INTEGRATED COMPONENT-SPECIFIC MEASUREMENTS TO DEVELOP EMISSION FACTORS FOR COMPRESSORS AND GAS GATHERING LINES

FINAL REPORT

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ACRONYMS AND ABBREVIATIONS

cf	cubic feet
CFR	Code of Federal Regulations
CH_4	methane
d	diameter
DL	detection limit
DOE	Department of Energy
DPV	distance piece vent
EF	emission factor
ER	emission rate
ESD	emergency shut-down
ft3	cubic feet
g/hr	grams per hour
GHGI	Greenhouse Gas Inventory
GHGRP	Greenhouse Gas Reporting Program
G&B	gathering and boosting
GRI	Gas Research Institute
IR	infrared
KS	Kolmogorov-Smirnov
LGR	Los Gatos Research
m	meter
MCF	thousand cubic feet
MET	meteorological
MQI	method quality indicator
n/a	not applicable
NETL	National Energy Technology Laboratory
OGI	optical gas imaging
OP-FTIR	open path – Fourier transform infrared
PMP	project management plan
PRV	pressure relief valve
RPV	rod packing vent
RRPR	Research Performance Progress Report
scf/hr	standard cubic feet per hour
SF_6	sulfur hexafluoride
TCS	Transmission Compressor Stations
USEPA	United States Environmental Protection Agency
USU	Utah State University

EXECUTIVE SUMMARY

The Department of Energy (DOE) National Energy Technology Laboratory (NETL) and other critical stakeholders (e.g., U.S. Environmental Protection Agency (USEPA), state regulators, and industry) seek to more accurately characterize and quantify methane emissions from compressors and gathering lines within the Gathering and Boosting (G&B) segment of the natural gas system network. These efforts will reduce uncertainties in estimates of these emissions in USEPA's current Green House Gas Inventory (GHGI) under their Greenhouse Gas Reporting Program (GHGRP; EPA, 2016). These estimates are primarily based on data from other types of pipeline segments and may not accurately reflect the different characteristics of emissions from G&B compressors and gathering lines. For example, emission factors used to estimate methane emissions from the G&B segment are the same factors used for onshore natural gas production (USEPA, 2015 and 2016). A robust and representative dataset of emissions from G&B station components will inform future enhancements to the current GHGI.

For this study, four G&B stations in the Gulf Coast Area were visited four times over the course of one year. Components were classified according to equipment and component type and emissions from select components were measured based on initial screening procedures. The following major equipment types were considered:

- compressors,
- separators,
- dehydrators,
- coalescers,
- slug catchers,
- yard piping,
- tanks, and
- gathering lines.

Individual components on each equipment type were further divided into the following main categories:

- connectors,
- valves,
- pressure relief valves (PRV),
- meters,
- gauges,
- regulators,
- pneumatic device vents, and
- compressor vents (e.g., distance piece vents [DPVs] and rod packing vents [RPVs]).

Components were screened for the presence of leaks and venting emissions with an optical gas imaging (OGI) camera, and methane emission rates were measured using a microdilution high volume sampler. Downwind emissions were measured using an Open Path Fourier Transform Infrared (OP-FTIR) Spectrometer. Data were evaluated to assess variability related to site, equipment, time, operational variables (e.g., pressure, flowrate, temperature), equipment characteristics (e.g., age, type), and sampling duration. Key findings and recommendations from the study include:

- **Component Population Counting Methodology:** Different counting methodologies can result in vastly different component counts, thus influencing total emissions calculations using Subpart W population EFs. A standard methodology should be adopted for classifying and counting components in order to minimize inconsistencies across studies and instruct stakeholders responsible for GHGI reporting.

- **Appropriateness of Component Categories in the GHGRP:** Results support current component subcategories listed in USEPA Subpart W, including the subdivision of connectors (flanged and “other”) and pneumatic device vents (intermittent, continuous low bleed, and continuous high bleed). Results warrant further study of emissions from compressor vents, meters, gauges, and regulators.
- **Emission Rate Variability by Site and Operational Parameters:** There is variation of emissions rates across sites and a relationship between higher emissions and compressor age for some components. More measurements should be taken on additional compressor components to further assess emissions rate variability by site and operational parameter.
- **Temporal Variability in Emission Rates:** Component emission rates varied between field campaigns. The type of components contributing to overall measured emissions also varied among field campaigns. However, the emission rate variability was larger between different components (of the same category) than the variability in one component over the four field campaigns. Therefore, when calculating emission factors, it is not necessary to take repeat measurements to capture component variability. Visiting many sites once is likely to capture more variability in emission rates than visiting sites multiple times.
- **Emission Rate Variability During Sampling Measurements:** Measuring the emission rate of a sample for an extended period of time is not necessary to capture the average component emission rate. Pneumatic devices, which are designed to actuate and/or throttle, did not show greater variability than other component types. This may indicate the sampling time was not sufficient for pneumatic devices; further investigation is recommended.
- **Emission Comparison – Gas vs Liquid Lines:** For reporting purposes, excluding liquid lines from site-wide screening may have a negligible effect on component-related emissions. However, from a site management perspective, malfunctioning components were not uncommon on liquid lines and contributed substantially to fugitive emissions at some sites.
- **Emissions Comparison - Measured vs. Estimated:** Population EFs, whether including or excluding liquid lines, were a conservative estimate of fugitive emissions. Leaker EFs consistently underestimated emissions at the field sites. Measurements at more sites, particularity sites in other areas of the country, need to be completed before determining the accuracy of EFs.

The results of this study are useful to regulators for updating the GHGI and GHGRP, highlighting areas of additional research, such as 1) developing a standard counting and classification protocol for components, 2) determining the importance of emissions from liquid lines, and taking additional measurements from compressors in the G&B segment to provide stronger statistical support for proposed updates to Subpart W EFs.

1.0 INTRODUCTION

Methane emissions from natural gas gathering and boosting (G&B) stations are reportable under the United States Environmental Protection Agency (USEPA) Greenhouse Gas Reporting Program (GHGRP) and tracked nationwide under the Greenhouse Gas Inventory (GHGI). Methane is a potent greenhouse gas that has a global warming potential of 28 (IPCC, 2014), which means that methane can store 28 times more heat in the atmosphere than carbon dioxide over a 100-year period. The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) has ongoing research efforts to accurately characterize and quantify methane emissions from compressors and gathering lines within the G&B segment of the natural gas system network. As defined in Title 40 of the Code of Federal Regulations (CFR) Part 98 Subpart W, onshore natural gas G&B means:

> *Gathering pipelines and other equipment used to collect natural gas from onshore production gas wells and used to compress, dehydrate, sweeten, or transport the natural gas to a natural gas processing facility, a natural gas transmission pipeline or to a natural gas distribution pipeline. Gathering and boosting equipment includes, but is not limited to gathering pipelines, separators, compressors, acid gas removal units, dehydrators, pneumatic devices/pumps, storage vessels, engines, boilers, heaters, and flares. (40 CFR1.98.230(9) [2016]).*

At present, methane emission estimates for G&B stations are primarily based on data from other sectors of the natural gas inventory, such as production and transmission, rather than emissions specifically from G&B stations. Consequently, efforts are needed to reduce uncertainties in estimates of these emissions in the current GHGI. A robust and representative dataset of emissions from G&B station components will ultimately inform future enhancements to the current GHGI.

This report describes the results from DOE Project DE-FE0029084: *Integrated Component-Specific Measurements to Develop Emission Factors for Compressors and Gas Gathering Lines*. For this study, component characterization and emissions measurements were performed using a suite of leak detection and measurement technologies at four G&B stations in the Gulf Coast area. Four G&B stations were visited four times over the course of one year (February 2017-March 2018). The technical approach, analyses, and results of this study are discussed in the following sections, with references to appendices for additional details and supporting information.

1.1 Background

1.1.1 *Regulations & Current Literature*

USEPA addresses methane emissions from natural gas production, processing, transmission, storage, and distribution segments under Subpart W (Petroleum and Natural Gas Systems) of the 2016 GHGRP, covered under Title 40 of the CFR. Emissions reported to the GHGRP support the accounting of total methane emissions from man-made sources to USEPA's GHGI.

The USEPA and Gas Research Institute (GRI) published the first comprehensive study to quantify methane emissions from the natural gas industry in 1996 (Harrison et al., 1996) as part of the GHGI. Since the *Mandatory Reporting of Greenhouse Gases Rule* was signed in 2009 (40 CFR §98, Subpart C and Subpart W), the emission factors (EF) published in 1996 have come under increased scrutiny and undergone several revisions (Clearstone Engineering, 2002; USEPA, 2006; Harrison et al., 2011; Marchese et al., 2015). Though the GHGI is updated and improved annually, recent studies have pointed to the inadequacies of GHGI methane emissions estimates, particularly in the G&B segment.

A study by Marchese et al. (2015) found that G&B operations contributed approximately 30% of total methane emissions in the natural gas systems GHGI. Results of the study invoked the 2016 update to the GHGRP, and prompted further study of the G&B segment as a significant source of methane emissions.

As of 2016, methane emissions from natural gas G&B stations are reportable under the USEPA GHGRP and tracked nation-wide under the GHGI. Further, emissions from process components (e.g., valves, connectors, pressure relief valves) at such stations are estimated using EFs in accordance with Subpart W of the GHGRP. Therefore, it is critical that data in the GHGI accurately represent the full range of expected field conditions, including temporal and operational variability in the G&B station segment.

USEPA is currently considering improving GHGI emissions estimates in the G&B segment by requesting "feedback on how to consider regional and temporal variability specifically for G&B (USEPA, 2018) as well as incorporating data collected in recent studies (Vaughn et al., 2017; Yacovitch et al., 2017; and Zimmerle et al., 2017). The results of this study can help to address the temporal variability of emissions highlighted in the USEPA memo.

1.1.2 *General Equipment at G&B Stations*

As natural gas moves long distances through pipelines, the pressure of the gas decreases. G&B stations are strategically placed along transfer pipelines to boost the gas pressure. This helps to maintain gas flow through the pipelines and ensures gas is at the proper pressure for end users. A general schematic of a G&B station is shown in **Figure 1-1**. Natural gas enters the station through the receiving side of the gathering lines and passes through a series of equipment that reduces moisture and/or filters impurities from the gas (e.g. slug catchers, dehydrators, separators, and coalescers). Slug catchers and large vertical separators, for example, are designed to remove high volumes of liquid from the gas stream using gravity. Equipment such as coalescers and filter separators are designed to remove additional liquids, as well as any particulate matter, oily liquids and condensate, and other impurities from the gas. Liquids that are removed from the gas are typically sent to holding tanks. Note that the type, number, and configuration of liquid handling equipment varies between stations, and depends on the moisture content and quality of the incoming gas and the facility gas throughput. Following gas conditioning, the pressure of the gas is then increased by the compressors and sent out of the facility through the discharge pipes of the gathering lines.

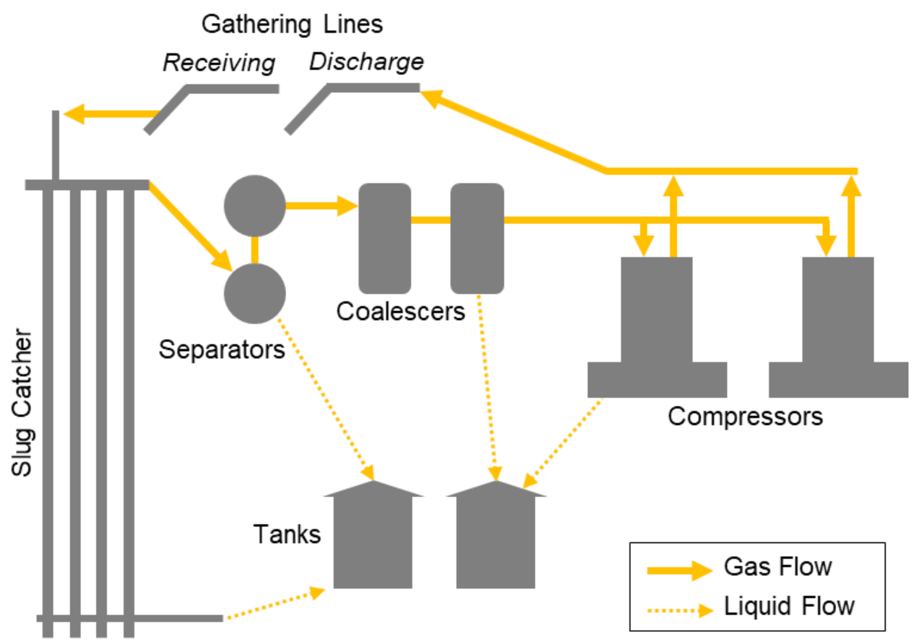


***Figure 1-1**. Example schematic of a G&B station from this study*

1.2 Overall Project Approach

The objective of this study is to characterize methane emissions from G&B station components within the G&B segment to improve the quantification of methane emission factors included in Subpart W of the USEPA's GHGRP. Main project tasks included: i) measuring methane emission rates from a variety of equipment components (e.g., connectors, valves, compressor vents) at multiple G&B stations using a suite of measurement and leak detection technologies (e.g., OGI camera, high volume sampler, OP-FTIR spectroscopy), ii) assessing the temporal variability of methane emission rates from equipment and components by returning to the same sites multiple times, and iii) evaluating the effect of operational parameters (e.g., throughput, gas composition) on emission rates. Key research questions and project activities are summarized below.

Key research questions addressed by this study include:

1. How are component populations counted on different equipment types and how are counts affected by counting methodology?
2. Do methane emissions data support component categories and subcategories currently identified in the GHGRP?
3. Do emission rates vary from site to site? Do site operational parameters (e.g., gas throughput, gas composition, compressor age) correlate with emission rates?
4. Do emissions from the same site or piece of equipment vary over time?
5. What effect does sample duration have on the measured emission rate?
6. How do measured emissions compare to estimated emissions calculated from published Subpart W emission factors?

The project consists of two major phases, with two field campaigns conducted in each phase (four total field events). Methane emission rates were collected from disaggregated components (e.g., connectors and valves) at different time periods, reflecting changes in operational and temporal conditions at G&B sites. The temporal variability in methane emission rates was assessed and will aid in the development of refined EFs for G&B stations. The following specific activities were performed:

- **Component Classification.** Developed a detailed protocol to classify and count components at G&B stations.
- **Emissions Measurement.** Employed a suite of measurement and leak detection technologies (i.e., optical gas imaging (OGI) camera, high-flow, Open path – Fourier transform infrared (OP-FTIR) spectroscopy) to characterize methane emissions from components at G&B stations.
- **Temporal Variability Assessment.** Evaluated temporal variability of emission rates by measuring components over multiple field campaigns. Assessed the magnitude of variability in emissions rates over varying sample durations (from 3 to 70 minutes).
- **Emission Factors.** Calculated EFs with a small data set from four sites, and used variability results to determine the importance of repeat measurements in EF calculation.
- **Data Visualization.** Developed a data visualization tool that uses a Gaussian dispersion model to estimate the methane plume associated with measured emissions. The model was also used to visualize how the methane plume changed throughout the day based on meteorological data collected in the field.
- **Technical Advisory Steering Committee.** As part of technology transfer activities, a Technical Advisory Steering Committee (TASC) was assembled to receive feedback on project scope and results from industry, regulatory, and academic participants. Presentations were given to the TASC at multiple times during the study and feedback from the committee was incorporated into the study.

2.0 METHODS

2.1 Participating Field Sites

In December 2016, 16 G&B station facilities located in the Gulf Coast area housing a total of 47 reciprocating compressors, were offered by operators as candidate field sites. Four facilities were randomly selected in which to perform the field activities, consisting of a total of 15 compressors and associated equipment (slug catchers, separators, coalescers, dehydrators, and yard piping) (**Table 1-2**). For confidentiality purposes, the four facilities are referred to as Sites 1-4.

2.2 Overview of Field Campaigns

Four field campaigns were conducted between February 2017 and March 2018. The dates of each field campaign for each site under the two project phases are provided in **Table 2-1**.

Table 2-1. *Summary of project field campaigns*

	Phase I		Phase II	
	Campaign 1	Campaign 2	Campaign 3	Campaign 4
Site 1	March 2-3, 2017	June 6, 2017	October 26-27, 2017	March 5-6, 2018
Site 2	March 1, 2017	June 8, 2017	October 24, 2017	March 8, 2018
Site 3	February 28, 2017	June 7, 2017	October 25, 2017	March 7, 2018
Site 4	February 27, 2017	June 7, 2017	October 23, 2017	March 9, 2018

Field sampling events were performed at the same facilities to capture variability in operational parameters, such as compressor operational modes, facility gas throughput, and gas composition. The field sites had throughputs that ranged from 5,000 to 250,000 thousand cubic feet per day (MCF/day). The sites also had different numbers and configurations of equipment (**Table 2-2**).

Table 2-2. *Equipment counts for participating field sites*

Equipment	Site 1	Site 2	Site 3	Site 4
Compressors *	5-6	4	2	2-3
Operational Compressors	2-3	1	1	1
Separators	2	3	3	4
Coalescers	2	1	1	2
Dehydrators	0	1	2	0
Slug Catchers	1	0	0	1

* Total number of compressors at a given site (Note: not all compressors were operational during all sampling campaigns). Counts for other equipment types represent operational equipment only.

It is important to note that operation schedules of compressor units varied over the four field campaigns (**Figure 2-1**). For example, at Site 4, Compressor 93 was operational during Field Campaigns 1 and 4, Compressor 95 during Field Campaign 2, and Compressor 94 during Field Campaign 3. Also, Compressor 95 was removed from the site between campaigns 2 and 3. In one instance, a new compressor was installed (Site 1, Field Campaign 4). The substitution of operating compressors over time resulted in limited repeat measurements that could be taken on compressor components. Only two compressors, located at Site 1, were operational during all four campaigns (1301 and 1501). On Figure 2-1, green boxes represent compressor units at Sites 1-4. Operational compressors at the time of sampling during the four field campaigns are outlined in dark green; remaining compressors were not operating. Compressors that were removed from the field sites during the study are denoted with red X’s.

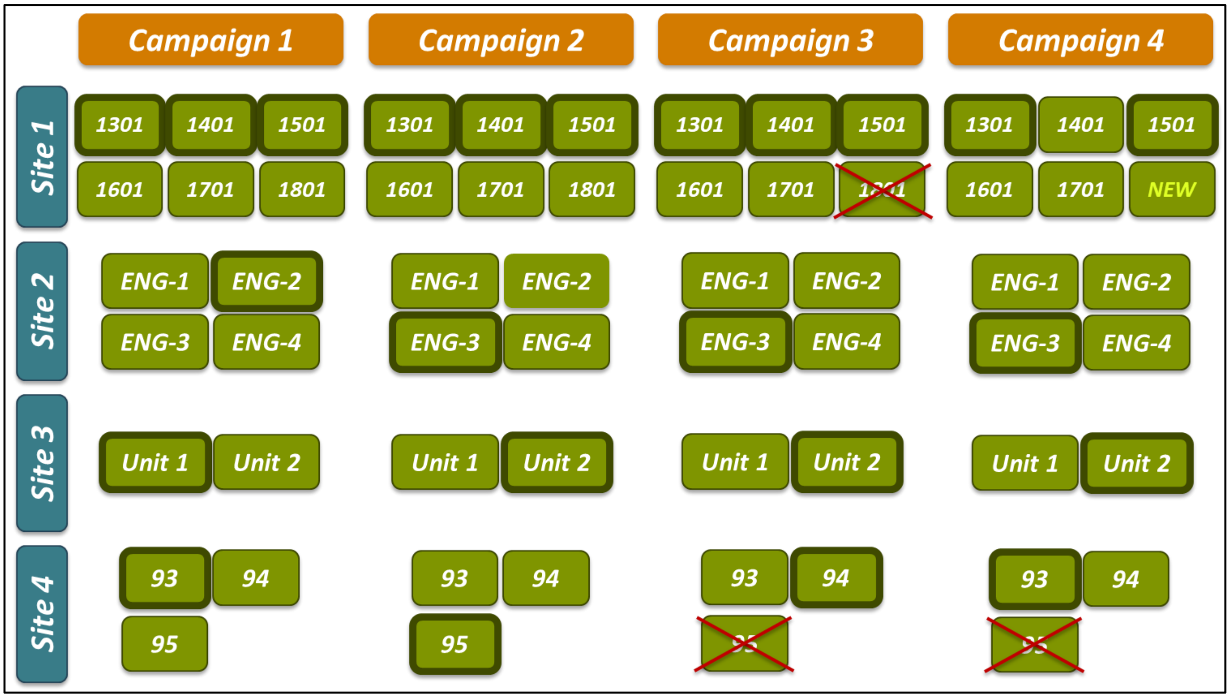


***Figure 2-1**. Operational compressors by site and field campaign.*

Field campaigns at the four sites consisted of three major steps: i) component classification and counting, ii) identification of leaks from equipment components using an OGI camera (FLIR GF320), and iii) measurement of methane emissions using a high volume sampler (**Figure 2-2**). In addition, during Field Campaign 1, an OP-FTIR spectrometer was employed to quantify methane concentration downwind of the compressors units. Operational parameters were provided by G&B station operators (facility gas throughput, gas composition, etc.).

***Figure 2-2.** Field method summary for component emissions*

To the extent possible, equipment leaks and vents that were identified and measured at a given component were measured during subsequent field campaigns. Detailed descriptions of the component classification and leak detection/measurement technologies are provided in Sections 2.3 and 2.4, respectively.

2.3 Component Classification and Count

A protocol was developed to classify and count disaggregated components of G&B stations. Counting and classification can be interpreted differently depending on the field personnel, making consistency difficult to achieve between field campaigns. A detailed classification protocol, provided in Appendix C, was developed to ensure consistent counts between field sites. Key components of the protocol are briefly described below.

2.3.1 *Equipment Type*

G&B stations were separated into eight main equipment types: compressors, separators, dehydrators, coalescers, slug catchers, yard piping, tanks, and gathering lines (**Figure 2-3**). Components associated with each equipment type were classified and counted. The purpose of classification by both component and equipment type was to more accurately quantify methane emissions from individual pieces of equipment at G&B stations rather than a facility wide component count and emission rate. Organizing the count in this manner may reduce uncertainty, as pieces of equipment are often operated under varying conditions from day to day, are relocated from site to site, and/or are decommissioned and removed from the G&B process entirely. Additionally, G&B stations are uniquely configured depending on station operational parameters such as gas throughput and gas moisture content. For example, a G&B station receiving wet gas will require more separation and possibly installation and management of slug catchers; tanks will flash more, and liquid level pneumatic controllers will actuate more, creating additional emissions.

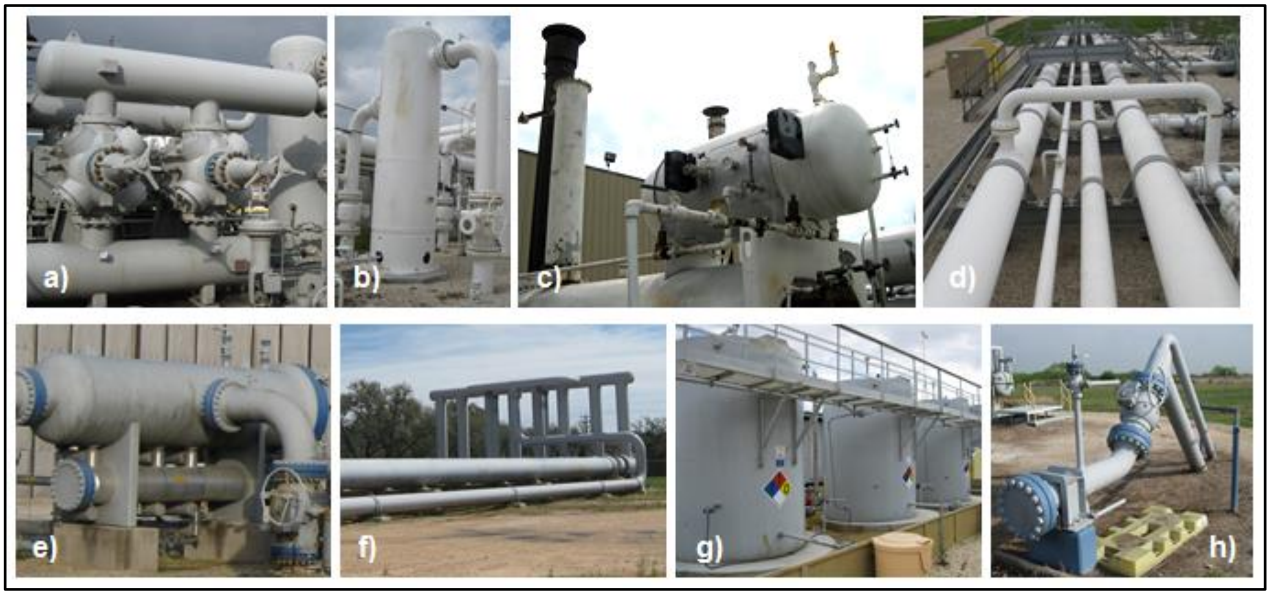


Figure 2-3. *Major equipment types at G&B Stations: a) compressor, b) separator, c) dehydrator, d) yard piping, e) coalescer, f) slug catcher, g) tanks, and h) gathering lines*

2.3.2 *Component Type*

Components were classified into eight major categories: connectors, valves, pressure relief valves, meters, gauges, regulators, pneumatic devices, and compressor vents. Where possible, these categories were subdivided into smaller groups and the function of the component was noted (**Table 2-3**). For example, connectors could be flanged or other (e.g., threaded, compression), and the function of a pneumatic device could be to control pressure, liquid level, or flow. Component counts for each piece of equipment were started and stopped at the equipment's isolation valve. Components moving liquid (e.g., liquid lines from separators to tanks) were differentiated from lines moving gas. Photos of each of the component types are shown on **Figure 2-4**. Pneumatic devices are used to operate mechanical devices, like valves, with compressed air or natural gas. When a signal is sent to the pneumatic device controller that a change in system parameters (e.g., pressure, level, or flow) is needed, the device will reposition a valve (open/close, throttle) to achieve the desired system condition. Compressed gas contained in the actuator diaphragm is released, or actuates, to operate the valve. A detailed description of the component count methodology for this project is provided in Appendix C.

Table 2-3. *Component categories and subcategories from the component classification protocol*

Major Component Categories	Major Component Subcategories	Component Specifics
Connector	Other or flanged; Size of other connector (d < 6", 6" ≤ d < 12", d ≥ 12"); Size of flanged connector (d=0.5", 0.5" < d < 6", d ≥ 6")	• Equipment category and location • Liquid or gas line • Within pneumatic loop? • Venting, leaking, or both • Function (e.g. level, pressure, temperature, ESD, etc.) • Make, model, age • Operational parameters (e.g. inlet and discharge pressure) • Other (visibility limitations)
Valve	Size (small, large); type (ball, gate, needle); and operating mechanism (manual, pneumatic, electronic)	
Pressure Relief Valve	n/a	
Meter	n/a	
Gauge	n/a	
Regulator	n/a	
Pneumatic Device Vent	Intermittent, continuous low-bleed, continuous high-bleed	
Compressor Vent	Rod packing, distance piece, pocket	

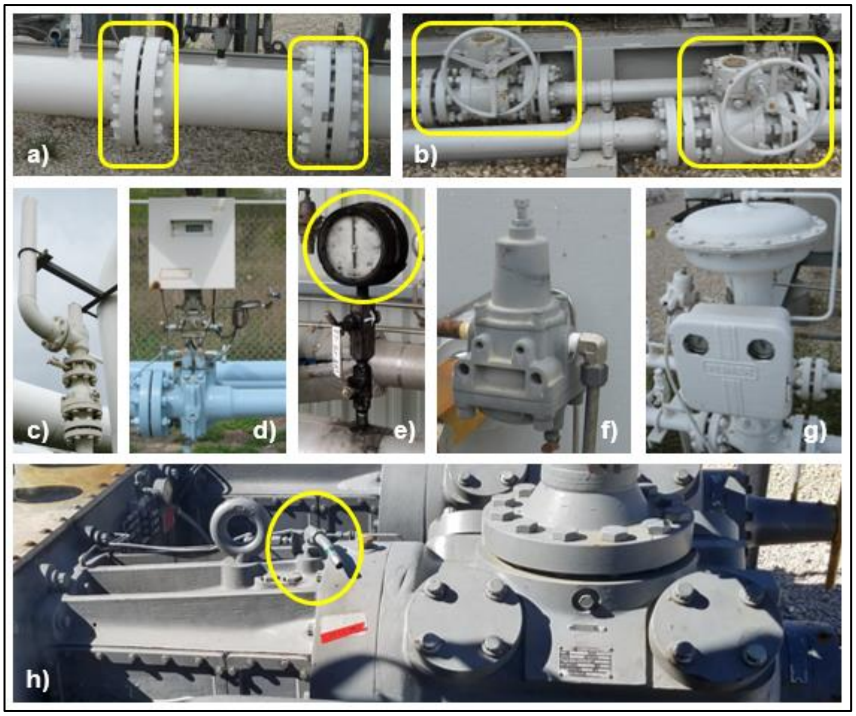


Figure 2-4. *Major component types: a) connector, b) valve, c) pressure relief valve, d) meter, e) gauge, f) regulator, g) pneumatic device, h) compressor vent.*

2.4 Technologies

2.4.1 *Optical Gas (FLIR) Imaging*

A FLIR GF320 infrared (IR) imaging OGI camera was used as a screening tool to visually locate (but not quantify) leaking and venting components of G&B stations. The FLIR GF320 creates images within a narrow range of the mid-IR spectrum (3.3-3.4 um wavelength) within which methane and other light hydrocarbons actively absorb (FLIR, 2011; **Figure 2-5**). Measurements using the FLIR were performed in accordance with 40 CFR Part 60, Subpart A, §60.18 of *Alternative Work Practice for Monitoring Equipment Leaks*. The detection limit of the FLIR GF320 is 60 grams per hour (g/h) (3.1 standard cubic feet per hour [scf/hr]) or less, which is consistent with the requirements of 40 CFR Part 60, Subpart A, Table 1: Detection Sensitivity Levels. The minimum detected leak rate for methane in FLIR lab testing is 0.8 g/hr. In the field, the FLIR is usually able to detect natural gas emissions in the range of 1 scf/hr or larger from 3 m away (Ravikumar et al., 2018). A spec sheet for the FLIR GF320 is provided in Appendix A.

Figure 2-5. *a) Screening a pneumatic device with the FLIR OGI Camera, b) compressor rod packing vent, c) FLIR view of compressor rod packing vent*

FLIR cameras utilize specialized spectral detectors that measure radiant energy incident within the field of view. This radiant energy, in a leak-detection setting, comes from four principal sources: (1) direct radiance from the methane plume, (2) transmitted radiance from the scene (background), (3) scene-reflected cold-sky radiance, and (4) direct atmospheric radiance. Radiance is a function of the temperature emissivity of a given source (e.g., object or substance).

Imaging is affected by factors such as viewing distance, wind velocity, and temperature contrast, depending upon the factors described above. For best survey results, equipment leak detection is performed under favorable conditions, such as during daylight hours in the absence of precipitation, in the absence of high wind (if possible), and in front of appropriate reflective backgrounds within the detection range of the instrument. Temperature contrast is essential for effective gas imaging. Imaging in High Sensitivity Mode (HSM) is utilized to detect emissions in less favorable conditions.

Facilities were surveyed for gas emissions using the FLIR camera by systematically examining process equipment and components in infrared mode. Video images of gas emissions from leaks and vents were recorded for reference, and each was identified with the date, site, and component type. Components identified during screening were classified as venting, leaking, or malfunctioning according to the following criteria:

- **Vent –** Component designed to emit gas (e.g., compressor vent, pneumatic device), and functioning properly
- **Leak –** Component not designed to emit gas (e.g., connector, valve)
- **Malfunction –** Component designed to emit gas, but not functioning properly (e.g., pneumatic device vent stuck open).

The FLIR was used in Field Campaigns 1, 3, and 4. A FLIR was not used in Field Campaign 2, which focused on high volume measurements on compressor vents.

2.4.2 *High Volume Sampling System*

Where individual equipment components (valve, connector, etc.) were identified as leaking or venting by the FLIR team, emission rates were quantified using a customized, microdilution high volume sampling system, built and operated by Utah State University (USU). This system was designed to distinguish between methane and other organics - a limitation of typical high volume sampling systems. The customized sampling system, which is housed in a generator-powered trailer (**Figure 2-6**), includes a Los Gatos Research (LGR) Ultraportable Greenhouse Gas Analyzer to measure methane concentrations in sample gas and a Fox Thermal Instruments Model FT1 mass flow meter to measure total flow. The field detection limit at G&B stations is 0.09 scf/hr (see details in Appendix B).

The trailer also houses a custom-built air scrubber system to generate methane-free air and a GPS system to record the location of the weather station measuring atmospheric conditions. An explosion-proof blower, attached to the trailer, generates flow from the bagged component to the trailer. All components of the high volume system are grounded to the trailer, which is attached to a ground rod to dissipate buildup of static electricity.

Figure 2-6. *a) USU sampling trailer with high volume tubing connected, b) interior of trailer, c) bagged pneumatic device for sampling*

2.4.3 *High Volume Field Measurements*

Methane emissions from G&B facility equipment and associated components were measured directly using the high volume sampling system in accordance with 40 CFR Part 98 Subpart W. Individual components were either taped with antistatic tape or bagged off with an antistatic polymer bag to ensure all emissions were captured (**Figure 2-6**). A hose was then inserted into the bag or taped around the component to sample the leak, and the blower pulled a high volume of gas from the partitioned component through antistatic ducting, into a flow measurement tube, and to the analyzer for sample collection and analysis. The background air concentrations were measured by a sample port that was positioned next to each partitioned component to ensure an accurate background concentration measurement. If a known leak was near the background port, caution was taken to ensure the sample was of ambient air and not of the elevated concentrations from the nearby leak.

Methane concentrations were measured, on average, in 10-minute intervals. This allowed for 2-3 minutes of calibration between sampled components, and about 8 minutes of usable data. Data was collected in 15- or 20-second intervals, and the average emission rate was reported (see Appendix B for details). The variability in the 15- and 20-second intervals is discussed in Section 3.6.2. During sampling, a set of pumps continuously pulled air from the sample hose and ambient air port through Teflon lines. An automated switching unit allowed the methane analyzer to alternately measure concentrations from the sample and background lines. A Fox Thermal Instruments Model FT1 mass flow meter measured total system flow; flow was corrected for temperature, pressure, water vapor, and methane concentration. A data logger recorded methane concentration, sample flow rate, and sample temperature as well as meteorological conditions (wind speed and direction, air temperature, barometric pressure, relative humidity).

The LGR Greenhouse Gas Analyzer was able to detect methane concentrations of up to 10% in air. However, if methane concentrations exceeded this threshold, a mass flow controller was used to dilute the analyzer flow with methane-free air to keep within the analyzer's range. This methane-free air was generated with a custom-built air scrubber system. Dilution was necessary for 12 samples.

During all gas measurements with the high volume sampler, field technicians ensured that data were complete and component location and type were accurately documented and backed up as soon as practical (no less frequently than daily). To confirm sample locations and IDs on field notes, photos were taken at each component showing a labeled whiteboard listing sample ID and time next to the sampled component. Further details on the high volume sampling system and methods are located in Appendix B.

2.4.4 *Open Path – Fourier Transform Infrared Spectrometer*

Methane concentrations downwind of operating compressor units were measured with OP-FTIR spectroscopy. Path-integrated gas concentrations were measured by Kassay Field Services, Inc., using a OP-FTIR spectrometer (**Figure 2-7**) and retroreflector. A controlled stream of inert sulfur hexafluoride (SF_6) tracer gas was released following protocols recommended by Lamb et al. (1995). Methane emission rates were determined based on the ratio of the measured methane and SF_6 concentrations during measurement periods with favorable atmospheric conditions. The general layout of the OP-FTIR and tracer release configuration at each wellhead is shown on **Figure 2-8**. The OP-FTIR was employed during Field Campaign 1, and due to the poor correlations

Figure 2-7. *OP-FTIR spectrometer*

between the methane plume and tracer gas, was not used in subsequent field campaigns. A detailed description of OP-FTIR methods is in Appendix D.

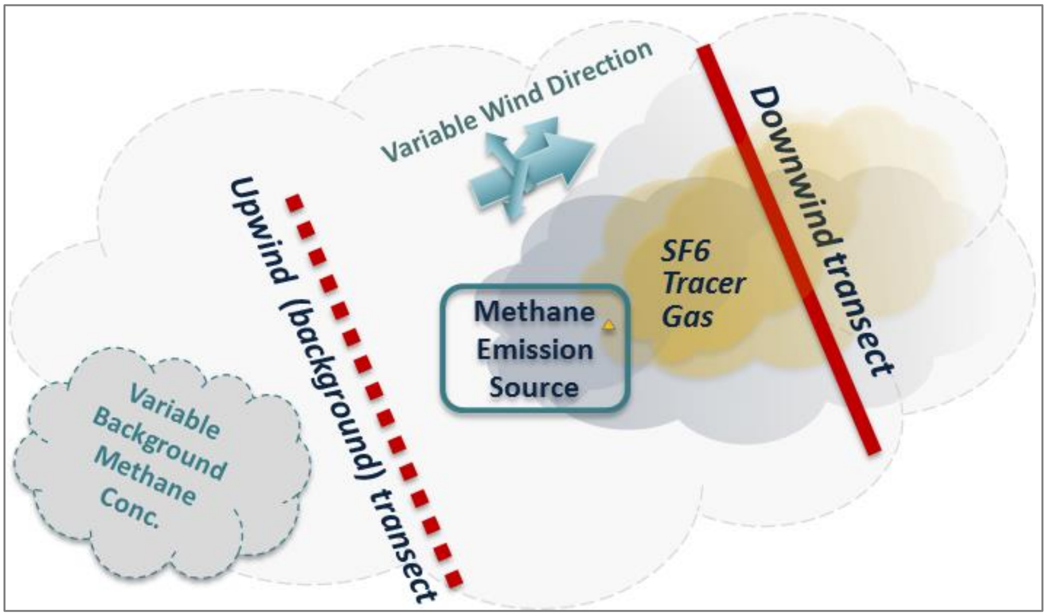


Figure 2-8. *OP-FTIR/tracer sampling schematic*

2.4.5 OP-FTIR and Tracer Release Field Measurements

Ambient upwind and downwind measurement data were collected using the RAM2000 monostatic OP-FTIR spectrometer with a corner cube retroreflector (**Figure 2-7**). This optical spectroscopy technology was adapted to perform real-time monitoring of gaseous compounds in ambient air. The OP-FTIR spectrometer was used to detect and quantify the mixed plumes of SF_6 and methane.

Measurements were averaged over 5-minute intervals and path lengths ranging from 50 to 130 meters (165 – 430 ft). Path-integrated concentrations of methane and SF_6, were determined using standard infrared spectra of known concentrations for these gases and converted to ppm by dividing by the path length. The onboard computer software and a spectral library allowed for real time determination of concentrations for each compound. On-site data including start time, end time, weather, location of reflector, location of OP-FTIR, site conditions, and other field parameters were recorded during sampling. The spectrometer was calibrated in accordance with manufacturer specifications. Synchronous meteorological data, including wind speed, wind direction, and ambient temperature, were collected at 5-minute intervals during OP-FTIR sampling at all transect locations. These data were collected using a portable, tower-mounted weather station positioned 6 m above ground level (affixed to the high volume sampler trailer). All meteorological and tracer release data were logged in conjunction with the high volume sampling data collected by USU.

2.5 Screening and Measurements Summary

A total of 52,500 components were screened with the FLIR during Field Campaigns 1, 3, and 4 (**Table 2-4**). A FLIR was not used for screening in Field Campaign 2, rather the campaign was focused on taking measurements from compressor vents. A total of 307 components were sampled with the high volume system over the four field campaigns, and an additional 15 field blanks were also sampled.

Table 2-4. *Screened population and measurement counts*

Component Type	Screened [a] Population	Measurement [b] Count
Valve	6,281	28
Connector, Flanged	6,457	8
Connector, Other	37,118	24
Pressure Relief Valve	385	8
Meter	86	1
Gauge	972	5
Regulator	762	10
Actuator	275	3
Distance Piece Vent	80	80
Rod Packing Vent	34	27
Pneumatic Device Vent	297	101
Other c	--	12
TOTAL	**52,744**	**307**

[a] Screening with a FLIR was conducted during field campaigns 1, 3, and 4. [b] Total measurement count for all 4 field campaigns. [C]"Other" category contains filters, thief hatches, pump vents, and compressor pocket vents.

Component screening with the FLIR was performed only on operational and pressurized equipment, therefore the number and type of equipment screened was subject to change between field events, as discussed in Section 2.2 (see **Figure 2-1**). Alternatively, equipment that was operational or pressurized during more than one field event was screened multiple times (e.g. compressor vents).

2.6 Data Analysis

2.6.1 High Volume Emission Rates and Non-Detects

The methane emission rate was calculated as the methane concentration in sampled air ($C_{CH4,\ sample}$) minus methane concentration in background air ($C_{CH4,\ background}$) (hereafter referred to as "effective sample concentration") multiplied by flow rate (Q) (**Equation 2-1**). Results were averaged over the measurement period and converted to units of scf/hr to align with component-level EFs currently found in 40 CFR Part 90 Subpart W.

$$ER_i = \left(C_{CH_4,sample} - C_{CH_4,background}\right) \times Q \qquad \textbf{(2-1)}$$

In some cases, negative effective sample concentrations were measured (methane concentration in background air was larger than methane in the sampled air), resulting in calculation of a negative emission rate. Although negative effective sample concentrations are possible in some rare cases (e.g., if the component being measured is located next to a second, higher emitting component, the emissions from the second component could be pulled into the background measurement for the first), for purposes of this study, negative emission rates were considered as non-detect.

The high volume sampling field detection limit (DL) was determined to be 0.09 scf/hr based on field blank measurements after removing outliers. Outliers were removed due to highly variable background methane concentrations or high methane concentrations in the sample line before the blank measurement was performed (details in Appendix B). Emission rates less than the field DL were classified as non-detects.

2.6.2 *Statistical Analyses*

A variety of statistical tests were used to analyze the collected data.

Component Category Comparison

The Kolmogorov-Smirnov (KS) test was used to identify statistical differences in emission rates between: i) two compressor vent subcategories – RPV and DPV, and ii) two connector subcategories – flanged and other (e.g., threaded, compression). The KS test is a nonparametric test used to determine if sample sets come from different distributions; it is sensitive to differences in shape, spread, and median of the sample sets.

The Mann-Whitney test with Bonferroni correction was used to identify statistical differences in emission rate distributions between more than two sample categories. The Mann-Whitney test is a nonparametric test used to compare sample distributions. The Bonferroni correction was used to counteract the increased rate of Type 1 errors (incorrectly rejecting the null hypothesis) that can occur when making multiple comparisons. Data sets that were compared using Mann-Whitney were the three pneumatic device vents categories (intermittent, high-, and low-bleed), and component emissions by site.

Emission Rate Correlations

Spearman's Rho was used to evaluate correlations between component emission rates and site parameters, including compressor age, inlet and discharge pressures, facility throughput, energy throughput, and gas composition (i.e., % methane). Spearman's Rho is a nonparametric test that measures the rank correlation between two sample sets. A value of 1 or -1 is a perfect correlation; a value of 0 is no correlation.

2.6.3 *Emission Factor Calculations*

Population and leaker EFs were calculated using **Equations 2-2, 2-3**, and **2-4**. Population EFs are used to estimate methane emissions by multiplying the EF by the total component counts. Leaker EFs are used to estimate methane emissions by multiplying the EF by the number of components identified as leaking (e.g., with OGI).

Emission factors were calculated from a small data set (four G&B stations). As such, the factors presented are likely not representative of national emissions. The data collected in this study is being incorporated into emission factor calculations being conducted by Colorado State University. Emission factors associated with data from this study, and the number of samples used for calculations, are presented in Appendix F.

Population Emission Factor

Population EFs are calculated differently for components that are leaking compared to venting. For leaking components (e.g., connectors), it was assumed that all leaks were detected and measured during the field campaigns. The population EF for leaking components was calculated as the total emissions from component type i normalized by the screened population of component type i:

$$Population\ EF_{i,leak} = \sum ER_{i,measured} \Big/ N_{i,screened\ population} \qquad \textbf{(2-2)}$$

Where:

$ER_{i,\ measured}$ = Methane emission rate if component type *i* measured with high volume (scf/hr)

$N_{i,\ screened\ population}$ = Total number of component type *i* screened with the FLIR during field campaigns

The same equation could not be used for venting components (compressor vents, pneumatic device vents), because not all vents were measured during the field work. It was assumed that all components designed to vent (on operational equipment) were venting; the screened population was equal to the emitting population. The population EF for venting components was calculated as the average measured emission rate:

$$Population\ EF_{i,vent} = Average(ER_{i,measured}) \qquad \textbf{(2-3)}$$

For the pneumatic device population EFs, there was some bias in the field toward measuring pneumatic devices that were actively emitting methane. This may have resulted in pneumatic device vent population EFs that are more likely leaker EFs, since the sample set includes a potentially biased number of actuating and/or malfunctioning devices.

Leaker Emission Factor

The leaker EF for component type *i* was calculated as the average leaking emission rate measured with high volume ($ER_{i,\ measured,\ leak}$):

$$Leaker\ EF_i = Average\left(ER_{i,measured,leak}\right) \qquad \textbf{(2-4)}$$

Leaker EFs were not calculated for components designed to vent.

2.6.4 *OP-FTIR Tracer Analysis*

Methane emission rates were calculated using tracer correlations, based on downwind methane and tracer concentrations and controlled tracer release rates. Tracer correlations were performed using three independent methods adapted from previous studies (USEPA, 2014; Galle et al., 2001; Mønster et al., 2014; Schuetz et al., 2011; and Foster-Wittig, 2015): (i) time-series plume integration, (ii) unconstrained slope, and (iii) mixing ratio methods. The plume integration method provides the most accurate estimate of emission rate given its effective consideration of an entire time series of measurements. However, to ensure the validity of these estimates several method quality indicators (MQIs, described below) were applied based on the agreement of emission rates estimates among the three methods. When MQIs were satisfied, the result of the plume integration method was adopted as the final calculated value for methane emission rate.

Due to the nature of tracer correlation methods, several precautions were taken to ensure that the recorded data was appropriately interpreted; most importantly, the methane and tracer plumes needed to be well mixed. Tracer correlation methods are not considered reliable for measurement periods during which downwind methane and tracer concentrations are poorly correlated or when there is substantial non-agreement among the three emission rate estimation methods described above. Such conditions suggest instability in either the methane or tracer plume, which may be caused by low wind speeds (causing pooling of the tracer, which is much heavier than methane), highly variable wind direction, variable upwind (background) methane concentrations during periods of downwind measurements, and other possible factors.

Foster-Wittig et al. (2015) propose that the coefficient of determination (R^2) between methane and tracer concentrations should be greater than 80% over five or more consecutive measurement intervals. Additionally, Foster-Wittig et al. (2015) recommend that i) the relative difference in emission rates calculated by the plume integration and mixing ratio methods be less than 20% and ii) the relative difference in emission rates calculated by the plume integration and unconstrained slope methods be less than 55%.

Overall, only a small portion of all downwind OP-FTIR measurement periods satisfied the MQIs required for these data to be relied on for total emissions quantification. Specific factors contributing to this condition include limitation of a single tracer release point (located adjacent to the running compressor/s at each site) to adequately represent a spatially distributed array of significant methane emissions, when OP-FTIR measurements are practicably attainable only within the boundaries of the participating facilities. Due to the limited amount of data that satisfied MQIs, OP-FTIR measurements were not continued after Field Campaign 1.

2.7 Plume Visualization Model

The Gaussian air dispersion model was used to visualize the methane plume associated with compressor component emissions measured with the high volume system (**Equation 2-5**). This model is a steady-state model, and therefore is a conservative estimate of the plume.

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \times \left[exp - \left(\frac{y^2}{2\sigma_y^2}\right)\right]\left[exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + exp\left(\frac{-(z=H)^2}{2\sigma_z^2}\right)\right] \qquad \textbf{(2-5)}$$

Where:

C = Concentration of methane in the air (mg/m^3)

Q = Rate of chemical emission (mg/s)

u = Wind speed in the x-direction (m/s)

σ_y = Standard deviation in the y-direction (m)

σ_z = Standard deviation in the z-direction (m)

y = Distance along axis horizontal to wind direction (m)

z = Distance along vertical axis (m)

H = Effective stack height (m)

The visualization tool calculates σ_y, σ_z, and H based on input parameters including date and time, site location, sky cover, and land surface cover. Up to three different emission sources can be input into the tool, and the resulting plume is calculated and plotted. Note that Q was set equal to the sum of measured emissions from a single compressor, and included compressor vents, pneumatic device vents, and leaking components. Details are provided in Appendix E.

3.0 RESULTS AND DISCUSSION

Results and key findings are summarized in the sections below. Research questions, relevant findings, and potential implications are highlighted in blue boxes, followed by a detailed summary of key results and recommendations.

3.1 Component Population Counting Methodology

Research Question 1

How are component populations counted on different equipment types and how are counts affected by counting methodology?

Key Findings

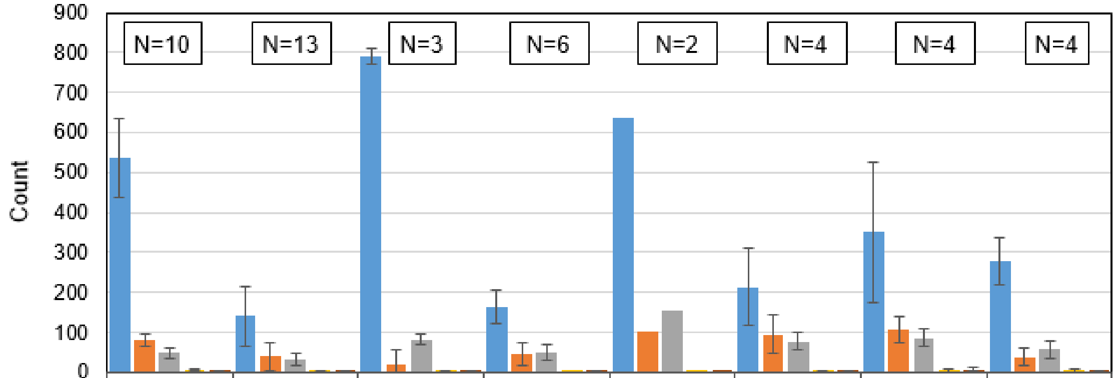
1. Component counts vary substantially based on classification and counting methodology (e.g., including/excluding components on liquid lines and pneumatic device loops).
2. Connectors and valves comprised the largest population of components at compressor sites.
3. Dehydrators and slug catchers had the highest total component counts when liquid lines were included in equipment component counting.
4. Yard piping, compressors, and gathering lines had the highest total component counts when components on liquid lines were *not* included in equipment component counting (i.e., only components on gas lines were included).
5. Eliminating components within pneumatic loops from component counts reduced the count on slug catchers, coalescers, separators, and gathering lines.

Summary

Different counting methodologies can result in vastly different component counts, thus influencing total emissions calculations using Subpart W population EFs. A standard methodology should be adopted for classifying and counting components in order to minimize inconsistencies across studies and instruct stakeholders responsible for GHGI reporting.

During the 4th field campaign conducted during March 2018, >22,000 components from 10 G&B equipment types were classified and counted according to the procedures discussed in Section 2.2 and Appendix C. Average component counts for both liquid and gas lines from 5 component categories that fall under Subpart W for G&B stations are presented in **Figure 3-1.** Average component counts for gas lines only (i.e., liquid line components excluded) are shown in **Figure 3-2**. Components on pneumatic device loops are included in total counts on both figures. Additional categories, such as compressor vents, meters, and regulators, were also classified and counted. Component count results for these additional categories are located in Appendix G.

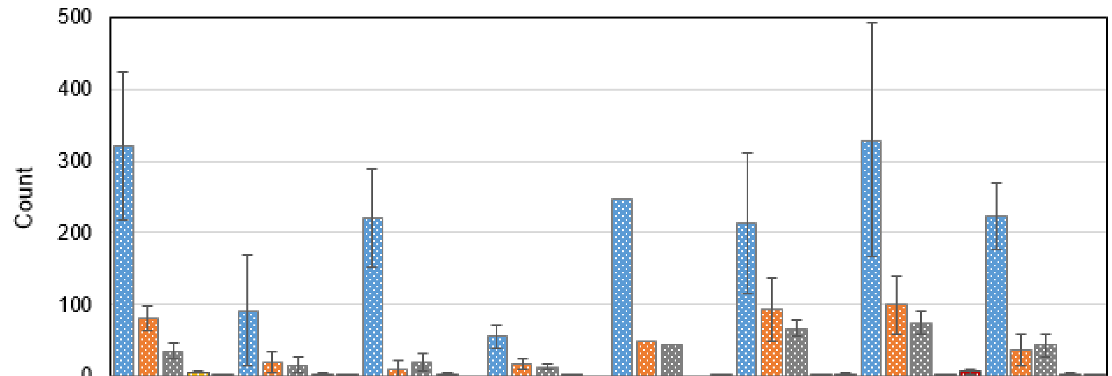
When liquid lines were included in equipment component counting, dehydrators and slug catchers had the highest number of individual components per piece of equipment (**Figure 3-1**). Yard piping, compressors, and gathering lines had the highest number of components per piece of equipment when liquid lines were *not* included (**Figure 3-2**). For both counting scenarios, the components with the highest counts were: “other” connectors; flanged connectors; and valves.



	C	S	D	CA	SC	GL	YP	FG
Connector, other	537	141	790	164	636	214	351	279
Connector, flanged	81	40	21	46	103	95	107	38
Valve	48	31	82	50	156	78	87	57
PRV	6.7	2.1	3.0	1.2	7.5	1.0	3.5	3.3
Pneumatic Device	3.2	1.8	3.3	1.8	5.5	2.3	6.5	1.3

The number of each equipment type that was counted is given as N. Error bars are standard deviations. Abbreviations: PRV = pressure relief valve, C = compressor, S = separator, D = dehydrator, CA = coalescer, SC = slug catcher, GL = gathering line, YP = yard piping, FG = fuel gas skid.

Figure 3-1. *Average component count by equipment type, including gas and liquid lines*



	C	S	D	CA	SC	GL	YP	FG
Connector, other	322	92	221	56	247	214	329	224
Connector, flanged	81	20	9.0	17	48	93	100	37
Valve	35	15	19	13	45	67	75	43
PRV	5.5	1.8	2.3	1.2	0	1.0	2.0	3.0
Pneumatic Device	1.4	0.9	0	0	1.5	2.3	6.5	0.3

Error bars are standard deviations. Abbreviations: PRV = pressure relief valve, C = compressor, S = separator, D = dehydrator, CA = coalescer, SC = slug catcher, GL = gathering line, YP = yard piping, FG = fuel gas skid.

Figure 3-2. *Average component count by equipment type, gas lines only*

There was a substantial difference in total counts when liquid lines were excluded. The total count dropped from >22,000 components to just over 14,000. In specific, “other” connectors reduced from an average of 537 to 322 when liquid lines were excluded from the count, as shown on **Figures 3-1** and **3-2**. As expected, this reduction was most notable for equipment designed to handle liquids (e.g. liquid separation). Since the majority of natural gas process equipment have some degree of liquid handling capabilities, the counts were also reduced on equipment that handle less liquid, such as compressors and fuel gas skids.

There was a further reduction in component count (<12,000 components) when components in pneumatic loops (regulators, small valves, connectors) were removed from the gas line counts. The average component count on slug catchers was affected the most, with a 46% reduction in the average count. Slug catchers were followed by coalescers (30% reduction), separators (29% reduction), and gathering lines (28% reduction). Components that were the most affected were regulators, gauges, and other connectors, which are the most common components in pneumatic loops.

The differences between these counts highlight the need for a consistent counting protocol, as different counting methodologies can result in vastly different component counts, thus influencing total emissions calculations using Subpart W population EFs.

3.2 Appropriateness of Component Categories in the GHGRP

Research Question 2

Do methane emissions data support component categories and subcategories currently identified in the GHGRP?

Key Findings

1. There is a significant difference ($p < 0.05$) between leaking emission rate distributions of flanged and other connectors in the current GHGRP.

2. There is a significant difference ($p < 0.05$) between venting emission rate distributions of different types of pneumatic devices in the current GHGRP.

3. There is a significant difference between compressor vent (DPVs, RPVs) emission rate distributions, and the current EF may not be representative for compressor venting.

4. Limited data sets for meters, gauges, and regulators did not allow for statistical analysis to determine if they should be added to the GHGRP.

Summary

Results support current component subcategories listed in USEPA Subpart W, including the subdivision of connectors (flanged and “other”) and pneumatic device vents (intermittent, continuous low bleed, and continuous high bleed). Results warrant further study of emissions from compressor vents, meters, gauges, and regulators.

Current Subpart W Subcategories

Under Subpart W of the GHGRP for G&B stations, the USEPA published population and leaker emission factors based on various component subcategories (**Table 3-1**). For example, pneumatic device vents are subdivided into low continuous, high continuous, and intermittent bleed vents. Further, connectors are separated into flanged and other (e.g. threaded, compression). As discussed in Section 2.4, statistical analyses were performed to evaluate the methane emission rate distributions among subcategories currently listed in Subpart W. The results of these analyses are discussed below.

Table 3-1. *Emission factors currently included in the GHGRP*

Subpart W Population EF Component Categories (USEPA, 2015)	Subpart W Leaker EF Component Categories (USEPA, 2016)
Valve	Valve
Connector[a]	Flange
Open-Ended Line	Connector (other)[b]
Pressure Relief Valve	Open-Ended Line
Low Continuous Bleed Pneumatic Device Vent	Pressure Relief Valve
High Continuous Bleed Pneumatic Device Vent	Pump Seal
Intermittent Bleed Pneumatic Device Vent	Other[c]
Pneumatic Pump	

[a] Includes all types of connectors (i.e., flanged and other), [b] Includes all non-flanged connectors (e.g., threaded and compression), [c] Includes any equipment leak emission not specifically listed in the table

The Kolmogorov-Smirnov (KS) test was used to determine whether emission rates for two component categories were significantly different. The KS test showed distributions of flanged and other connectors were significantly different ($p = 0.047$). The Mann-Whitney pairwise test with Bonferroni correction was also used to determine if more than two component categories had significantly different distributions. The Mann-Whitney test results showed:

- Distributions of continuous low-bleed and continuous high-bleed pneumatic device vents were significantly different ($p = 0.003$)
- Distributions of continuous high-bleed and intermittent pneumatic device vents were significantly different ($p = 0.001$)
- Continuous low-bleed and intermittent pneumatic device vents may have come from the same distribution ($p = 0.80$)

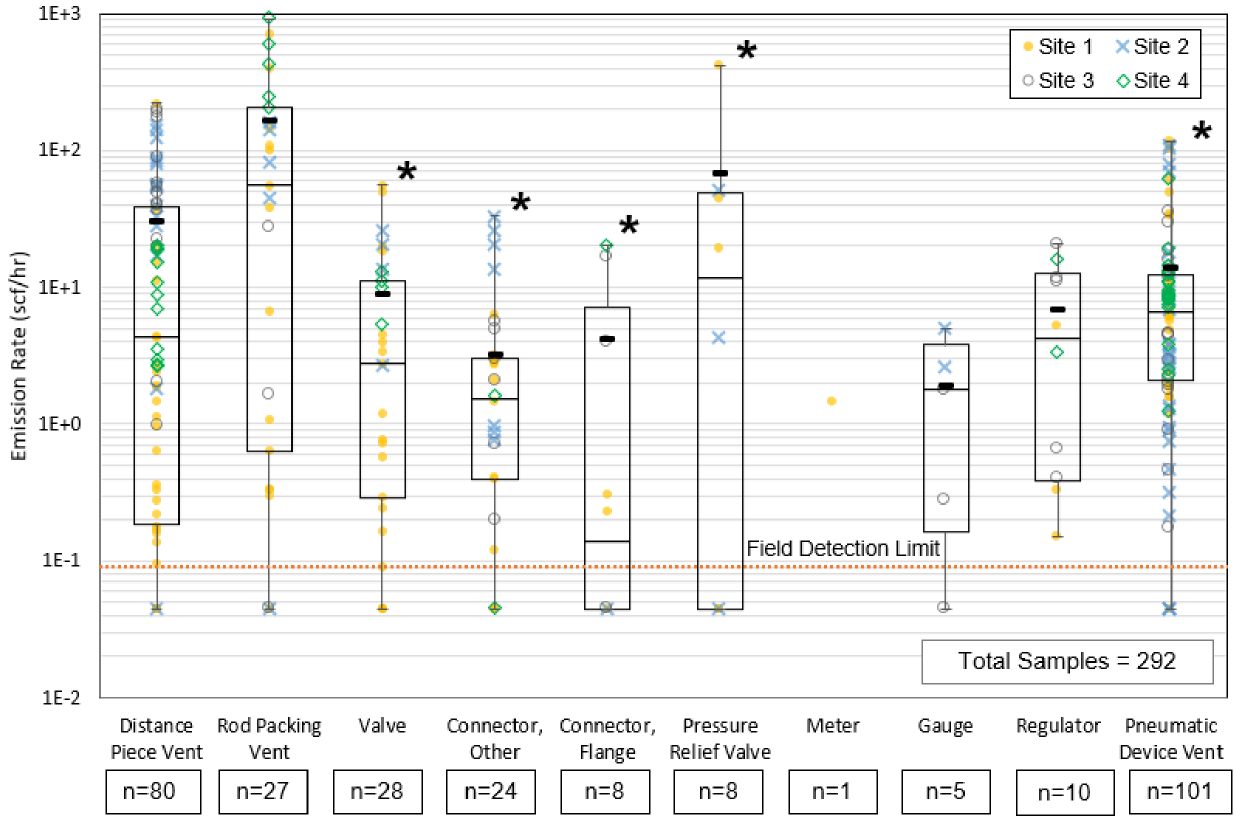
Although it could not be shown that continuous low-bleed and intermittent pneumatic device vents came from different distributions, the significant differences between continuous low- and high-bleed, and continuous high-bleed and intermittent support the current subcategorization of pneumatic device vents in the population factor table from the 2015 update (USEPA, 2015), and the division of connectors into flanged and other in the 2016 leaker factor addition (USEPA, 2016).

Potential Subpart W Categories/Subcategories

General trends in emission rates showed venting components, such as DPVs, RPVs, and pneumatic device vents, had higher emission rates than leaking components (e.g., connectors, gauges, valves). All components had emission rates that ranged at least two orders of magnitude. RPVs and pressure relief valves (PRVs) had the largest emission range, with approximately four orders of magnitude difference between minimum and maximum emission rates. However, the large emission range for PRVs was due to one measurement (424 scf/hr) from Field Campaign 1, which was repaired by the operator prior to Field Campaign 2. Leaking components (valves, connectors, gauges, regulators) had a smaller overall range of emissions than venting components.

Although compressor vents (DPVs, RPVs) are not currently sub-classified in Subpart W, they exhibited relatively wide ranges of emission rates (**Figure 3-3**) and the highest average emissions (i.e., 30.4 and 165 scf/hr, respectively) of the major categories. Results of the KS test showed the emission rate distributions of RPVs and DPVs to be significantly different (p = 0.0083), warranting consideration of compressor venting sub-classification, as opposed to a single EF. Further, in Subpart W a single EF of 9.48×10^3 scf/yr/compressor (1.1 scf/hr/compressor; Harrison et al., 1996) is currently used for compressor venting at G&B stations (USEPA, 2011). This EF may not accurately represent (i.e., may be significantly lower than) measured compressor venting rates.

It should be noted that compressor vent emissions rates measured for this study, however, are based on a small data set (10 compressors; 4 G&B stations in Gulf Coast area) and are not representative of national averages. A more robust dataset of emission measurements of compressor vents, including sites outside the Gulf Coast area would be needed to properly add compressor venting components and develop specific emission factors for DPVs and RPVs.



Notes:
* Component categories currently included in leaker and/or population emission factors in the GHGRP
Measured rates less than the detection limit were assigned the value of ½ the field detection limit.
For comparison, a standard cubic foot is approximately 7.5 gallons, or the size of a small kitchen-sized trash bag. A typical water heater pilot light has a flow rate between 0.25 and 1 scf/hr (Energuide 2018).

Figure 3-3. *Measured methane emission rates by component type and site*

Measured emission rates for additional component categories are presented in **Figure 3-3**. Due to the limited sample size of valves, additional subcategorization (e.g., by size or type as outlined in **Table 2-3**) could not be analyzed. Additionally, the limited data sets for meters, gauges, and regulators did not allow for statistical analysis to determine if these component types should be incorporated as new categories in the GHGRP.

3.3 Emission Rate Variability by Site and Operational Parameters

Research Question 3

Do emission rates vary from site to site? Do site operational parameters (e.g., gas throughput, gas composition, compressor age) correlate with emission rates?

Key Findings

1. Emission rates from DPVs are significantly different by site.
2. Emissions rates from pneumatic devices and RPVs showed no significant difference by site due to the intermittent nature of leaking components.
3. Compressor age does not appear to play a statistically significant role in emission rate; however greater variability in emission rates (including higher emissions) from DPVs was observed on older (e.g., >10 years) compressors.
4. Site inlet pressure had a statistical correlation with emission rates on compressor RPVs.
5. Other site operational parameters, including gas throughput, composition, discharge pressure and energy throughput, did not have statistically significant correlations with emission rates from DPVs and RPVs.

Summary

There is variation of emissions rates across sites and a relationship between higher emissions and compressor age for some components. More measurements should be taken on additional compressor components to further assess emissions rate variability by site and operational parameter.

Emission Rate Variability by Site

The number and type of malfunctioning/leaking components at a site and point in time appear to be random, and in general, had a low frequency of occurrence. As a result, the sample size of leaking components was insufficient for identifying statistically significant trends among sites. Distance piece vents (DPVs) were the only component with a sufficient number of detected emissions (n=80) that showed a diversity of emissions across 2 or more sites. Other venting components with sufficient observations of emissions (e.g., RPVs and pneumatic device vents) showed no significant difference in methane emissions by site typically due to the intermittent nature of leaking components.

DPV emissions for all sites and field campaigns were ranked in order by magnitude of emission rate, with the rank plotted against the corresponding emission rate (**Figure 3-4**). Data from the four sites were plotted with different symbols to support evaluation of site-related trends. There appears to be a link between DPV emission rates and site, as indicated by "groupings" of emission rates. For example, Site 1 emission rates were consistently lower (<50 scf/hr) than Sites 3 and 4 (50-200 scf/hr). It is important to note, however, that each site had occasional DPV emission rates that were on the low and high ends of the observed emission rate range. This implies that emissions from compressor DPVs are not necessarily uniform, and may be dependent upon site and compressor specific operational conditions (e.g., maintenance, vent configuration).

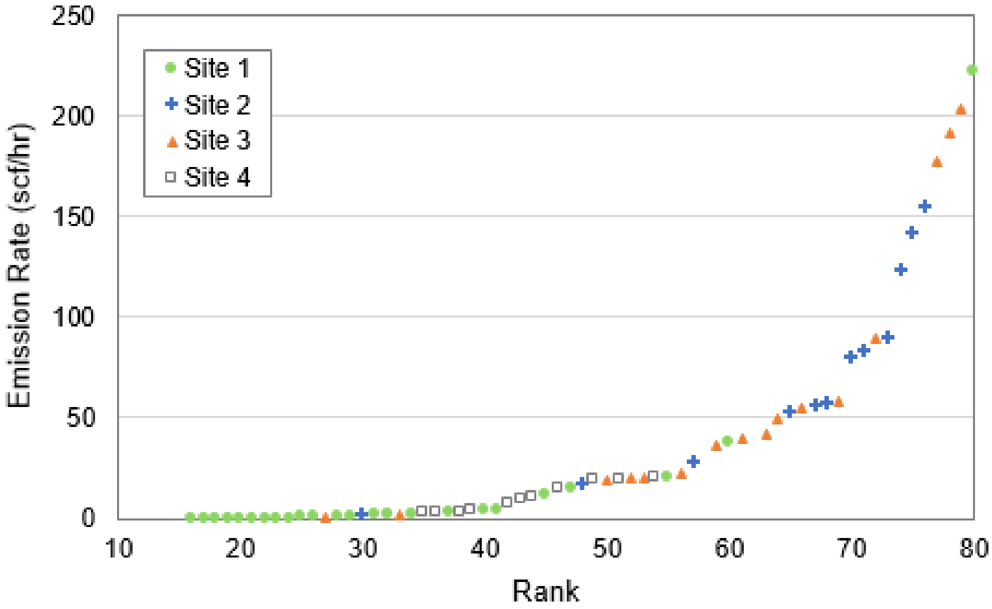


Figure 3-4. *Distance piece vent emissions vs. emission rate rank*

DPV emission rates by site were compared using the Mann-Whitney pairwise test with Bonferroni correction. Results showed a significant difference ($p < 0.05$) between all site pairs except between Sites 2 and 3. The similarity between Sites 2 and 3 is noticeable in **Figure 3-4** by the apparent overlap in the data points compared to other sites.

RPVs and pneumatic device vent data were also evaluated using the Mann-Whitney pairwise test. Test results showed no significant difference in pneumatic device emissions by site. For RPVs, the only potential difference in emissions was between Sites 1 and 4; however statistical significance cannot be concluded as the p-value (0.0499) is nearly equal to the significance level of 0.05 for a 95% confidence level. Emission rates from pneumatic device vents may be influenced by operational conditions of the equipment the device is located on rather than the site. It is recommended that more measurements be taken at components on additional compressors to assess emissions rate variability of a greater population of components by site.

Emission Rate Correlation by Operational Parameter

As mentioned above, the number of malfunctioning/leaking components observed during our repeat field investigations had a low frequency of occurrence. As a result, the sample size of most leaking components was insufficient for identifying statistically significant trends by operational parameter. For those components that produced sufficient data populations (rod packing vents and distance piece vents), Spearman's rho was used to evaluate correlations between component emission rates and operational parameters, including compressor age, inlet and discharge pressures, gas throughput, energy throughput, and gas composition (i.e., % methane). A correlation was identified between compressor RPV emissions and increased site inlet pressure (Spearman's rho = 0.72). However, this result was based on a limited data set (site inlet pressure was not available for Site 1). The correlation makes sense conceptually, as increased pressures around rod packing seals could increase the amount of gas vented from the rod packing units.

No significant correlation was observed between emission rate and compressor age for DPVs (R^2=0.22; Spearman's rho=0.34). However, as shown in **Figure 3-5**, the highest emission rates were from older compressors and there was an increase in emission rate variability with compressors 10 years and older. Other site operational parameters, including gas throughput, composition, discharge pressure and energy throughput, did not have statistically significant correlations with emission rates with DPVs and RPVs. A greater dataset of emissions measurements from additional compressor components is needed to assess emissions rate variability of components by operational parameter.

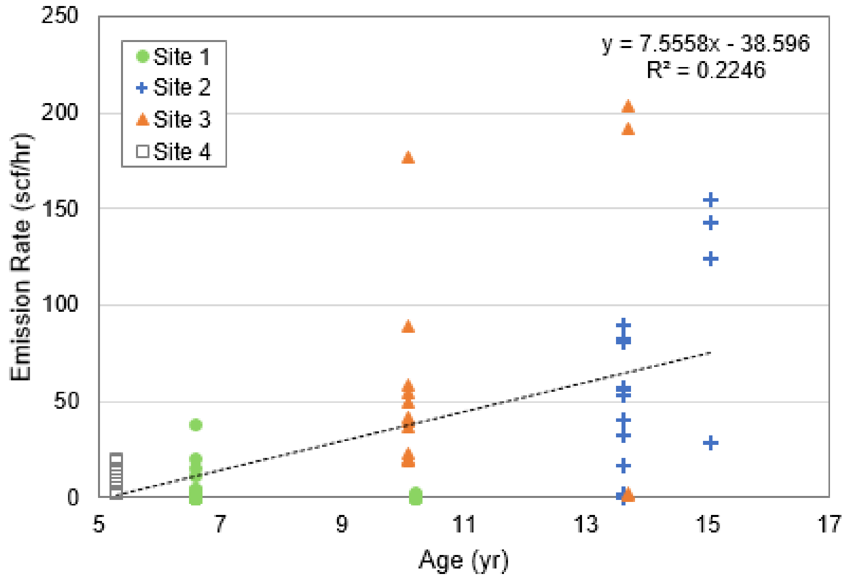


Figure 3-5. *Distance piece vent emissions by site plotted against compressor age*

3.4 Temporal Variability in Emission Rates

<u>Research Question 4</u>

Do emissions from the same site or piece of equipment vary over time?

<u>Key Findings</u>

1. Variation in site and compressor component emissions was significant between field campaigns.
2. The type and proportion of component(s) contributing to compressor emissions also varied across field campaigns.

<u>Summary</u>

Component emission rates varied between field campaigns, especially on compressors. The type of components contributing to overall measured emissions also varied among field campaigns. However, the emission rate variability was larger between different components (of the same category) than the variability in one component over the four field campaigns.

Variability in emission rates was analyzed under two scenarios: i) variability across four quarterly field campaigns and ii) measurement variability during 3- to 72-minute high-flow measurements. Results are presented in the following sections.

3.4.1 *Quarterly Emission Rate Variability*

Emission rates from compressor vents, other vents (i.e., pneumatic device vents), and leaks for each site and field campaign are plotted in **Figure 3-6**. Note that leaking or malfunctioning components are not designed to emit methane (e.g., connectors), or are designed to vent methane but are not functioning properly (e.g., pneumatic device vent that is stuck open). It is evident that emissions vary over time among field campaigns. For example, compressor-vented emissions at Site 1, Field Campaign 1 were 3 times higher than Field Campaign 2, 90 times higher than Field Campaign 3, and 15 times higher than Field Campaign 4. Leaks also varied substantially between field campaigns. One leaking component measured at Site 1 during Field Campaign 1 (a PRV at 424 scf/hr) was fixed prior to returning to the site, and was not leaking during subsequent field campaigns. Similarly, Site 4 had minimal leaks during Field Campaigns 1, 2, and 4; however, a malfunctioning RPV was measured during Field Campaign 3.

Using the density of methane (19.17 g/ft3), the measured methane emissions from the four facilities can be converted from volumetric flow rate (scf/hr) to mass flow rate (kg/hr). The mass flow rate ranged from 3.11 kg/hr (Site 3, FC2) to 36.2 kg/hr (Site 1, FC1).

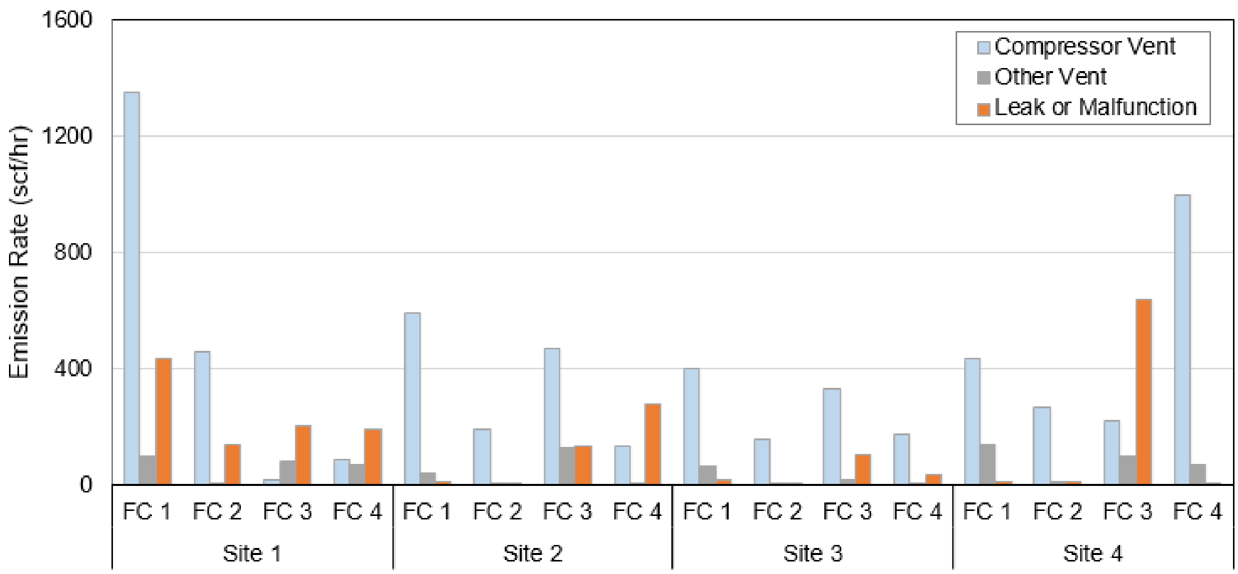
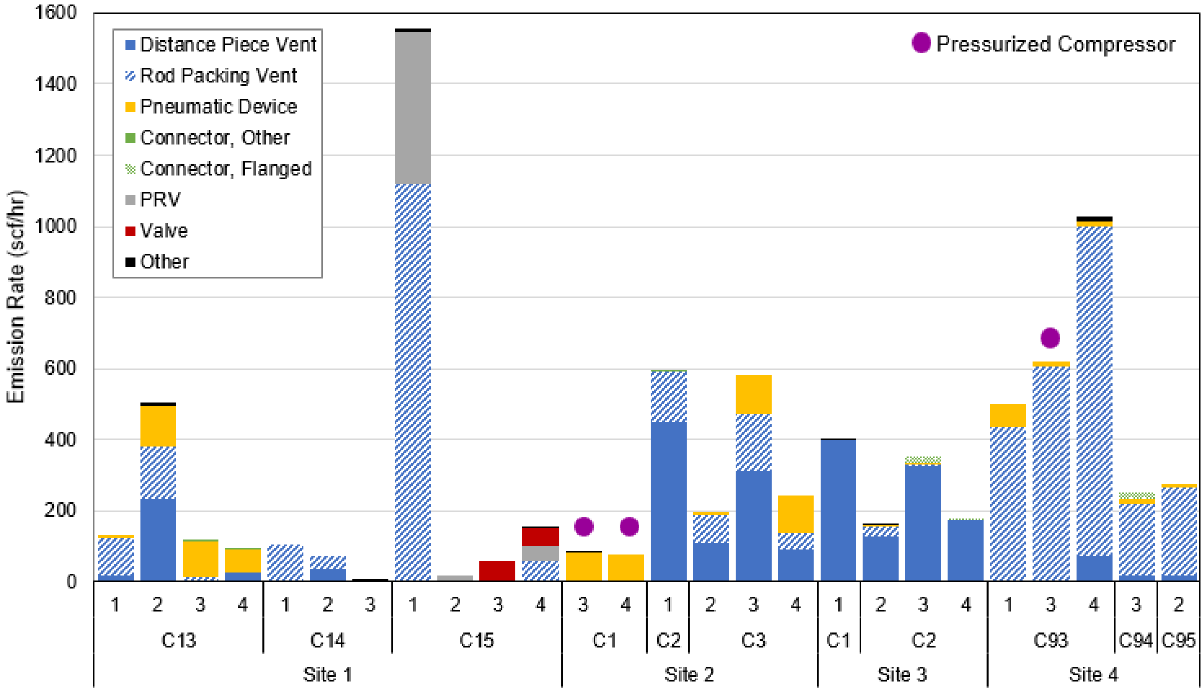


Figure 3-6. *Component leak/malfunction and vent rates by site and field campaign*

Emissions from specific equipment varied among field campaigns, as shown for compressor components in **Figure 3-7**. For example, Site 1, Compressor 15 (C15) emissions were approximately 2 orders of magnitude higher in Field Campaign 1 compared to Field Campaigns 2 and 3. At Site 4, Compressor 93 (C93) emissions doubled from Field Campaign 1 to Field Campaign 4.



Note: The order of the x-axis from bottom to top is Site ID, compressor ID, field campaign. Components in the "Other" category: actuator, regulator, gauge, meter, filter, other vents.

Figure 3-7. *Component leak and vent rates by individual compressor and field campaign*

Not only did the magnitude of total measured emission rates from specific equipment vary between field campaigns, but the type of components contributing to overall equipment emissions also varied. To illustrate, emissions from Compressor 13 (C13) at Site 1 during Field Campaign 1 resulted predominantly from RPVs (see **Figure 3-7**). In Field Campaign 2, this transitioned to DPVs, and ultimately was dominated by pneumatic controllers in Field Campaigns 3 and 4. Further, at Site 2, Compressor 3 (C3), the ratio of pneumatic controller emissions increased to nearly half of total C3 emissions from Field Campaigns 2 to 4.

Note that the emission rate variability was larger between different components (of the same category) than the variability in one component over the four field campaigns. This finding suggests that when calculating emission factors, it is not necessary to take repeat measurements on the same component to capture variability.

3.4.2 *Emission Rate Variability During Sample Measurements*

Research Question 5

What effect does sample duration have on the measured emission rate?

Key Findings

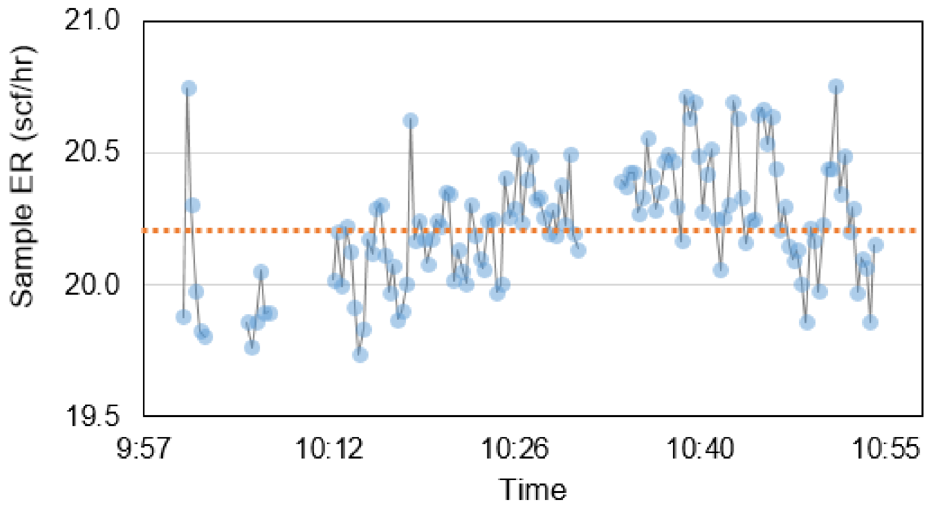
1. Longer sample duration did not result in greater variability within the sample measurement; short sample durations (~10 minutes) adequately capture variability within measurements for most components.
2. Pneumatic device vents did not have greater variability than other types of components, which is unexpected considering the throttling and actuation of pneumatic devices.

Summary

Measuring the emission rate of a sample for an extended period of time is not necessary to capture the average component emission rate. Pneumatic devices, which are designed to actuate and/or throttle, did not show greater variability than other component types. This may indicate the sampling time was not sufficient for pneumatic devices; further investigation is recommended.

Throughout the field campaigns, samples were measured for ~4 to 72 minutes, with the average high-flow sample duration equal to ~12 minutes. To determine whether prior sample periods were adequate to capture the variability that occurs *during* those periods, longer measurement durations were implemented.

Emission rate variability was evaluated on select components (i.e., components that had sufficient datasets and data from at least 3 multiple events) using the high flow system. The system measured methane concentrations in sample air and air flowrate in 15 or 20 second intervals. In other words, an emission rate was logged every 15 or 20 seconds throughout the measurement duration. For example, a 20-second interval emission measurements on a DPV that was measured for approximately 55 minutes is shown in **Figure 3-8**. This figure highlights the variability in emission rate during sample collection.



Note: The orange line represents the average emission rate

Figure 3-8. *High-flow 20-second emission rate measurements on a distance piece vent*

To conclude that an average sample duration of 12 minutes is not sufficient to capture variability, longer duration (30-72 minutes) samples should exhibit greater variability (i.e., larger standard deviation) than shorter duration samples. To test this theory, variability *within* a sample measurement (i.e., standard deviation) was plotted against sample duration (see **Figure 3-9**). As shown, a few of the longer duration samples had relatively high "within-measurement" variability; however, some of the short duration samples also exhibited wide variability. Conversely, the majority of both the short and long duration samples had relatively low within measurement variability (standard deviation <5 scf/hr). Based on these observations, within measurement variability does not appear to trend with sample duration. These results imply that measuring the emission rate of a sample for an extended period of time is not necessary to capture the average component emission rate.

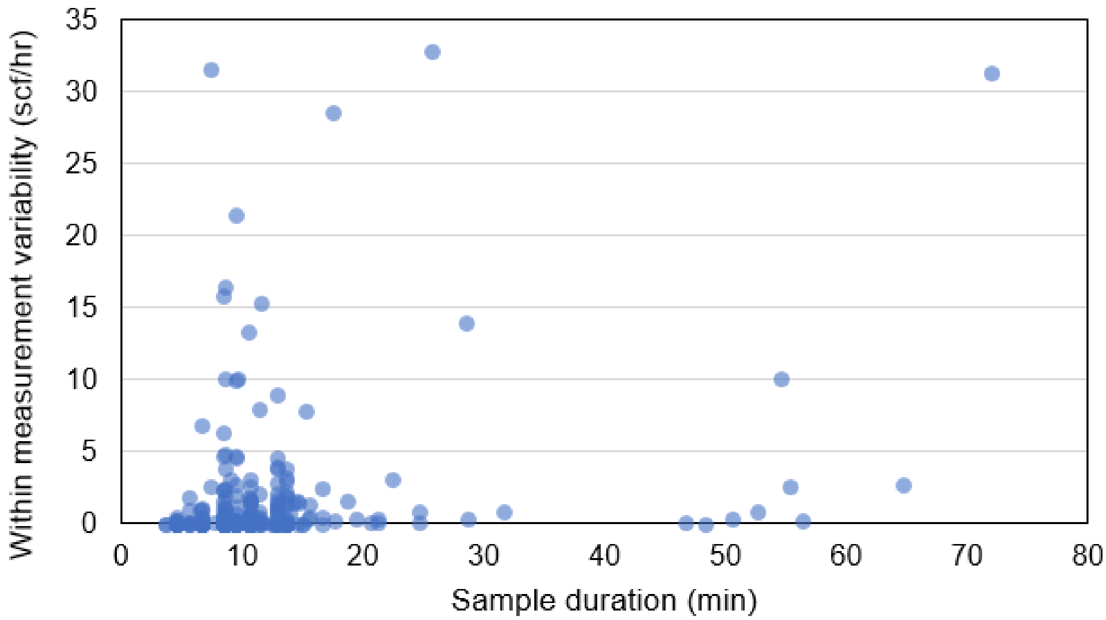


Figure 3-9. *Within measurement variability vs. high-flow sample duration for all components and field campaigns*

Note that the emission rate from many pneumatic devices is designed to vary, for example, during actuation or throttling. Therefore, it would be consistent with the component's designed function for emissions rates to be more variable. To determine if pneumatic device emissions had greater variability than other types of components variability in measurements of pneumatic device vents were separated from the rest of the data (**Figure 3-10**).

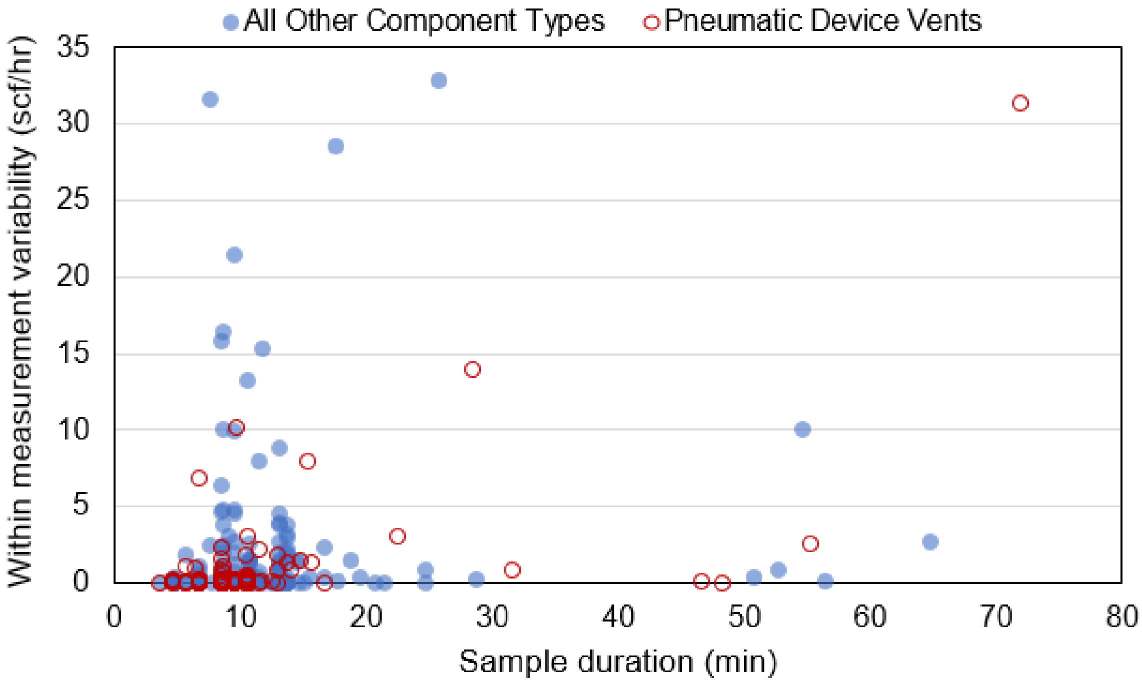


***Figure 3-10**. Comparison of within measurement variability between pneumatic device vents and all other component types*

As shown in **Figure 3-10**, greater within measurement variability was not observed for pneumatic device vents compared to other component types. A possible explanation is that measured devices may not have actuated during the sampling period. A pneumatic device that actuates during the measurement period is expected to have greater within measurement variability due to spikes in emissions during actuation. As a result, an average sample duration of 10 minutes may not be sufficient to capture pneumatic device variability, and further research on emission variability of pneumatic device vents is recommended.

3.4.3 *Temporal Emission Rate Variability Comparison*

<u>Research Question 6</u>

When calculating emission factors, is it important to take repeat measurements on the same component to capture variability?

<u>Key Findings</u>

1. "Within" measurement variability is small compared to quarterly (repeat) sampling or component variability.
2. In general, quarterly sampling variability is smaller than component variability.

Summary

When calculating emission factors, it is not necessary to take repeat measurements to capture component variability. Visiting many sites once is likely to capture more variability in emission rates than visiting sites multiple times.

When possible, repeat measurements were taken on the same component during the field campaigns. Leaking components were often random between field campaigns, which resulted in few repeat measurements on components such as connectors, valves, and PRVs. Operational compressors often changed between field campaigns, which also reduced the number of repeat DPV and RPV measurements. Eleven components were measured during all four field campaigns (4 repeat measurements), and 34 components were measured at three field campaigns (3 repeat measurements). The variability over field campaigns for these repeat measurements is summarized in **Table 3-2**. Since field campaigns were conducted three months apart, these repeat measurements are referred to as quarterly measurements. The quarterly sampling variability was compared to "within" measurement variability (see Research Question 5) and component variability (e.g., variability among all RPVs).

In general, component variability was larger than quarterly (repeat) sampling variability, with the exception of PRVs. However, the relatively large quarterly sampling variability for PRVs was based on one PRV. This PRV had a large emission rate during Field Campaign 1 (424 scf/hr) and was repaired prior to subsequent field campaigns.

Within measurement variability was consistently much smaller than quarterly sampling and component variability, indicating variations in emission rates during the sampling event were insignificant compared to variability between components and between field campaigns.

Table 3-2: *Emission rate variability comparison by component type*

Component Type	Average ER, all data (scf/hr)	"Within" measurement variability (scf/hr)	Quarterly sampling variability (scf/hr)	Component variability, all data (scf/hr)
Distance Piece Vent	30.40	1.40	21.70	51.12
Rod Packing Vent	165.14	5.60	143.22	244.76
Pneumatic Device Vent	14.06	1.07	14.64	24.21
Connector, Other	3.21	0.17	n/a	6.65
Connector, Flange	5.26	0.06	n/a	8.44
Valve	9.86	0.38	3.43	14.64
PRV	67.99	3.30	201.91	145.16

Note: Variability was calculated as the average of the standard deviations of multiple samples

Additional comparisons were done between quarterly sampling variability and component variability within field campaigns. The variability within a field campaign (spatial) was generally larger than the quarterly variability (temporal). In other words, variability between a unique component over time was less than the variability between two unique components from the same category. This indicates that emission factors calculated from emission rates measured from single visits to multiple site will likely capture temporal emission variability.

3.5 Emission Comparison – Gas vs. Liquid Lines

Research Question 7

Should liquid lines be included in the population count? How much do liquid lines contribute to measured emissions?

Key Findings

1. Emissions from liquid lines accounted for an average of 1.3% of the total emissions measured.
2. On average, 16% of fugitive emissions came from liquid lines.

Summary

For reporting purposes, excluding liquid lines from site-wide screening may have a negligible effect on component-related emissions. However, from a site management perspective, malfunctioning components were not uncommon on liquid lines and contributed substantially to fugitive emissions at some sites.

As discussed in Section 3.1 (Component Counts), including liquid lines had a substantial effect on the component counts (~36%). Emissions from gas lines were compared to emissions from liquid lines to determine if liquid lines should be included in component counting and screening. Pneumatic devices that controlled liquid level were counted as part of the gas line because these devices are operated using site gas. The percent of total emissions that were measured from liquid lines is presented in **Table 3-3**. On average, emissions from liquid lines accounted for 1.3% of the total emissions measured at the sites.

Table 3-3. *Percent of total emissions from liquid lines*

Field Campaign	Site 1	Site 2	Site 3	Site 4
1	0.1%	2.3%	0.04%	0%
3	1.2%	2.8%	0%	0%
4	1.5%	7.4%	0%	0%

Field Campaign 2 not included because a FLIR was not used to screen liquid lines for emissions

It should be noted that not all pneumatic device vents were measured during the field events. Therefore, it is expected that emissions from gas lines (i.e., pneumatic devices not sampled) may be higher than measured values. Based on the sites in this study, excluding emissions from liquid lines will likely have a negligible effect on total component-related methane emissions.

Although emissions from liquid lines were small when compared to emissions from all components measured at the sites, emissions from liquid lines made up a larger portion of fugitive emissions. As shown in **Table 3-4**, there was large variability in fugitive emissions from liquid lines. Site 2 had the largest relative amount of fugitive emissions from liquid lines (36-100% depending on field campaign), while Site 4 had none. On average, fugitive emissions from liquid lines accounted for 16% of all fugitive emissions. From a site management perspective, operators may want to include liquid lines in screening protocols as it is possible that malfunctioning components are located on liquid lines.

Table 3-4. *Percent of fugitive emissions from liquid lines*

Field Campaign	Site 1	Site 2	Site 3	Site 4
1	0.4%	100%	10%	0%
3	3.5%	36%	0%	0%
4	4.0%	36%	0%	0%

Field Campaign 2 not included because a FLIR was not used to screen liquid lines for emissions

3.6 Emissions Comparison – Measured vs. Estimated

Research Question 8

How do measured emissions compare to estimated emissions calculated from published Subpart W emission factors?

Key Findings

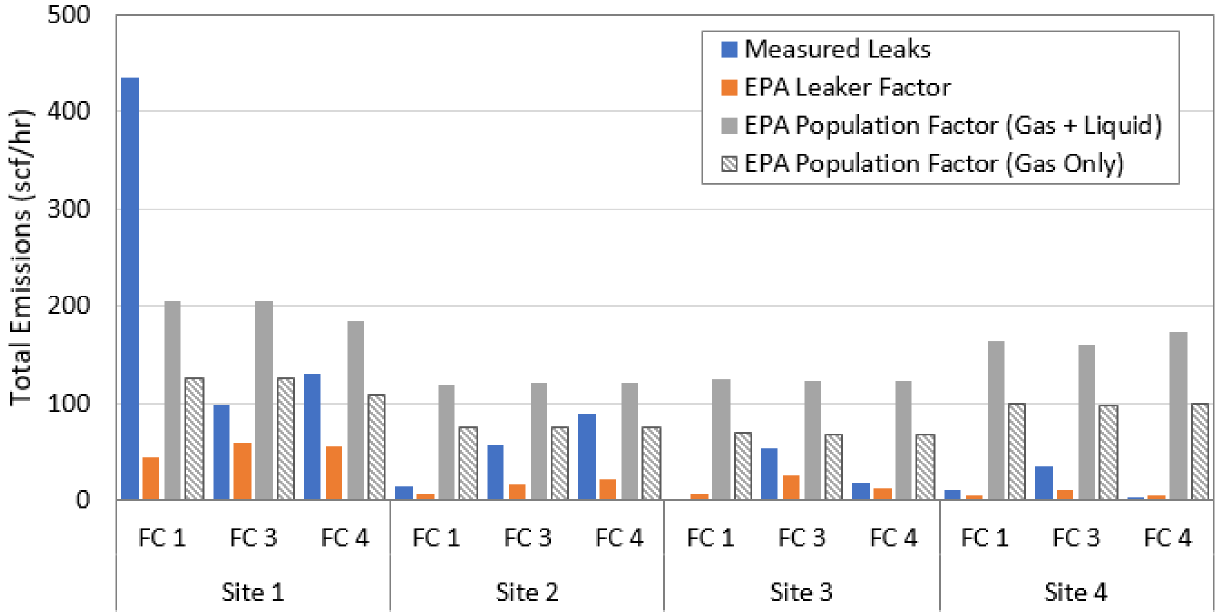
1. Total emissions based on leaks identified with a FLIR camera and leaker EFs underestimated emissions calculated using USEPA Subpart W EFs.
2. Total emissions based on component population counts and population EFs generally overestimated emissions calculated using USEPA Subpart W EFs.
3. Including liquid lines in the site-wide population counts substantially increased the estimated leaking emission rates compared to rates calculated with counts only from gas lines.

Summary

Population EFs, whether including or excluding liquid lines, were a conservative estimate of fugitive emissions. Leaker EFs consistently underestimated emissions at the field sites. Measurements at more sites, particularity sites in other areas of the country, need to be completed before determining the accuracy of EFs.

Leaker and population emission factors were calculated using emission results from the 4 field campaigns and compared against USEPA Subpart W EFs. For leaker EFs, total measured emission rates were calculated using the number and types of leaks identified in the FLIR survey and compared against calculated emissions (**Figure 3-11**). Field Campaign 2 was not included because a site-wide FLIR survey was not performed. For population EFs, emission rates were calculated using the component counts for each site, which typically varied by field campaign since different compressors were in operation.

Component categories included in the comparison were connectors (other and flanged), valves, and PRVs since these components had both population and leaker EFs available in Subpart W. Connectors were separated into other and flanged with leaker EFs, but kept as one category with population EFs. All other component types were excluded for this analysis.



Leaker and population factors from Tables W-1E and W-1A in the Mandatory Greenhouse Gas Reporting Subpart W (USEPA 2015; USEPA 2016). Population factor estimations calculated using population counts including both gas and liquid lines, as well as only gas lines.

Figure 3-11. *Measured site-wide leaks compared to leaks calculated using USEPA leaker and population factors*

Total emissions based on leaks identified with a FLIR camera and *leaker* EFs underestimated emissions calculated using USEPA Subpart W EFs. Results indicate that the study sites had fewer leaks than sites used to develop current Subpart W population EFs. However, leaks measured at each of the study sites had larger emission rates than those used to develop the current Subpart W leaker EFs.

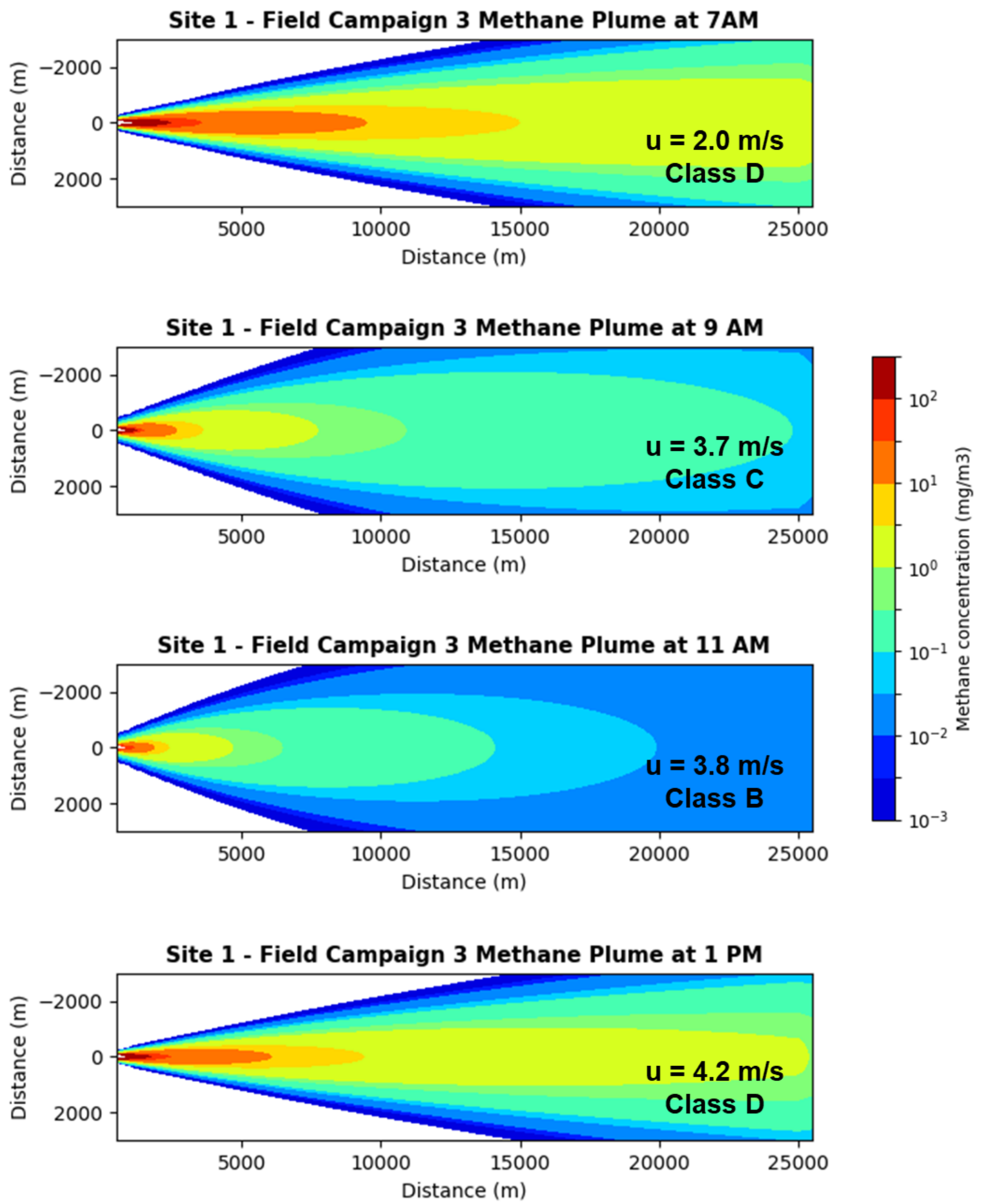
Total emissions based on component population counts and *population* EFs generally overestimated emissions calculated using USEPA Subpart W EFs. Even when components on liquid lines were removed from the population count, which reduced calculated emissions by 41%, the population factor estimates were generally higher than the measured leaks. This could be due to population factors accounting for emissions that were below the detection limit of the FLIR. For example, a leak from a valve that was too small to be seen by the FLIR would not be measured by the high-flow system. The emissions from that valve would contribute to the total leaking emissions from the site, but would not be included in measured emissions. Measurements at more sites, particularity sites in other areas of the country, need to be completed before determining the accuracy of EFs.

3.7 Data Visualization

A data visualization tool was developed to conservatively estimate the extent of the plume generated by the measured emissions from a hypothetical compressor(s). The results of the visualization package for Site 1, Field Campaign 2 were exported to Python to generate contour plots (**Figure 3-12**). Three input sources were included in the model which were summed emissions from Compressors 13, 14, and 15. Since the model was designed for a steady-state source, compressor emissions were assumed to be constant throughout the day.

Plume concentration and shape changed with variations in wind speed and stability class. Pasquill Stability Classes range from A - very unstable, to F- very stable. As the atmosphere becomes less stable (i.e., more turbulent) the estimated plumes become more dilute. This is seen as the plume progresses from 7 am to 11 am (**Figure 3-12**). Within the same stability class, a faster wind speed also results in a more dilute plume (e.g., 7 am vs. 1 pm).

The data visualization tool was designed to be user friendly. It can be used to generate steady state plumes for gaseous chemicals or to determine the stability class of specific atmospheric conditions. Details of the tool are in Appendix D, and it can be downloaded as < url >.



u = Measured wind speed at 10 m, Class refers to Pasquill Stability Class

Figure 3-12. *Hypothetical estimated methane plume for measured methane emissions from Compressors 13, 14, and 15 at Site 1 during Field Campaign 2*

4.0 TECHNOLOGY TRANSFER

The high level of interest and participation on this project from industry and regulatory stakeholders concerned with methane emissions from G&B stations and updates to Subpart W increased its value to GSI and DOE NETL. Technical Advisory Steering Committees (TASCs) consisting of participants from industry, regulatory agencies, non-governmental organizations, academia, and consulting were assembled to provide recommendations and feedback on project activities over the two-year program. A list of TASC participants is provided in **Table 4-1**.

Table 4-1. *List of TASC Participants*

Industry			
Anadarko	Dominion	GE	Pioneer
Apache	Enbridge	Gulf Coast Green Energy	QEP Resources
Chevron	Energy Transfer	Haliburton	Shell
Devon	FLIR	Kinder Morgan	Spectra
Regulatory Agencies			
BLM	KGS	PA DEP	UT DEW
CADOC	MDE	TRRC	WVDEP
COGCC	MI DEQ	USEPA	
DOE NETL	NDIC	USEPA Region 6	
IL DNR	NY DEC	UT DAQ	
Non-Governmental Organizations			
AGA	EDF	HARC	PHMSA
API	GTI	INGAA	
Academia & Consulting			
Colorado State University	Indaco Air Quality Services, Inc.	University of Colorado-Boulder	University of Utah
GHD	University of Cincinnati	University of Kentucky	

TASCs formed for this project represented two-way exchanges of information. This open communication provided an excellent opportunity for GSI to inform TASC participants of recent project findings, and for TASC participants to increase project efficiency by giving GSI real-time feedback on sampling protocols and data analysis. GSI and our teaming partners hosted twelve conference calls under this project to solicit feedback from TASC participants. During one of the TASC calls, for example, API representatives expressed concern over explosive atmospheres associated with elevated methane flow rates (e.g., 100+ scfm). During that call, our Utah State University partner was able to quell those fears by outlining explosion-proof components that were built into their high volume sampler. An industry participant asked how our team will address episodic challenges associated with EF's, which are difficult to measure or predict. To address that concern, we ensured that we considered activity data (e.g., facility throughput, material types, maintenance/blowdowns) while performing EF calculations.

In addition, a memo with preliminary results was issued to coincide with the final set of TASC calls to inform TASC members in advance of project findings and encourage input and discussion. Specific feedback from participants was compiled and considered as GSI planned and implemented next steps throughout the project. Knowledge gained from this program was also disseminated through technical presentations at conferences (as shown in **Table 4-2**) and development of public education brochures and fact sheets summarizing project highlights and findings.

Table 4-2. *Technology Transfer Events*

Event Title	Date	Organization	Description
API Technical Meeting	February-2017	American Petroleum Institute	Susan Stuver, Ann Smith and Richard Bowers presented project scope and objectives to industry representatives and solicited participation in the I-TASC
Environmentally Friendly Drilling (EDF) Sponsors Meeting	April-2017	Houston Advanced Research Center	Susan Stuver and Richard Bowers presented project accomplishments and challenges.
AUVSI XPONENTIAL 2017	May-2017	Association for Unmanned Vehicle Systems International	Susan Stuver and Richard Bowers presented information on sampling technologies used in field programs and how automation could improve the accuracy of data collected.
TCEQ Tradefair	May-2017	Texas Commission on Environmental Quality	Susan Stuver attended meetings with TCEQ Commissioners regarding the value of the project.
KOGA Annual Meeting	July-2017	Kentucky Oil and Gas Association	Susan Stuver and Ann Smith presented preliminary results obtained from Field Campaign 1 Sampling Events 1 and 2.
SPE Annual Technical Conference and Exhibition	October-2017	Society of Petroleum Engineers	Susan Stuver disseminated brochures and fact sheets highlighting project findings.
O&G Environmental Conference	November-2017	Environmental Training Institute	Susan Stuver disseminated brochures and fact sheets highlighting project findings.
CH4 Connections Conference	December-2017	Groundwater Technology Inc.	Susan Stuver disseminated brochures and fact sheets highlighting project findings.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Key findings and *recommendations* for the project are summarized below:

Component count and classification

- Adjusting the component counting methodology (e.g., including components on liquid lines or pneumatic loops) impacts component population counts. *A standard methodology should be adopted for classifying and counting components in order to minimize inconsistencies across studies and instruct stakeholders responsible for GHGI reporting*.
- Results support current component subcategories listed in USEPA Subpart W, including the subdivision of connectors (flanged and "other") and pneumatic device vents (intermittent, continuous low bleed, and continuous high bleed). *Results warrant further study of emissions from compressor vents, meters, gauges, and regulators*.

Emission Rate Variability by Site, Operation and Time

- There is variation of emissions rates across sites and a relationship between higher emissions and compressor age for some components. *More measurements should be taken on additional compressor components to further assess emissions rate variability by site and operational parameter.*
- Site inlet pressure had a statistical correlation with emission rates on compressor RPVs. Other site operational parameters, including gas throughput, composition, discharge pressure and energy throughput, did not have statistically significant correlations with emission rates from DPVs and RPVs.
- Variation in site and compressor component emissions was significant between field campaigns. The type and proportion of component(s) contributing to compressor emissions also varied across field campaigns.
- Measuring the emission rate of a sample for an extended period of time is not necessary to capture the average component emission rate.

Liquid Lines Contribution to Measured Emissions

- For reporting purposes, excluding liquid lines from site-wide screening may have a negligible effect on component-related emissions. However, from a site management perspective, malfunctioning components were not uncommon on liquid lines and contributed substantially to fugitive emissions at some sites.

Comparisons to Current EPA EFs

- Population EFs, whether including or excluding liquid lines, were a conservative estimate of fugitive emissions. Leaker EFs consistently underestimated emissions at the field sites. *Measurements at more sites, particularity sites in other areas of the country, need to be completed before determining the accuracy of EFs.*

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