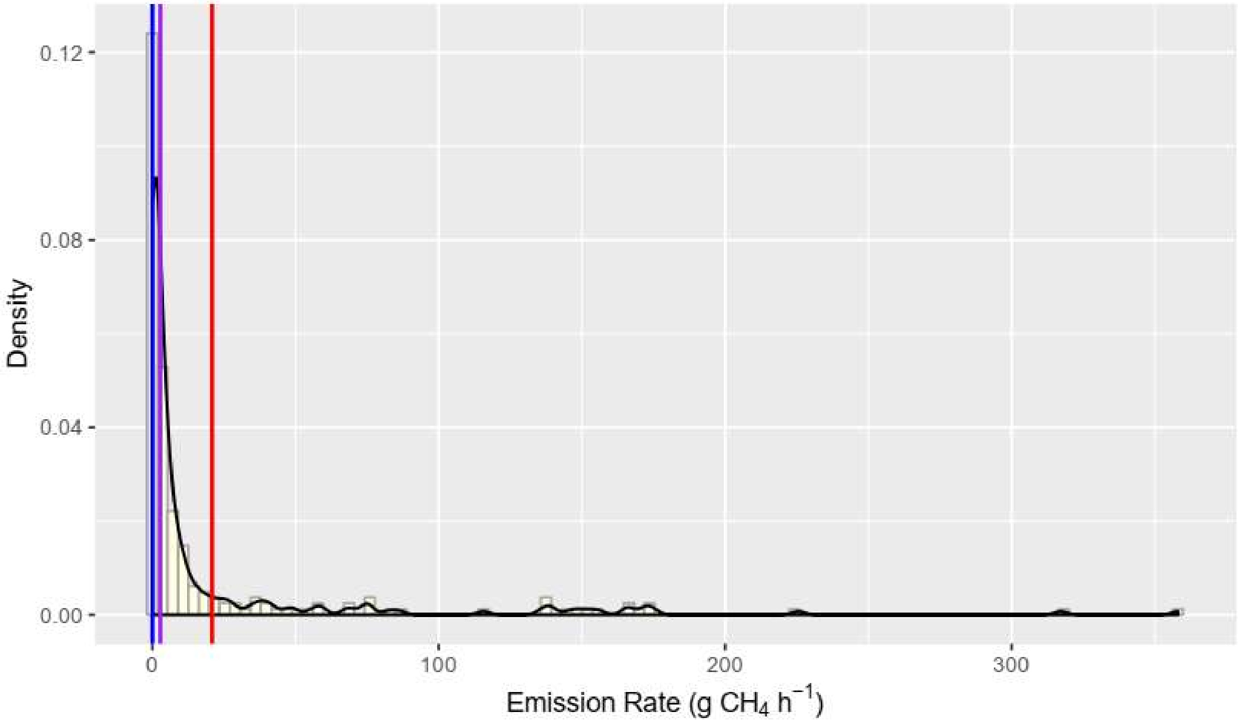


Figure 13. Distribution of Meter Set Emission Rates

The heavy-tailed distribution meant that a limited number of meter sets were driving overall emissions from this category. Specifically, 30 of the 225 meter sets (13.3%) with a quantifiable leak contributed 80% of emissions. The contribution of meter sets to emissions can be seen in Figure 14.

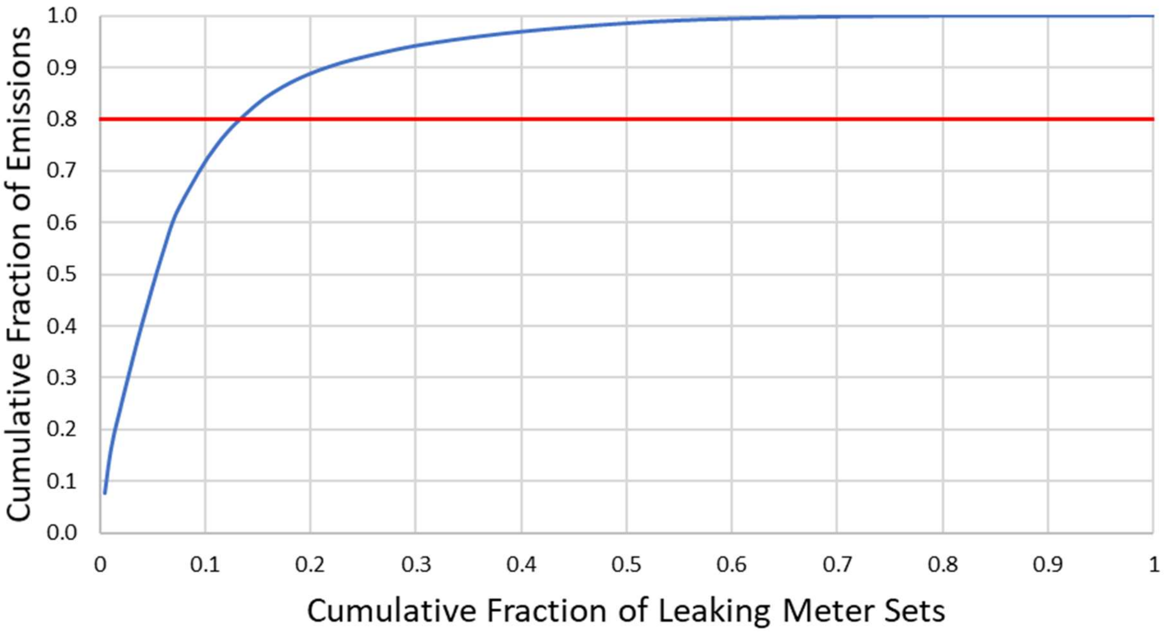


Figure 14. Cumulative Fraction of Leaking Meter Sets Contributing to Emissions.

Meter set emissions had a slightly larger range of emissions than the individual component emissions as can be seen in Figure 15. This was due to the summation of all quantified individual component emissions to obtain each individual meter set emission rate. The highest emitting meter set was 358.1 g CH_4 h^{-1} which was the combination of three quantified leaks at a turbine meter set in the Southwest region. The second highest emitting meter set (317.2 g CH_4 h^{-1}) was a turbine meter in the Southeast that included the highest emitting component along with five other small leaks. Four of the ten highest emitting meter sets were in the Southwest region, which is potentially due to differences in company practices in this region such as longer times between leak surveys. The only other region with an emission rate in the top five was the Southeast. The Northeast had one and the Rocky region had two individual meter set emission rates in the top ten.

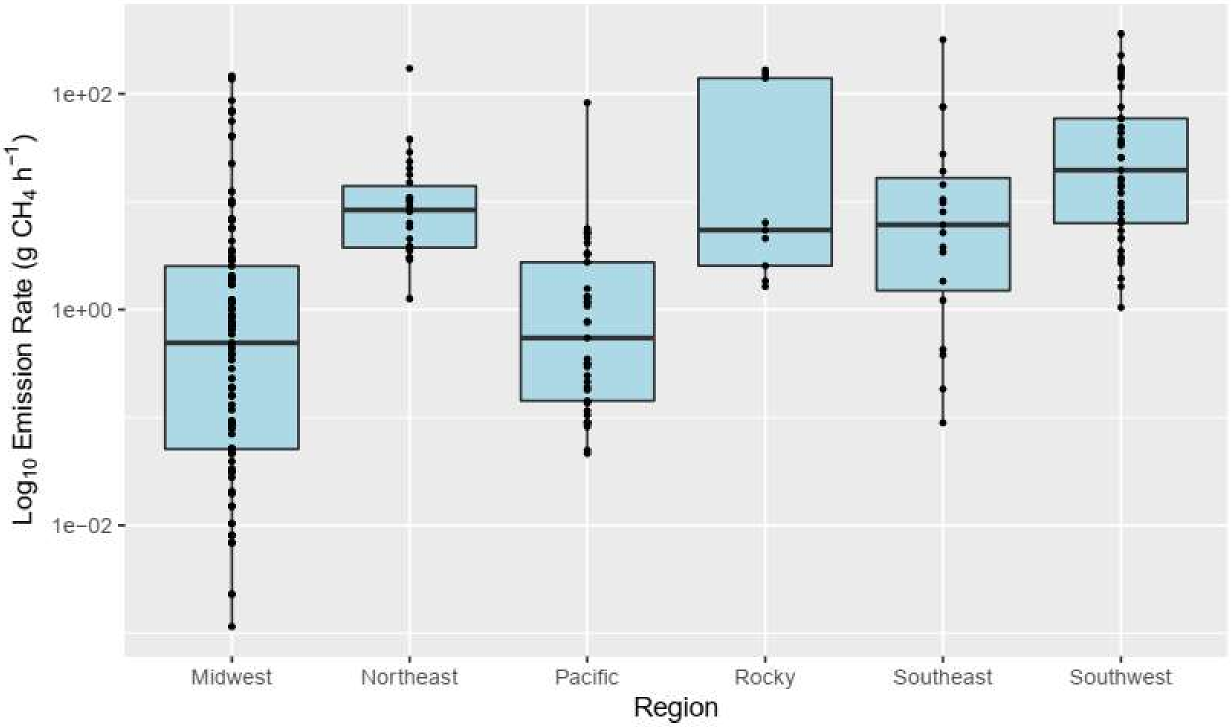


Figure 15. Box and Whisker Plot of Meter Set Emission Rates by Region

In Figure 16, the effect of adding the smaller, modeled leaks can be seen to cause only minor increases in the overall emission rates for meter sets. For example, the mean population emission rate for all meter sets nationwide (All), using the quantified-only emission rates was 9.00 ± 34.4 g h^{-1}. Adding the modeled small leaks only raised the mean population emission rate to 9.61 ± 34.5 g h^{-1}. This small difference highlights that the large leaks had the greatest potential to drive overall emissions since the addition of small, non-quantified leaks did not significantly change the calculated mean population emission rate or the standard deviation (34 g h^{-1}). Because of this, the remainder of the report will focus on leak rates estimated directly from field measurements only. An important assumption to reiterate is that for the mean population meter set emission rates, smaller leaks that were considered non-quantifiable were assumed to add insignificant emissions to the total emissions from an individual meter set. Therefore, if a meter set had no quantifiable leaks, then the emission rate for that meter set was assumed to be zero.

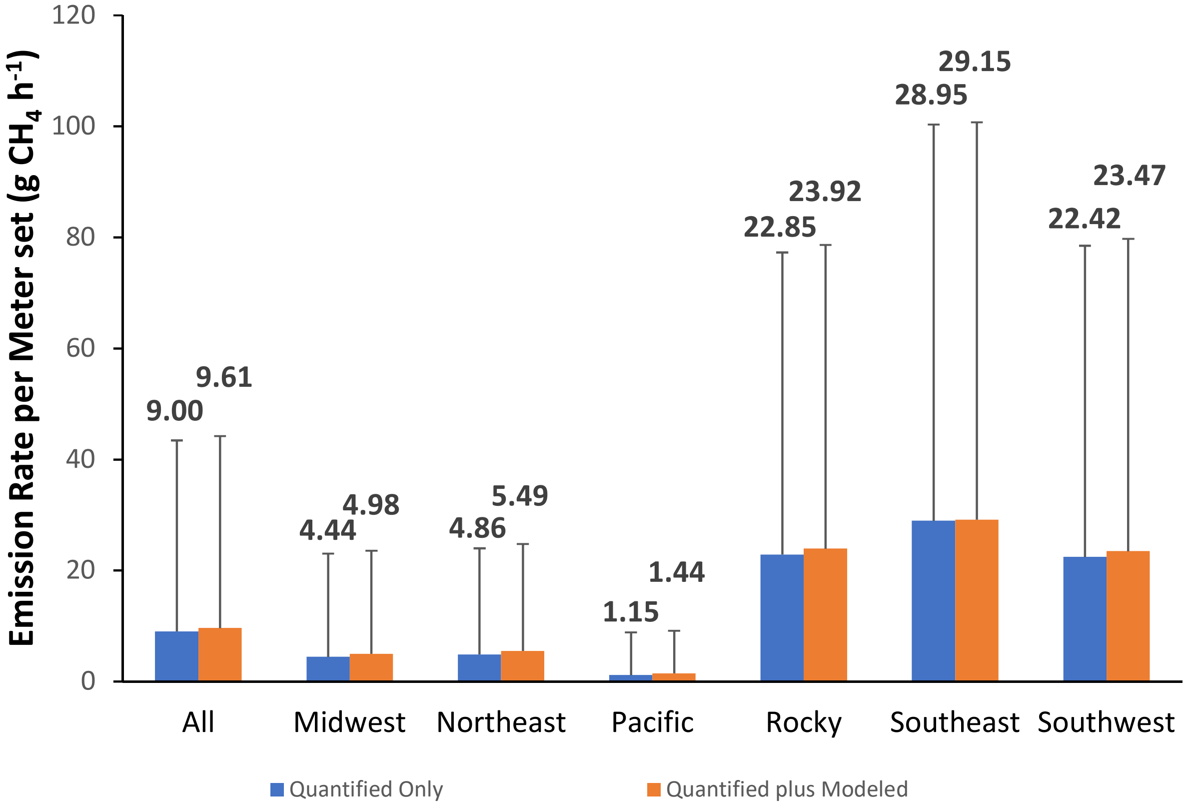


Figure 16. Mean Population Meter Set Emission Rates by Region

Figure 16 also reveals differences in mean leak rates by region. Due to the skewed distributions of data, normal parametric statistics do not apply. Therefore, to examine differences in emissions by region, Bayesian statistics were used, which are discussed in Section 3.2.4 below.

Combining all meter sets (including those with zero emissions) into a single mean leak rate may not be the most ideal way to represent emissions. However, the analysis was designed in this way to conform closely to EPA methods for EF development in the GHGI. For example, the EPA currently uses a single activity factor (the number of commercial and industrial customers from the EIA dataset) to multiply by a single per meter set emission rate on a per year basis to determine annual national methane emissions from industrial/commercial meters. Figure 17 shows the mean leak rate per meter set – scaled to an annual population EF by region. The mean population EF calculated from the mean per meter set emission rate for all industrial/commercial meters sampled nationwide was 79 ± 301 kg year^{-1} meter set^{-1}. The current EF used in the EPA GHGI is 9.7 kg year^{-1} meter set^{-1} for industrial/commercial meter sets.

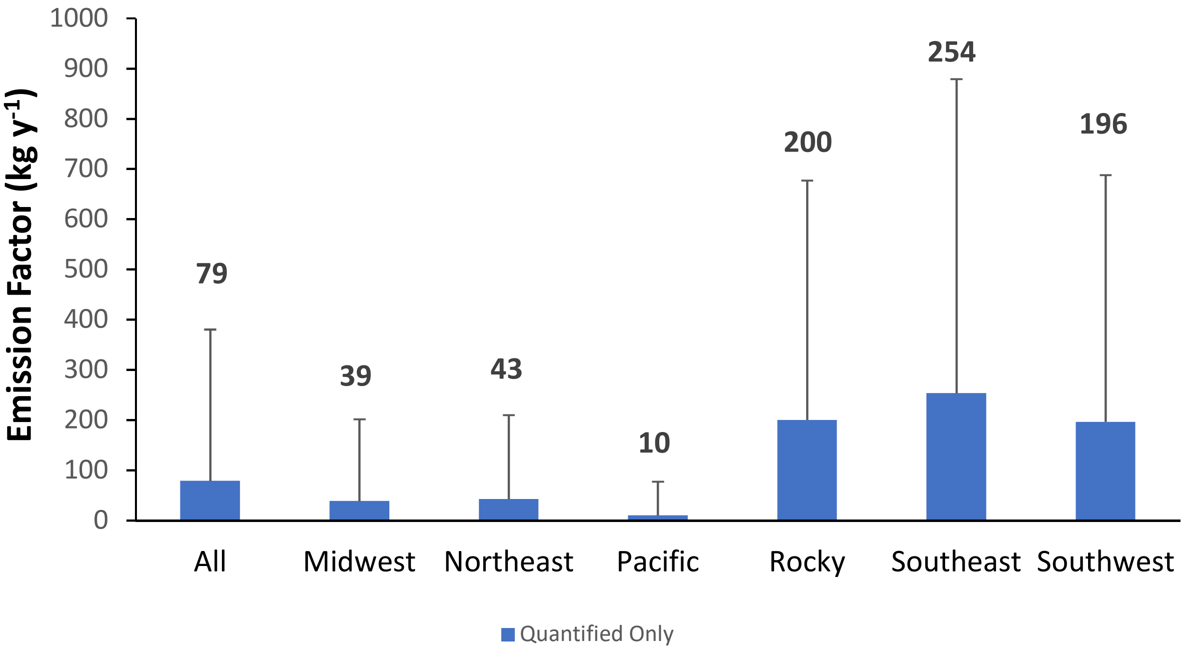


Figure 17. Meter Set population EFs by Region

The calculated population EFs for industrial/commercial meter sets sampled in this project were consistent with higher EFs found in a previous OTD study (OTD, 2009) which suggested that commercial meters had an EF of 9.7 kg year^{-1} meter set^{-1} and industrial meters had an EF of 3,910 kg year^{-1} meter set^{-1}. When EPA updated meter set EFs in 2016 based on feedback they received, they elected to use the lower "commercial only" EF to apply to the broader industrial/commercial meter category. However, our study indicates that this combined industrial/commercial meter EF may be low.

3.2.3 Total Meter Set Leaker Rates and Leak Factors by Region

Despite the incorporation of total population EFs in the EPA GHGI, leaker-only rates or leaker-only EFs may be a more accurate way of representing emissions data from a category of NG components. Since instruments are not capable of measuring a true "0" emission rate, leaker factors use only the emissions that can be quantified. Use of these rates to calculate large scale emissions require a different type of activity factor. Instead of using the entire population of industrial/commercial meters, only the number of meters with a quantifiable leak can be applied to the leaker factors. These leaker-only rates and factors are higher than a factor that gets applied to an entire population.

As discussed in Section 3.2.1, the number of meter sets with a quantifiable leak was 225 (43%) of the total 523 meter sets sampled (Table 4). A leaker factor only then gets applied to 43% of the overall population. Also, for this data set, the leaker factors were 43% higher than the EFs, resulting in similar total emission estimates if scaled up to nationwide total emissions. Thus, if seeking a more accurate representation of measurements when scaling up to the nationwide estimates, using leaker factors is recommended.

The mean emission rates for meter sets varied among the regions (Figure 18). The lowest mean emission rates for both the entire population of meter sets as well as leakers only were found in the Pacific region. On the contrary, higher population-level emission rates as well as leaker rates were observed in Rocky, Southeast, and Southwest regions. The potential causes for these differences are further discussed in the sections that follow (3.2.4 and 3.3.3). For example, the larger number of turbine meters sampled in the Southeast region could be a partial cause for the higher emission rates observed in that region. Another possibility could include different leak identification and repair procedures for finding and fixing industrial/commercial meter set leaks for different regions (and individual companies).

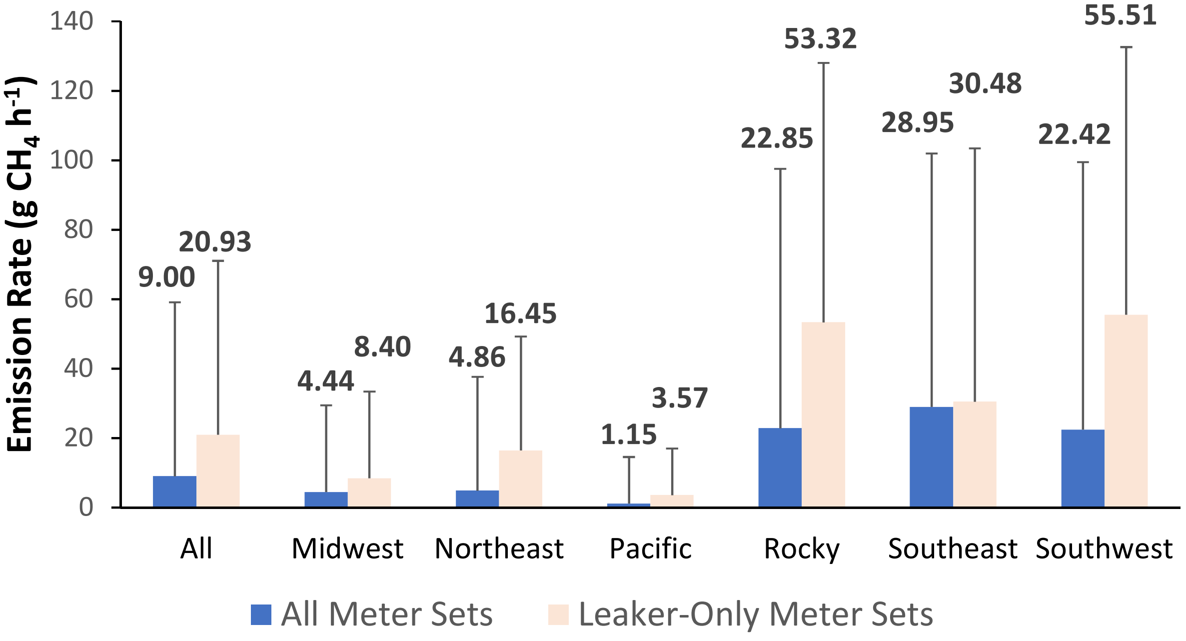


Figure 18. Comparison of Leaker Emission Rates with Population Emission Rates by Region

The differences in mean population and leaker-only emission rates carried through to the calculation of regional EFs as shown in Figure 19. The low mean population emission rates for the Pacific region (10.5 ± 67.6 kg CH_4 y^{-1} meter^{-1}) was similar to that currently used by EPA in the GHGI (9.7 kg CH_4 y^{-1} meter^{-1}). However, other regions are more than an order of magnitude higher than what is used in the GHGI. Therefore, delineating EFs by region is recommended due to the wide range of emissions observed for both population and leaker-only meter sets.

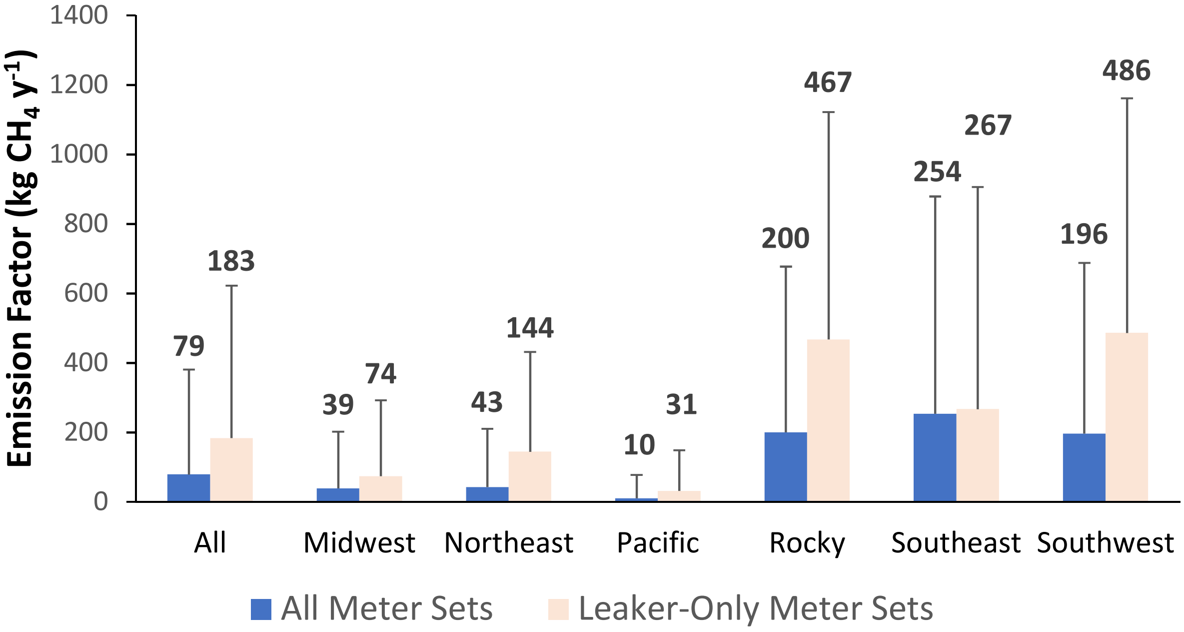


Figure 19. Comparison of Leaker Factors with Population EFs by Region

It is also important to note that the use of leaker factors could provide additional incentive for LDCs to focus on finding and fixing leaks. With the current single EF applied to *all* meters, the only way to reduce calculated emissions is to reduce the number of customer meters. Instead, placing the focus on leaks and leaking meters allows companies to focus on the number of leaking meters and reduce the size of leaks by removing the heavy-tailed emissions. In fact, repairing the top 10% emitting meter sets would result in a 72.5% reduction in emissions and create a need to adjust the EFs down the road. This is a very important nuance and is part of the impetus behind major NG industry initiatives such as ONE Future (https://onefuture.us/), which has pledged to have CH_4 emissions from the entire NG value chain remain below 1.0% of total production.

3.2.4 Bayesian Analysis – Probability of Leak Size by Region

Due to the skewness of the emission rate data, GTI elected to use Bayesian analysis to examine probabilistic differences in potential emission rates by region. In each of the six regions, a Bayesian analysis was performed to estimate the probability of encountering different leak sizes for a randomly chosen meter set. Different from conventional data-only approaches, Bayesian analysis incorporates a prior assumption in addition to field measurements which avoids imposing too much confidence on field collected data, especially in situations where data is limited or highly skewed.

Initially, data was binned or categorized by leak size. As stated in Section 3.1.2, field instruments were not capable of measuring true "0" emissions. Therefore, GTI used a "below quantifiable limit (BQL)" method to represent meter sets that have no leak detected or an emission rate below the quantifiable detection limit. Table 6 below lists the number of quantified leaks per region delineated into seven emission size categories. For each geographical region, probabilities of different leak size categories were modeled using the Dirichlet distribution. The number of quantified leaks for different leak sizes (i.e. BQL, BQL – 0.09, 0.09 – 0.75, 0.75 – 2.77, 2.77 – 6.11, 6.11 – 25.38, and >25.38 g CH_4 h^{-1}) constituted the basis of a multinomial distribution parameterized by each of the leak size probabilities shown in the blue column.

Table 6. Quantified Meter Set Leaks per Region by Leak Size

Emission Size	Total	Midwest	Northeast	Pacific	Rocky	Southeast	Southwest
BQL	298	83	62	78	12	1	62
BQL – 0.09	38	31	0	6	0	1	0
0.09 – 0.75	37	21	0	13	0	3	0
0.75 – 2.77	37	18	1	9	3	2	4
2.77 – 6.11	38	8	10	8	2	4	6
6.11 – 25.38	37	7	12	0	1	5	12
>25.38	38	8	3	1	3	4	19
Total	523	176	88	115	21	20	103

The Bayesian analysis process is illustrated below by taking the Midwest region as an example. Since data regarding the number of quantified leaks in individual emission rate categories was limited, it was assumed that the prior Dirichlet distribution had an ignorant prior, thus expressed as:

Equation 9

$$\boldsymbol{f(x_1, \ldots, x_k; \alpha_1 = 1, \ldots, \alpha_k = 1) = \frac{1}{B(\alpha)} \prod_{i=1}^{K} x_i^{\alpha_i - 1}}$$

Using an ignorant prior was equivalent to assuming that the leak size of a meter set falls into each of the seven emission rate categories with equal probabilities. After Bayesian updating, the expected probability for emission rates in the BQL category was:

Equation 10

$$E(X_1) = \frac{\alpha_1 + N_1}{\alpha + n} = \frac{1 + 83}{7 + 176} = 45.90\%$$

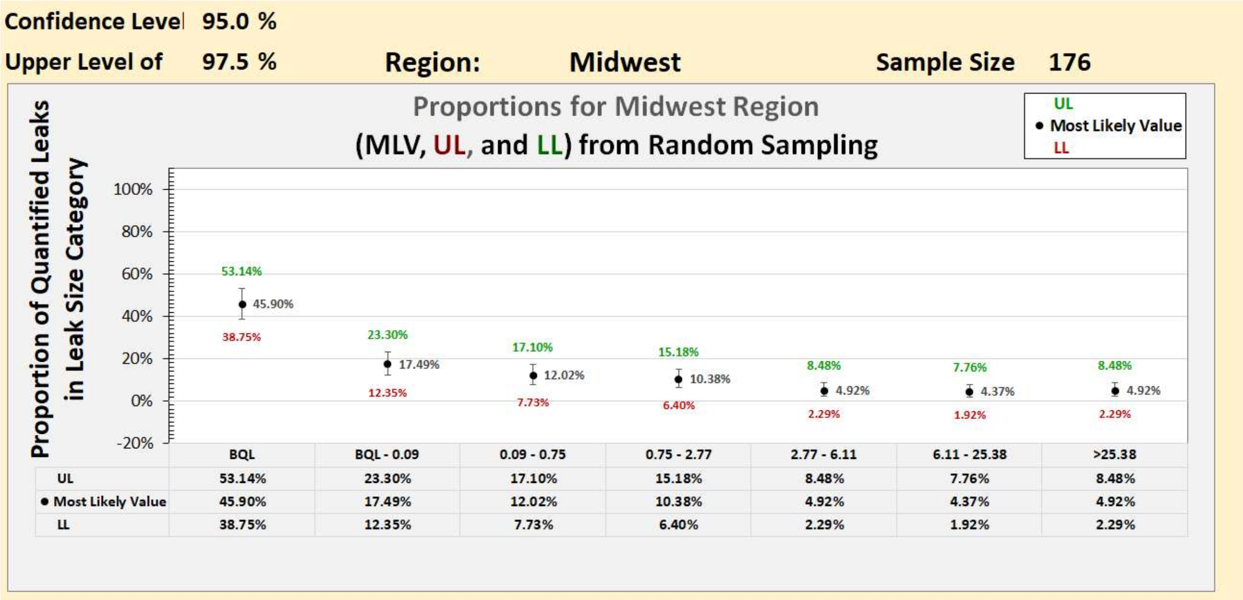
The lower and upper 95% confident bounds were computed as:

Equation 11

$$L = InverseBeta(2.5\%, \alpha_1 + N_1, \alpha_0 - \alpha_1 + n - N_1) = 38.75\%$$

$$U = InverseBeta(97.5\%, \alpha_1 + N_1, \alpha_0 - \alpha_1 + n - N_1) = 53.14\%$$

Similarly, the mean and confidence bounds were generated for the remainder of leak size categories (Figure 20).



	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	53.14%	23.30%	17.10%	15.18%	8.48%	7.76%	8.48%
● Most Likely Value	45.90%	17.49%	12.02%	10.38%	4.92%	4.37%	4.92%
LL	38.75%	12.35%	7.73%	6.40%	2.29%	1.92%	2.29%

Figure 20. Probability of Quantified Leak Sizes for Midwest region

In Figure 20, the most likely value (MLV) of 45.90% indicates that there is a 45.90% possibility that a randomly chosen meter set does not have a quantifiable leak (BQL). Likewise, 38.75% and 53.14% are the lower and upper 95% confidence bounds respectively. Probabilities of encountering various emission rates are summarized for the remainder of the regions as well as nationwide (Total) in Table 7 below. Additional details on the Bayesian method as well as upper and lower bounds for the remainder of the regions can be found in Section 8.10 Appendix - Additional Bayesian Analysis by Region.

Table 7. Bayesian Probability of Encountering a Leak Size by Region

Leak Size	Total	Probability
BQL	298	56.42%
BQL – 0.09	38	7.36%
0.09 – 0.75	37	7.17%
0.75 – 2.77	37	7.17%
2.77 – 6.11	38	7.36%
6.11 – 25.38	37	7.17%
>25.38	38	7.36%
Total	523	100%

Leak Size	Midwest	Probability	Northeast	Probability	Pacific	Probability
BQL	83	45.90%	62	66.30%	78	64.80%
BQL – 0.09	31	17.50%	0	1.10%	6	5.70%
0.09 – 0.75	21	12.00%	0	1.10%	13	11.50%
0.75 – 2.77	18	10.40%	1	2.10%	9	8.20%
2.77 – 6.11	8	4.90%	10	11.60%	8	7.40%
6.11 – 25.38	7	4.40%	12	13.70%	0	0.80%
>25.38	8	4.90%	3	4.20%	1	1.60%
Total	176	100%	88	100%	115	100%

Leak Size	Rocky	Probability	Southeast	Probability	Southwest	Probability
BQL	12	46.40%	1	7.40%	62	57.30%
BQL – 0.09	0	3.60%	1	7.40%	0	0.90%
0.09 – 0.75	0	3.60%	3	14.80%	0	0.90%
0.75 – 2.77	3	14.30%	2	11.10%	4	4.50%
2.77 – 6.11	2	10.70%	4	18.50%	6	6.40%
6.11 – 25.38	1	7.10%	5	22.20%	12	11.80%
>25.38	3	14.30%	4	18.50%	19	18.20%
Total	21	100%	20	100%	103	100%

The Bayesian analysis highlights important differences by region. For example, Table 7, when combined with the figures in Section 8.10 Appendix - Additional Bayesian Analysis by Region reveals with high confidence that the likelihood of finding either no leaks (BQL) or small leaks in the BQL – 0.09 or 0.09 – 0.75 g CH_4 h^{-1} range was greatest in the Pacific region. This observation corresponds to the lowest mean emission rates and lowest calculated EFs for that region.

For larger emissions, we can see in Table 7 that the Rocky, Southeast, and Southwest regions have the highest likelihood of finding a leak in the largest two categories of emissions 6.11 – 25.38 and >25.38 g CH_4 h^{-1}. This corresponds to these regions having higher mean emission rates and EFs. However, due to the low numbers of samples in these higher categories the figures in Section 8.10 Appendix - Additional

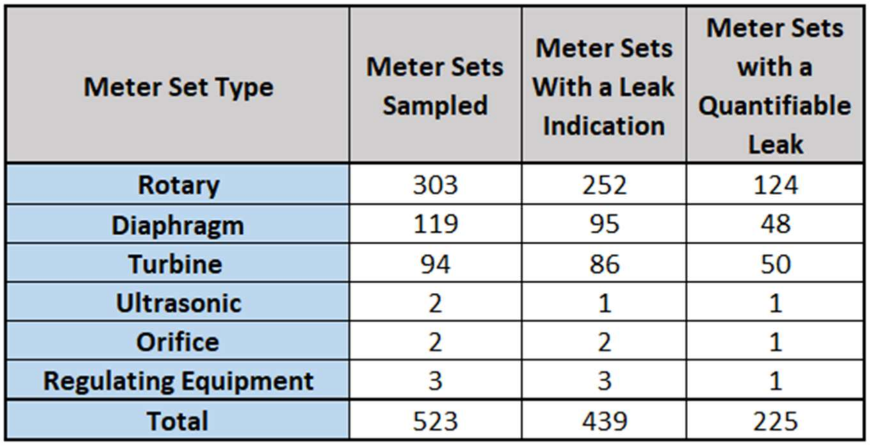
Bayesian Analysis by Region reveal that the uncertainty around these percentages is higher than for the small emission rates in the Pacific region.

3.3 Emission Rates and EFs by Meter Type

3.3.1 Meter Set Counts by Meter Type

The meter sets sampled were also categorized by meter type to explore possible differences in emissions. Previous work by OTD (2009) indicated that large differences in emissions exist among meter set types. GTI chose to largely focus sampling on three main meter set types, rotary, diaphragm, and turbine, as can be seen in Table 8. When categorized in this fashion, some clear patterns emerge.

Table 8. Meter Sets Sampled, Leak Indications, and Quantifications by Meter Type



Meter Set Type	Meter Sets Sampled	Meter Sets With a Leak Indication	Meter Sets with a Quantifiable Leak
Rotary	303	252	124
Diaphragm	119	95	48
Turbine	94	86	50
Ultrasonic	2	1	1
Orifice	2	2	1
Regulating Equipment	3	3	1
Total	523	439	225

For example, rotary meter sets accounted for 59.3% of leak indications, followed by turbine meters with 19.6% of leak indications, and with diaphragm meter sets representing 18.2% of leak indications. This corresponds to the numbers of components scanned by meter type as shown in Table 9. The largest number of components scanned were rotary meter sets accounting for 58.4% of total components scanned (14,420 scanned components). The second largest number of components scanned were turbine meter sets, accounting for 24.2% (5,987 scanned components), followed by diaphragm meters with 15.3% (3,774 scanned components). For emission rate quantification measurements, 57.4% occurred at rotary meter sets, followed by 25.1% at turbine meter sets, and 15.2% at diaphragm meter sets. Also consistent with the number of components scanned.

Table 9. Number of Components Scanned, Leak Indications, and Leaks Quantified by Meter Set Type

		Rotary	Diaphragm	Turbine	Ultrasonic	Orifice	Regulating Equipment	Total
Valve	Scanned	3389	784	1482	15	44	71	5785
	Leak Indications	163	45	95	0	10	12	325
	Quantifications	58	14	54	0	4	0	130
Pneumatic Device	Scanned	1	0	1	0	1	0	3
	Leak Indications	0	0	0	0	1	0	1
	Quantifications	0	0	0	1	0	0	1
Regulator	Scanned	720	213	256	0	6	4	1199
	Leak Indications	73	15	15	0	1	0	104
	Quantifications	33	5	3	0	1	0	42
Meter	Scanned	351	132	121	2	3	3	612
	Leak Indications	3	15	7	0	0	0	25
	Quantifications	3	5	3	0	0	0	11
Elbow	Scanned	1915	693	619	1	7	26	3261
	Leak Indications	115	30	15	0	0	0	160
	Quantifications	39	7	4	0	0	0	50
Tee	Scanned	860	206	221	2	14	7	1310
	Leak Indications	47	16	6	0	2	0	71
	Quantifications	5	2	0	0	0	0	7
Coupling	Scanned	1694	505	775	10	20	26	3030
	Leak Indications	78	31	19	0	3	0	131
	Quantifications	26	11	6	0	0	0	43
Cap	Scanned	225	115	74	4	2	4	424
	Leak Indications	15	6	1	0	0	0	22
	Quantifications	3	2	1	0	0	0	6
Plug	Scanned	2132	375	884	10	20	37	3458
	Leak Indications	85	18	24	0	4	1	132
	Quantifications	22	4	7	0	1	1	35
Flange	Scanned	3133	751	1554	28	77	45	5588
	Leak Indications	179	48	68	1	1	1	298
	Quantifications	29	5	23	0	1	0	58
Other	Scanned							
	Leak Indications	116	44	39	1	1	4	205
	Quantifications	45	15	14	1	0	0	75

It is important to consider the average number of components that make up different types of meter sets. Our measurements indicate that the more components that make up a meter set, the more potential leak points. Therefore, the average number of components found on each meter set type is shown in Table 10. For example, although Turbine meter sets contain a similar number of tees, elbows, and plugs as the other meter set types, turbine meter sets are typically located at larger installations, and therefore tend to contain more valves and flanges than the other meter set types. Diaphragm meter sets contained the fewest number of components in all the main categories of components.

Table 10. Mean Number of Components by Meter Type

Meter Type	Valve	Pneumatic	Regulator	Meter	Elbow	Tee	Coupling	Cap	Plug	Flange
Rotary	11.18	0.00	2.38	1.16	6.32	2.84	5.59	0.74	7.04	10.34
Diaphragm	6.59	0.00	1.79	1.11	5.82	1.73	4.24	0.97	3.15	6.31
Turbine	15.77	0.01	2.72	1.29	6.59	2.35	8.24	0.79	9.40	16.53

3.3.2 Meter Set Emission Rates and EFs by Meter Type (Population and Leaker)

As can be seen in Figure 21, the range of meter set emission rates is comparable between the diaphragm and rotary meters. Ultrasonic, Orifice, and Regulating Equipment are not included due to the low number of samples (n < 5) collected in each of those categories. Although the range of rates is smaller for turbine meters, overall the emission rates tended to be higher for turbine meters. The largest emission rates were measured at turbine meters, with three of the top five highest emission rates were measured at turbine meters.

Originally, it was thought that the higher emissions could be directly linked to the higher mean number of components found on turbine meter sets. However, on further examination no correlation exists between the number of components present at a meter set and the number of leak indications or mean emission rate. In fact, the meter sets with the most total number of components were rotary meters. Four of the top five largest number of components were at rotary meter sets with between 135 and 190 total components. Only one meter set with 135 components or more had a quantifiable leak. That emission rate was not large – 6.7 g CH_4 h^{-1}. Therefore, the number of components was likely not directly affecting the number of leaks per meter set.

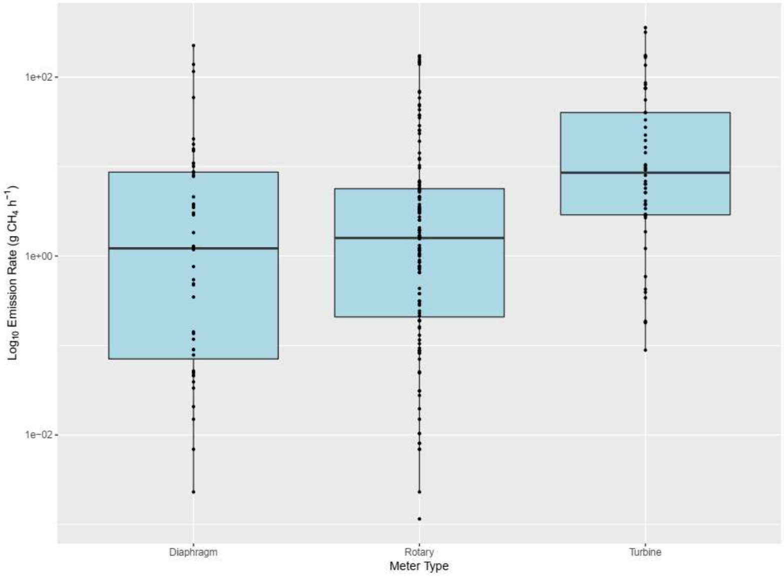


Figure 21. Box and Whisker Plot of the Meter Set Emission Rates by Meter Type.

The mean emission rates are shown in Figure 22 for the population (All Meter Sets) and leaker-only meter sets by meter type. Consistent with the median emission rates shown earlier, the mean emission rate (and standard deviation) for both rotary and diaphragm meters were nearly identical for both the population and leakers-only, while the mean emission rate from the Turbine meters was 3.8 – 3.9 times higher than Rotary and Diaphragm meters. Further discussion of the differences in emission rates by meter type can be seen in the Bayesian analysis section (3.3.4). Since this difference was not directly related to the number of components at the different meter sets, it was most likely due to the higher operating pressures at turbine meter sets.

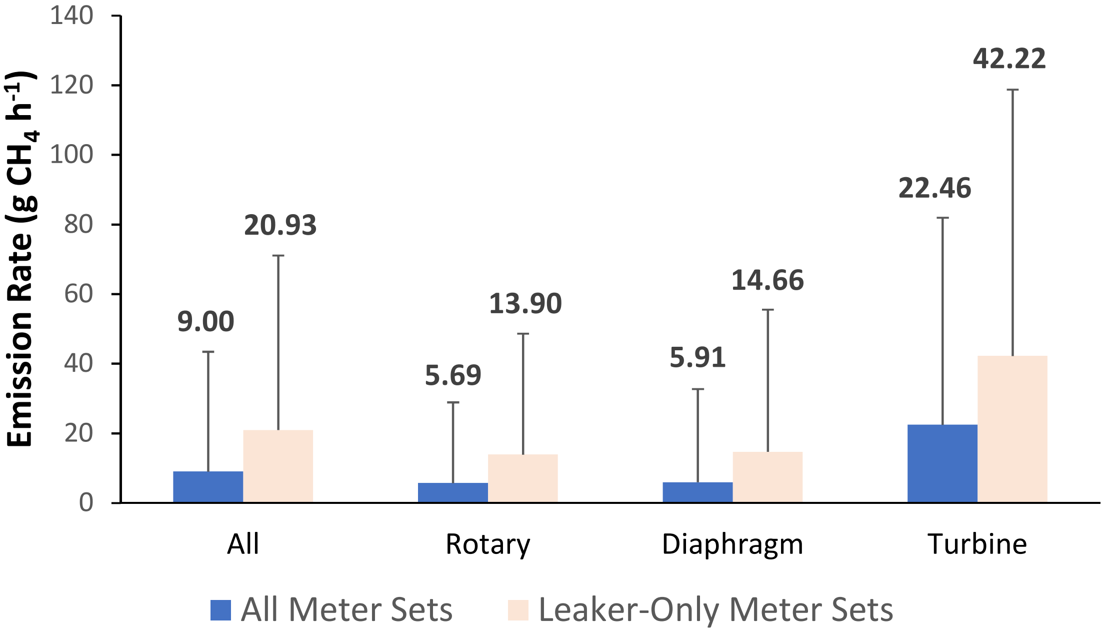


Figure 22. Comparison of Mean Leaker Rates and Population Emission Rates by Meter Set Type

As shown in Figure 23, the higher emitting Turbine meters increased the nationwide population EF (All) substantially over the Rotary and Diaphragm meters alone. Even so, Diaphragm and Rotary meter EFs still showed a significant increase over the 9.7 kg CH_4 y^{-1} $meter^{-1}$ population EF currently used for the EPA GHGI. GTI believes that a useful exercise to more accurately determine the annual CH_4 emissions from industrial/commercial NG meters would be to create separate factors for Rotary, Diaphragm, and Turbine meters. Unfortunately, according to EPA, there is currently no historical annual data source that would provide the needed activity data to properly scale these factors to nationwide estimates. Therefore, to make this estimate possible, EPA would have to work directly with LDCs to obtain historical records of these types of meters.

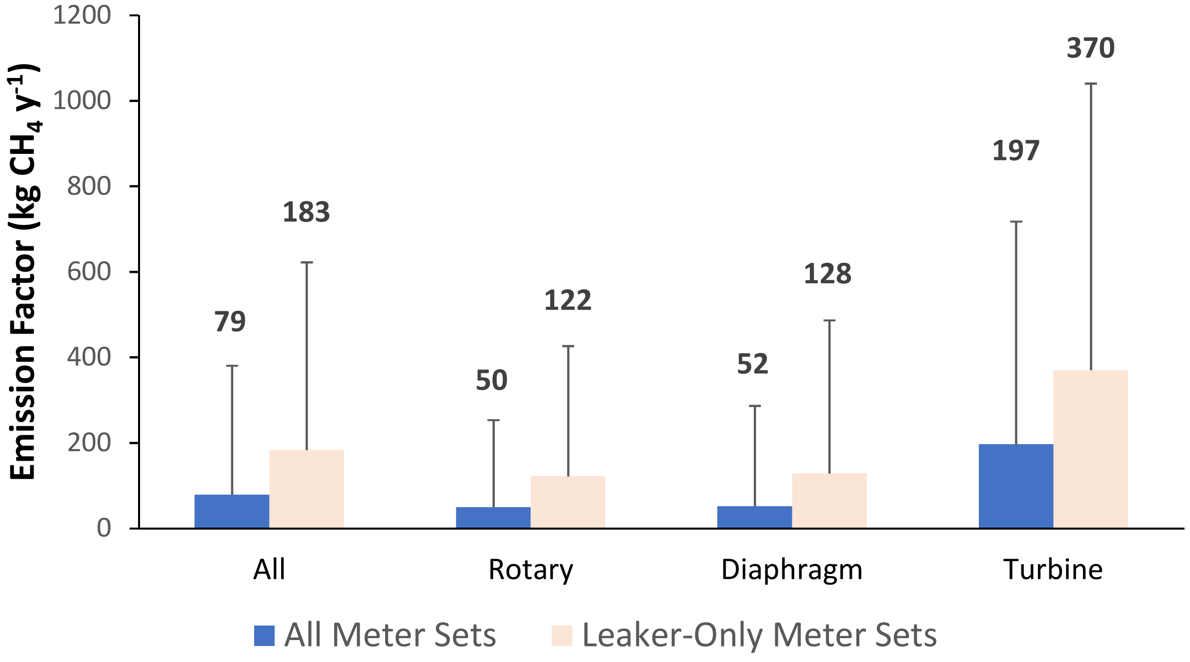


Figure 23. Comparison of Leaker Factors and Population EFs by Meter Set Type

3.3.3 Meter Types Sampled by Region

Turbine meters have been shown to have a higher leak rate than the other types of meters. To fully understand the variability by region, the influence that turbine meters have on EFs from an individual region was examined. Turbine meters accounted for 15 of the 20 meter sets sampled in the Southeast region (Table 11).

Table 11. Numbers of Meter Sets Delineated by Meter Type and by Region

	Rotary	Diaphragm	Turbine	Ultrasonic	Orifice	Equipment
Midwest	112	37	27	0	0	0
Northeast	33	39	16	0	0	0
Pacific	76	20	18	0	1	0
Rocky	15	2	3	0	1	0
Southeast	4	1	15	0	0	0
Southwest	63	20	15	2	0	3
Total	303	119	94	2	2	3

Therefore, population emission rates as well as leaker-only emissions rates for the Southeast region may seem larger, due to fact that more turbine meters were encountered in that region. Delineating EFs by meter type may pose a viable solution to overinflated EFs that may occur in the event a random sampling of the population produces a large number of turbine meters. This is discussed further in Section 3.6 EFs by Combined Category.

3.3.4 Bayesian Analysis – Probability of Leak Size by Meter Type

A Bayesian analysis was conducted to determine the probability of encountering emission rates in different size categories for all meter types. Table 12 illustrates the updated probability of quantified leak sizes for Rotary, Diaphragm, Turbine, Ultrasonic, Orifice, and Regulating style meter sets. For example, there was a 58.06% probability that a randomly chosen Rotary meter set had a leak below the quantifiable limit. Additional information, such as the lower and upper 95% confidence bounds for this estimated probability, were performed and are available in Section 8.11 Appendix – Additional Bayesian Analysis by Meter Set Type. Details describing the Bayesian methods used are in Section 3.2.4.

As mentioned earlier, in Bayesian analysis, a prior distribution was assumed to balance the weight between existing knowledge and collected field measurements. As shown below, an ignorant prior was applied to estimate the probability of encountering a leak with an emission rate in one of seven ranges. The prior distribution was eventually washed out when a large number of samples was collected, while it played an important role when sample size was small. For example, the probability of encountering a leak size "0.09 – 0.75" for Orifice was calculated as

Equation 12

$$E(X_{0.09\,-\,0.75}) = \frac{\alpha_1 + N_1}{\alpha + n} = \frac{1+0}{7+2} = 11.1\%$$

Similarly, the probability of encountering a leak size "0.09 – 0.75" for Regulating Equipment was:

Equation 13

$$E(X_{0.09\,-\,0.75}) = \frac{\alpha_1 + N_1}{\alpha + n} = \frac{1+0}{7+3} = 10.0\%$$

Different probabilities were obtained for emission rates in categories with zero collected field samples. This was due to the total number of samples (i.e., two for Orifice and three for Regulating Equipment) being different for those two meter types. That changed the weight of prior knowledge in the probability calculation. Conceptually, more samples further reduced the weight of the prior belief. However, the prior assumption was imperative because it prevented us from being over confident about the data, especially when there were only a limited number of samples.

Table 12. Bayesian Probability of Encountering a Leak Size by Meter Type

Leak Size	Total	Probability
BQL	298	56.42%
BQL – 0.09	38	7.36%
0.09 – 0.75	37	7.17%
0.75 – 2.77	37	7.17%
2.77 – 6.11	38	7.36%
6.11 – 25.38	37	7.17%
>25.38	38	7.36%
Total	523	100%

Leak Size	Rotary	Probability	Diaphragm	Probability	Turbine	Probability
BQL	179	58.10%	71	57.10%	44	44.60%
BQL – 0.09	22	7.40%	15	12.70%	1	2.00%
0.09 – 0.75	23	7.70%	7	6.30%	7	7.90%
0.75 – 2.77	29	9.70%	5	4.80%	3	4.00%
2.77 – 6.11	21	7.10%	6	5.60%	10	10.90%
6.11 – 25.38	12	4.20%	11	9.50%	13	13.90%
>25.38	17	5.80%	4	4.00%	16	16.80%
Total	303	100%	119	100%	94	100%

Leak Size	Ultrasonic	Probability	Orifice	Probability	Reg. Equip.	Probability
BQL	1	22.20%	1	22.20%	2	30.00%
BQL – 0.09	0	11.10%	0	11.10%	0	10.00%
0.09 – 0.75	0	11.10%	0	11.10%	0	10.00%
0.75 – 2.77	0	11.10%	0	11.10%	0	10.00%
2.77 – 6.11	0	11.10%	0	11.10%	1	20.00%
6.11 – 25.38	1	22.20%	0	11.10%	0	10.00%
>25.38	0	11.10%	1	22.20%	0	10.00%
Total	2	100%	2	100%	3	100%

The Bayesian analysis allows us to further understand the differences in mean emission rates among meter types. For example, Table 12 shows that with reasonable certainty there is a much lower probability of finding leaks on Turbine meters with emission rates in the BQL and the BQL – 0.09 g CH_4 h^{-1} ranges and a much higher probability of finding a leak with an emission rate in the 6.11 – 25.38 and >25.38 g CH_4 h^{-1} categories. Therefore, it can be stated with reasonable certainty (confidence limits shown in figures in Section 8.11) that emissions from turbine meters were likely higher than rotary or diaphragm meters.

3.4 Meter Set Emissions by Company

Meter sets were also categorized by company to make recommendations to the companies that may have higher emissions than other companies. Ten companies were visited throughout the study with an additional meter set sampled opportunistically at Company D as shown in Table 13 below.

Table 13. Meter Sets Sampled, Leak Indications, and Quantified Leaks by Company

Company	Meter Sets Sampled	Meter Sets With a Leak Indication	Meter Sets with a Quantifiable Leak
A	60	51	20
B	78	69	64
C	88	74	26
D	1	1	0
E	43	34	12
F	43	42	21
G	63	37	33
H	20	19	19
I	52	48	4
J	54	44	17
K	21	20	9
Total	523	439	225

The numbers of components scanned, individual component leak indications, and leak quantifications are shown in Table 14. These two tables show that the largest number of meter sets visited (88) and components scanned (3,902) was at Company C. Company I had the sixth most meter sets sampled (52) but the second highest number of components (3,678) and by far the largest number of valves scanned (1,036).

Taking a more detailed look at the components (not meter sets) with leak indications tells a widely varying story among the companies sampled. For example, Company E had the highest number of leak indications (234) but had one of the lowest numbers of meter sets sampled, with only three of eight other companies having fewer sampled. This was followed by Companies B (225), C (215), and A (210), who had the three highest numbers of meter sets sampled. Company E had the highest number of leak indications per meter set sampled (5.4), followed by Company F (4.8), K (4.3), A (3.5), D (3), H (3), B (2.9), C (2.4), I (2.0), J (1.3), and G (0.8). Company G was the only one who had less than one leak indication per meter set.

The largest number of quantifications occurred at Company B, a company surveyed using the 100 ppm leak quantification threshold. In fact, the only reason that all 225 leak indications were not quantified was due to a battery malfunction with the LGR UGGA, leading to 43 small leaks being logged and not quantified under the 22,500 ppm leak quantification threshold.

Table 14. Components Scanned, Leak Indications, and Leaks Quantified by Company

		A	B	C	D	E	F	G	H	I	J	K	Total
Valve	Scanned	487	475	738	20	551	526	597	287	1036	828	240	5785
	Leak Indications	23	38	48	0	40	76	9	28	13	33	17	325
	Quantifications	5	33	9	0	3	21	9	28	3	14	5	130
Pneumatic Device	Scanned	1	1	0	0	0	0	0	0	0	0	1	3
	Leak Indications	0	0	0	0	0	0	0	0	0	0	1	1
	Quantifications	0	0	0	0	0	0	0	0	0	0	1	1
Regulator	Scanned	100	175	184	3	99	46	131	33	239	103	86	1199
	Leak Indications	7	24	8	0	26	8	3	3	6	9	10	104
	Quantifications	1	20	2	0	5	1	3	3	0	5	2	42
Meter	Scanned	60	101	131	1	47	47	66	21	56	55	27	612
	Leak Indications	2	7	12	0	0	0	2	0	0	1	1	25
	Quantifications	2	4	3	0	0	0	2	0	0	0	0	11
Elbow	Scanned	267	513	838	2	266	164	190	72	539	236	174	3261
	Leak Indications	17	49	37	1	27	9	5	0	5	3	7	160
	Quantifications	0	43	3	0	0	0	3	0	0	1	0	50
Tee	Scanned	105	109	216	3	127	177	66	30	337	99	41	1310
	Leak Indications	7	6	12	0	10	16	0	0	17	0	3	71
	Quantifications	1	4	0	0	2	0	0	0	0	0	0	7
Coupling	Scanned	315	301	464	0	253	349	218	188	366	501	75	3030
	Leak Indications	18	45	13	0	30	6	5	1	11	1	1	131
	Quantifications	3	30	1	0	2	2	4	1	0	0	0	43
Cap	Scanned	124	45	102	1	31	14	12	32	33	14	16	424
	Leak Indications	8	4	1	0	3	0	0	2	4	0	0	22
	Quantifications	1	3	0	0	0	0	0	2	0	0	0	6
Plug	Scanned	325	333	312	12	391	355	409	138	671	349	163	3458
	Leak Indications	21	8	10	1	21	31	5	4	14	5	12	132
	Quantifications	2	6	1	0	3	11	4	4	1	1	2	35
Flange	Scanned	715	459	917	8	494	341	739	415	401	662	437	5588
	Leak Indications	79	13	48	0	70	22	11	12	23	8	12	298
	Quantifications	5	10	10	0	6	2	8	12	0	2	3	58
Other	Scanned												
	Leak Indications	28	31	26	1	7	40	11	10	13	11	27	205
	Quantifications	7	29	6	0	0	5	11	10	0	2	5	75

The types of meter sets sampled by company are shown in Table 15. The numbers of each type of meter set are similar across companies, with one notable exception. At Company H, the focus was almost entirely on turbine meter sets, with 15 of the 20 samples being at Turbine meters. At the other companies, the number of samples in each category of meter set was driven entirely by the pseudo-random sampling plan that was optimized to minimize driving time.

Table 15. Number of Meter Sets Sampled by Company

Company	Rotary	Diaphrgam	Turbine	Total
A	27	19	12	58
B	51	21	6	78
C	33	39	16	88
D	1	0	0	1
E	31	8	4	43
F	36	1	3	40
G	41	17	5	63
H	4	1	15	20
I	35	3	13	51
J	29	8	17	54
K	15	2	3	20
Total	303	119	94	516

3.4.1 Meter Set Emission Rates and Leaker Rates by Company

The range of measured emission rate data varied widely by company as can be seen in Figure 24. Company B had the largest range of emission rates covering almost four orders of magnitude but the lowest median. This was due to the 100 ppm leak quantification threshold used at that company. Company G had the next lowest median emission rate. It is important to note that Company G only had leak indications at 58% of the meter sets sampled, the lowest percentage of any company and the leaks that were quantified were small. At Company I, 48 meter sets had leak indications. However, only four of those leaks were quantified due to the utilization of the 22,500 ppm leak quantification threshold. Although many of the meter sets had leak indications, nearly all of the leaks were too small to quantify (BQL).

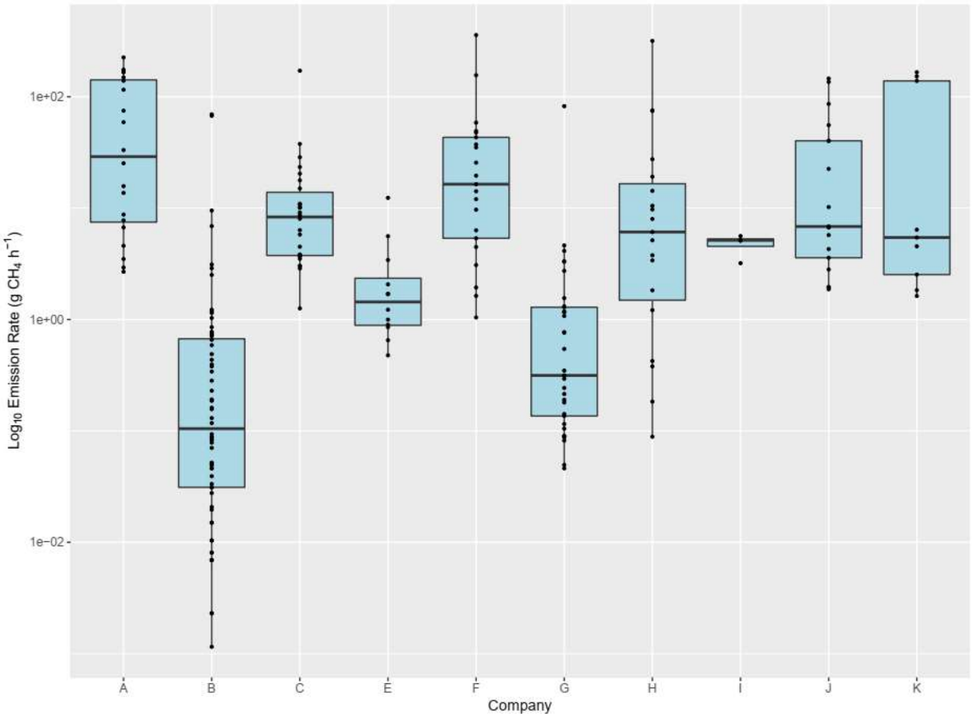


Figure 24. Box and Whisker Plot of Measured Emission Rates by Company

Mean emission rates for meter sets varied widely among the ten main companies sampled as shown in Figure 25. For example, while Company A had a mean of 3.5 leak indications per meter set and the highest mean leaker-only emission rate of 70.12 ± 75.09 g CH_4 h^{-1}, Company H had the highest emission rate when using all meter sets in the population (28.95 ± 71.37 g CH_4 h^{-1}). There appears to be two tiers of performers when examining mean emission rates by company. For example, emission rates for Companies B, E, G, and I were lower than the other companies. One observation already noted earlier was that meter sets sampled at Company H were almost entirely turbine meters. Due to turbine meters having generally higher emission rates, this likely biased the emission rates for this company slightly higher.

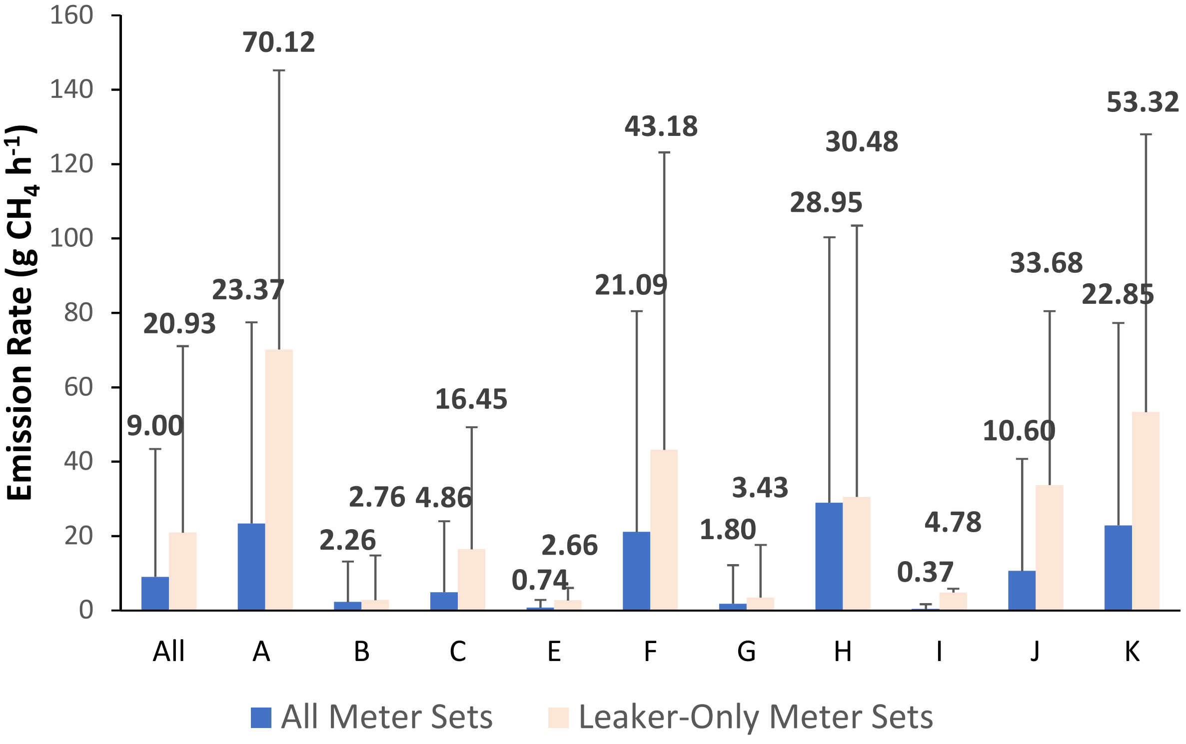


Figure 25. Comparison of Mean Meter Set Emission Rates and Leaker Rates by Company

To further emphasize the differences by Company, Figure 26 shows a comparison of population and leaker-only EFs calculated from their respective mean emission rates. Examining these factors further highlights the differences between the individual companies. For example, Companies E (7 kg CH_4 y^{-1}) and I (3 kg CH_4 y^{-1}) were performing better than the current EPA GHGI population EF (9.7 kg CH_4 y^{-1}). For companies other than Company H, it appeared that the number of each type of meter set sampled at each company was also playing a role in these differences. However, upon closer examination this was not the case, since Company I had some of the lowest mean leak rates, yet also had 13 turbine meters sampled (Table 15), more than were sampled at A, F, and K, and the second highest number of components scanned (Table 14). This would indicate that some other company-related factor was driving these differences. The differences by company may indicate that some LDCs should advocate for the calculation of a company-specific emission/leaker factor to reflect their individual practices and actual emissions.

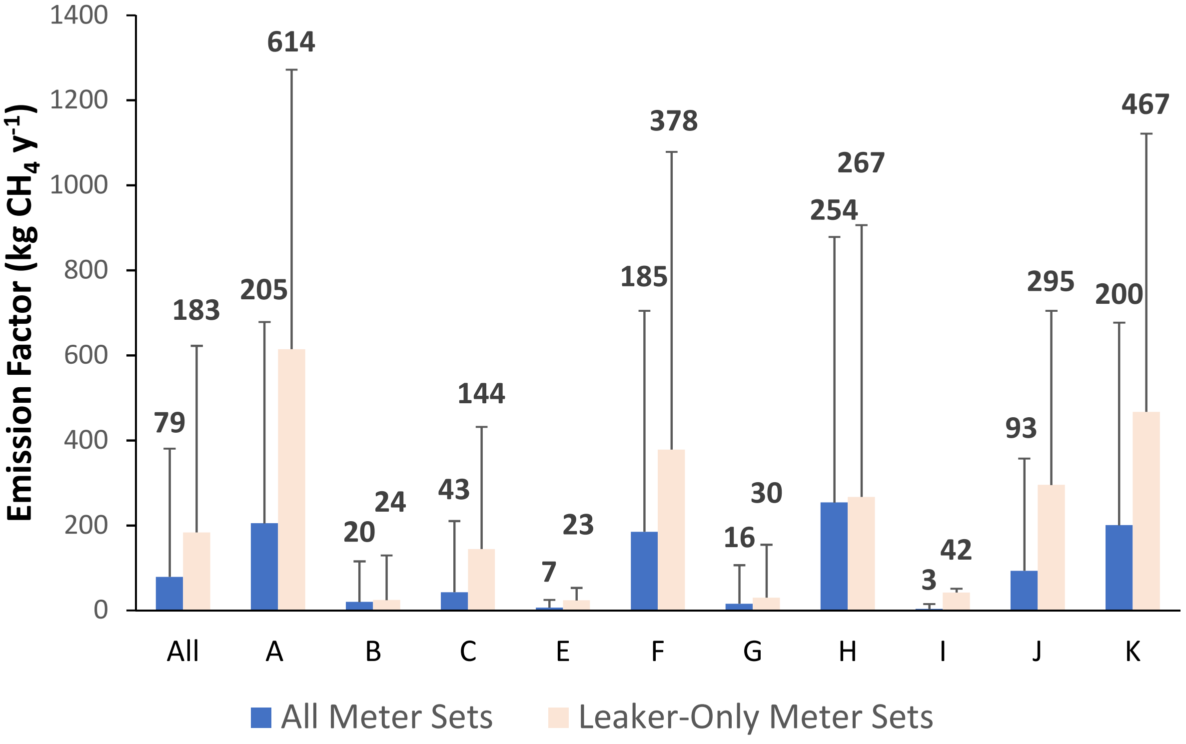


Figure 26. Comparison of Leaker Factors and Population EFs by Company

A subset of meter sets at Companies B, C, and G were visited twice. Company B had 32 of an original 46 meter sets revisited, Company C had 31 of an original 57 meter sets revisited, and Company G had 25 of an original 38 meters revisited. The relationship between first visit and revisit emission rates is shown in Figure 27, with two outliers removed. One outlier was a leak with an emission rate of 69.4 g h^{-1} that was found during the first visit and subsequently repaired so was not found during the revisit. A second outlier removed was a leak with an emission rate of 23.6 g h^{-1} was found during the revisit but was not there during the first visit. With these two outliers removed, the relationship shown in Figure 27 below indicates that most meter sets are consistently emitting methane year-round, as the visits took place one year apart.

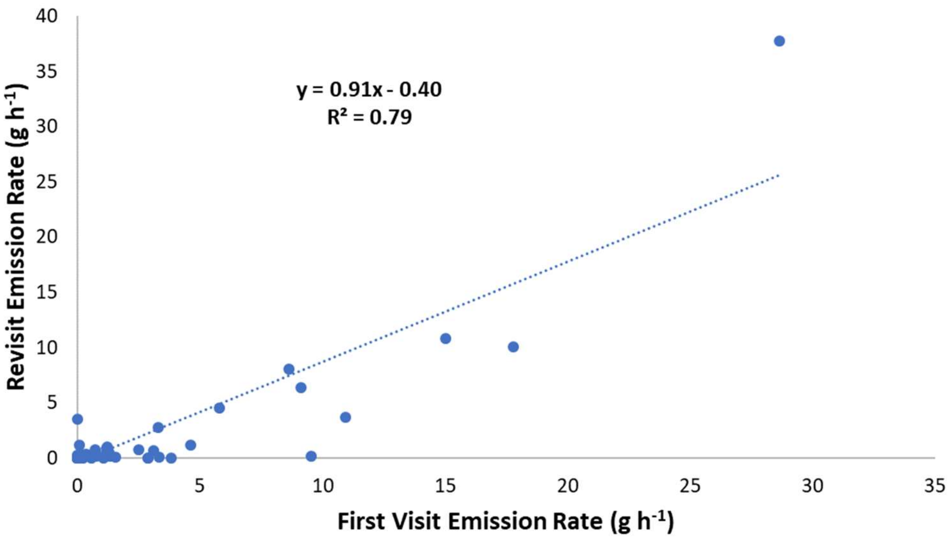


Figure 27. First Visit Emission Rates vs. Revisit Emission Rates

3.4.2 Bayesian Analysis – Probability of Leak Size by Company

As with the regional and meter type categories, a Bayesian analysis was performed to estimate the probability of encountering a leak at specific emission rate categories for different companies. Table 16 illustrates the updated probability of quantified leak sizes for each of the 11 companies participating in the project. Details describing the Bayesian methods used is in Section 3.2.4 and Section 8.11 Appendix - Additional Bayesian Analysis by Company.

Table 16. Bayesian Probability of Encountering a Leak Size by Company

Leak Size	Total	Probability	A	Probability	B	Probability	C	Probability
BQL	298	56.42%	40	61.20%	14	17.60%	62	66.30%
BQL – 0.09	38	7.36%	0	1.50%	31	37.60%	0	1.10%
0.09 – 0.75	37	7.17%	0	1.50%	19	23.50%	0	1.10%
0.75 – 2.77	37	7.17%	1	3.00%	8	10.60%	1	2.10%
2.77 – 6.11	38	7.36%	3	6.00%	2	3.50%	10	11.60%
6.11 – 25.38	37	7.17%	6	10.40%	2	3.50%	12	13.70%
>25.38	38	7.36%	10	16.40%	2	3.50%	3	4.20%
Total	523	100%	60	100%	78	100%	88	100%
Leak Size	**D**	**Probability**	**E**	**Probability**	**F**	**Probability**	**G**	**Probability**
BQL	1	25.00%	31	64.00%	22	46.00%	30	44.30%
BQL – 0.09	0	12.50%	0	2.00%	0	2.00%	6	10.00%
0.09 – 0.75	0	12.50%	2	6.00%	0	2.00%	13	20.00%
0.75 – 2.77	0	12.50%	7	16.00%	3	8.00%	9	14.30%
2.77 – 6.11	0	12.50%	2	6.00%	3	8.00%	4	7.10%
6.11 – 25.38	0	12.50%	1	4.00%	6	14.00%	0	1.40%
>25.38	0	12.50%	0	2.00%	9	20.00%	1	2.90%
Total	1	100%	43	100%	43	100%	63	100%
Leak Size	**H**	**Probability**	**I**	**Probability**	**J**	**Probability**	**K**	**Probability**
BQL	1	7.40%	48	83.10%	37	62.30%	12	46.40%
BQL – 0.09	1	7.40%	0	1.70%	0	1.60%	0	3.60%
0.09 – 0.75	3	14.80%	0	1.70%	0	1.60%	0	3.60%
0.75 – 2.77	2	11.10%	0	1.70%	3	6.60%	3	14.30%
2.77 – 6.11	4	18.50%	4	8.50%	4	8.20%	2	10.70%
6.11 – 25.38	5	22.20%	0	1.70%	4	8.20%	1	7.10%
>25.38	4	18.50%	0	1.70%	6	11.50%	3	14.30%
Total	20	100%	52	100%	54	100%	21	100%

As with the regional and meter type categories, the Bayesian analysis reveals some differences in the types of leaks encountered at each company. For example, although Company B had some of the lowest mean population emission rates and leaker-only emission rates, it also had a lower probability of finding a leak in the BQL category than most other companies. Company B also exhibited a very low probability of finding a leak in the four higher emission rate categories. This highlights that Company B was sampled using the 100 ppm leak quantification threshold and had few leaks that were not quantified. In contrast, nearly all leaks at Company I fell into the BQL category, which was sampled using the 22,500 ppm threshold, equating to an 83.1% probability of finding a leak in that category at that Company. This is an example of two different ways of arriving at similar low emission rates.

Companies with high probabilities of emission rates in the higher emitting categories, on the other hand, tended to have higher mean emission rates and EFs. For example, Companies A, F, H, and K had the highest probabilities of finding a leak in the largest emission rate category. Therefore, it is likely that these chance of finding a heavy-tailed emission was greatest at these companies driving the mean emissions higher.

3.5 Meter Set Emissions by Facility Type

The current EPA GHGI uses a single factor for combined industrial/commercial meters. For this study, both commercial and industrial facilities were sampled and are shown in Table 17 below.

Table 17. Meter Sets Sampled, Leak Indications and Quantifiable Leaks by Facility Type

Facility Type	Meter Sets Sampled	Meter Sets With a Leak Indication	Meter Sets with a Quantifiable Leak
Commercial Sector	337	278	146
Industrial Sector	186	161	79
Total	523	439	225

LDCs do not classify customer meters as "commercial" or "industrial". Rather, they install meter set types based on the amount NG supply needed. In general, industrial sector facilities (which are typically larger than commercial sector facilities) require more NG supply and therefore have a higher percentage of larger turbine meter sets (Table 18).

Table 18. Number of Meter Set Types in each Sector

Sector	Rotary	Diaphragm	Turbine	Total
Commercial	195	96	41	332
Industrial	108	23	53	184
Total	303	119	94	516

As shown in Table 19, the largest number of components, leak indications, and quantifications were found on commercial meters. However, the larger number of components did not appear to impact total emissions from commercial facilities.

Table 19. Meter Sets and Components Scanned by Facility Sector

		Commercial	Industrial	Total
Valve	Scanned	3150	2635	5785
	Leak Indications	172	153	325
	Quantifications	56	74	130
Pneumatic Device	Scanned	2	1	3
	Leak Indications	0	1	1
	Quantifications	0	1	1
Regulator	Scanned	669	530	1199
	Leak Indications	64	40	104
	Quantifications	30	12	42
Meter	Scanned	389	223	612
	Leak Indications	16	9	25
	Quantifications	8	3	11
Elbow	Scanned	2007	1254	3261
	Leak Indications	107	53	160
	Quantifications	36	14	50
Tee	Scanned	723	587	1310
	Leak Indications	49	22	71
	Quantifications	6	1	7
Coupling	Scanned	1806	1224	3030
	Leak Indications	65	66	131
	Quantifications	25	18	43
Cap	Scanned	276	148	424
	Leak Indications	9	13	22
	Quantifications	1	5	6
Plug	Scanned	1883	1575	3458
	Leak Indications	78	54	132
	Quantifications	21	14	35
Flange	Scanned	3197	2391	5588
	Leak Indications	154	144	298
	Quantifications	26	32	58
Other	Scanned			0
	Leak Indications	132	73	205
	Quantifications	46	29	75
Total	Scanned	14102	10568	24670
	Leak Indications	846	628	1474
	Quantifications	255	203	458

3.5.1 Total Emissions and EFs by Facility Type

As shown in Figure 28, the number of larger leaks is similar for both commercial and industrial facilities. However, the number of small emissions is larger for the commercial facilities which reduces the overall median emission rates.

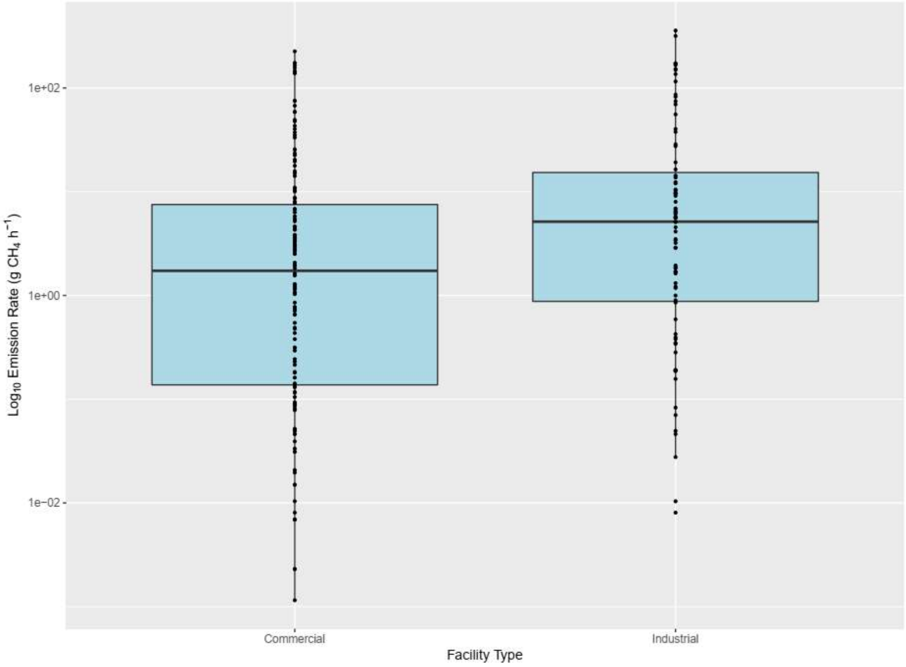


Figure 28. Box and Whisker Plot of the Measured Emission Rates by Facility Type

Figure 29, further shows the difference in mean emission rates between meter sets at commercial and industrial facilities, with industrial facilities exhibiting slightly higher mean emission rates - despite both facilities having similar numbers of higher emitters. This trend appears to be driven by the higher number of small leaks found at commercial facilities. Further statistical details can be seen in Section 8.8 Appendix – Facility Type Meter Set Data Statistical Summary Tables.

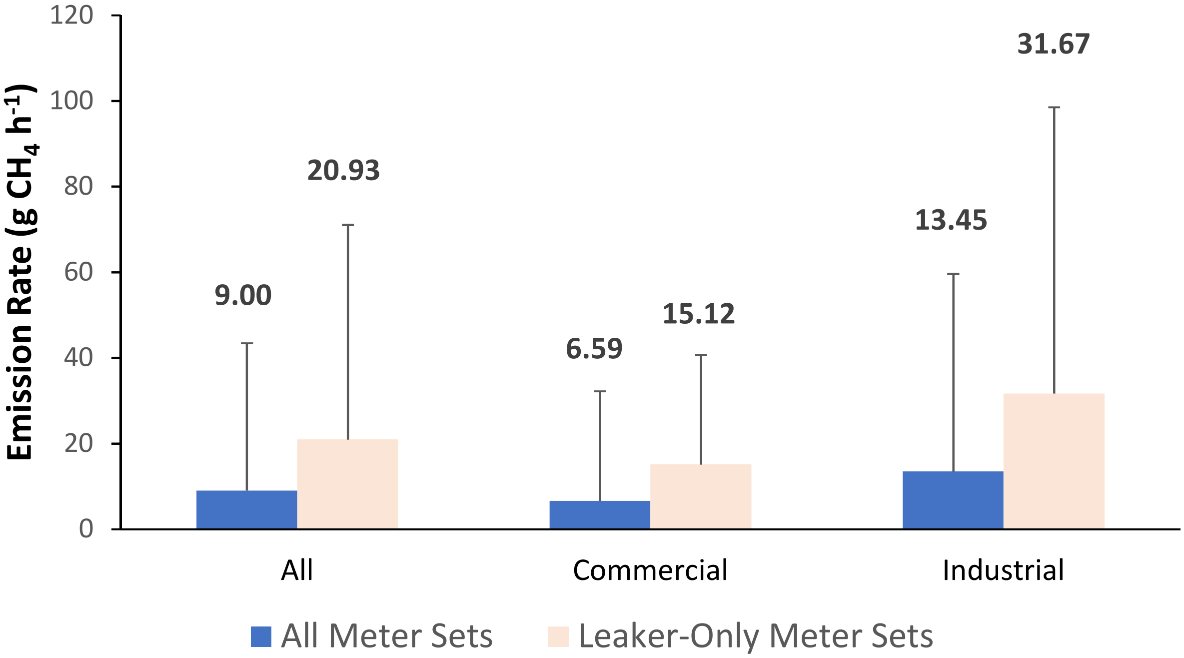


Figure 29. Comparison of Meter Set Leaker and Emission Rates by Sector

The differences in mean emissions between commercial and industrial facilities led to lower mean population and leaker-only EFs calculated for commercial facilities. It is important to note that the differences between the two facility types was not as large as was reported by OTD in 2009. However, there remains enough of a difference that GTI recommends using separate population and leaker EFs for commercial and industrial facilities.

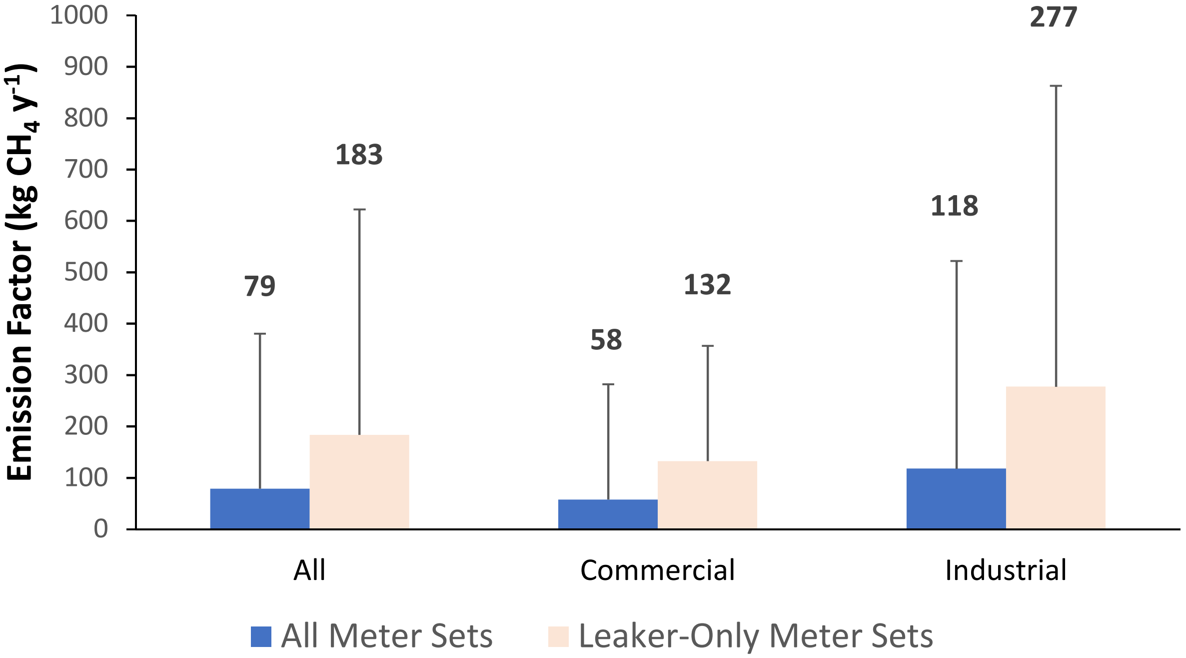
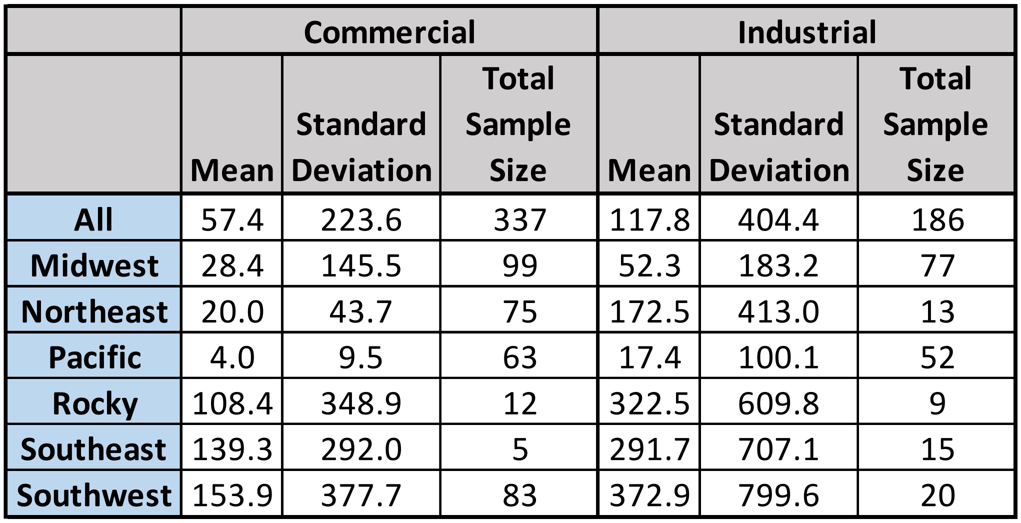


Figure 30. Comparison of Meter Set Leaker Factors and Population EFs by Sector

3.6 EFs by Combined Category

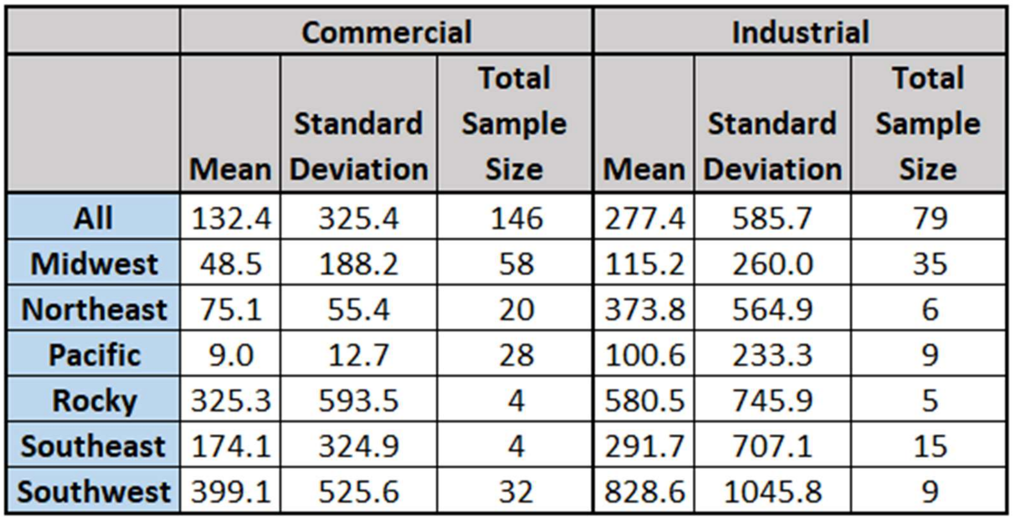
To further categorize emissions from industrial/commercial meters, the mean emission rates and EFs by combined categories were examined. In this section, only the summarized population and leaker-only EFs for the combined categories will be presented. Additional statistics can be found in Section 8.9 Appendix – Facility Type Meter Set by Region Data Statistical Summary Tables. Table 20 and Table 21 show the calculated population and leaker-only EFs for commercial and industrial meters by region. The EFs are highly variable with the industrial facilities being nearly two times larger than the commercial facilities in all regions. GTI recommends that the greatest accuracy in reporting would be gained by using these combined EFs.

Table 20. Population EFs for Industrial/Commercial Meters by Region



	Commercial			Industrial		
	Mean	Standard Deviation	Total Sample Size	Mean	Standard Deviation	Total Sample Size
All	57.4	223.6	337	117.8	404.4	186
Midwest	28.4	145.5	99	52.3	183.2	77
Northeast	20.0	43.7	75	172.5	413.0	13
Pacific	4.0	9.5	63	17.4	100.1	52
Rocky	108.4	348.9	12	322.5	609.8	9
Southeast	139.3	292.0	5	291.7	707.1	15
Southwest	153.9	377.7	83	372.9	799.6	20

Table 21. Leaker-Only EFs for Industrial/Commercial Meters by Region



	Commercial			Industrial		
	Mean	Standard Deviation	Total Sample Size	Mean	Standard Deviation	Total Sample Size
All	132.4	325.4	146	277.4	585.7	79
Midwest	48.5	188.2	58	115.2	260.0	35
Northeast	75.1	55.4	20	373.8	564.9	6
Pacific	9.0	12.7	28	100.6	233.3	9
Rocky	325.3	593.5	4	580.5	745.9	5
Southeast	174.1	324.9	4	291.7	707.1	15
Southwest	399.1	525.6	32	828.6	1045.8	9

Ideally, data would be further disaggregated into meter type, however, there were not enough samples collected to disaggregate that deeply (e.g. industrial and commercial facilities disaggregated by region then further disaggregated by meter type).

4 Modern vs. Vintage Plastic Pipe - Emissions Analysis and Results

4.1 Surface Enclosure Measurements

GTI visited 339 potential underground leak sites for the project in five of the six sampling regions (Table 22). Vintage plastic pipe leaks could not be located on an industry partner network in the Southeast. This was likely due to 1) aggressive installation of modern plastic pipe in that region, leading to less vintage plastic pipe in the network; 2) fewer industry partners in this region; or 3) the LDCs do not have the exact locations of older pipes documented in their databases.

Of the 339 sites visited, 186 sites had quantifiable leaks. Many of the sites visited had recently been repaired and had not been closed in the company leak tracking systems. This is a testament to how often and quickly the companies find and fix many leaks. Leaks cannot be removed from the leak tracking records until they have been repaired then rechecked usually two weeks to 30 days later, therefore there is a lag between when the leak is fixed and when it is removed from the leak records. For this study, GTI field crews visited each location and performed an independent leak survey to verify whether a leak existed. If the leak could not be located within 10 minutes of surveying based on the notes provided by the LDC partner, the field crew proceeded to the next leak location.

Table 22. Sites Visited for Modern and Vintage Plastic Pipe

Region	Sites Visited	Verfied Modern Plastic Pipeline Leaks	Verfied Vintage Plastic Pipeline Leaks
All	339	45	58
Midwest	104	4	19
Northeast	77	12	8
Pacific	82	18	27
Rocky	14	3	3
Southwest	62	8	1

GTI was able to verify that 103 leaks were located on either modern or vintage plastic pipe. However, verification of material type for leaks found on other types of vintage pipe (e.g., bare steel, cast iron, coated steel) was not possible as these pipelines had not yet been excavated for repair.

A total of 45 leaks were measured on post-1986 installed modern plastic pipe and 58 leaks were measured on vintage pipe. As for the other leaks quantified, 52 were unknown or not verified (not yet repaired), eight were verified as steel, 11 as coated steel, nine as bare steel, and three as cast-iron. The differences often exist in urban areas where several different types of pipe, mains, and services may be nearby. The leak may express over the entire area where the plastic pipe was located, but on excavation, the leak was found to be migrating from a different type of pipe. At other times, company data had not been updated to properly show locations of the pipe, thus leading to discrepancies. This illustrates the importance of excavating and verifying the leaking pipeline material when attempting to attribute leaks to a specific material type.

As shown in Figure 31, one vintage plastic pipe leak of 2,254 g CH_4 h^{-1} was heavily influencing the distribution leaks. This single data point was causing the mean emission rate (and standard deviation) of the vintage plastic pipe to be higher than for the modern plastic pipe. Removal of this single data point revealed that the modern and vintage plastic pipe had almost identical distributions (Figure 32).

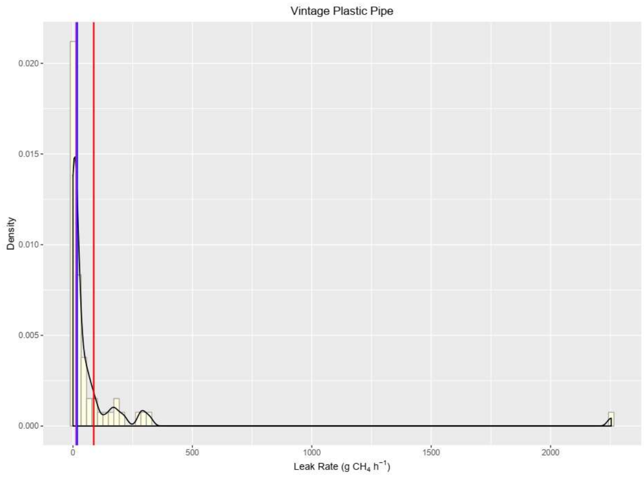


Figure 31. Leak Rate Distribution for all Vintage Plastic Pipe

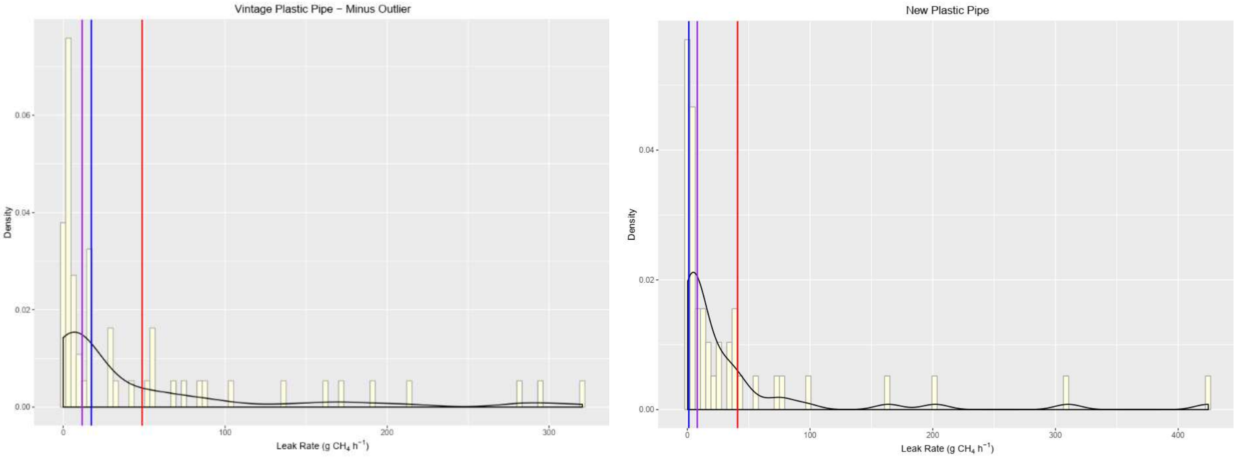


Figure 32. Leak Rate Distributions for Vintage Plastic Pipe minus one Outlier and New (Modern) Plastic Pipe

Upon removal of the single outlier for vintage plastic pipe, Figure 33 shows that only small differences were observed between modern pipe (mean emission rate of 40.9 ± 83.2 g CH_4 h^{-1}) and vintage plastic pipe (mean emission rate of 48.7 ± 78.4 g CH_4 h^{-1}, Figure 33). Figure 33 also shows the small impact that the unverified leaks would likely have on the overall means for modern and vintage plastic pipe as the means emission rates were lower from the unverified leaks, indicating a lack of heavy-tailed emissions in that category leaks. The mean emission rates for this study fall between those reported in Lamb et al 2015 which were 19.8 g CH_4 h^{-1} for plastic mains and 7.8 g CH_4 h^{-1} for plastic services and the 71.5 g CH_4 h^{-1} reported by OTD (2013) for plastic mains.

Due to the small number of verified leaks, this dataset may not be conclusive. We did capture one leak in the heavy-tail of the distribution for vintage plastic pipe. Therefore, the possibility cannot be ruled out that heavy-tailed emissions are more prevalent in vintage plastic pipe since we were able to locate one in our limited data. However, we cannot rule out that heavy-tailed emissions exist for modern plastic pipe because of our limited sample size. Additional sampling and data would be required to specifically address the presence of heavy tailed emissions on both modern and vintage plastic pipe.

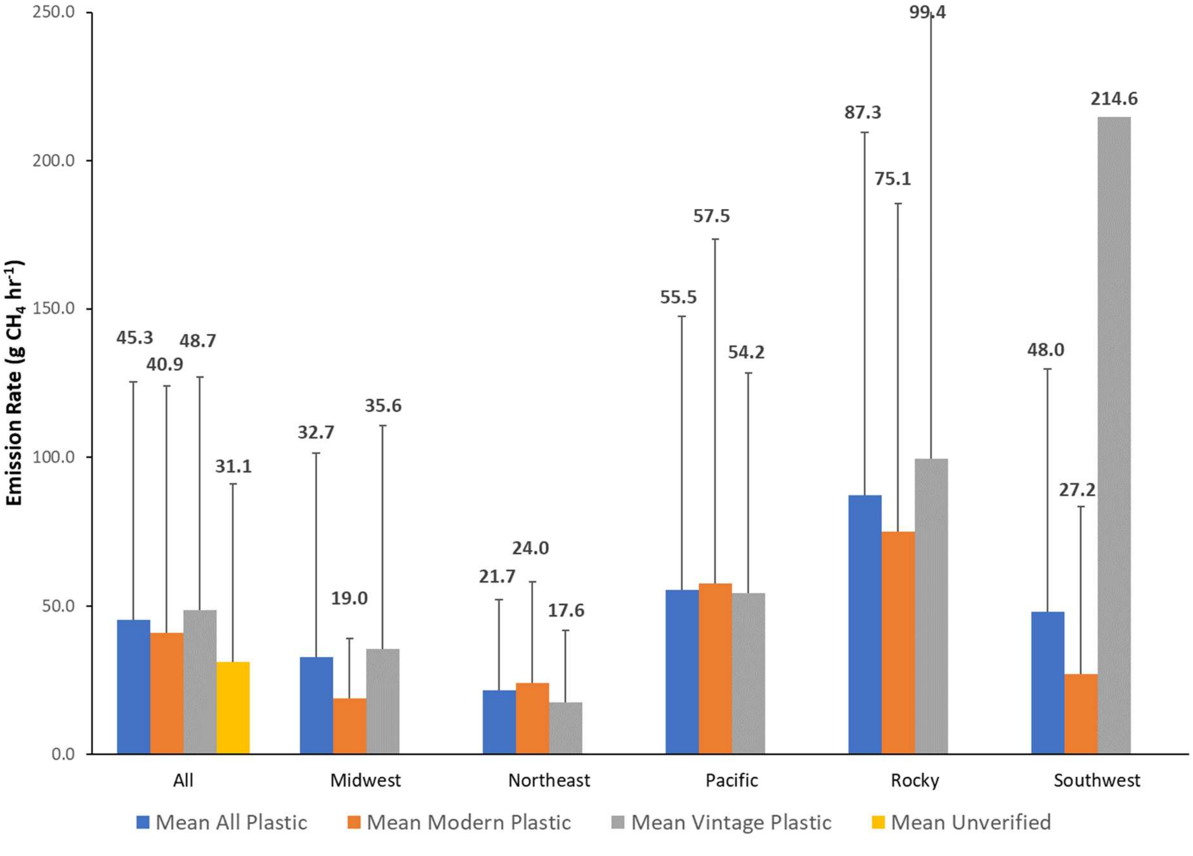


Figure 33. Comparison of Mean Leak Rates for Vintage and Modern Plastic pipe

4.2 Quality Assurance - Tracer Ratio Results

4.2.1 Emission Rate Data Rankings

For 17 locations in the Northeast, Midwest and Rocky regions, tracer methods were used simultaneously with the surface enclosure methods to perform quality assurance data checks. The tracer system was not applied at any other locations for differing reasons including too weak of a CH_4 source, poor access to the plume with the van, or too much variability in wind direction. Even at the locations where tracer was released, the two methods were not always comparable. For example, in cases where multiple enclosure grids were required to capture the surface expression of the leak, the single point tracer release did not provide a correct simulation of the source, and the correlation between CH_4 and tracer was poor.

In Table 23, the tracer ratio and corresponding surface enclosure emission rate estimates are listed for field measurements in the Northeast, Midwest, and Rocky regions. The data are ranked by the correlation coefficient. Overall, the comparison of the tracer ratio method with the surface enclosure method demonstrated good agreement. The amount of agreement between the methods was within the estimated experimental uncertainties in each method. In terms of the total CH_4 emissions summed over all leaks, the total for the enclosure method was 257.7 g CH_4 h^{-1} and the total for the tracer method was 269.2 g CH_4 h^{-1}; these totals agree to within less than 5 percent.

Table 23. Comparison of Tracer Emission Rate and Surface Enclosure CH_4 Emission Rate

Tracer Test ID	CH_4 Tracer Ratio Rate $(g\ h^{-1})$	CH4 Enclosure Rate $(g\ h^{-1})$	R^2	Excluded from Analysis
7.2	5.54	0.19	0.999	xx
30.1	0.55	0.69	0.998	
26	1.04	0.56	0.996	
6.5	4.47	2.82	0.996	xx
21.3	0.29	0.34	0.996	
20.2	0.10	0.08	0.995	
23.1	1.48	1.93	0.995	
21.2	0.27	0.34	0.994	
25	3.44	2.72	0.993	
23.3	1.42	1.93	0.993	
30.2	0.72	0.69	0.991	
29.1	1.11	0.61	0.991	
6.4	8.15	2.82	0.989	xx
24	0.29	0.17	0.988	
29.2	0.75	0.61	0.987	
34.7	0.36	1.08	0.983	
7.3	4.60	0.19	0.983	xx
11.1	0.48	0.73	0.981	
11.2	0.41	0.73	0.980	
1.4	5.22	0.36	0.987	xx
6.3	0.75	2.82	0.953	xx
34.3	0.49	1.08	0.945	xx
1.5	6.75	0.36	0.928	xx
19	0.50	0.09	0.920	
16.2	3.86	0.09	0.889	xx
11.3	0.23	0.73	0.839	

5 Plastic Lined Steel and Cast-Iron – Emission Analysis and Results

GTI conducted a walking survey of segments of lined pipe in the Northeast region. As mentioned earlier, plastic liners are not installed in long continuous stretches. Instead, they exist in short segments of between a few meters to over a thousand meters. This makes identification of leaks specifically on these lined stretches more difficult.

GTI completed walking surveys of 18 segments of cured-in-place plastic lined steel and cast-iron totaling 3,057.4 m. The randomly selected sites covered roughly 10% of the 33.6 km of the reconditioned cast iron reported by PHMSA in 2016 (signified by RCI in the data). During the walking survey, one leak was found. However, two mains and a service line were present at the location of leak. The utility immediately went into official leak protocols, finding and fixing the leak. Upon digging, the utility was able to officially verify that the leak was two smaller leaks, one on the nearby low pressure **unlined** main and one on an **unlined** service. This verified that our method of surveying was effective at finding leaks. However, no leaks were found on any of the cured-in-place plastic lined steel or cast-iron segments surveyed.

Do to the limited amount of lined pipe in the distribution pipeline system, GTI gathered information from industry partners on the limited use. Findings include the following:

1) Utilities in the Northeast, where the most cast-iron pipe still exists, are reluctant to use liners because even after lining the pipe, it is still classified as "leak-prone." Therefore, the lining does nothing to help with their replacement requirements.
2) Due to the curing process, gas must be shut off to customers for up to 24 hours. This is not always an option and limits utility implementation.
3) The liners can only be installed in very specific locations that have long continuous runs with few services to have to "punch out" once installed. This makes installation in dense urban areas impractical.
4) If these hurdles could be addressed, the use of plastic liners may increase.

6 Conclusions and Recommendations

6.1 Leaker-Only Factors

Leaker factors appear to be a more accurate means of determining emissions than population EFs that consider the entire population of meter sets (including zeros). Since instruments are not capable of measuring a true "zero" emission rate, leaker factors use only the emissions that can be quantified. Use of these rates to calculate large scale emissions require a different type of activity factor. Instead of using the entire population of industrial/commercial meters, only the number of meters with a quantifiable leak can be applied to the leaker factors. These leaker-only rates and factors are higher than a factor that gets applied to an entire population.

It is also important to note that the use of leaker factors could provide additional incentive for LDCs to focus on finding and fixing leaks. With the current single EF applied to *all* meters, the only way to reduce calculated emissions is to reduce the number of customer meters. Instead, placing the focus on leaks and leaking meters allows companies to focus on the number and size of leaks by removing the heavy-tailed emissions.

6.2 Industrial/Commercial Meter EFs

Our results indicate that industrial/commercial meter sets are likely emitting more CH_4 than currently presented in the GHGI. The current factor used in the GHGI for a combined nationwide industrial/commercial meter category is 9.7 kg CH_4 meter^{-1} yr^{-1}, whereas data from this study indicate that this nationwide value may be closer to 78.9 kg CH_4 meter^{-1} yr^{-1}. It is important to note that although the aggregated industrial/commercial EF is higher, significant differences in emissions were observed between industrial and commercial meters, across regions, and among meter types with less than 9% of the data driving 80% of the emissions.

To produce a more accurate picture of emissions from the industrial/commercial meters, GTI first recommends the use of individual component emission estimates in the future. However, in the absence of accurate historical nationwide counts of components, it is recommended that separate emission factors are used for commercial and industrial meters at a minimum. To further increase the accuracy of emission estimates, it is recommended to deepen the classification by delineating first by facility type then region for both industrial and commercial sectors. Ultimately, an accurate representation could go even further by including facility type, region, and meter. However additional data would need to be collected to achieve this deep level of disaggregation.

Unfortunately, data becomes increasingly uncertain as more categories are added and the number of samples in each combined category are reduced. The high-level, nationwide data set presented in this report should serve as a good starting point for future more targeted regional studies. Future measurements should focus on obtaining high numbers of samples in specific sub-categories to increase understanding of emissions estimates at a detailed level. For example, a beneficial study would be one that samples a high number of commercial rotary meter sets in the Southeast region to better understand the emissions in that specific category, and so on for all other categories.

High emitting meter set components that produced data outliers demonstrated a significant impact on meter set emission rates and thus EFs. Addressing these “heavy-tailed” emitters (top 10% of leaks) presents an important opportunity for emission reductions and EF reductions for NG utilities. Additionally, company policies and leak detection practices appear to impact meter set leaks. Enabling a streamlined process for company specific EFs may be useful exercises for companies and EPA combined.

6.3 Modern vs. Vintage Plastic Pipe

Two key findings were identified in the modern vs. vintage plastic pipe portion of the study. First, after removal of one vintage pipe emission rate outlier, mean emission rates for the two types of pipe were nearly identical. However, the limited sample size and/or removal of one outlier data point for vintage plastic pipe could indicate that either heavy-tailed emissions are more prevalent in vintage plastic pipe, or outliers for the modern plastic pipe were undetected due to the small sample size. The second key finding was that emission rate quantification measurements used to attribute leak rates to specific types of pipe using surface enclosures may be unreliable without excavation and verification of pipe material type.

6.4 Plastic Lined Steel and Cast-Iron Pipe

We determined that the use of plastic-liners by industry may be limited due to liners being difficult to install in urban areas, as well as the pipe still being classified as a "leak-prone" pipe – even after installation of the liner.

7 Citations

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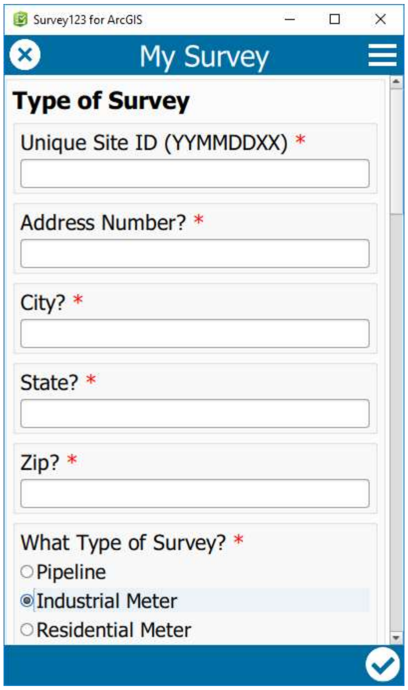
8 Appendices

8.1 Appendix - Industrial Meter Data Collection Survey

The following is the list of steps that was completed upon visiting an industrial meter set.

> Upon arriving at a site, regardless of whether a leak is found, enter the Unique Site ID in the form YYMMDDXX where XX is the sequential number of the site on that date. The first site visited during the day will be 01, the second will be 02, third will be 03, and so on for the rest of the day. This ID will be a shorthand way of representing that site visit throughout analysis. Every visit to a site will get a “Unique Site ID” even if the site has been visited previously (linking to previous visits will occur later in the survey).

1. The next fields (Address Number, City, State, Zip) are obtained from a map or company records for the site
2. Choose "Industrial Meter"



Survey123 for ArcGIS

My Survey

Type of Survey

Unique Site ID (YYMMDDXX) *

Address Number? *

City? *

State? *

Zip? *

What Type of Survey? *

○ Pipeline
● Industrial Meter
○ Residential Meter

Figure 34. Industrial Meter Data Collection Survey - General Information

3. Choose the primary organization making the measurements
4. Choose the primary person with the organization who is responsible for measurements at this site
5. Date and Time of Inspection will automatically be populated by the program

Survey123 for ArcGIS

My Survey

Group Collecting

What organization do you represent? *

● GTI
○ GHD
○ AECOM

Who are You? *

○ Kristine Wiley
○ Mike Adamo
○ Chris Moore
○ Other

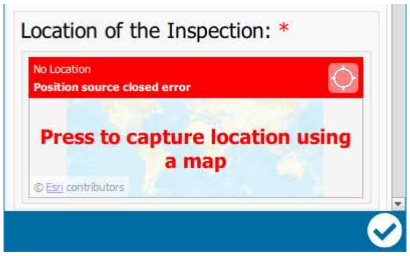
Date and Time of Inspection

Arrival Date and Time *

3/7/2017 1:04 PM

Figure 35. Industrial Meter Data Collection Survey – Group Collecting

6. Choose the Utility Company who is responsible for the site.
7. Verify that the Location of the Inspection is accurately represented on the map. Press the locator icon in the top right hand corner of the map if the map needs updated


Location of the Inspection: *

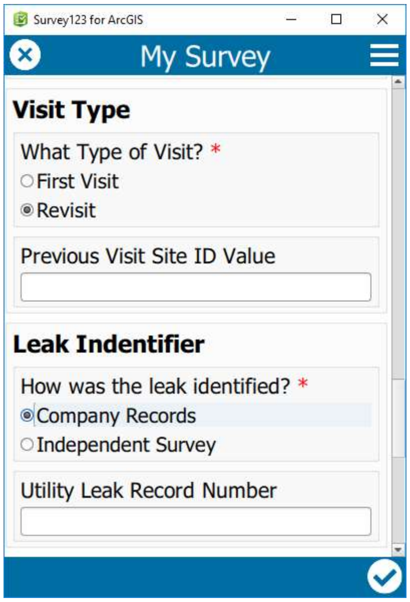
No Location
Position source closed error

Press to capture location using a map

© Esri contributors

Figure 36. Industrial Meter Data Collection Survey – Location Information

8. Select the type of visit. If this is the first time for any of the field crews participating in the study to visit this exact site, then select "First Visit" and no further information is required. A subset of sites will get revisited at later date. If this is the second time this site has been sampled then select "Revisit" which will up will open a box for "Previous Site ID Value." If known enter the "Unique Site ID" from the previous. If not known type "EL" in the box which stands for "enter later"
9. Next enter information on how the leak was found. If information from a utility company was used to directly find the leak select "Company Records," which will open a field called "Utility Leak Record Number." This field is to record the unique leak identifier/number used by the host company to track the leak. If not known at the time of the site visit enter "EL." If the leak was found by performing a random independent leak survey then select "Independent Survey". For instructions on performing these surveys refer to the Independent Surveys section below



Visit Type

What Type of Visit? *
○ First Visit
● Revisit

Previous Visit Site ID Value

Leak Indentifier

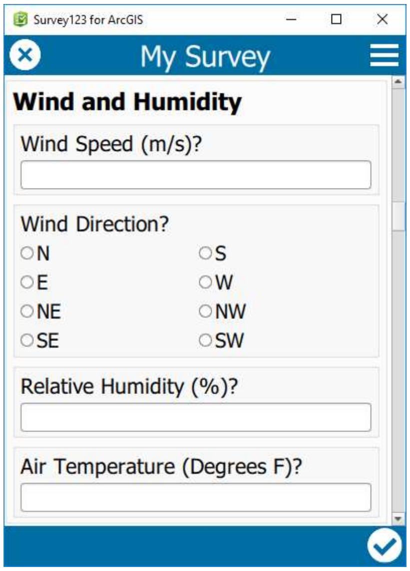
How was the leak identified? *
● Company Records
○ Independent Survey

Utility Leak Record Number

Figure 37. Industrial Meter Data Collection Survey – Visit Type and Leak Identifier

10. The next step is to determine if there is actually a leak present at the site. If no leak can be found answer "No" to the question "Upon visiting the site was a leak found?" **and proceed to step 24**. If a leak is found answer "Yes" which will open a new series of questions to be answered

11. The next information to be collected is on the local wind speed, direction, relative humidity and air temperature. These can be obtained from a weather app for the local area



Wind and Humidity

Wind Speed (m/s)?

Wind Direction?

○N	○S
○E	○W
○NE	○NW
○SE	○SW

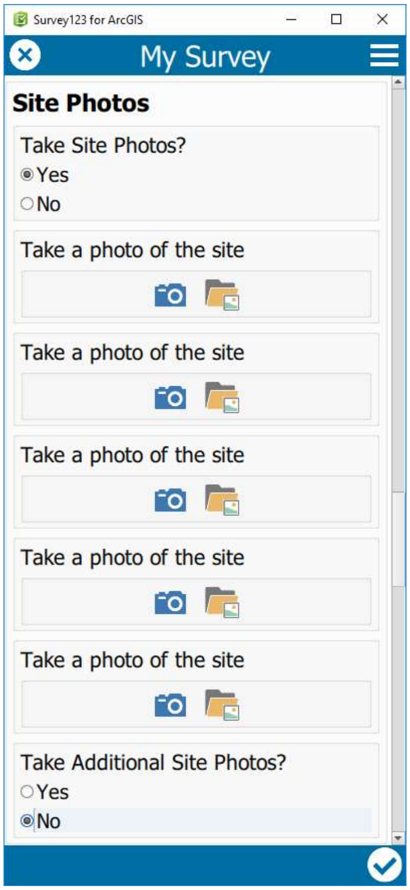
Relative Humidity (%)?

Air Temperature (Degrees F)?

Figure 38. Industrial Meter Data Collection Survey – Wind and Humidity

13. Next, document the site with photos by clicking "Yes" for "Take Site Photos". Select the camera icon to directly access the devices camera and attaching the photos to this record. If more than 5 photos are

needed, select “Yes” for “Take Additional Site Photos?” and 5 more options for photos will open



Site Photos

Take Site Photos?
● Yes
○ No

Take a photo of the site

Take a photo of the site

Take a photo of the site

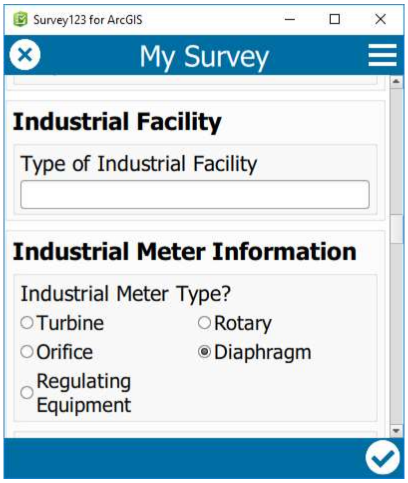
Take a photo of the site

Take a photo of the site

Take Additional Site Photos?
○ Yes
● No

Figure 39. Industrial Meter Data Collection Survey – Site Photos

14. Record the type of facility. This should be answered either based on company records, information from the company escort, or others (i.e., signs).
15. Determine the type of Industrial Meter from inspection.



Industrial Facility

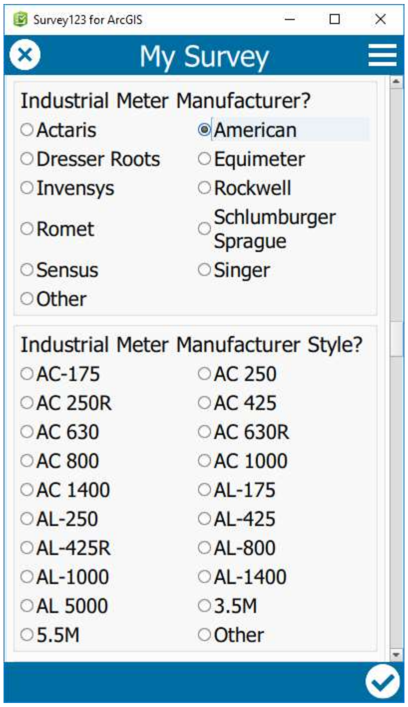
Type of Industrial Facility

Industrial Meter Information

Industrial Meter Type?
○ Turbine
○ Rotary
○ Orifice
● Diaphragm
○ Regulating Equipment

Figure 40. Industrial Meter Data Collection Survey –Meter Information

16. Determine the manufacturer and style/model of the industrial meter itself. When a particular manufacturer is selected the most well-known styles/models for that manufacturer appear. If the manufacturer and/or style/model do not show up select "Other" and text box will appear to record this information.



Industrial Meter Manufacturer?

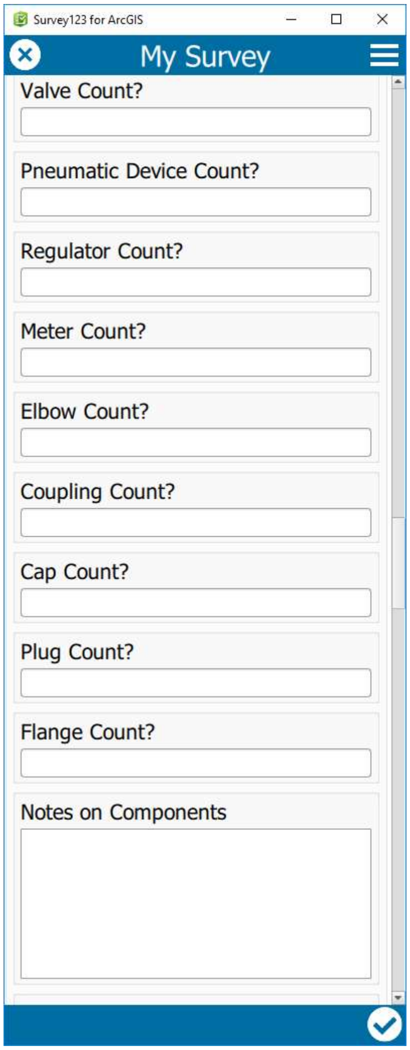
○ Actaris	● American
○ Dresser Roots	○ Equimeter
○ Invensys	○ Rockwell
○ Romet	○ Schlumburger Sprague
○ Sensus	○ Singer
○ Other	

Industrial Meter Manufacturer Style?

○ AC-175	○ AC 250
○ AC 250R	○ AC 425
○ AC 630	○ AC 630R
○ AC 800	○ AC 1000
○ AC 1400	○ AL-175
○ AL-250	○ AL-425
○ AL-425R	○ AL-800
○ AL-1000	○ AL-1400
○ AL 5000	○ 3.5M
○ 5.5M	○ Other

Figure 41. Industrial Meter Data Collection Survey –Meter Manufacturer

17. Next record the number of components associated with the entire meter set



Valve Count?

Pneumatic Device Count?

Regulator Count?

Meter Count?

Elbow Count?

Coupling Count?

Cap Count?

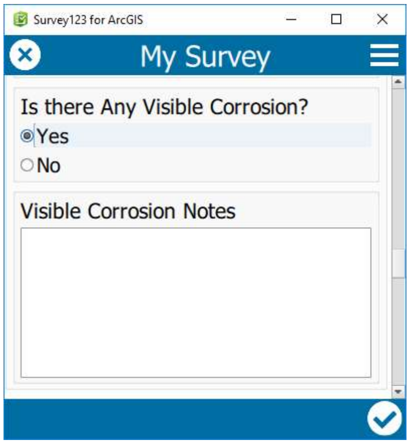
Plug Count?

Flange Count?

Notes on Components

Figure 42. Industrial Meter Data Collection Survey – Component Counts

18. Record and describe any visible corrosion the components



Is there Any Visible Corrosion?

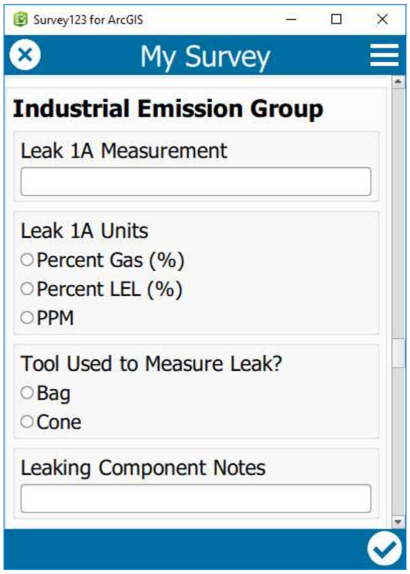
● Yes

○ No

Visible Corrosion Notes

Figure 43. Industrial Meter Data Collection Survey – Corrosion Notes

19. For each component that is found to be leaking record the highest concentration identified during the leak survey procedures associated with the first component being measured under "Leak 1A Measurement"
20. Select the type of enclosure for the component
21. In the "Leaking Component Notes" text box describe what type of component is being measured (i.e., valve, regulator, fitting).


Survey123 for ArcGIS

My Survey

Industrial Emission Group

Leak 1A Measurement

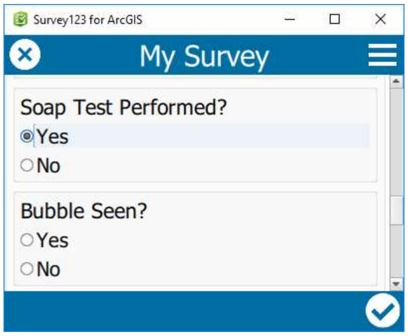
Leak 1A Units
○ Percent Gas (%)
○ Percent LEL (%)
○ PPM

Tool Used to Measure Leak?
○ Bag
○ Cone

Leaking Component Notes

Figure 44. Industrial Meter Data Collection Survey – Industrial Emission Information

22. Record whether a soap test was performed on the component and if so whether a bubble was seen


Survey123 for ArcGIS

My Survey

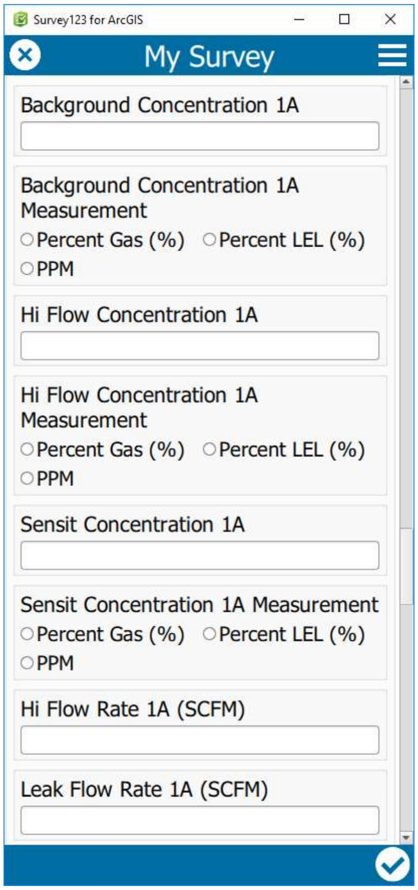
Soap Test Performed?
● Yes
○ No

Bubble Seen?
○ Yes
○ No

Figure 45. Industrial Meter Data Collection Survey – Soap Testing Results

12. Once the equipment is placed over the leak, the Hi Flow system is operated in the Hi-Low option for two minutes. Readings from the first two minutes are recorded under the 1A categories. "Background Concentration" is taken prior to attaching the Hi Flow to the leak (can be from the CGI attached to the Hi Flow hose). "Hi Flow Concentration" is what the reading was at the end of the 2 minute period on the Hi Flow readout. "Sensit Concentration" is an average of the concentration on the Sensit display during the two minute sampling. "Hi Flow Rate" is the flow rate measured by the sampler and "Leak Flow Rate" is the leak flow rate on the readout of the Hi Flow. Once one two minute sampling is completed, the measurements are repeated and recorded under the 1B categories (not shown), then repeated a third time and recorded under 1C (not shown). If other components are leaking, the equipment can be moved and then the option for

“More Readings?” can be answered yes to open a new set of measurements labeled 2A, 2B, and 2C. This can be repeated up to 5 times



Background Concentration 1A

Background Concentration 1A Measurement
○Percent Gas (%) ○Percent LEL (%)
○PPM

Hi Flow Concentration 1A

Hi Flow Concentration 1A Measurement
○Percent Gas (%) ○Percent LEL (%)
○PPM

Sensit Concentration 1A

Sensit Concentration 1A Measurement
○Percent Gas (%) ○Percent LEL (%)
○PPM

Hi Flow Rate 1A (SCFM)

Leak Flow Rate 1A (SCFM)

Figure 46. Industrial Meter Data Collection Survey – Leak Concentration Information

13. Once the flow rate measurement section of the survey is completed (or if there was no leak found) the next question asks whether the leak has been repaired. The answer to this question is likely not known at the time of sampling. Within six months of sampling the company records will be examined to answer this question at that time, regardless of whether a leak was found on the day to determine whether the leak had be fixed prior to (no leak found) or after (leak found) the visit.

Leak Repair

Was this Leak Repaired? *
● Yes
○ No

Repair Date
Date

What was Leaking?

What was Repaired or Replaced?

Figure 47. Industrial Meter Data Collection Survey – Leak Repair Information

14. The last question in the survey asks whether to attach a site drawing. For complex sites that cannot be fully document via the site photos, a drawing of the site may be needed. This drawing can be created either in a lab notebook or in a sketching app on the device being used to fill out the survey. In the case of the hand drawn lab notebook figure, use the camera option to take a photo of the page so that it will stay with this site. If a sketch is generated on the device, save it to the device then use the folder option to attach the file to this site.

Site Drawings and Photos

Attach Site Drawings?
● Yes
○ No

Attach a drawing of the site

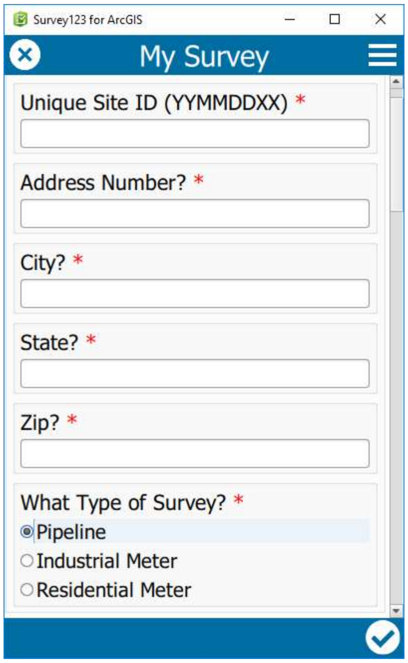
Figure 48. Industrial Meter Data Collection Survey – Site Drawings and Photos

8.2 Appendix - Buried Pipeline Data Collection Survey

The following is the list of steps to be completed upon visiting a site with an underground pipeline leak.

1. Upon arriving at a site, regardless of whether a leak is found, enter the Unique Site ID in the form YYMMDDXX where XX is the sequential number of the site on that date. The first site visited during the day will be 01, the second will be 02, third will be 03, and so on for the rest of the day. This ID will be a shorthand way of representing that site visit throughout analysis. Every visit to a site will get a "Unique Site ID" even if the site has been visited previously (linking to previous visits will occur later in the survey).

2. The next fields (Address Number, City, State, Zip) are obtained from a map or company records for the site.
3. Choose “Pipeline”.



Unique Site ID (YYMMDDXX) *

Address Number? *

City? *

State? *

Zip? *

What Type of Survey? *
● Pipeline
○ Industrial Meter
○ Residential Meter

Figure 49. Bured Pipeline Data Collection Survey – General Information

4. Choose the primary organization making the measurements
5. Choose the primary person with the organization who is responsible for measurements at this site
6. Date and Time of Inspection will automatically be populated by the program

Group Collecting

What organization do you represent? *
● GTI
○ GHD
○ AECOM

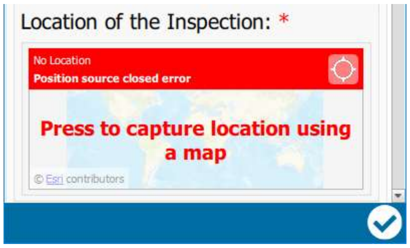
Who are You? *
○ Kristine Wiley
○ Mike Adamo
○ Chris Moore
○ Other

Date and Time of Inspection

Arrival Date and Time *
3/7/2017 1:04 PM

Figure 50. Bured Pipeline Data Collection Survey – Group Collecting

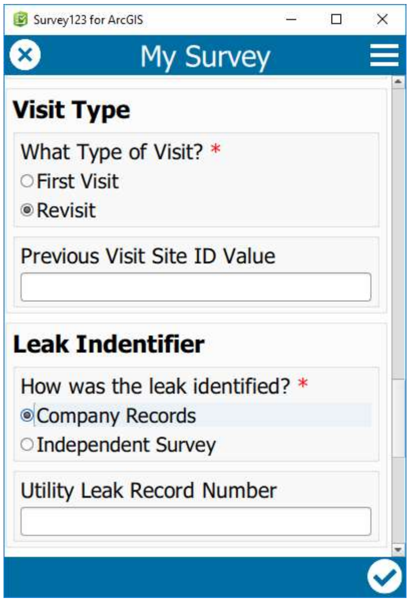
7. Choose the Utility Company who is responsible for the site.
8. Verify that the Location of the Inspection is accurately represented on the map. Press the locator icon in the top right hand corner of the map if the map needs updated


Location of the Inspection: *

No Location
Position source closed error

Figure 51. Bured Pipeline Data Collection Survey – Location Information

9. Select the type of visit. If this is the first time for any of the field crews participating in the study to visit this exact site then select "First Visit" and no further information is required. A subset of sites that will get revisited at later date. If this is the second time this site has been sampled then select "Revisit" which will open a box for "Previous Site ID Value." If known enter the "Unique Site ID" from the previous. If not known type "EL" in the box which stands for "enter later".
10. Next enter information on how the leak was found. If information from a utility company was used to directly find the leak select "Company Records," which will open a field called "Utility Leak Record Number." This field is to record the unique leak identifier/number used by the host company to track the leak. If not known at the time of the site visit enter "EL." If the leak was found by performing a random independent leak survey then select "Independent Survey". For instructions on performing these surveys refer to the Independent Surveys section below.



Visit Type

What Type of Visit? *
○ First Visit
● Revisit

Previous Visit Site ID Value

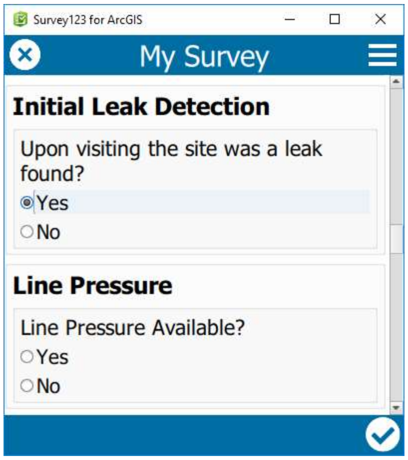
Leak Indentifier

How was the leak identified? *
● Company Records
○ Independent Survey

Utility Leak Record Number

Figure 52. Bured Pipeline Data Collection Survey – Visit Type and Leak Identifier

11. The next step is to determine if there is actually a leak present at the site. If no leak can be found answer "No" to the question "Upon visiting the site was a leak found?" **and proceed to step 21**. If a leak is found answer "Yes" which will open a new series of questions to be answered.



Initial Leak Detection

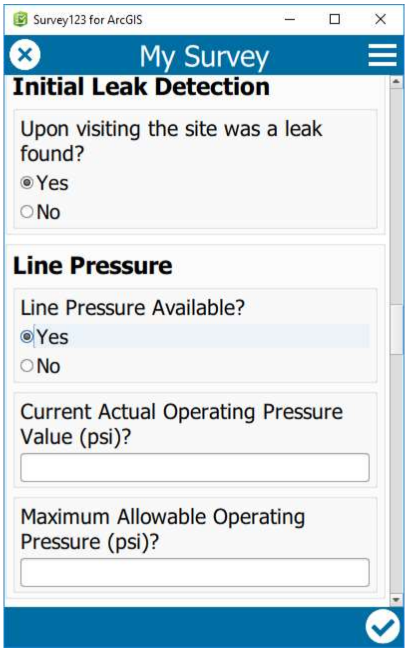
Upon visiting the site was a leak found?
● Yes
○ No

Line Pressure

Line Pressure Available?
○ Yes
○ No

Figure 53. Bured Pipeline Data Collection Survey – Leak Indication and Line Pressure

12. If a leak is found the first question to be answered pertains to the line pressure for the pipeline that is leaking. If any information is available select "Yes" which opens two additional fields "Current Actual Operating Pressure Value (psi)?" and "Maximum Allowable Operating Pressure (psi)?" Either or both of these values can be obtained from company records or it is also acceptable to obtain an estimate from the utility company representative.



Initial Leak Detection

Upon visiting the site was a leak found?
● Yes
○ No

Line Pressure

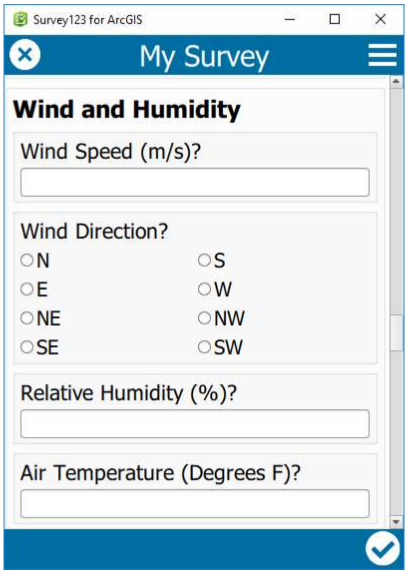
Line Pressure Available?
● Yes
○ No

Current Actual Operating Pressure Value (psi)?

Maximum Allowable Operating Pressure (psi)?

Figure 54. Bured Pipeline Data Collection Survey – Line Pressure Information

13. The next information to be collected is on the local wind speed, direction, relative humidity and air temperature. These can be obtained from a weather app for the local area.



Wind and Humidity

Wind Speed (m/s)?

Wind Direction?

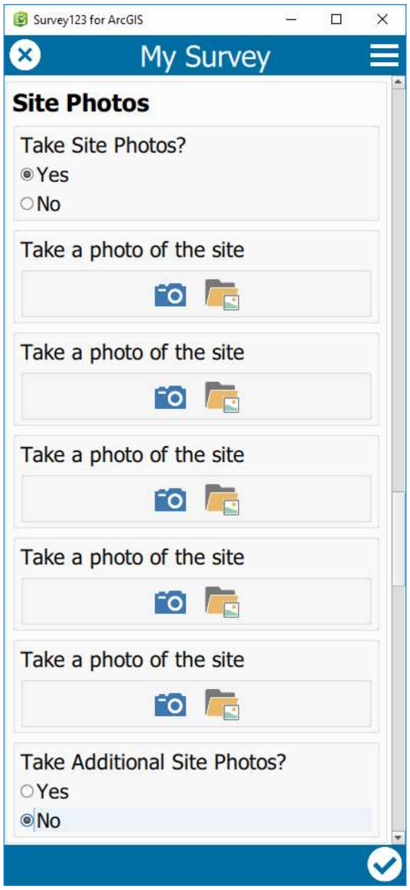
○ N	○ S
○ E	○ W
○ NE	○ NW
○ SE	○ SW

Relative Humidity (%)?

Air Temperature (Degrees F)?

Figure 55. Bured Pipeline Data Collection Survey – Wind and Humidity

14. Next, document the site with photos by clicking "Yes" for "Take Site Photos". Select the camera icon to directly access the devices camera and attaching the photos to this record. If more than 5 photos are needed, select "Yes" for "Take Additional Site Photos?" and 5 more options for photos will open.



Site Photos

Take Site Photos?
● Yes
○ No

Take a photo of the site

Take a photo of the site

Take a photo of the site

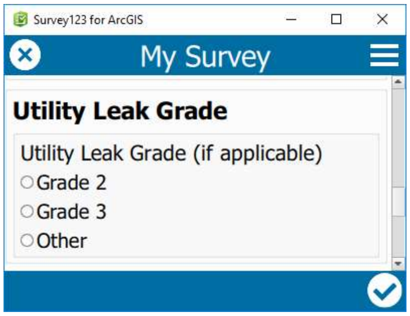
Take a photo of the site

Take a photo of the site

Take Additional Site Photos?
○ Yes
● No

Figure 56. Bured Pipeline Data Collection Survey – Site Photos

15. Determine the grade of leak from company records if this information exist.

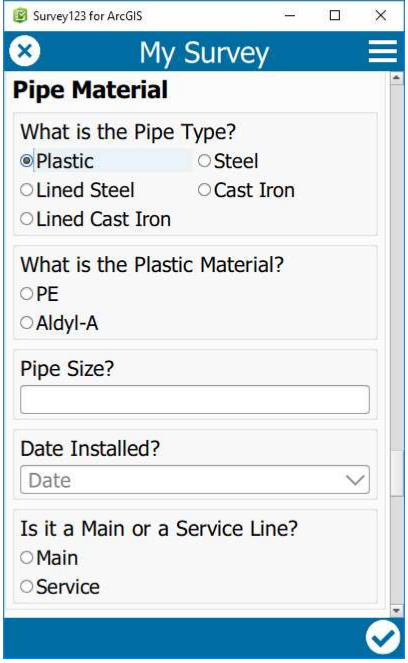


Utility Leak Grade

Utility Leak Grade (if applicable)
○ Grade 2
○ Grade 3
○ Other

Figure 57. Bured Pipeline Data Collection Survey – Leak Grade Information

16. Under Pipe Material enter as much information as possible, if unknown do not make a selection.
    a. If "Plastic" is selected new questions will appear asking whether it is PE or Aldyl-A, what the "Pipe Size" is, the "Date Installed", and whether it is a "Main" or "Service"
    b. If "Steel" is selected new questions will appear asking the "Pipe Size", whether the steel is "Protected" (if so how is it protected, "Wrapped" or "Cathodically Protected" or both) or "Unprotected/Bare," the "Date Installed", and whether it is a "Main" or "Service" (not shown).
    c. If "Lined Steel" is selected new questions will appear asking the "Pipe Size", whether the steel is "Protected" (if so how is it protected, "Wrapped" or "Cathodically Protected" or both) or "Unprotected/Bare," the "Date Installed", the "Date Lined (if different from original installation)" and whether it is a "Main" or "Service" (not shown).
    d. If "Cast Iron" is selected new questions will appear asking the "Pipe Size", the "Date Installed", and whether it is a "Main" or "Service" (not shown).
    e. If "Lined Cast Iron" is selected new questions will appear asking the "Pipe Size", the "Date Installed", the "Date Lined (if different from original installation)" and whether it is a "Main" or "Service" (not shown).



Pipe Material

What is the Pipe Type?
● Plastic ○ Steel
○ Lined Steel ○ Cast Iron
○ Lined Cast Iron

What is the Plastic Material?
○ PE
○ Aldyl-A

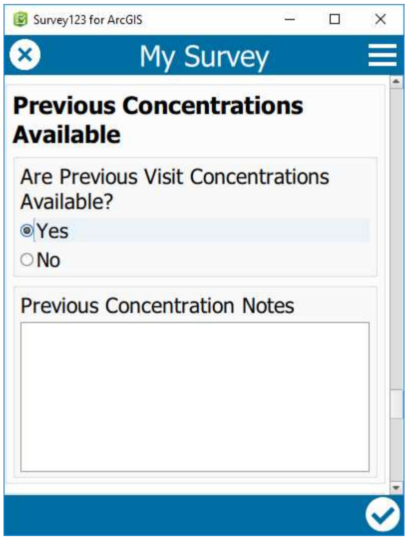
Pipe Size?

Date Installed?
Date

Is it a Main or a Service Line?
○ Main
○ Service

Figure 58. Bured Pipeline Data Collection Survey – Pipe Material

17. For “Previous Concentrations Available” select “Yes” if the site has been visited by company personnel and there are notes available on the CH_4 concentrations observed. A text box appears to type these notes. If notes are known to exist but are not available at the time of the site visit enter “EL”



Previous Concentrations Available

Are Previous Visit Concentrations Available?

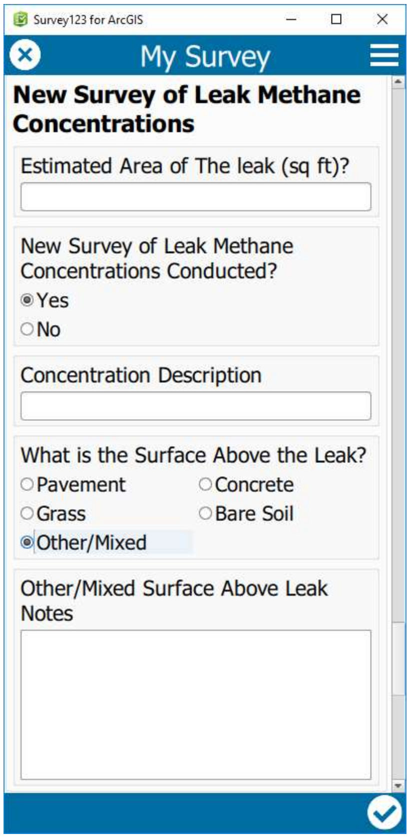
● Yes

○ No

Previous Concentration Notes

Figure 59. Bured Pipeline Data Collection Survey – Concentration Information

18. Now begins the active sampling procedures to determine the extent and rate of the leak. The ground above the leak should be surveyed with a combustible gas indicator (CGI) or similar instrument to determine the center point (i.e., the highest concentration). This is done by placing the inlet of the CGI right at the surface, *and inserted below the surface*. If this is an existing leak, there may already be a bar hole at the center of the leak. From the center point walk approximately north, south, east and west until no gas is detected. Place a marker and measure the approximate area of the leak with a tape measurer. Enter this area in the box for “Estimated Area of The leak (sq ft)?” Select “Yes” for “New Survey of Leak CH_4 Concentrations Conducted?” Then enter the concentration measured at the center point. If the center point is a bar hole, record the concentration level with the top of the opening of the bar hole.
    a. Also take note of the surface type by answering the question “What is the Surface Above the Leak?” If “Other/Mixed” is selected a text box appears to make notes on the type of surface.



New Survey of Leak Methane Concentrations

Estimated Area of The leak (sq ft)?

New Survey of Leak Methane Concentrations Conducted?
● Yes
○ No

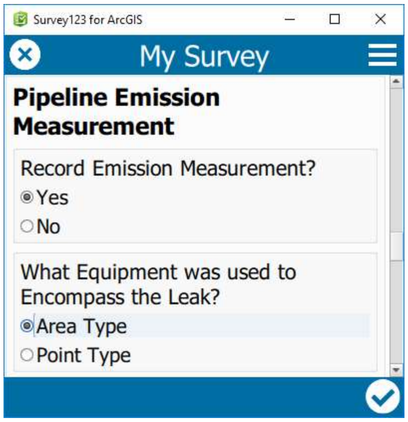
Concentration Description

What is the Surface Above the Leak?
○ Pavement ○ Concrete
○ Grass ○ Bare Soil
● Other/Mixed

Other/Mixed Surface Above Leak Notes

Figure 60. Bured Pipeline Data Collection Survey – Concentration Information

19. Now perform the leak flow rate quantification with a Hi Flow sampler. Select "Yes" for the "Record Emission Measurement?" question. Then select the type of enclosure used to measure the leak. "Area Type" indicates a large enclosure such as a 4' x 8' inflatable pool while "Point Type" indicates the plunger attachment for the Hi Flow



Pipeline Emission Measurement

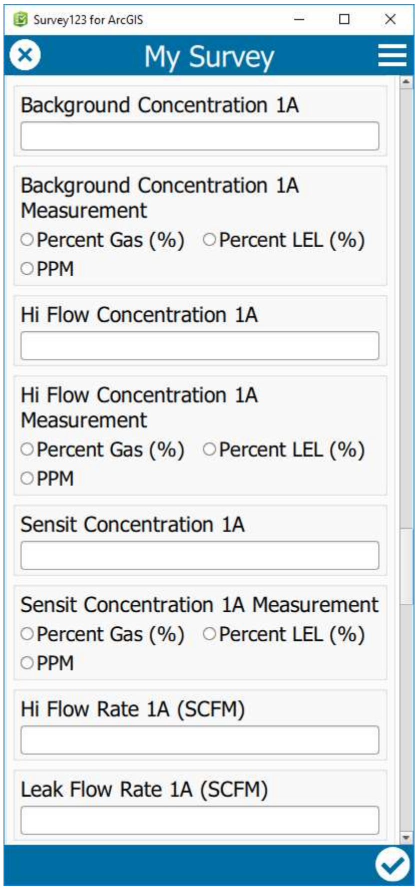
Record Emission Measurement?
● Yes
○ No

What Equipment was used to Encompass the Leak?
● Area Type
○ Point Type

Figure 61. Bured Pipeline Data Collection Survey – Emission Measurement Infomation

20. Once the equipment is placed over the leak, the Hi Flow system is operated in the Hi-Low option for two minutes. Readings from the first two minutes are recorded under the 1A categories. "Background Concentration" is taken prior to attaching the hose to the pool enclosure or placing

the plunger over the leak (from a CGI attached to the Hi Flow hose). “Hi Flow Concentration” is what the reading was at the end of the 2 minute period on the Hi Flow readout. “Sensit Concentration” is an average of the concentration on the Sensit display during the two minute sampling. “Hi Flow Rate” is the flow rate measured by the sampler and “Leak Flow Rate” is the leak flow rate on the readout of the Hi Flow. Once one two minute sampling is completed, the measurements are repeated and recorded under the 1B categories (not shown), then repeated a third time and recorded under 1C (not shown). If the leak is too large to be encompassed by a single pool or point measurement, the equipment can be moved and then the option for “More Readings?” can be answered yes to open a new set of measurements labeled 2A, 2B, and 2C. This can be repeated up to 20 times



Background Concentration 1A

Background Concentration 1A Measurement
○ Percent Gas (%) ○ Percent LEL (%)
○ PPM

Hi Flow Concentration 1A

Hi Flow Concentration 1A Measurement
○ Percent Gas (%) ○ Percent LEL (%)
○ PPM

Sensit Concentration 1A

Sensit Concentration 1A Measurement
○ Percent Gas (%) ○ Percent LEL (%)
○ PPM

Hi Flow Rate 1A (SCFM)

Leak Flow Rate 1A (SCFM)

Figure 62. Bured Pipeline Data Collection Survey – Flow Rate and Concentration Information

21. Once the flow rate measurement section of the survey is completed (or if there was no leak found) the next question asks whether the leak has been repaired. The answer to this question is likely not known at the time of sampling. Within six months of sampling the company records will be examined to answer this question at that time, regardless of whether a leak was found on the day to determine whether the leak had be fixed prior to (no leak found) or after (leak found) the visit

Leak Repair

Was this Leak Repaired? *
● Yes
○ No

Repair Date
Date

What was Leaking?

What was Repaired or Replaced?

Figure 63. Bured Pipeline Data Collection Survey – Leak Repair Information

22. The last question in the survey asks whether to attach a site drawing. For complex sites that cannot be fully document via the site photos, a drawing of the site may be needed. This drawing can be created either in a lab notebook or in a sketching app on the device being used to fill out the survey. In the case of the hand drawn lab notebook figure, use the camera option to take a photo of the page so that it will stay with this site. If a sketch is generated on the device, save it to the device then use the folder option to attach the file to this site.

Site Drawings and Photos

Attach Site Drawings?
● Yes
○ No

Attach a drawing of the site

Figure 64. Bured Pipeline Data Collection Survey – Site Drawings and Photos

8.3 Appendix – Leak Quantification Threshold Discussion

Figure 65 shows the quantified emission rate vs. the leak indication concentration for all leaks. Several things can be gathered from this figure. First, there was no correlation between measured emission rate and leak indication concentration. Second, the red line on Figure 65 shows an indication concentration of 22,500 ppm, to the left of this line shows the 245 leaks that were quantified that had an indication concentration between 100 ppm and 22,500 ppm. Based on that red line, we can conclude that our 22,500 ppm quantification threshold was effective at capturing larger leaks, since no larger leaks were measured with an indication concentration below 22,500 ppm.

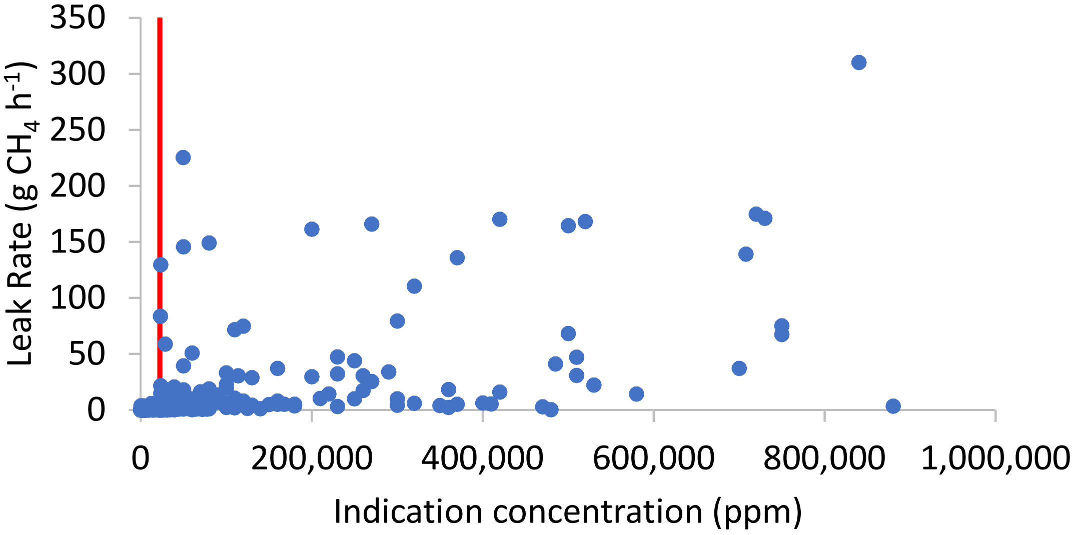


Figure 65. Indication concentration vs. quantified leak rate.

8.4 Appendix – Component-Based Data Statistical Summary Tables

Table 24. Summary Statistics for Leaker-Only Quantified Component Emission Rates (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Quantified
All	0.001	0.048	0.593	4.524	310.330	10.290	32.500	458
Cap	0.008	0.106	0.554	0.834	149.104	25.184	60.709	6
Coupling	0.001	0.017	0.059	0.340	170.299	9.594	33.968	43
Elbow	0.001	0.011	0.039	0.149	68.446	2.635	10.719	50
Flange	0.007	0.189	1.172	5.589	310.330	13.709	46.295	58
Meter	0.008	0.074	0.165	5.895	161.469	22.956	50.967	11
Other	0.001	0.059	1.014	4.057	225.589	7.222	29.693	75
Plug	0.001	0.171	1.571	5.415	37.299	5.037	8.795	35
Regulator	0.001	0.036	0.768	4.297	166.128	12.772	35.432	42
Tee	0.005	0.020	0.032	2.039	4.831	1.284	1.999	7
Valve	0.003	0.141	2.272	6.049	174.893	12.823	31.961	130

Table 25. Summary Statistics for Leaker-Only Quantified Plus Mean Modeled Component Emission Rates (g CH4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Quantified
All	0.001	0.302	0.310	0.318	310.330	3.411	18.683	1474
Cap	0.008	0.302	0.307	0.313	149.104	7.091	31.720	22
Coupling	0.001	0.293	0.308	0.314	170.299	3.357	19.797	131
Elbow	0.001	0.297	0.307	0.313	68.446	1.036	6.048	160
Flange	0.007	0.304	0.311	0.317	310.330	2.917	20.966	298
Meter	0.008	0.287	0.308	0.324	161.469	10.274	34.843	25
Other	0.001	0.302	0.312	0.319	225.589	2.839	18.192	205
Plug	0.001	0.303	0.310	0.318	37.299	1.563	4.946	132
Regulator	0.001	0.301	0.311	0.323	166.128	5.343	23.184	104
Tee	0.005	0.300	0.307	0.314	4.831	0.404	0.654	71
Valve	0.003	0.305	0.312	0.479	174.893	5.316	21.081	325

Table 26. Summary Statistics for Leaker-Only Quantified plus Median Modeled Component Emission Rates (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Quantified
All	0.001	0.051	0.052	0.053	310.330	3.233	18.713	1474
Cap	0.008	0.052	0.052	0.053	149.104	6.906	31.761	22
Coupling	0.001	0.051	0.052	0.053	170.299	3.184	19.825	131
Elbow	0.001	0.051	0.052	0.053	68.446	0.859	6.070	160
Flange	0.007	0.052	0.052	0.053	310.330	2.710	20.992	298
Meter	0.008	0.051	0.053	0.142	161.469	10.130	34.886	25
Other	0.001	0.051	0.052	0.112	225.589	2.675	18.215	205
Plug	0.001	0.051	0.053	0.054	37.299	1.374	4.995	132
Regulator	0.001	0.051	0.053	0.132	166.128	5.189	23.218	104
Tee	0.005	0.051	0.052	0.053	4.831	0.173	0.692	71
Valve	0.003	0.051	0.053	0.479	174.893	5.161	21.118	325

Table 27. Summary Statistics for Population Quantified Component Emission Rates (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.000	0.000	0.000	0.000	310.330	0.191	4.636	24670
Cap	0.000	0.000	0.000	0.000	149.104	0.356	7.241	424
Coupling	0.000	0.000	0.000	0.000	170.299	0.136	4.158	3030
Elbow	0.000	0.000	0.000	0.000	68.446	0.040	1.353	3261
Flange	0.000	0.000	0.000	0.000	310.330	0.142	4.878	5588
Meter	0.000	0.000	0.000	0.000	161.469	0.413	7.199	612
Plug	0.000	0.000	0.000	0.000	37.299	0.051	1.007	3458
Regulator	0.000	0.000	0.000	0.000	166.128	0.447	6.963	1199
Tee	0.000	0.000	0.000	0.000	4.831	0.007	0.165	1310
Valve	0.000	0.000	0.000	0.000	174.893	0.288	5.138	5785

Table 28. Summary Statistics for Population Quantified Plus Mean Modeled Component Emission Rates (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.000	0.000	0.000	0.000	310.330	0.204	4.636	24670
Cap	0.000	0.000	0.000	0.000	149.104	0.368	7.241	424
Coupling	0.000	0.000	0.000	0.000	170.299	0.145	4.158	3030
Elbow	0.000	0.000	0.000	0.000	68.446	0.051	1.354	3261
Flange	0.000	0.000	0.000	0.000	310.330	0.156	4.878	5588
Meter	0.000	0.000	0.000	0.000	161.469	0.420	7.199	612
Plug	0.000	0.000	0.000	0.000	37.299	0.060	1.008	3458
Regulator	0.000	0.000	0.000	0.000	166.128	0.463	6.962	1199
Tee	0.000	0.000	0.000	0.000	4.831	0.022	0.177	1310
Valve	0.000	0.000	0.000	0.000	174.893	0.299	5.137	5785

Table 29. Summary Statistics for Population Quantified Plus Median Modeled Component Emission Rates (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.000	0.000	0.000	0.000	310.330	0.193	4.636	24670
Cap	0.000	0.000	0.000	0.000	149.104	0.358	7.241	424
Coupling	0.000	0.000	0.000	0.000	170.299	0.138	4.158	3030
Elbow	0.000	0.000	0.000	0.000	68.446	0.042	1.353	3261
Flange	0.000	0.000	0.000	0.000	310.330	0.145	4.878	5588
Meter	0.000	0.000	0.000	0.000	161.469	0.414	7.199	612
Plug	0.000	0.000	0.000	0.000	37.299	0.052	1.007	3458
Regulator	0.000	0.000	0.000	0.000	166.128	0.450	6.963	1199
Tee	0.000	0.000	0.000	0.000	4.831	0.009	0.165	1310
Valve	0.000	0.000	0.000	0.000	174.893	0.290	5.138	5785

8.5 Appendix – Regional-Based Meter Set Data Statistical Summary Tables

Table 30. Summary Statistics for Leaker-Only Regional Industrial/Commercial Meter Set Emission Rates (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Quantified
All	0.001	0.283	2.815	10.26	358.1	20.9	50.1	225
Midwest	0.001	0.051	0.489	2.51	145.8	8.4	25.0	93
Northeast	1.259	3.758	8.335	14.01	171.3	16.4	32.8	26
Pacific	0.046	0.142	0.545	2.73	82.3	3.6	13.4	37
Rocky	1.629	2.532	5.449	138.74	166.1	53.3	74.7	9
Southeast	0.089	1.523	6.108	16.74	317.2	30.5	73.0	19
Southwest	1.043	6.322	19.581	59.10	358.1	56.3	77.9	41

Table 31. Summary Statistics for Population Regional Industrial/Commercial Meter Set Emission Rates (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.000	0.000	0.000	1.27	358.1	9.0	34.4	523
Midwest	0.000	0.000	0.007	0.65	145.8	4.4	18.6	176
Northeast	0.000	0.000	0.000	3.15	171.3	4.9	19.1	88
Pacific	0.000	0.000	0.000	0.13	82.3	1.2	7.7	115
Rocky	0.000	0.000	0.000	4.55	166.1	22.9	54.4	21
Southeast	0.000	1.017	5.627	15.52	317.2	29.0	71.4	20
Southwest	0.000	0.000	0.000	10.86	358.1	22.4	56.1	103

8.6 Appendix – Meter Type Based Meter Set Data Statistical Summary Tables

Table 32. Summary statistics for Leaker-Only Industrial/Commercial Meter Set Emission Rates by Meter Type (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Quantified
All	0.001	0.283	2.815	10.26	358.1	20.9	50.1	225
Rotary	0.001	0.209	1.593	5.66	173.1	13.9	34.8	124
Diaphragm	0.002	0.072	1.221	8.66	225.6	14.7	40.9	48
Turbine	0.089	2.892	8.564	40.23	358.1	42.2	76.6	50

Table 33. Summary Statistics for Population Industrial/Commercial Meter Set Emission Rates by Meter Type (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.000	0.000	0.000	1.27	358.1	9.0	34.4	523
Rotary	0.000	0.000	0.000	0.81	173.1	5.7	23.2	303
Diaphragm	0.000	0.000	0.000	0.25	225.6	5.9	26.8	119
Turbine	0.000	0.000	0.185	9.42	358.1	22.5	59.5	94

8.7 Appendix – Company Based Meter Set Data Statistical Summary Tables

Table 34. Summary statistics for Leaker-Only Industrial/Commercial Meter Set Emission Rates by Company (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Quantified
All	0.001	0.283	2.815	10.26	358.1	20.9	50.1	225
A	2.684	7.508	29.264	141.69	225.6	70.1	75.1	20
B	0.001	0.031	0.106	0.67	69.5	2.8	12.0	64
C	1.259	3.758	8.335	14.01	171.3	16.4	32.8	26
D	NA	NA	NA	NA	NA	NA	NA	0
E	0.477	0.888	1.457	2.41	12.4	2.7	3.4	12
F	1.043	5.365	16.402	43.20	358.1	43.2	80.0	21
G	0.046	0.136	0.315	1.29	82.3	3.4	14.2	33
H	0.089	1.523	6.108	16.74	317.2	30.5	73.0	19
I	3.208	4.626	5.145	5.30	5.6	4.8	1.1	4
J	1.870	3.584	6.842	40.23	145.8	33.7	46.8	17
K	1.629	2.532	5.449	138.74	166.1	53.3	74.7	9

Table 35. Summary Statistics for Population Industrial/Commercial Meter Set Emission Rates by Company (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.000	0.000	0.000	1.27	358.1	9.0	34.4	523
A	0.000	0.000	0.000	6.98	225.6	23.4	54.1	60
B	0.000	0.007	0.051	0.42	69.5	2.3	10.9	78
C	0.000	0.000	0.000	3.15	171.3	4.9	19.1	88
D	0.000	0.000	0.000	0.00	0.0	0.0	NA	1
E	0.000	0.000	0.000	0.56	12.4	0.7	2.1	43
F	0.000	0.000	0.000	15.29	358.1	21.1	59.4	43
G	0.000	0.000	0.050	0.33	82.3	1.8	10.4	63
H	0.000	1.017	5.627	15.52	317.2	29.0	71.4	20
I	0.000	0.000	0.000	0.00	5.6	0.4	1.3	52
J	0.000	0.000	0.000	2.60	145.8	10.6	30.2	54
K	0.000	0.000	0.000	4.55	166.1	22.9	54.4	21

8.8 Appendix – Facility Type Meter Set Data Statistical Summary Tables

Table 36. Summary statistics for Leaker-Only Industrial/Commercial Meter Set Emission Rates by Facility Type (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Quantified
All	0.001	0.283	2.815	10.26	358.1	20.9	50.1	225
Industrial	0.008	0.877	5.146	15.35	358.1	31.7	66.9	79
Commercial	0.001	0.138	1.732	7.54	225.6	15.1	37.1	146

Table 37. Summary Statistics for Population Industrial/Commercial Meter Set Emission Rates by Facility Type (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.000	0.000	0.000	1.27	358.1	9.0	34.4	523
Industrial	0.000	0.000	0.000	2.89	358.1	13.5	46.2	186
Commercial	0.000	0.000	0.000	1.03	225.6	6.5	25.5	337

8.9 Appendix – Facility Type Meter Set by Region Data Statistical Summary Tables

Table 38. Summary Statistics for Industrial Facility Meter Set Leaker-Only Emission Rates by Region (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.008	0.877	5.146	15.35	358.1	31.7	66.9	79
Midwest	0.008	0.187	0.999	6.80	136.0	13.1	29.7	35
Northeast	2.878	7.043	18.890	35.47	171.3	42.7	64.5	6
Pacific	0.190	1.182	3.208	5.10	82.3	11.5	26.6	9
Rocky	1.629	4.548	6.399	152.63	166.1	66.3	85.2	5
Southeast	0.380	2.614	8.003	16.74	317.2	33.3	80.7	15
Southwest	3.493	12.040	16.402	149.10	358.1	94.6	119.4	9

Table 39. Summary Statistics for Commercial Facility Meter Set Leaker-Only Emission Rates by Region (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.001	0.138	1.732	7.54	225.6	15.1	37.1	146
Midwest	0.001	0.035	0.305	1.21	145.8	5.5	21.5	58
Northeast	1.259	3.727	6.919	10.84	23.4	8.6	6.3	20
Pacific	0.046	0.113	0.304	1.19	5.2	1.0	1.4	28
Rocky	1.834	2.357	3.990	38.77	138.7	37.1	67.8	4
Southeast	0.089	0.160	1.980	21.70	75.5	19.9	37.1	4
Southwest	1.043	5.172	22.436	51.56	225.6	45.6	60.0	32

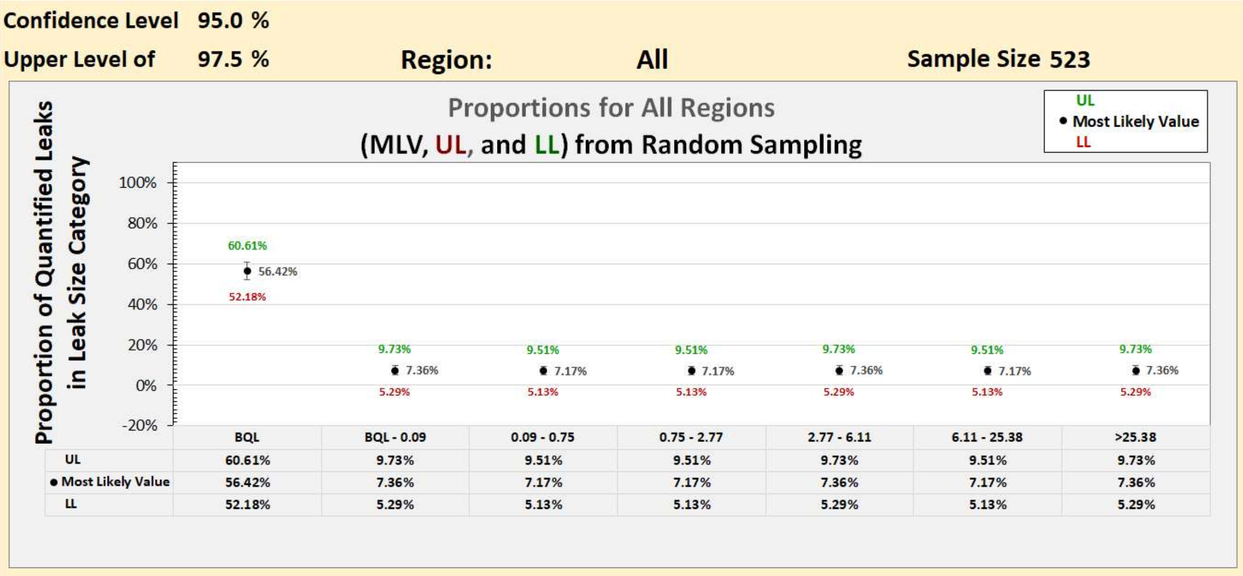
Table 40. Summary Statistics for Industrial Facility Meter Set Population Emission Rates by Region (g CH_4 h^{-1})

	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.000	0.000	0.000	2.89	358.1	13.5	46.2	186
Midwest	0.000	0.000	0.000	0.85	136.0	6.0	20.9	77
Northeast	0.000	0.000	0.000	9.13	171.3	19.7	47.1	13
Pacific	0.000	0.000	0.000	0.00	82.3	2.0	11.4	52
Rocky	0.000	0.000	1.629	6.40	166.1	36.8	69.6	9
Southeast	0.380	2.614	8.003	16.74	317.2	33.3	80.7	15
Southwest	0.000	0.000	0.000	14.38	358.1	42.6	91.3	20

Table 41. Summary Statistics for Commercial Facility Meter Set Population Emission Rates by Region (g CH_4 h^{-1})

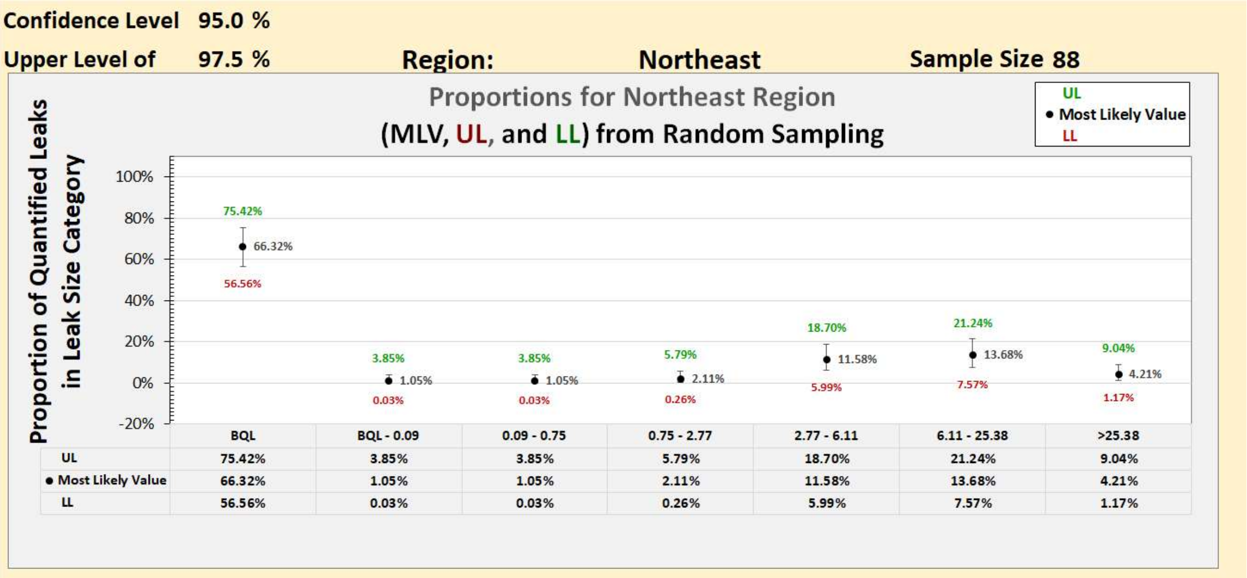
	Minimum	25% Percentile	Median	75% Percentile	Maximum	Mean	Standard Deviation	Total Sample Size
All	0.001	0.138	1.732	7.54	225.6	15.1	37.1	146
Midwest	0.001	0.035	0.305	1.21	145.8	5.5	21.5	58
Northeast	1.259	3.727	6.919	10.84	23.4	8.6	6.3	20
Pacific	0.046	0.113	0.304	1.19	5.2	1.0	1.4	28
Rocky	1.834	2.357	3.990	38.77	138.7	37.1	67.8	4
Southeast	0.089	0.160	1.980	21.70	75.5	19.9	37.1	4
Southwest	1.043	5.172	22.436	51.56	225.6	45.6	60.0	32

8.10 Appendix - Additional Bayesian Analysis by Region



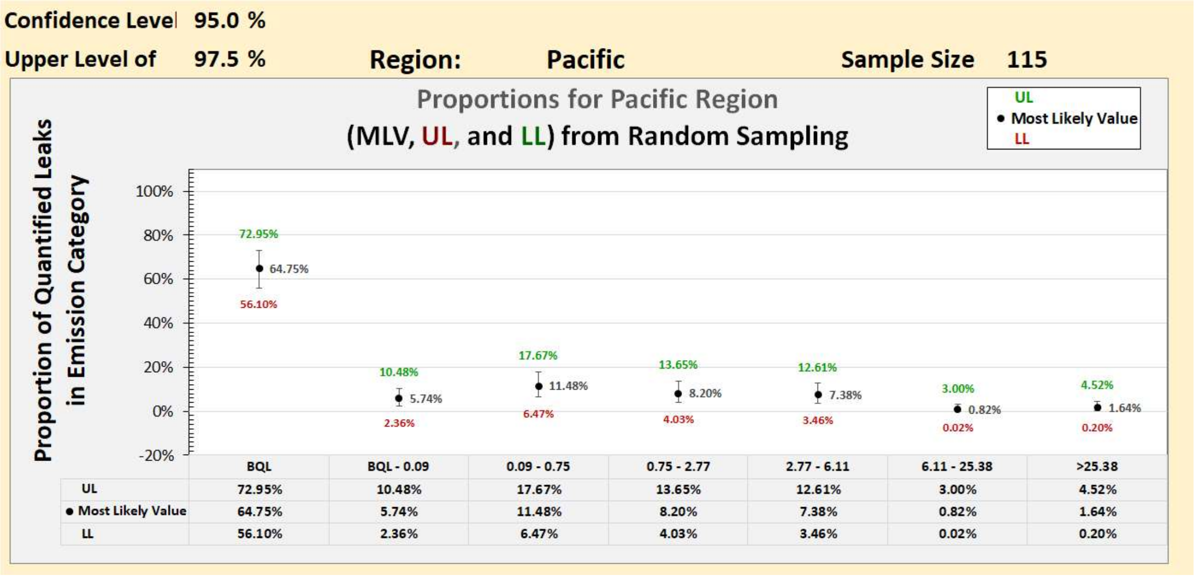
	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	60.61%	9.73%	9.51%	9.51%	9.73%	9.51%	9.73%
● Most Likely Value	56.42%	7.36%	7.17%	7.17%	7.36%	7.17%	7.36%
LL	52.18%	5.29%	5.13%	5.13%	5.29%	5.13%	5.29%

Figure 66. Updated Probability of Quantified Leak Sizes for All Regions



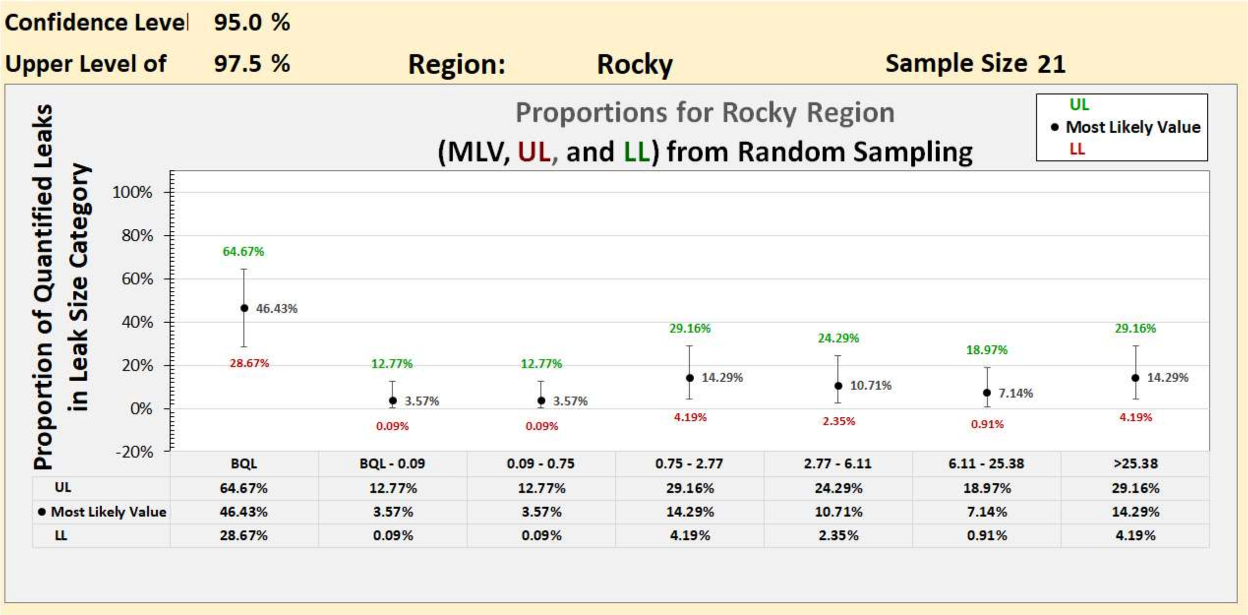
	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	75.42%	3.85%	3.85%	5.79%	18.70%	21.24%	9.04%
● Most Likely Value	66.32%	1.05%	1.05%	2.11%	11.58%	13.68%	4.21%
LL	56.56%	0.03%	0.03%	0.26%	5.99%	7.57%	1.17%

Figure 67. Updated Probability of Quantified Leak Sizes for the Northeast Region



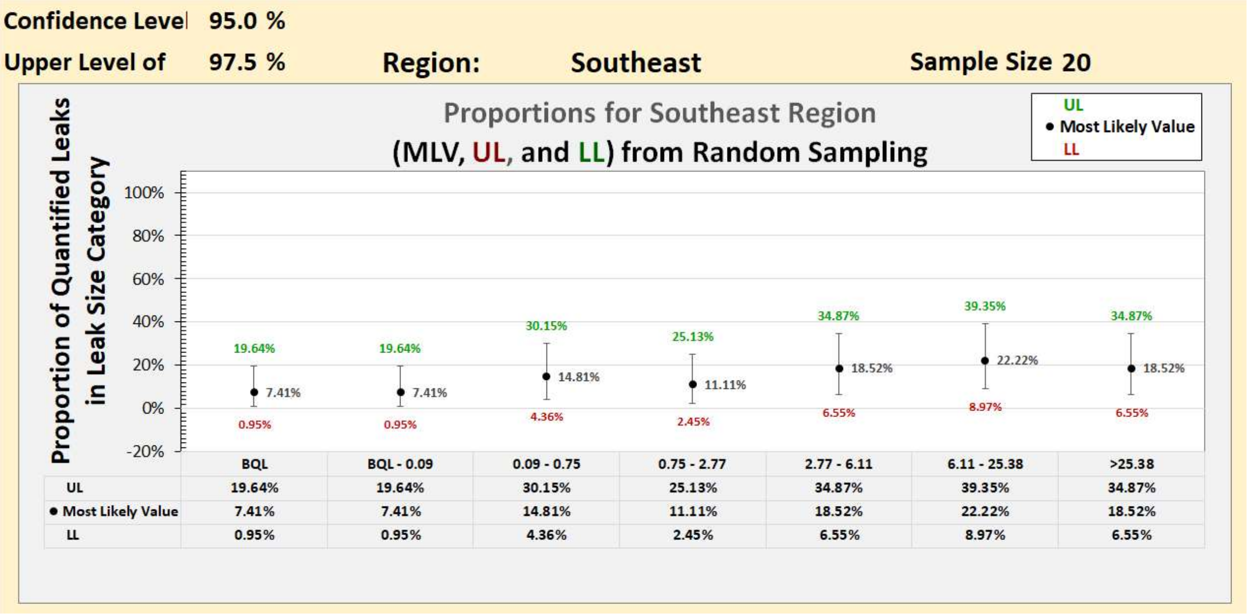
	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	72.95%	10.48%	17.67%	13.65%	12.61%	3.00%	4.52%
● Most Likely Value	64.75%	5.74%	11.48%	8.20%	7.38%	0.82%	1.64%
LL	56.10%	2.36%	6.47%	4.03%	3.46%	0.02%	0.20%

Figure 68. Updated Probability of Quantified Leak Sizes for the Pacific Region



	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	64.67%	12.77%	12.77%	29.16%	24.29%	18.97%	29.16%
● Most Likely Value	46.43%	3.57%	3.57%	14.29%	10.71%	7.14%	14.29%
LL	28.67%	0.09%	0.09%	4.19%	2.35%	0.91%	4.19%

Figure 69. Updated Probability of Quantified Leak Sizes for the Rocky Region



Confidence Level 95.0 %

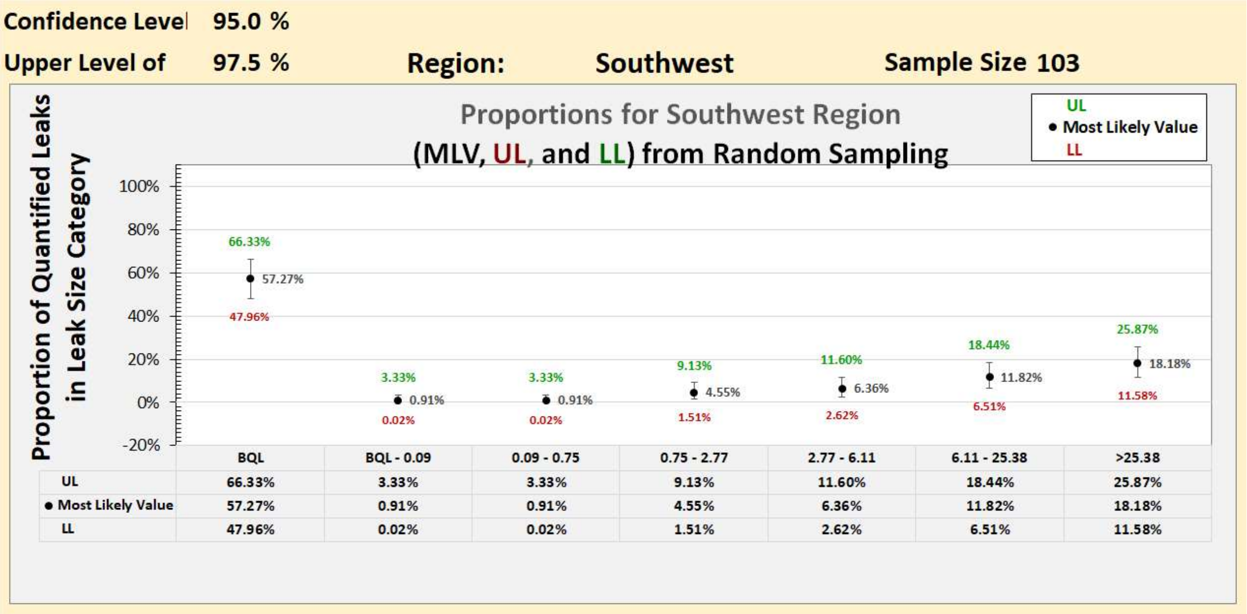
Upper Level of 97.5 %

Region: Southeast

Sample Size 20

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	19.64%	19.64%	30.15%	25.13%	34.87%	39.35%	34.87%
● Most Likely Value	7.41%	7.41%	14.81%	11.11%	18.52%	22.22%	18.52%
LL	0.95%	0.95%	4.36%	2.45%	6.55%	8.97%	6.55%

Figure 70. Updated Probability of Quantified Leak Sizes for the Southeast Region



Confidence Level 95.0 %

Upper Level of 97.5 %

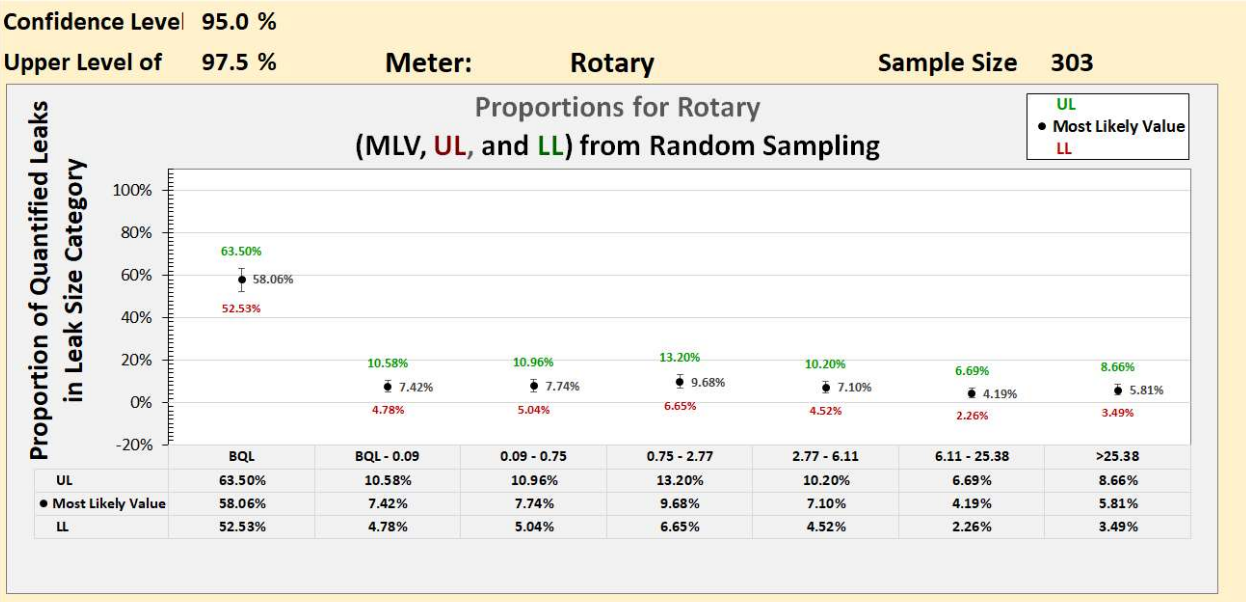
Region: Southwest

Sample Size 103

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	66.33%	3.33%	3.33%	9.13%	11.60%	18.44%	25.87%
● Most Likely Value	57.27%	0.91%	0.91%	4.55%	6.36%	11.82%	18.18%
LL	47.96%	0.02%	0.02%	1.51%	2.62%	6.51%	11.58%

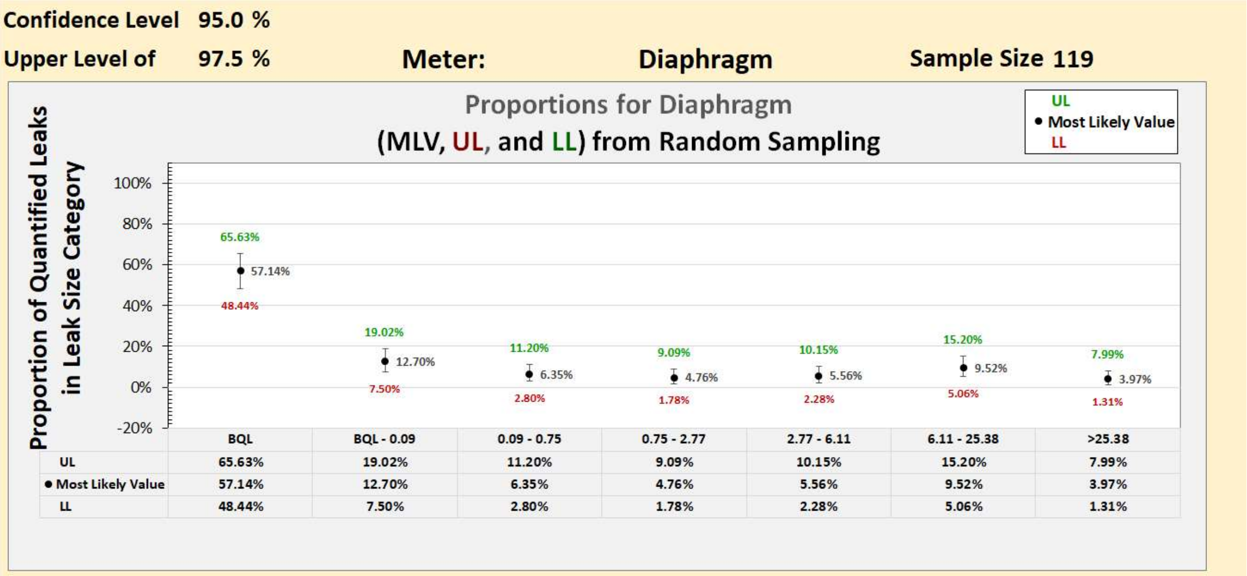
Figure 71. Updated Probability of Quantified Leak Sizes for the Southwest Region

8.11 Appendix – Additional Bayesian Analysis by Meter Set Type


Confidence Level 95.0 %
Upper Level of 97.5 %
Meter: Rotary
Sample Size 303

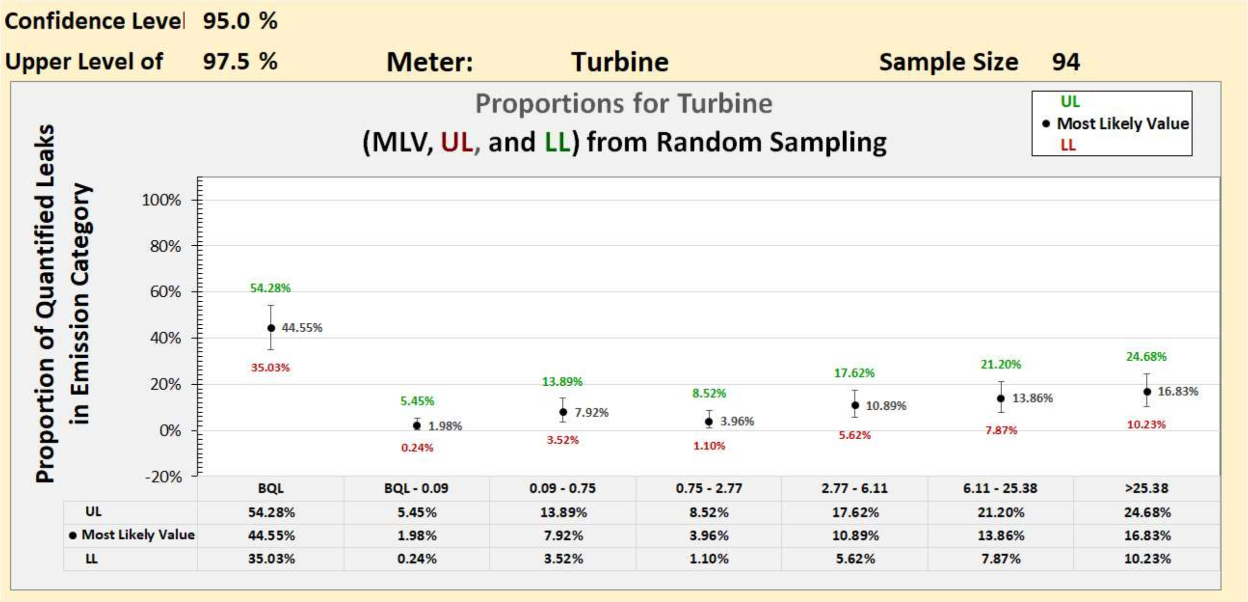
	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	63.50%	10.58%	10.96%	13.20%	10.20%	6.69%	8.66%
● Most Likely Value	58.06%	7.42%	7.74%	9.68%	7.10%	4.19%	5.81%
LL	52.53%	4.78%	5.04%	6.65%	4.52%	2.26%	3.49%

Figure 72. Updated Probability of Quantified Leak Sizes for Rotary Meters


Confidence Level 95.0 %
Upper Level of 97.5 %
Meter: Diaphragm
Sample Size 119

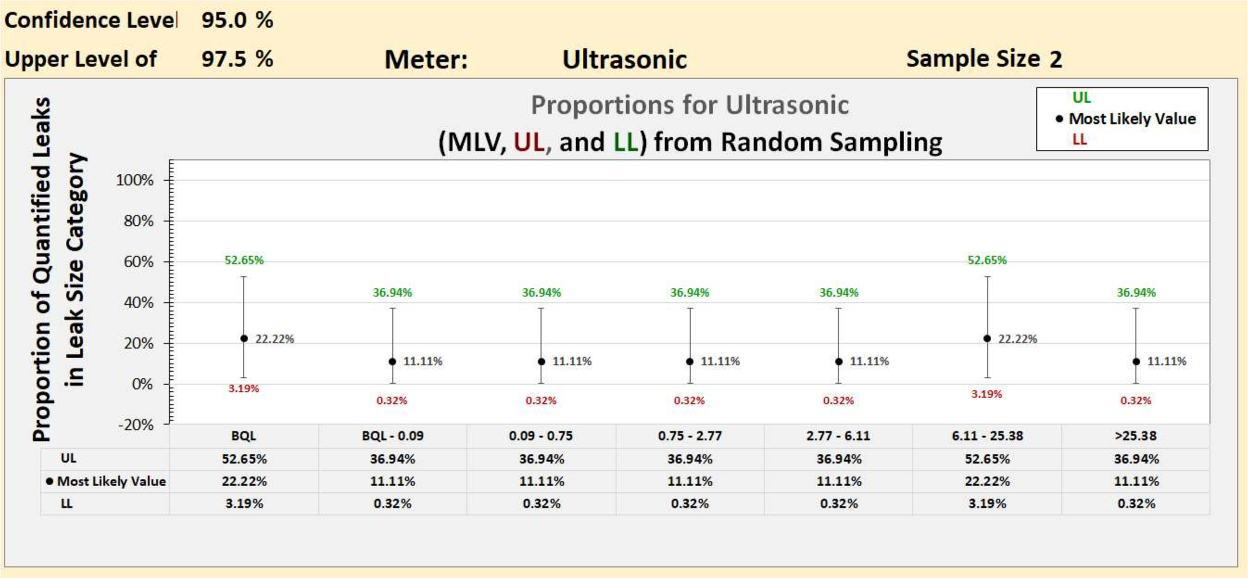
	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	65.63%	19.02%	11.20%	9.09%	10.15%	15.20%	7.99%
● Most Likely Value	57.14%	12.70%	6.35%	4.76%	5.56%	9.52%	3.97%
LL	48.44%	7.50%	2.80%	1.78%	2.28%	5.06%	1.31%

Figure 73. Updated Probability of Quantified Leak Sizes for Diaphragm Meters



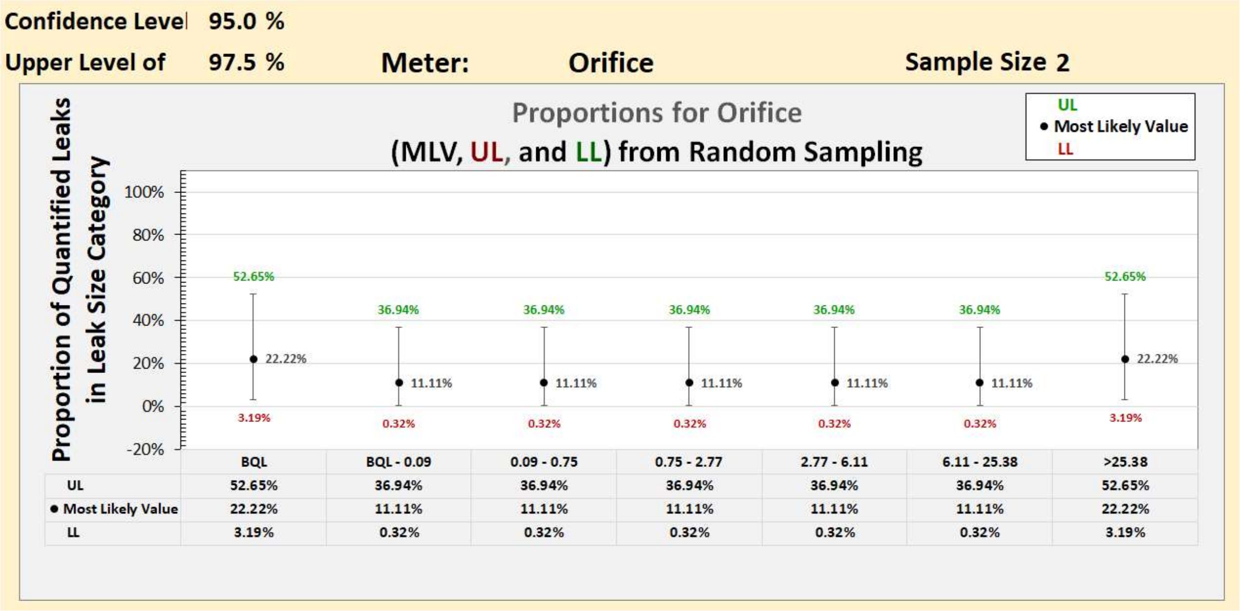
	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	54.28%	5.45%	13.89%	8.52%	17.62%	21.20%	24.68%
● Most Likely Value	44.55%	1.98%	7.92%	3.96%	10.89%	13.86%	16.83%
LL	35.03%	0.24%	3.52%	1.10%	5.62%	7.87%	10.23%

Figure 74. Updated Probability of Quantified Leak Sizes for Turbine Meters



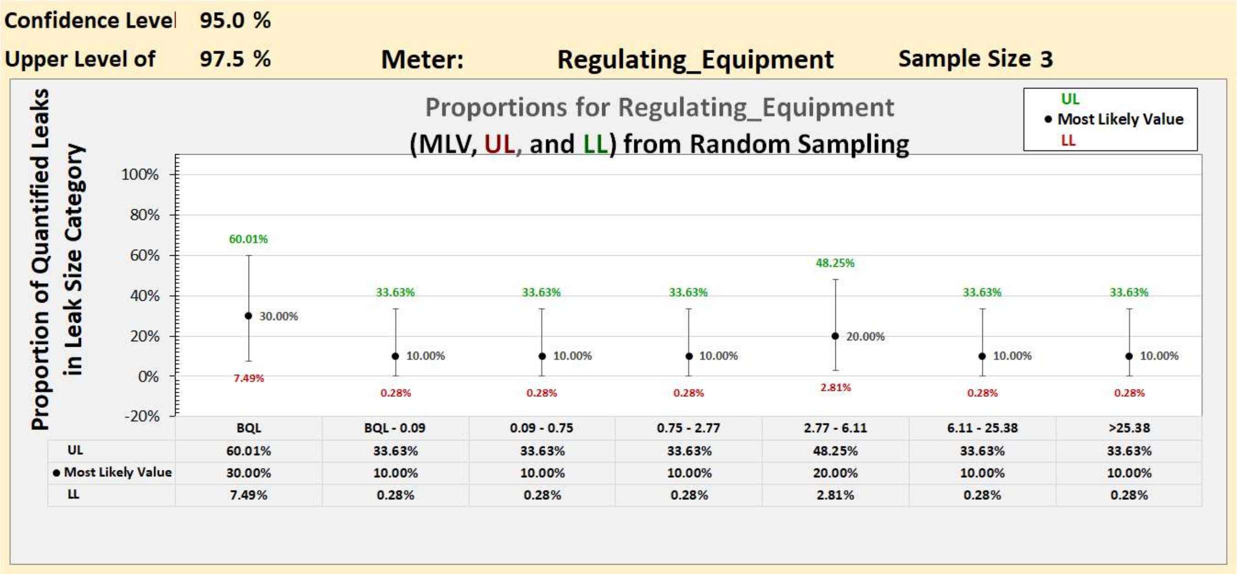
	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	52.65%	36.94%	36.94%	36.94%	36.94%	52.65%	36.94%
● Most Likely Value	22.22%	11.11%	11.11%	11.11%	11.11%	22.22%	11.11%
LL	3.19%	0.32%	0.32%	0.32%	0.32%	3.19%	0.32%

Figure 75. Updated Probability of Quantified Leak Sizes for Ultrasonic Meters


Confidence Level 95.0 %
Upper Level of 97.5 %
Meter: Orifice
Sample Size 2

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	52.65%	36.94%	36.94%	36.94%	36.94%	36.94%	52.65%
● Most Likely Value	22.22%	11.11%	11.11%	11.11%	11.11%	11.11%	22.22%
LL	3.19%	0.32%	0.32%	0.32%	0.32%	0.32%	3.19%

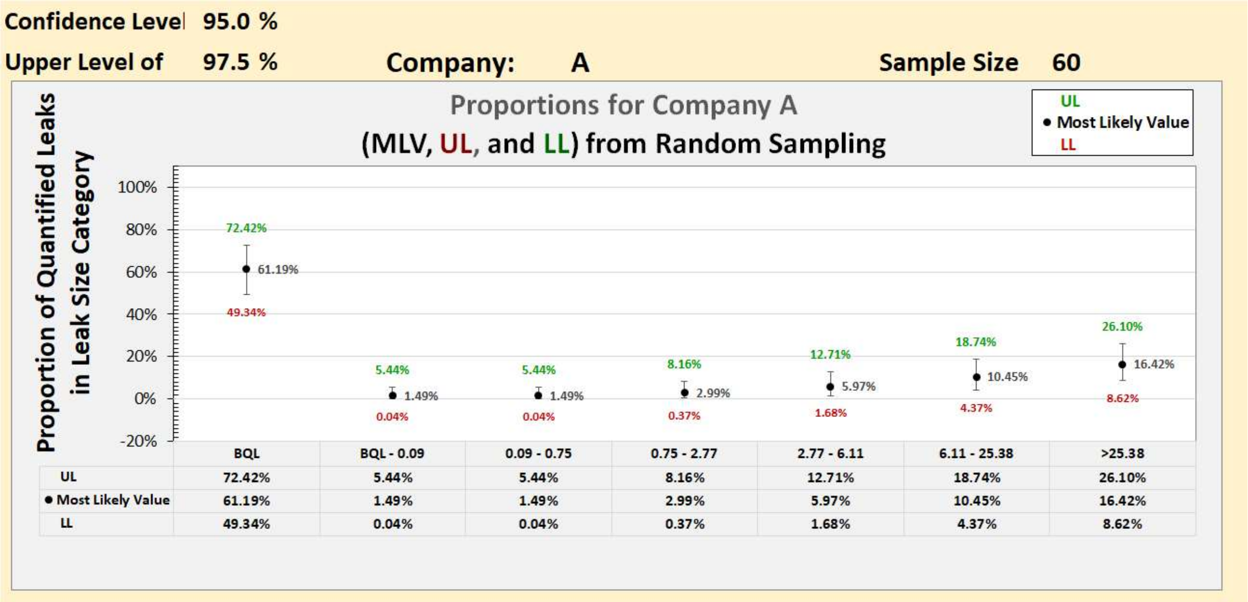
Figure 76. Updated Probability of Quantified Leak Sizes for Orifice Meters


Confidence Level 95.0 %
Upper Level of 97.5 %
Meter: Regulating_Equipment
Sample Size 3

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	60.01%	33.63%	33.63%	33.63%	48.25%	33.63%	33.63%
● Most Likely Value	30.00%	10.00%	10.00%	10.00%	20.00%	10.00%	10.00%
LL	7.49%	0.28%	0.28%	0.28%	2.81%	0.28%	0.28%

Figure 77. Updated Probability of Quantified Leak Sizes for Regulating Equipment

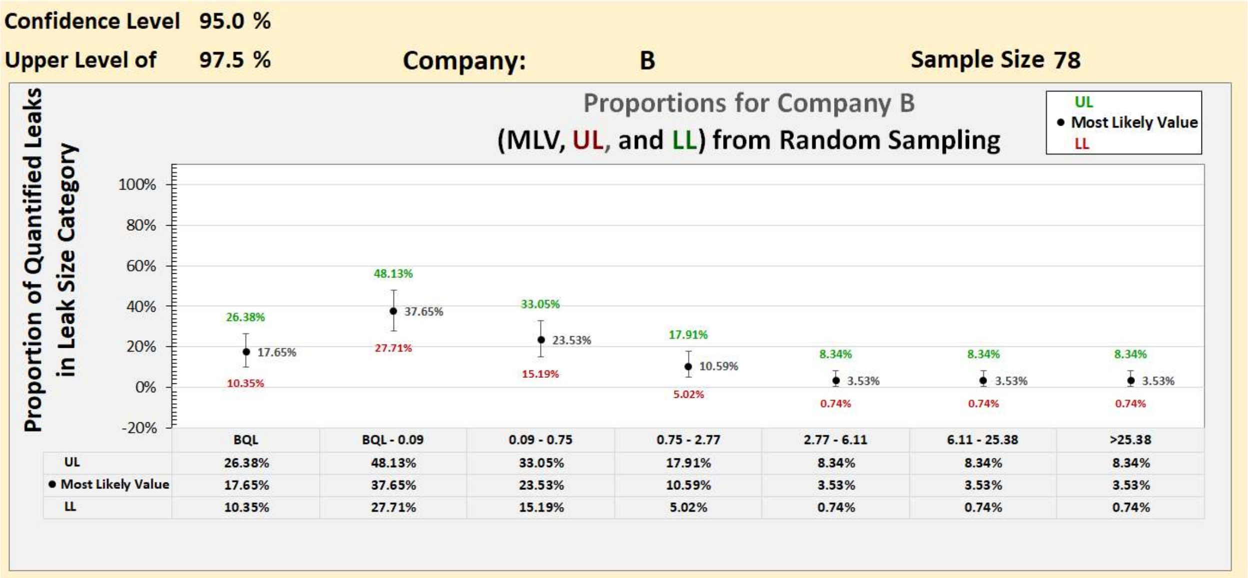
8.12 Appendix – Additional Bayesian Analysis by Company



Confidence Level 95.0 %
Upper Level of 97.5 %
Company: A
Sample Size 60

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	72.42%	5.44%	5.44%	8.16%	12.71%	18.74%	26.10%
● Most Likely Value	61.19%	1.49%	1.49%	2.99%	5.97%	10.45%	16.42%
LL	49.34%	0.04%	0.04%	0.37%	1.68%	4.37%	8.62%

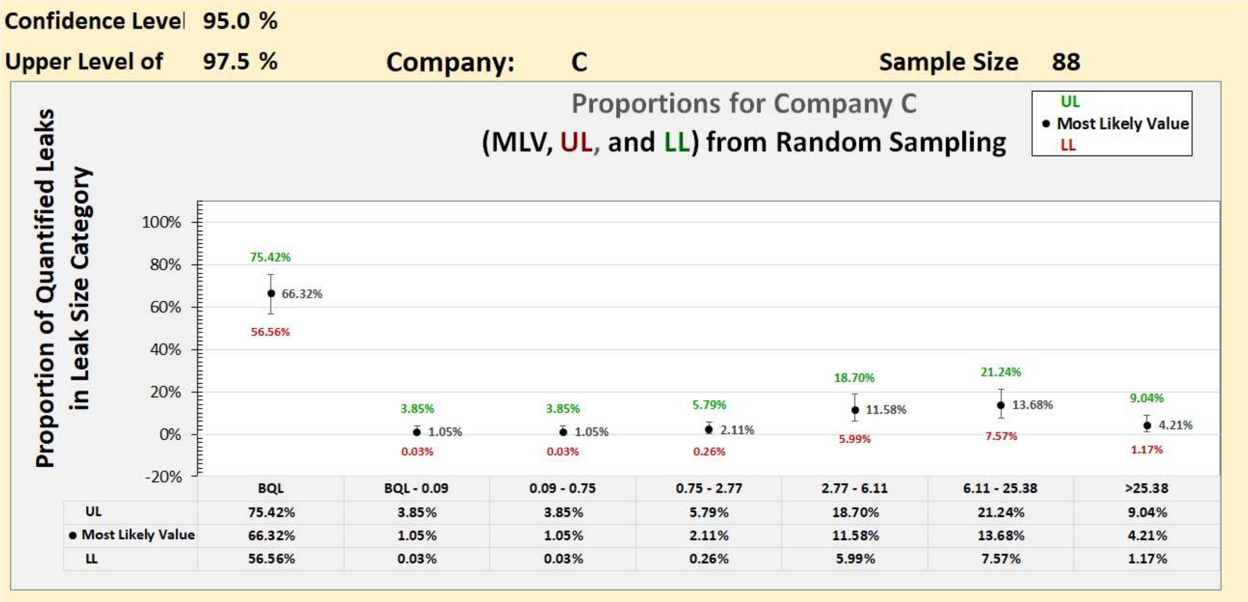
Figure 78. Updated Probability of Quantified Leak Sizes for Company A



Confidence Level 95.0 %
Upper Level of 97.5 %
Company: B
Sample Size 78

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	26.38%	48.13%	33.05%	17.91%	8.34%	8.34%	8.34%
● Most Likely Value	17.65%	37.65%	23.53%	10.59%	3.53%	3.53%	3.53%
LL	10.35%	27.71%	15.19%	5.02%	0.74%	0.74%	0.74%

Figure 79. Updated Probability of Quantified Leak Sizes for Company B


Confidence Level 95.0 %

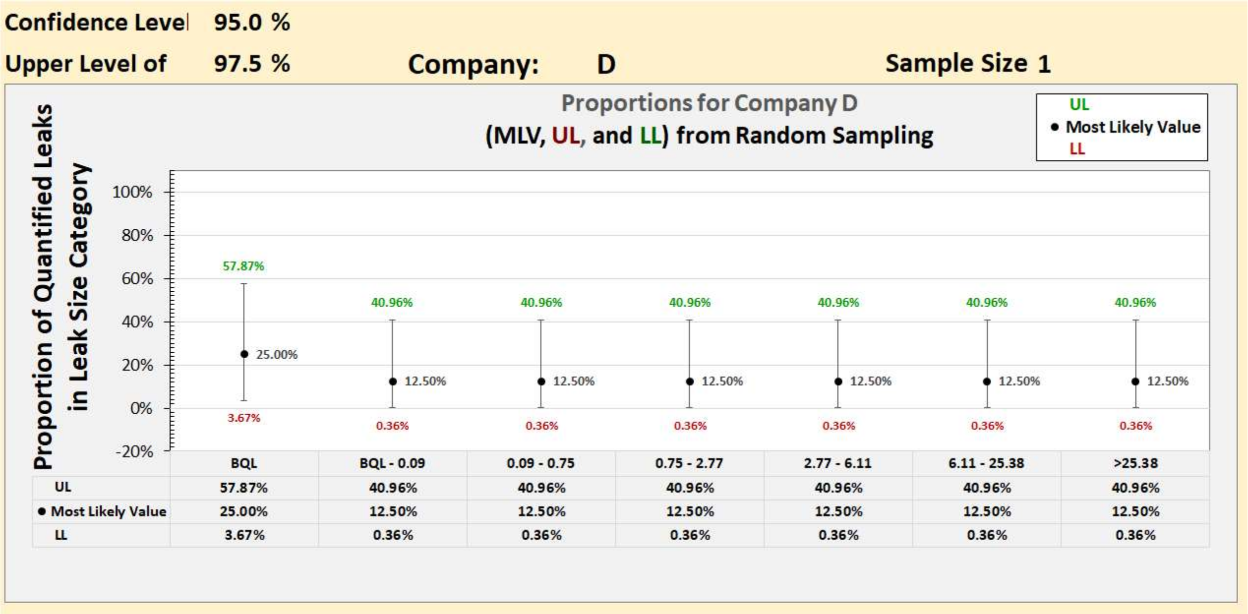
Upper Level of 97.5 %

Company: C

Sample Size 88

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	75.42%	3.85%	3.85%	5.79%	18.70%	21.24%	9.04%
● Most Likely Value	66.32%	1.05%	1.05%	2.11%	11.58%	13.68%	4.21%
LL	56.56%	0.03%	0.03%	0.26%	5.99%	7.57%	1.17%

Figure 80. Updated Probability of Quantified Leak Sizes for Company C


Confidence Level 95.0 %

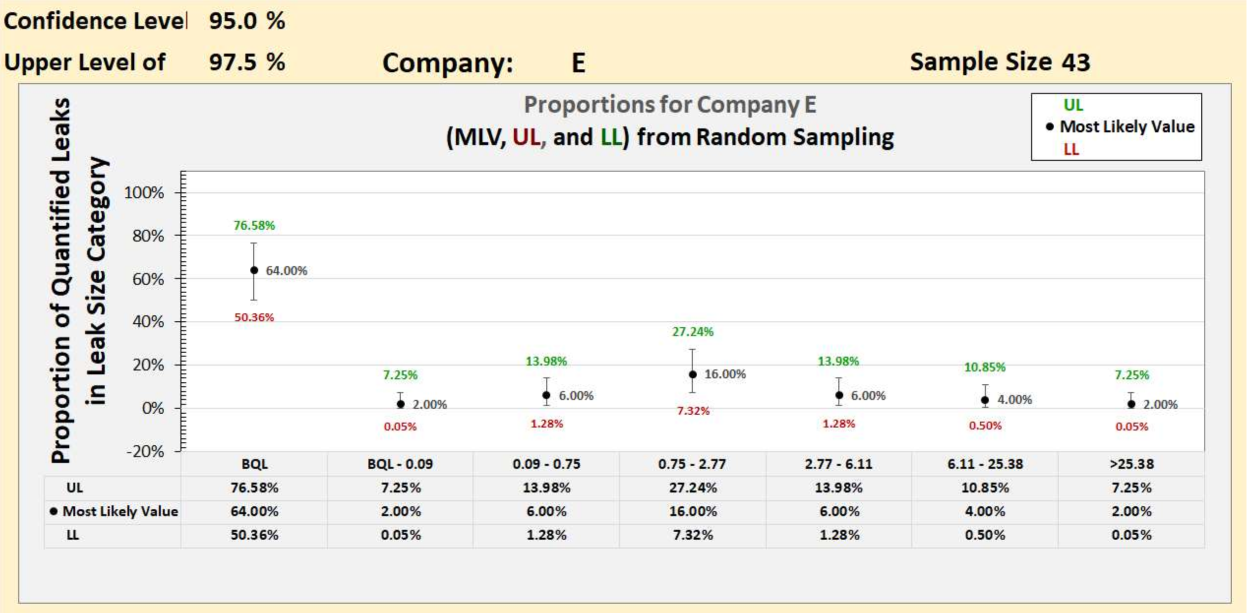
Upper Level of 97.5 %

Company: D

Sample Size 1

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	57.87%	40.96%	40.96%	40.96%	40.96%	40.96%	40.96%
● Most Likely Value	25.00%	12.50%	12.50%	12.50%	12.50%	12.50%	12.50%
LL	3.67%	0.36%	0.36%	0.36%	0.36%	0.36%	0.36%

Figure 81. Updated Probability of Quantified Leak Sizes for Company D



Confidence Level 95.0 %

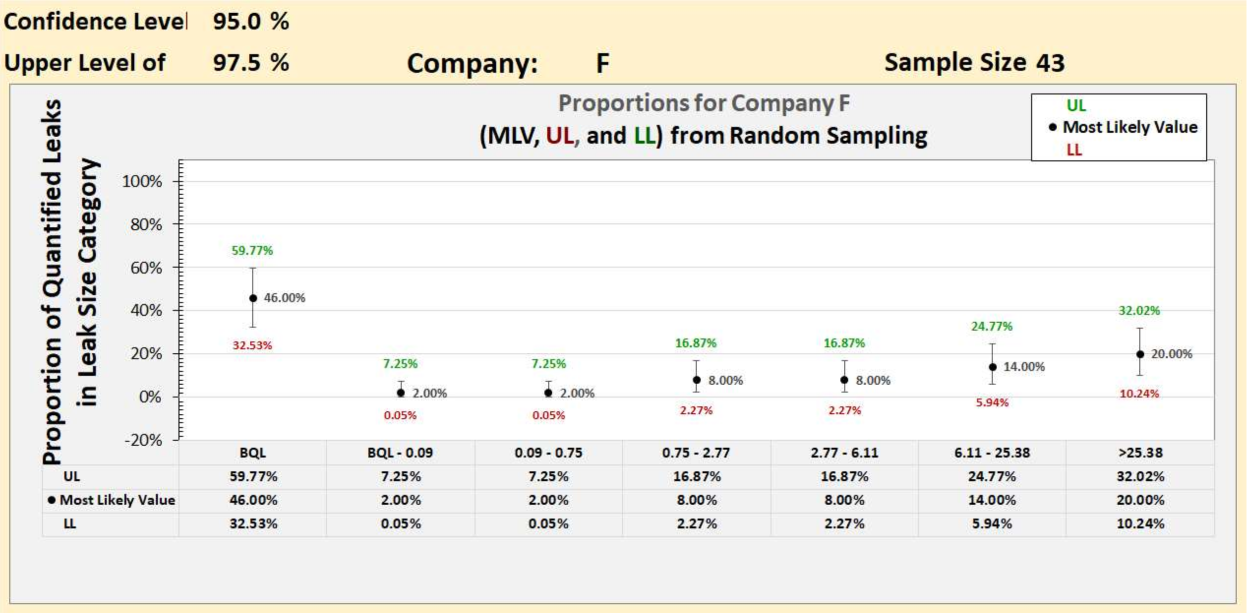
Upper Level of 97.5 %

Company: E

Sample Size 43

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	76.58%	7.25%	13.98%	27.24%	13.98%	10.85%	7.25%
● Most Likely Value	64.00%	2.00%	6.00%	16.00%	6.00%	4.00%	2.00%
LL	50.36%	0.05%	1.28%	7.32%	1.28%	0.50%	0.05%

Figure 82. Updated Probability of Quantified Leak Sizes for Company E



Confidence Level 95.0 %

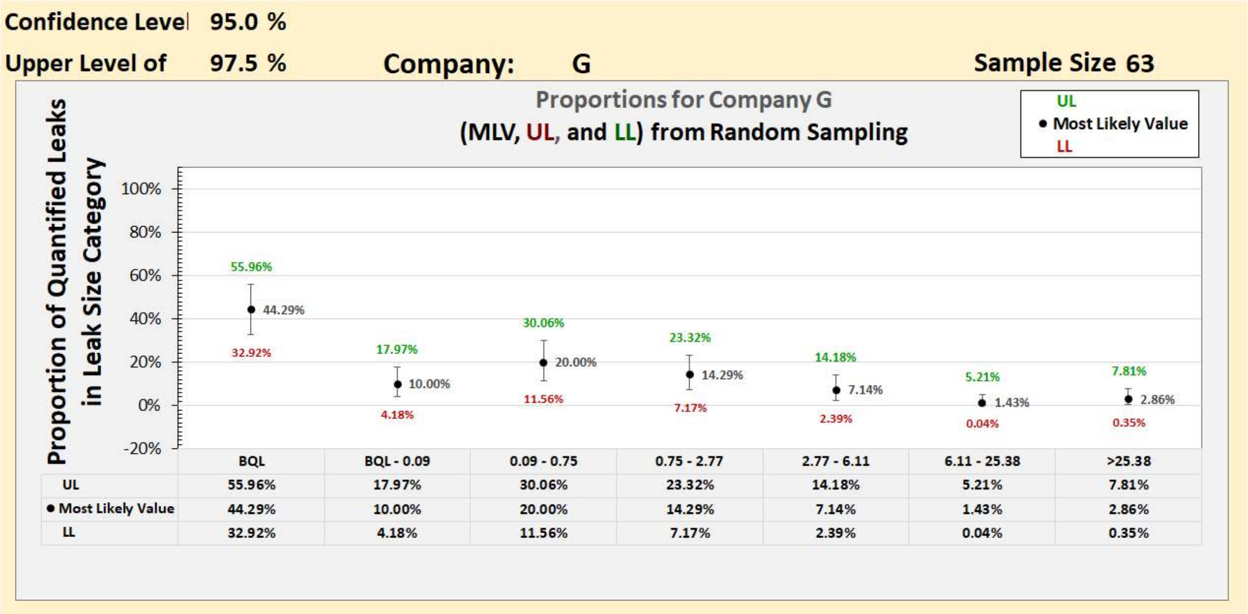
Upper Level of 97.5 %

Company: F

Sample Size 43

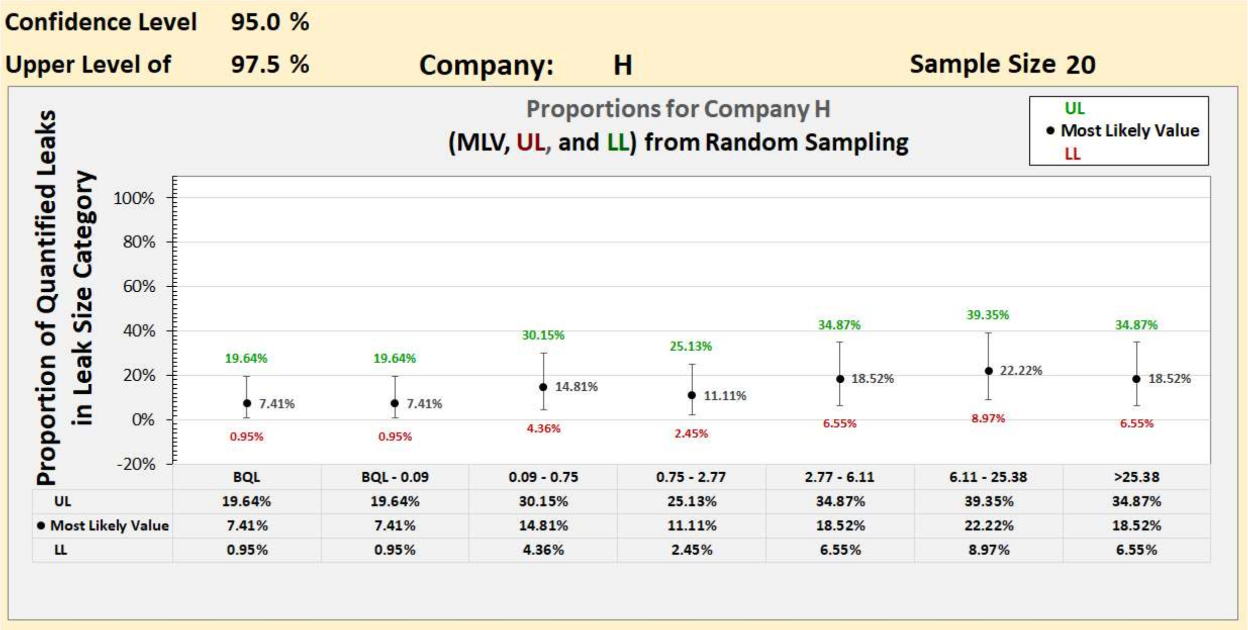
	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	59.77%	7.25%	7.25%	16.87%	16.87%	24.77%	32.02%
● Most Likely Value	46.00%	2.00%	2.00%	8.00%	8.00%	14.00%	20.00%
LL	32.53%	0.05%	0.05%	2.27%	2.27%	5.94%	10.24%

Figure 83. Updated Probability of Quantified Leak Sizes for Company F



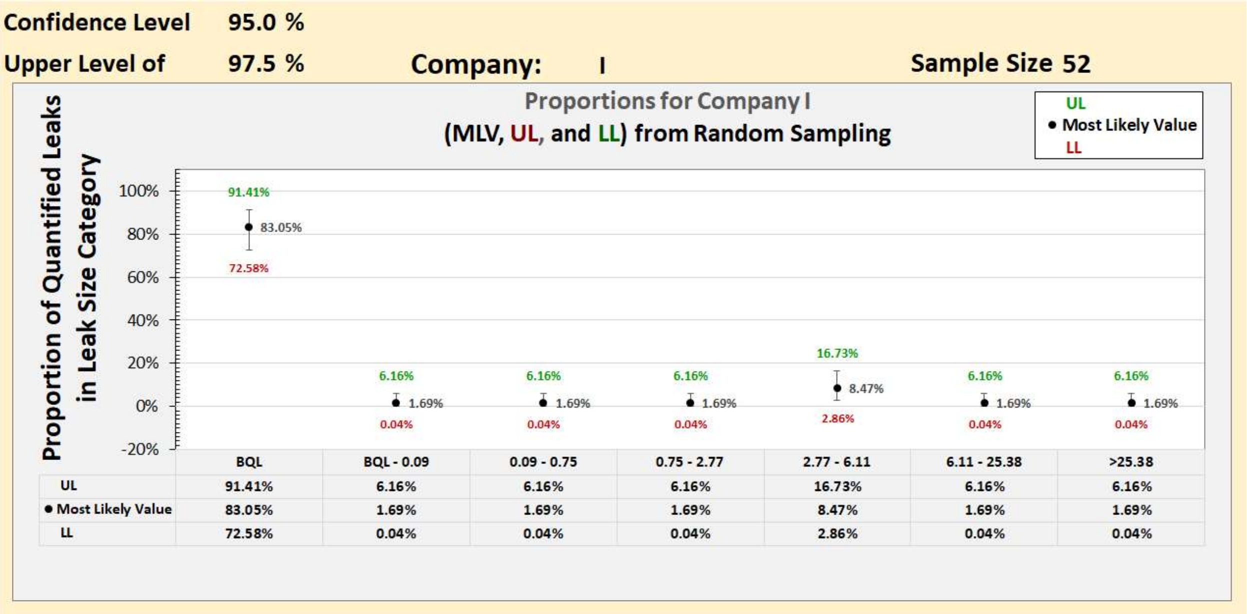
	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	55.96%	17.97%	30.06%	23.32%	14.18%	5.21%	7.81%
● Most Likely Value	44.29%	10.00%	20.00%	14.29%	7.14%	1.43%	2.86%
LL	32.92%	4.18%	11.56%	7.17%	2.39%	0.04%	0.35%

Figure 84. Updated Probability of Quantified Leak Sizes for Company G



	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	19.64%	19.64%	30.15%	25.13%	34.87%	39.35%	34.87%
● Most Likely Value	7.41%	7.41%	14.81%	11.11%	18.52%	22.22%	18.52%
LL	0.95%	0.95%	4.36%	2.45%	6.55%	8.97%	6.55%

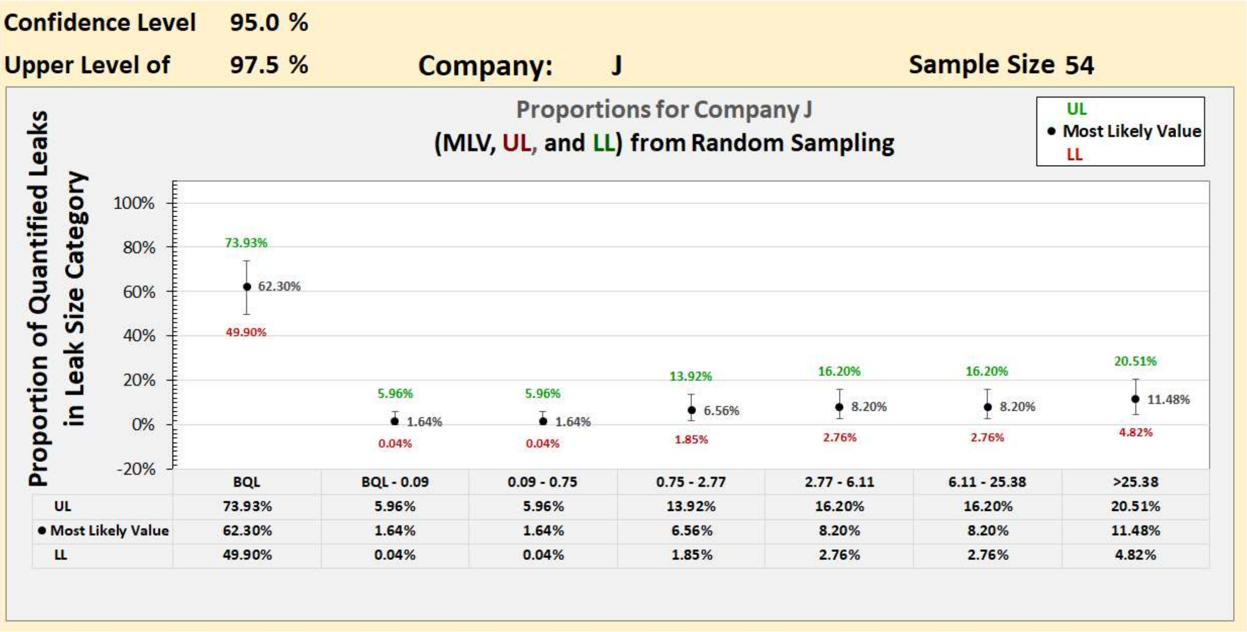
Figure 85. Updated Probability of Quantified Leak Sizes for Company H



Confidence Level 95.0 %
Upper Level of 97.5 %
Company: I
Sample Size 52

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	91.41%	6.16%	6.16%	6.16%	16.73%	6.16%	6.16%
● Most Likely Value	83.05%	1.69%	1.69%	1.69%	8.47%	1.69%	1.69%
LL	72.58%	0.04%	0.04%	0.04%	2.86%	0.04%	0.04%

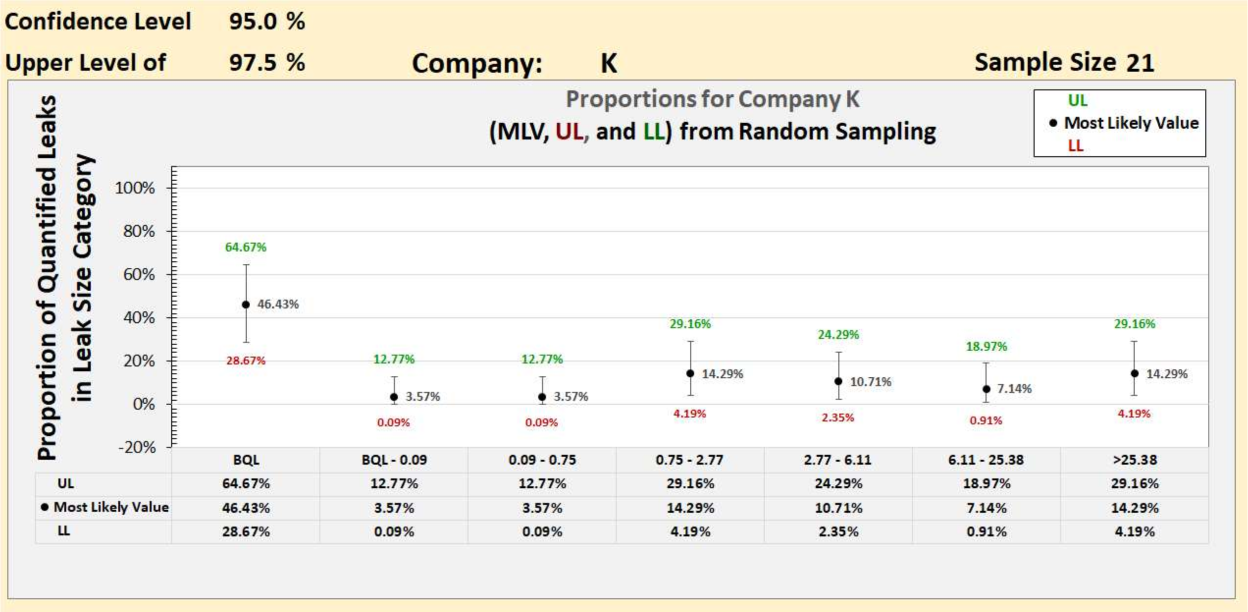
Figure 86. Updated Probability of Quantified Leak Sizes for Company I



Confidence Level 95.0 %
Upper Level of 97.5 %
Company: J
Sample Size 54

	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	73.93%	5.96%	5.96%	13.92%	16.20%	16.20%	20.51%
● Most Likely Value	62.30%	1.64%	1.64%	6.56%	8.20%	8.20%	11.48%
LL	49.90%	0.04%	0.04%	1.85%	2.76%	2.76%	4.82%

Figure 87. Updated Probability of Quantified Leak Sizes for Company J



	BQL	BQL - 0.09	0.09 - 0.75	0.75 - 2.77	2.77 - 6.11	6.11 - 25.38	>25.38
UL	64.67%	12.77%	12.77%	29.16%	24.29%	18.97%	29.16%
● Most Likely Value	46.43%	3.57%	3.57%	14.29%	10.71%	7.14%	14.29%
LL	28.67%	0.09%	0.09%	4.19%	2.35%	0.91%	4.19%

Figure 88. Updated Probability of Quantified Leak Sizes for Company K

8.13 Appendix – Additional Tracer Method Results

At each location, data were recorded for 5 to 15 minutes into a data file. In some cases, the van was moved to a different location and additional data were recorded. For 15 measured leak locations, there were 26 data files processed. Data processing involved correction of the data streams for the CH_4 and tracer lag times, identification and subtraction of appropriate background concentrations for each measurement period, and application of the tracer calibration factor to convert the tracer signal to ppb units.

Typical results are shown in Figure 89 through Figure 91. This is an example where there is generally good correlation overall as shown by the similarity in the CH_4 and tracer time series and concentration roses and by the linear regression of the accumulated CH_4 sum versus the accumulated tracer sum.

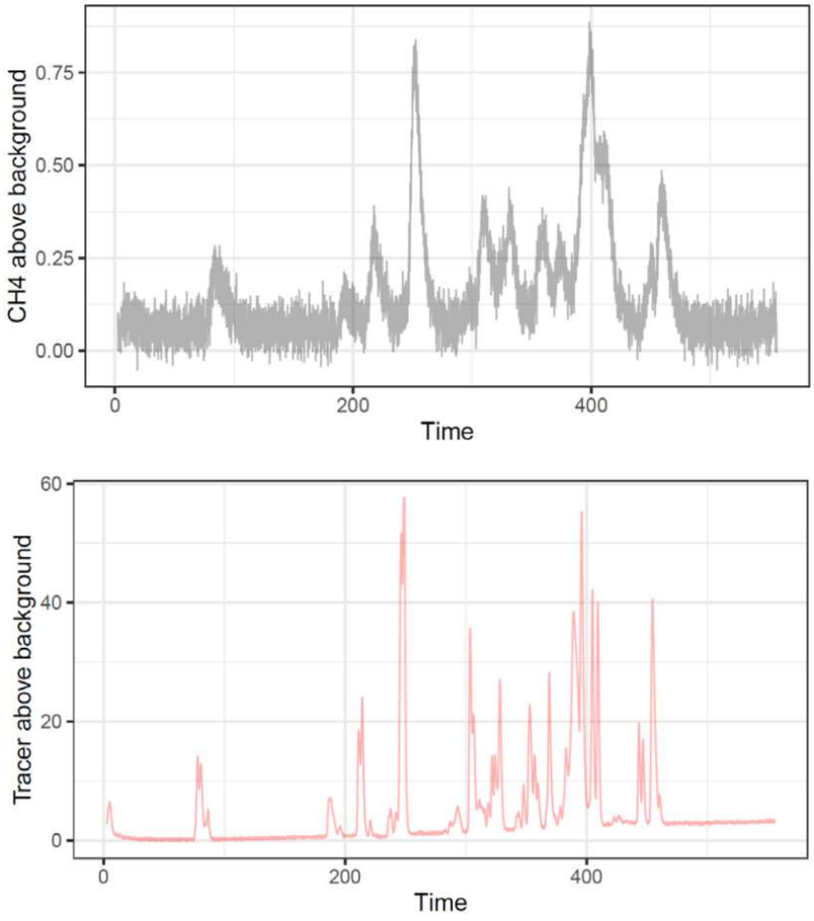


Figure 89. Example Time Series of CH_4 and Tracer Background Concentrations

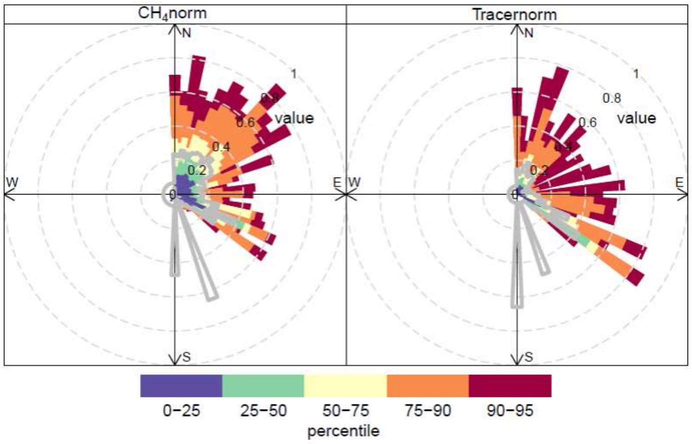


Figure 90. Comparison of CH_4 and Tracer Concentration Roses

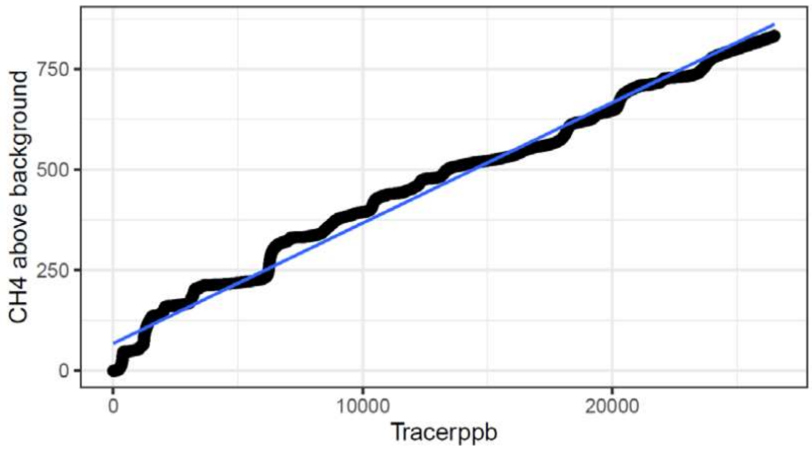


Figure 91. Accumulated Sum Regression of CH_4 vs. Tracer Concentrations

For each tracer test file, the results were examined in terms of the similarity of time series and concentration roses, and the correlation coefficient from the accumulated sums regression was used to filter the results. These results were then compared with the corresponding CH_4 emission rate obtained using the surface enclosure system as summarized in Figure 92.

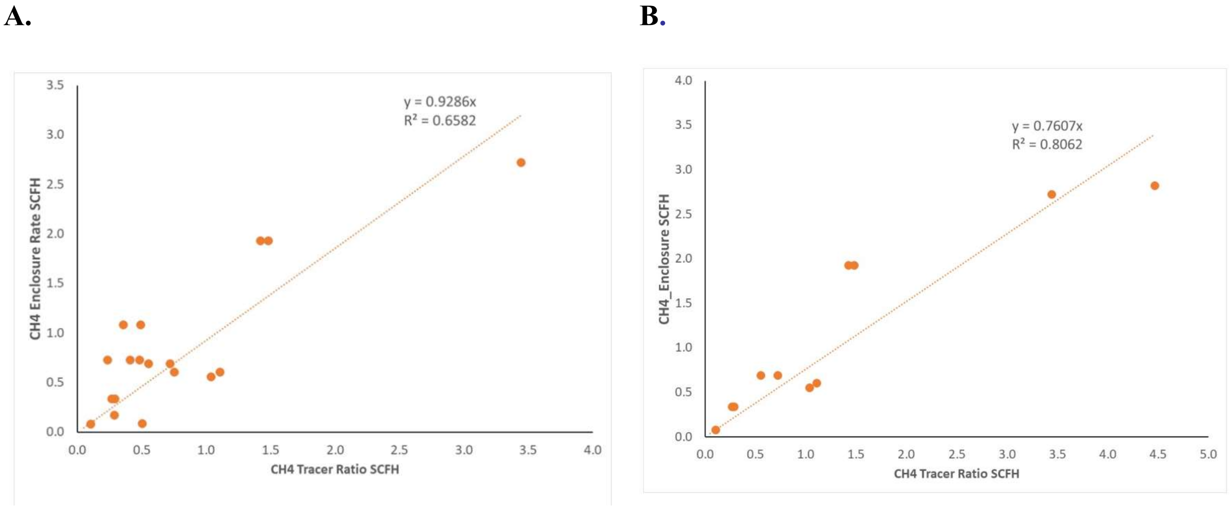


Figure 92. CH_4 Emission Rate Comparisons

Figure 92A compares the CH_4 emission rates obtained using the surface enclosure system and the tracer ratio approach. Three locations were excluded where it appears there were interfering CH_4 sources and one location was excluded with variable tracer test conditions and multiple leak locations. All other tests were included with accumulated sum correlation coefficients (r^2) ranging from 0.839 to 0.998.

These comparisons show that there was relatively good agreement between surface enclosure measurements and results obtained using the tracer ratio method. As such, these results provide confidence in the leak rate data obtained with the surface enclosure. At the same time, the need to exclude some locations and filter tests with poor correlations illustrate the complexity of measuring pipeline leak emissions using downwind ambient measurements in suburban and urban environments.

Figure 92B demonstrates a more refined comparison of the CH_4 emission rates obtained using the surface enclosure system and the tracer ratio approach. Results have been filtered to include only those tracer tests with accumulated sum correlation $r^2 > 0.990$.