APPENDIX A

Fugitive Emissions Screening Procedures, Equipment, and Specifications

APPENDIX A

FUGITIVE EMISSIONS SCREENING PROCEDURES, EQUIPMENT, AND SPECIFICATIONS

1.0 TECHNOLOGY BACKGROUND

As a component of field investigation activities, a FLIR™ GF320 infrared imaging camera was used as a screening tool to visually locate (but not quantify or speciate) losses and leaks from components of compressors and other equipment (e.g., separators, dehydrators). Optical gas imaging instruments were used in accordance with 40 CFR Part 60, Subpart A, §60.18 of the *Alternative Work Practice for Monitoring Equipment Leaks*. Field personnel operating the FLIR™ GF320 received training and certification for proper operation of the camera for optical gas imaging prior to use.

Infrared cameras convert thermal signatures to optical images. The GF320 camera is lightweight with features designed to detect gas emissions in field applications, resulting in efficient screening of large areas. The GF320 is capable of detecting methane emissions with temperatures up to 350 °C and within ±1 °C accuracy. The spectral response is in the range of 3.2-3.4 μm with a resolution of 320x240. Total pixels is 76,800. Minimum acceptable accuracy is ±1°C for temperature ranges of 0 °C to 100 °C or ± 2% of reading for temperature range >100 °C. 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)

1.1 Field methods

When imaging an object during field activities that was of a temperature similar to the surroundings, such contrast was not evident. In order to compensate for this, a background material of differing thermal properties was placed behind the object to create contrast. The camera was also moved to different angles to find a background with sufficient thermal contrast. Shifting through the various color palettes also afforded better images.

At the beginning of daily field activity, the FLIR camera was powered up, commencing an automatic startup sequence. This sequence included cooling of the internal spectral detector and other electronic system checks. After the automatic startup sequence was concluded, a Non-Uniformity Correction (NUC) check was performed to assure that the camera was functioning properly prior to conducting gas imaging activities.

2.0 FLIR GF320 SPEC SHEET

Specifications

Model	GF300 / GF320
Detector Type	FLIR Indium Antimonide (InSb)
Spectral Range	3.2 – 3.4 µm
Resolution	320 x 240 pixels
Detector Pitch	30 µm
NETD/Thermal Sensitivity	<15 mK @ +30°C (+86°F)
Sensor Cooling	Stirling Microcooler (FLIR MC-3)
Electronics / Imaging	
Image Modes	IR Image, visual image, high sensitivity mode (HSM)
Frame Rate (Full Window)	60 Hz
Dynamic Range	14-bit
Video Recording / Streaming	Real-time non-radiometric recording: MPEG4/H.264 (up to 60 min./clip) to memory card Real-time non-radiometric streaming: RTP/MPEG4
Visual Video	MPEG4 (25 min./clip) to memory card
Visual Image	3.2 MP from integrated visible camera
GPS	Location data stored with every image
Camera Control	Remote camera control via USB
Measurement	
Standard Temperature Range	–20°C to +350°C (–4°F to +662°F)
Accuracy*	±1°C (±1.8°F) for temperature range (0°C, to +100°C, +32°F to +212°F) or ±2% of reading for temperature range (>+100°C, >+212°F)
Optics	
Camera f/number	f/1.5
Available Fixed Lenses	14.5° (38 mm), 24° (23 mm)
Focus	Automatic (one touch) or manual (electric or on the lens)
Image Presentation	
On-Camera Display	Built-in widescreen, 4.3 in. LCD, 800 x 480 pixels
Automatic Gain Control	Continuous/manual, linear, histogram
Image Analysis*	10 spotmeters, 5 boxes with max./min./average, profile, delta temperatures, emissivity & measurement corrections
Color palettes	Iron, Gray, Rainbow, Arctic, Lava, Rainbow HC
Zoom	1-8x continuous, digital zoom
General	
Operating Temperature Range	–20°C to +50°C (–4°F to +122°F)
Storage Temperature Range	–30°C to +60°C (–22°F to +140°F)
Encapsulation	IP 54 (IEC 60529)
Bump / Vibration	25 g (IEC 60068-2-27) / 2 g (IEC 60068-2-6)
Power	AC adapter 90-260 VAC, 50/60 Hz or 12 V from a vehicle
Battery System	Rechargeable Li-ion battery
Weight w/ Battery & Lens	1.94 kg (4.27 lbs)
Size (L x W x H) w/ Lens	305 × 169 × 161 mm
Mounting	Standard, 1/4"-20

* GF320 model only

FLIR Systems, Inc.
9 Townsend West
Nashua, NH 03063
USA
PH: +1 866.477.3687

PORTLAND
Corporate Headquarters
FLIR Systems, Inc.
27700 SW Parkway Ave.
Wilsonville, OR 97070
USA
PH: +1 866.477.3687

EUROPE
FLIR Systems
Luxemburgstraat 2
2321 Meer
Belgium
PH: +32 (0) 3665 5100

www.flir.com/ogi
NASDAQ: FLIR

CANADA
FLIR Systems, Ltd.
920 Sheldon Court
Burlington, ON L7L 5L6
Canada
PH: +1 800.613.0507

CHINA
FLIR Systems Co., Ltd
Rm 1613-16, Tower II
Grand Central Plaza
138 Shatin Rural
Committee Road Shatin
New Territories
Hong Kong
PH: +852 2792 8955

LATIN AMERICA
FLIR Systems Brasil
Av. Antonio Bardella, 320
Sorocaba, SP 18052-852
Brasil
PH: +55 15 3238 7080

APPENDIX B

High-Flow Sampling Procedures, Equipment, and Specifications

APPENDIX B

HIGH-FLOW SAMPLING PROCEDURES, EQUIPMENT, AND SPECIFICATIONS

1.0 INTRODUCTION

High flow samplers have been used in the oil and gas industry to detect natural gas leaks for decades, have been used in a number of scientific studies (Allen et al., 2013; Johnson et al., 2015) and are approved by USEPA for leak quantification (CFR, 2016). However, only one commercial high flow sampler exists, the backpack-mounted Bacharach HI FLOW, and it suffers from several biases. The Bacharach sampler uses detectors that do not distinguish between methane and other organics, and that do not detect all organic compounds with the same sensitivity, leading to uncertainty in measurements, especially for sources for which non-methane organics make up a high percentage of total emissions. Because of the size of its pump, the Bacharach sampler is limited to leaks smaller than about 1,000 standard cubic feet per hour (SCFH). Most importantly, the sampler uses two detectors, and its software doesn’t switch from the low-range to the high-range detector reliably, leading to a low bias in measurements (Howard et al., 2015; Ravikumar et al., 2018). Bacharach has stopped manufacturing the HI FLOW, and the instrument is difficult to obtain from equipment rental companies.

Alternatives to high flow sampling exist for measuring emissions from oil and gas infrastructure. Traditional bag sampling techniques (EPA, 1995) are more complicated, take longer to set up, and only work for low flows. Bag-filling techniques (CFR, 2016; Subramanian et al., 2015) suffer from poor accuracy, especially at low and high flows. Methods that directly measure actual emission flow rates from exhaust streams (Hendler et al., 2009) can provide as much or more accuracy than high flow sampling methods but are only applicable for equipment with an exhaust pipe to which a flow measurement tube can be attached. For most fittings, valves, meters, or other small components of gas infrastructure, high flow sampling provides the simplest and most versatile method to quantify emission rates.

A custom high-flow sampling system was constructed by Utah State University (USU) Bingham Research Center to quantify methane leaks from gas infrastructure. This system is similar to that developed by Johnson et al. (2015). The following sections describe this system and report on its performance.

2.0 SYSTEM DESCRIPTION

2.1 System Overview

A diagram of the high flow sampling system is shown in **Figure B-1**, and photographs of the system are shown in **Figure B-2**. The system operates by:

1. Pulling sample gas from a leaking component into a sampling duct.
2. Precisely measuring the total flow rate of sample gas through the sampling duct.
3. Analyzing the sample gas to determine the methane concentration.
4. Correcting sample gas concentrations for the methane concentrations in ambient air near the leaking component.

The methane emission rate is calculated as:

$$E = C \times F$$ **(Equation C-1)**

where E is the methane emission rate (g s^{-1}), C is the concentration of methane in the sample gas (g m^{-3}; corrected for the concentration in ambient air), and F is the flow rate of sample gas (m^3 s^{-1}). The ideal gas law was used to convert E to the commonly-used units of SCFH at standard temperature of 60° F.

The system was mounted in a generator-powered trailer and included 40 m of sample ducting, which allowed for a large area to be sampled without moving the trailer. The entire flow path was intrinsically safe or conductive and grounded to the trailer, which was grounded to the earth.

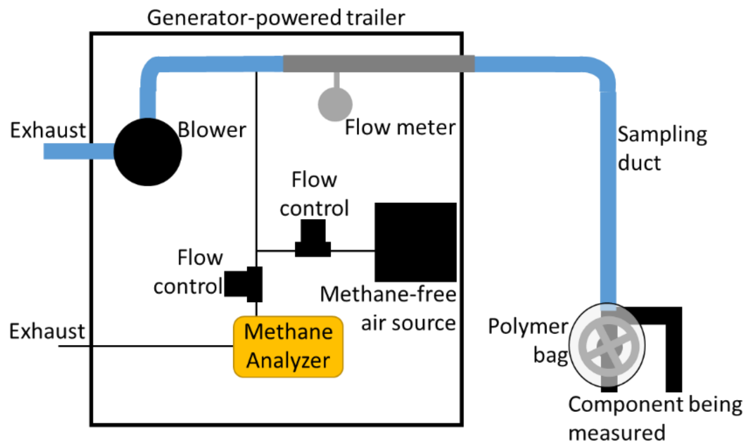

Figure B-1. *Diagram of high flow sampling system.*

Figure B-2. *Photographs of the high flow sampling system in operation: a) entire system, b) interior of the trailer, and c) bagging a pneumatic device vent for sampling.*

2.2 Detailed System Description

2.2.1 Locating Leaks

Leak locations were detected with a FLIR GF320 optical gas imaging camera and/or a Bascom Turner Gas Rover (see Appendix A for details on FLIR screening). The Bascom Turner Gas Rover is a handheld instrument used to measure methane concentrations. It can detect methane in air at 10 ppm or greater. The Gas Rover is generally able to detect smaller emission sources than the FLIR camera, but the camera is better able to pinpoint the exact source of emissions.

After locating a leak, it was flagged, given an identification number, and then the leak rate was quantified with the high flow sampling system.

2.2.2 Isolating Leaks for Measurement

The high flow system's sampling duct was constructed of 13 cm diameter conductive ducting in 8-m lengths. Aluminum foil tape was used to seal the duct connections. In most cases, an antistatic polymer bag was wrapped around the component and the duct inlet. This isolated the sample from surrounding air and ensured that all of the leaking gas was entrained into the sampling duct. Metal clips and aluminum foil tape were used to aid in this process. In some cases, leaking components could be inserted into the end of the sampling duct, allowing for all leaking gas to be entrained without bagging. In all cases, after connecting the duct to the leaking component, a Bascom Turner Gas Rover was used to measure methane all around the leaking component, sample duct, and bag to ensure that all leaking gas was entrained in the duct.

2.2.3 Sample Flow System

An explosion-proof vacuum blower pulled a high volume of gas (between 0.5 and 2.5 $m^3 min^{-1}$) from the sampled component, through the sample duct, and through a flow measurement tube. A manual flow damper was used to adjust the flow if needed. A Fox Thermal Instruments Model FT1 mass flow meter was used to measure flow. The flow meter was housed in a 3 m long, 11 cm diameter stainless steel tube with a stainless-steel flow conditioner at the upstream end. The flow meter was positioned 1.7 m from the upstream end of the tube.

One shortcoming of all mass flow measurements is that the measured flow depends on the composition of the gas sampled. This was compensated for by correcting flows for the methane concentration in the sample gas. However, non-methane organic compounds in emitted gas were not measured and could have resulted in a flow bias, especially for components with high emission rates of gas with high concentrations of non-methane organics, such as liquid storage tanks (Hendler et al., 2009).

For example, emissions were measured from a leaking thief hatch on a liquid storage tank at a compressor station. The average sample gas methane concentration during this measurement was 135,895 ppm, while the ambient methane concentration was less than 100 ppm, and the sample flow rate was 1.27 $m^3 min^{-1}$ (mass flow at standard conditions of 0 °C and 1 atm). The flow was corrected based on the methane concentration (MKS, 2017) to 1.21 $m^3 min^{-1}$. With and without the correction, the methane emission rate was 1.96 $g s^{-1}$ and 2.06 $g s^{-1}$ (368 and 387 SCFH), respectively, a difference of 5%. However, liquid storage tank emissions likely contained significant amounts of non-methane hydrocarbons, which were not measured. If the sample gas consisted of the measured methane concentration, 20% propane, 10% ethane, and remainder air, the corrected flow rate would be 0.86 $m^3 min^{-1}$, and the corrected emission rate of methane would be 1.40 $g s^{-1}$ (263 SCFH), a difference of 40%.

2.2.4 Methane Measurement

A Los Gatos Research (LGR) Ultraportable Greenhouse Gas Analyzer was used to measure methane concentrations in sample gas. Sample lines leading to and from the analyzer were composed either of PFA tubing or Tygon 2475 high-purity tubing. The analyzer detects methane concentrations of up to 10% in air. It detects up to 1000 ppm with a low-concentration laser and greater than 1000 ppm with a separate high-concentration laser. The results were recorded from both lasers for all samples. When the methane concentration in sample gas exceeded 10%, the analyzer flow was diluted with methane-free air to keep within the analyzer's range. Methane-free air was generated with a custom-built air scrubber system, and the system was tested daily to ensure air produced by the system contained less than 0.2 ppm methane. The flow into the analyzer was measured, as well as the flow rate of methane-free dilution air, with Alicat mass flow controllers. The calibration of the mass flow controllers was checked with a NIST-traceable flow standard prior to each measurement campaign.

2.2.5 Correction for Background Methane

The methane concentration in sample gas was equal to the ambient methane concentration in the air being pulled into the high flow sampling duct plus any methane added from the leaking component. To correct for ambient methane, the ambient methane concentration was measured through a PTFE filter and a 0.5 cm line composed of Tygon 2475 high-purity tubing. The inlet of this line was positioned as close to the sample duct inlet as possible. A LGR Multiport Inlet Unit allowed the methane analyzer to switch between analyzing sample gas and analyzing air from the background line. Usually, the system was programmed to measure sample gas for three minutes and then background air for two minutes. Data for the first minute was discarded after each valve switch. The background methane concentration was subtracted from the sample gas concentration prior to calculating emission rates.

2.2.6 Sampling Intervals

All measurement data was sampled once every 5 s and stored data as 20 s averages. In most cases, emissions from each measured component were quantified for 8-12 min. If the emission rate was variable, or as an occasional test of emission stability, the measurement time was extended. A 10-min sampling time resulted in about ten separate 20-sec emission rate measurements.

2.2.7 Measurement System Calibrations

The calibration of the methane analyzer was checked daily at four or five points along its measurement range, including points within the range of both methane lasers. The analyzer was also periodically checked at 15-20 points to ensure its response was linear across its range. The scrubber system mentioned above was used to generate methane-free air, and NIST-traceable compressed gas standards or an ultra-high purity methane cylinder was diluted to generate methane at specific concentrations. Alicat mass flow controllers were used to control and measure flows in the calibration system. The calibration of all mass flow controllers was checked with a NIST-traceable flow standard prior to each measurement campaign.

A mass flow controller was used to add methane from an ultra-high purity methane cylinder to the upstream end of the high flow sampling duct daily to verify the performance of the high flow measurement system. Methane was added at two different flow rates between 0.1 and 30 L min^{-1}. As a blank test, the emission rate was measured daily while the high flow duct was not sampling any emission source.

The Fox FT1 mass flow meter was calibrated at the factory annually, and its flow was checked prior to each measurement campaign with a Pacer DA420 anemometer. Wind speed output of the Pacer anemometer was converted to mass flow by multiplying the speed by the orifice size and correcting for temperature and ambient pressure.

2.2.8 Meteorological Measurements

Basic meteorology was measured during all measurement periods from a retractable 6 m pole attached to the measurement trailer. A New Mountain NM150WX was used to measure temperature, relative humidity, barometric pressure, GPS location, and GPS heading. A Campbell CS300 was used to measure solar radiation. A Gill WindSonic was used to measure wind speed and direction, and wind direction was automatically corrected based on the GPS heading. All meteorological measurements were checked against NIST-traceable standards annually.

2.2.9 Data Collection, Processing, and Storage

All measurement data was collected with a Campbell Scientific CR1000 data logger. Sample names, times, and all other notes were recorded electronically throughout each measurement day. At the end of each day, all collected data and notes were uploaded to an automatically archived, cloud-based server. All collected data and generated final results were processed in Microsoft Excel. Every 30 days all data was backed up in three locations, including a cloud-based server, a local hard drive, and a separate local hard drive that was disconnected from the internet except during archival operations.

2.2.10 Safety

All external components of the high flow system were grounded to the trailer (all components were conductive), and the trailer was attached to an earth ground. All components that came into contact with sample gas were antistatic and/or explosion proof, including all pumps, flow controllers, and flow meters. The interior of the trailer was not rated for environments that may be rich in flammable gases, so the trailer was kept 10 m or more from potential sources of flammable gas, and the generators that powered the trailer were kept 20 m or more from flammable gas sources. Additionally, a natural gas monitor was mounted in the trailer to provide a warning if combustible gas concentrations in the trailer built up to dangerous concentrations.

3.0 DETECTION LIMITS

3.1 Method Detection Limit

The method detection limit of the high flow system was calculated as (a) three times the standard deviation of a set of 20-s emission measurements when the instrument was not measuring any emission source (i.e., a blank) (EPA, 2016), and (b) three times the standard deviation of a set of 20-s emission measurements when the system was sampling a very low emission rate generated with a mass flow controller (1.1×10^{-3} SCFH). Method detection limits calculated using (a) and (b) were 2.3×10^{-4} and 1.0×10^{-4} SCFH, respectively.

Figure B-3 shows emission rate data from (a) and (b), which were collected outside the laboratory in Vernal, Utah, distant from oil and gas industrial facilities, but in the vicinity of urban and agricultural sources of methane. Gaps in the emission rate data shown in **Figure B-3** are from periods when the ambient (background) methane concentration was measured. It is expected, but be cannot confirmed, that the variability in blank values observable in **Figure B-3** was due to variation in ambient methane concentrations. The blank variability shown in **Figure B-3** corresponds to a variability in methane concentration of ± 35 ppb.

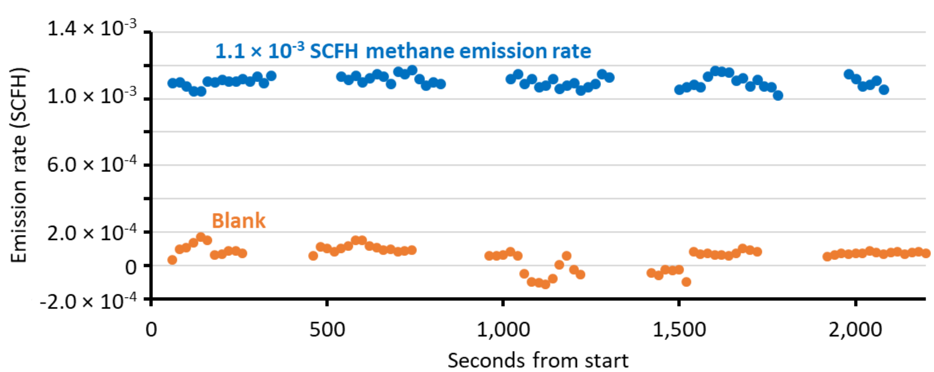

Figure B-3. *Methane emission measurement data from a detection limit test, including blank measurements and measurements of a 1.1 × 10-3 SCFH emission rate produced with a mass flow controller.*

3.2 Practical Detection Limit in Field Conditions

Industrial gas facilities have many methane emission sources and variable ambient methane levels. Because the high flow measurement system does not measure background methane and methane in sample gas simultaneously, short-term variations in ambient methane are not adequately corrected for in emission measurements, leading to a decrease in measurement precision (but not accuracy) at industrial facilities. To assess the practical detection limit (a measure of precision) in field conditions, emission measurement blanks were collected (~10 min each) at natural gas compressor stations (n = 14). These data were used to calculate practical detection limits for G&B stations as described above. These values are shown in **Table B-1**.

Table B-1. *Statistical information for blank emission measurements collected outside the laboratory and at G&B stations, in units of SCFH. Values shown were calculated from 20 s data.*

SCFH	Lab Blank	Compressor Stations	Compressor Stations (no outliers)
Average	4.8 × 10-5	7.5 × 10-3	8.6 × 10-3
Median	7.0 × 10-5	2.2 × 10-3	2.4 × 10-3
Std. Deviation	7.8 × 10-5	7.9 × 10-2	3.0 × 10-2
Detection Limit	2.3 × 10-4	0.23	9.0 × 10-2
95% Conf. Interval	1.6 × 10-5	4.7 × 10-3	1.8 × 10-3

In addition to having higher detection limits (a measure of precision), emission measurement blanks collected at compressor stations had higher average and median values than the laboratory blank (**Table B-1**). In other words, the sample duct had higher methane concentrations than the background measurement line. It was found that sample methane concentrations remained higher than ambient methane for at least 30 min after sampling strongly leaking components, indicating that residual methane remained in the sample flow path. It is not clear whether this residual methane was in the sample duct, the sample line from the duct to the analyzer, or the switching unit. Assuming the residual methane in the sample line is released at a steady rate, it likely had only a small impact on calculated detection limits.

A few of the blank samples (n = 2) were statistical outliers, determined as 10-min average blanks that were higher or lower than 1.5 times the interquartile range. These outliers were either the result of high methane in the sample line prior to the blank measurement or highly variable background methane. With these outliers removed, the practical detection limit was lowered by an order of magnitude (**Table B-1**). A histogram of all field blank values is shown in **Figure B-4**.

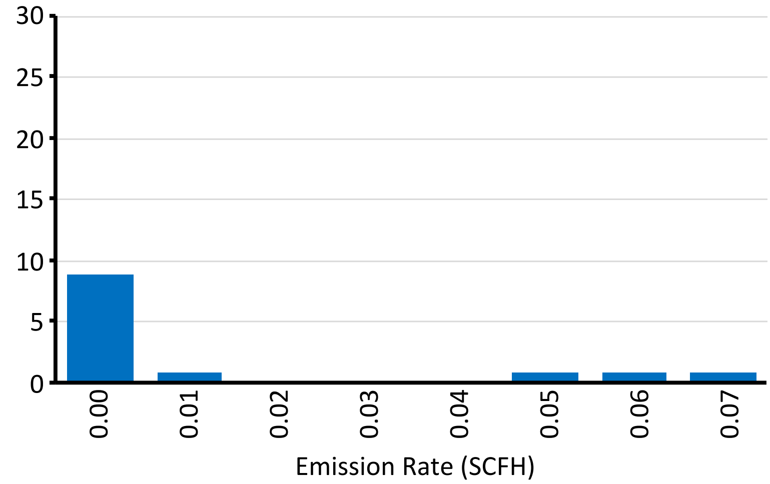

Figure B-4. *Histogram of methane emission rate for all emission measurement blanks collected at field sites (outliers included). 10-min averages are shown. Values shown on the x-axis are the lower-most bound of each bin.*

3.3 Detection Limit Sensitivity Analysis

Sensitivity analysis was conducted to determine the effect of using different values for non-detects. The analysis included the scenarios presented in **Table B-2**.

Table B-2. *Non-detect sensitivity analysis scenarios*

	Values less than DL set to:		
Detection Limit	**1/2 DL**	**DL**	**0**
No DL	Unadjusted Value		
0.09 scf/hr	0.045	0.09	0
0.23 scf/hr	0.115	0.23	0

When no DL was applied, the unadjusted values included negative emission rates and small positive emission rates

Results were not sensitive to the various DL scenarios. The difference in average emission rates by component type for the different scenarios was less than 0.5% except for connectors, which had a difference of 1.5%. For data analysis, non-detects were assigned the value of one half the 0.09 scf/hr DL, or 0.045 scf/hr.

4.0 CALIBRATION RESULTS

Table B-3 provides a summary of the results of calibration checks performed on field measurement days.

Table B-3*. Summary of field calibration results. Zero indicates the analyzer response when methane-free air was sampled. The analyzer's low laser was used for methane concentrations less than 1000 ppm, and the high laser was used for concentrations greater than 1000 ppm.*

	Zero (ppm)	Low Laser (% Recovery)	High Laser (% Recovery)	High Flow System (% Recovery)
Average	0.10	101.0	99.7	104.1
Count	49	67	86	95
95% Conf. Interval	0.04	0.8	1.0	1.2

5.0 MEASUREMENT RANGE

The method detection limit of 2.3×10^{-4} SCFH is, by definition, the lower end of the measurement range for the high flow sampling system. The maximum flow rate of the sample duct was about 2,500 L min^{-1}, and was limited by the flow producible by the blower. Thus, the maximum methane emission rate the system could measure was 2,500 L min^{-1} methane, or 5,727 SCFH. A larger blower, or two blowers in series, could perhaps double the flow rate, leading to a maximum of 11,454 SCFH, eight orders of magnitude higher than the method detection limit. The highest emission rate measured was a thief hatch on a liquid storage tank at a G&B station, which had a methane emission rate of 1,288 SCFH. **Figure B-5** presents a histogram of all emission samples collected by the high flow system (n = 649).

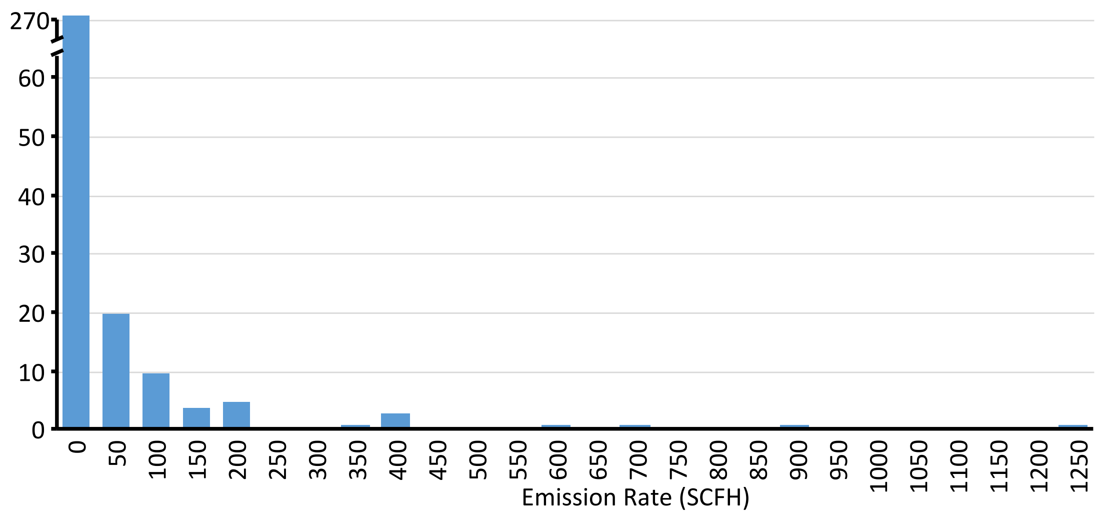

Figure B-5. *Histogram of methane emission rate for all emission measurement samples that have been collected by the high flow system. Note the change in scale at the top of the y-axis. Values shown on the x-axis are the lower-most bound of each bin.*

6.0 SAMPLE VARIABILITY

Variability in measured emissions can be due either to instability in the measurement system, short-term variability in background methane, or actual variability in methane emission rates. **Figure B-6** shows emission rates from four G&B station components and emissions regulated with a mass flow controller, and **Table B-4** provides summary statistics for the same dataset. Relative standard deviation, shown in **Table B-4**, is a measure of variability relative to the sample average. The variability in emission rates generated by the mass flow controller is caused by the measurement system and the mass flow controller itself and was 0.68 at an emission rate of 42.5 SCFH. When we used the mass flow controller to generate an emission rate of 0.4 SCFH, the relative standard deviation of the measurements was 1.23. The relative standard deviation of the 1.1×10^{-3} SCFH emission mentioned above was 3.05. The relative standard deviations of emissions from the components shown in **Table B-4** are in the same range as those for emissions generated with a mass flow controller, with the exception of the pressure relief valve.

Table B-4. *Statistical information for emission measurements from four G&B station components and emissions regulated with a mass flow controller over 35 min. Relative standard deviation was calculated as the standard deviation divided by the average, multiplied by 100. Values shown were calculated from 20 s data.*

	Mass Flow Controller	Rod Packing Vent (high)	Pneumatic Controller	Rod Packing Vent (low)	Pressure Relief Valve
Average	42.5	928	12.8	45.2	4.82
95% Conf. Interval	0.07	2.03	0.04	0.09	0.28
Relative Std. Deviation	0.68	1.05	1.38	0.89	18.7

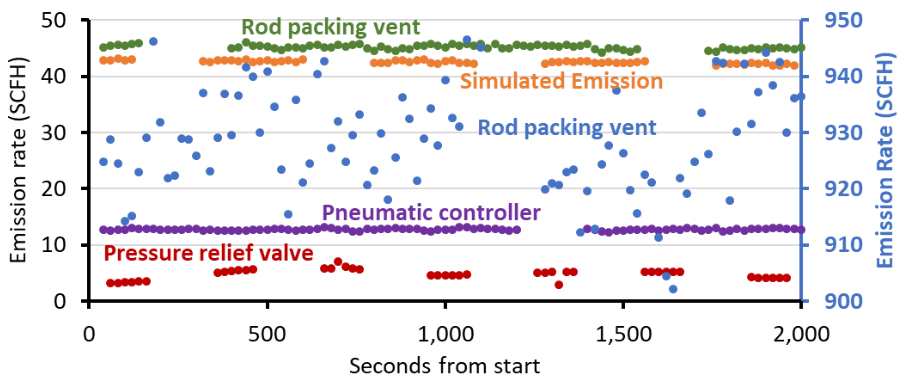

Figure B-6. *Methane emissions over 35 min from three G&B station components and simulated emissions regulated with a mass flow controller. The y-axis for emissions from the rod packing vent shown in blue is on the right side.*

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APPENDIX C

Component Classification and Count Protocol

APPENDIX C

COMPONENT CLASSIFICATION AND COUNT PROTOCOL

1.0 INTRODUCTION

Component classification and counts were completed at four gathering and boosting (G&B) stations in the Gulf Coast area. Component counting was conducted during each of four separate field campaigns, and after each campaign the counting and classification procedure was refined. As a result, an organized and reliable methodology was developed for classifying and counting components at natural gas G&B stations. The purpose of this appendix is to describe the final refined component classification and counting protocol developed and employed for purposes of this study. In general, this protocol explains the methods used to:

- Separate major equipment units by identifying isolation boundaries,
- Identify components, and assign them to a major equipment category,
- Classify components into major component specific categories, and
- Disaggregate components into various subcategories

Details of the component classification and counting protocol are discussed in the following sections, and figures referenced in each section are provided at the end of this document, unless noted otherwise.

2.0 COMPONENT COUNT PROTOCOL

2.1 Component Classification by Equipment Type

At each G&B station, individual components were classified and counted on nine major types of equipment: compressors, separators, dehydrators, coalescers, slug catchers, yard piping, tanks, gathering/discharge lines, and ancillary equipment (e.g. fuel and instrument gas skids, methanol skids). Components were counted on all operating equipment (i.e., pressurized with gas flowing through), as well as some equipment in standby mode (i.e., compressors that were pressurized but not running). A summary of major equipment present at each site is given in **Table C-1**.

Table C-1. *Major equipment counts for each site. Apart from compressors, only operational and/or pressurized equipment was counted.*

Equipment Type	Site 1	Site 2	Site 3	Site 4
Operational Compressors	2-3	1	1	1
Pressurized Compressors	0	1	0	1
Depressurized Compressors	3-4	2	1	0-1
Separators	2	3	3	4
Coalescers	2	1	1	2
Dehydrators	0	1	2	0
Slug Catchers	1	0	0	1
Skids (fuel gas. Methanol)	1	1	1	2
Tanks	0*	10	1	0

* Tanks at Site 1 were outside the accessible area for the field campaigns

2.1.1 Separating Equipment Units

Due to the complexity of the G&B stations' equipment configurations, it was often difficult to assign components to a specific equipment category, depending on their location in the G&B process. For example, a pneumatic valve located between a separator and a dehydrator could be assigned to either piece of equipment. Further, an emergency shutdown (ESD) valve located on the suction line to a compressor could be assigned to the compressor or to yard piping. To address this, each equipment type was given a "boundary" defined by isolation points, and all components within the assigned boundary (including isolation devices) were included in the component count for that equipment. For this study isolation points were defined as: ***any device (e.g., isolation valve), process, or configuration that separates a specific equipment unit, either spatially or operationally, from other units in the G&B process.***

An example of a spatial separation would be a separator with both inlet and discharge lines coming from or returning to the ground prior to advancing to the next equipment unit in the process. Similarly, gathering lines were physically separated from station operations (**Figure C-1**).

Figure C-1*. Examples of spatial separation: a) gathering lines separated from other equipment, b) slug catcher liquid lines returning to the ground*

Operational separations were typically identified by an isolation device (e.g., manual valve, ESD) that would make the equipment non-operational if activated. A common example encountered during this study was a manual valve or ESD located on the suction and discharge lines of compressors, as shown in **Figure C-2** below. In this scenario, both the suction and discharge line ESDs, and all components in-between (i.e., on compressor skid) were counted as part of the compressor.

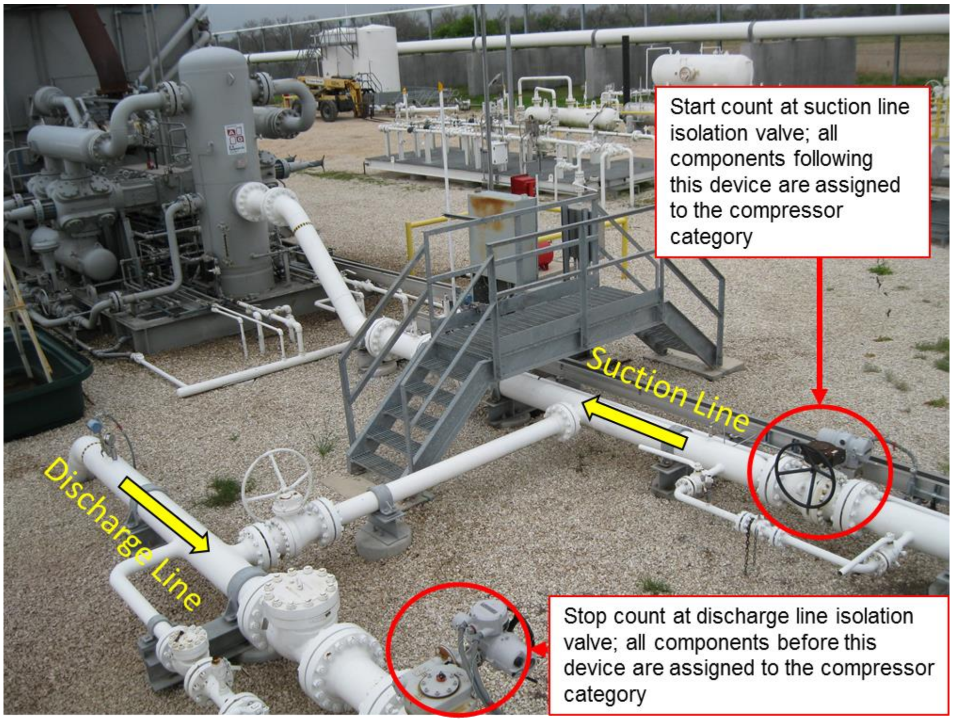


Figure C-2*. Example of operational separation: Isolation valves on compressor suction and discharge lines*

It should be noted that even following the above isolation methodology, assigning components to their respective equipment was not trivial for some equipment configurations. In situations where a component could not be confidently assigned to a specific equipment unit, the yard piping category was used. Other equipment which were included in the yard piping category included i) main header and discharge lines and manifolds to/from compressors (before and after isolation valves), ii) facility-wide ESDs located on isolated segments of pipe, and iii) other isolated segments of process piping or equipment not associated with specific equipment.

2.2 Component Classification and Subcategorization

Component types were separated into the following main categories: connectors (flanged and other), valves, pressure relief valves (PRVs), open ended lines (OELs), pneumatic device vents, actuators, meters, gauges, regulators, and compressor vents. The categories of connectors, valves, PRVs, OELs, and pneumatic device vents are consistent with EPA's Greenhouse Gas Reporting Program Subpart W (Tables W-1A and W-1E) (U.S. EPA 2015, U.S EPA 2016). Meters, gauges, regulators, actuators, and compressor vents were added to the counting protocol due to i) the relatively large number of these components at the sites (actuators, gauges, regulators), ii) the large contribution the components made to measured emissions (compressor vents), or iii) the presence of the category in different sections of Subpart W (meters).

When applicable, classified components were further subdivided based on physical and/or operational characteristics. A summary of major component categories and subcategories is presented in **Table C-2**.

Table C-2. *Component categories used in classification and count protocol*

<table>
<tr><th>Major Component Categories</th><th>Major Component Subcategories</th><th>Component Specifics</th></tr>
<tr><td>Connector</td><td>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”)</td><td rowspan="8">• Equipment category and location
• Liquid or gas line
• 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)</td></tr>
<tr><td>Valve</td><td>Size (small, large); type (ball, gate, needle); and operating mechanism (manual, pneumatic, electronic)</td></tr>
<tr><td>Pressure Relief Valve</td><td>n/a</td></tr>
<tr><td>Meter</td><td>n/a</td></tr>
<tr><td>Gauge</td><td>n/a</td></tr>
<tr><td>Regulator</td><td>n/a</td></tr>
<tr><td>Pneumatic Device Vent</td><td>Intermittent, continuous low-bleed, continuous high-bleed</td></tr>
<tr><td>Compressor Vent</td><td>Rod packing, distance piece, pocket</td></tr>
</table>

Additional component specifics were documented to support further subcategorizations and/or data analyses, as discussed below:

- Components that were on smaller pieces of equipment located on one of the major equipment types were classified under both pieces of equipment. An example is a valve on a separator/scrubber that was located on a compressor skid.
- Lines carrying gas were counted separately from lines carrying liquid.
- Components within a pneumatic device loop, such as small valves, regulators, filters, control boxes, actuators, and connectors were all counted individually and documented as being associated with a pneumatic device. These components were added into the overall count for the specific piece of equipment on which the device was located.
- All components were classified as: leak, loss (vent), or malfunction. Components categorized as a malfunction were those that were designed to vent, but were confirmed to be malfunctioning during the field event.
- The primary function of each component was also documented. Major component functions include: flow, pressure, level, and temperature control and/or measurement; emergency relief or shutdown; and process metering.
- When available, other information was collected on pneumatic device vents, including make and model, action (snap or throttle), and emission frequency (continuous or intermittent).
- Additional operational information was collected for specific equipment types when available/visible including inlet and discharge pressures, age, and make and model.
- When portions of equipment were covered in thermal insulation, counts were estimated based on visible components. For example, at Site 4 the handles of valves were visible above thermal insulation and were used to estimate the counts of covered components: large valves were assumed to have three flanged connectors, and small valves were assumed to have two other connectors.

2.3 Component Specific Details

Detailed descriptions of various component types and classification and subcategorization procedures are discussed in the following sections. Figures containing examples of component classification and counting scenarios are provided at the end of this document.

2.3.1 Connector, Other

Examples of other connectors and counts are shown in **Figure C-3**. These components connect piping or tubing together (e.g., **Figure C-3f** and **g**), connect piping/tubing to other components (e.g., **Figure C-3b**), or connect piping/tubing to equipment (e.g., **Figure C-3h**, network of components connected to a separator). This category includes all non-flanged connections, such as threaded (e.g., **Figure C-3c**) and compression (e.g., **Figure C-3e**) fittings.

- Other connectors were subdivided based on the diameter of tube/pipe that was being connected: d = 0.5”, 0.5” < d < 6”, and d ≥ 6”. Connectors on tubing less than 0.5” were seen infrequently and not counted.
- Threaded or compression connections that connected tubing/piping to a component (regulators, meters, valves) were counted as individual connectors, and **<u>not</u>** part of the connected component. In other words, emissions from these connections were classified as connectors, not emitting regulators, meters, valves, etc.
- Connectors (threaded, compression) located within a pneumatic loop were counted individually. If a connector within a pneumatic loop was leaking, it was classified as a connector, as opposed to a pneumatic device (e.g., **Figure C-3b** and **e**).
- Connectors (threaded, compression) that were part of a larger component and not used to connect tubing/piping or other components were **<u>not</u>** counted as separate connections. For example, a grease fitting on a large valve would not be included in the connector count. Emissions from these fittings were included as part the larger component.

2.3.2 Connector, Flanged

Examples of flanged connectors and counts are shown on **Figure C-4**. These components connect lengths of pipe together (e.g., **Figure C-4b**), connect other large components to pipes (e.g., valve in **Figure C-4a**), or cap pieces of equipment (e.g., **Figure C-4d**) with a ring of bolts.

- Flanged connectors were subdivided based on the diameter of the flange: d < 6”, 6” ≤ d < 12”, d ≥ 12”.
- Flanges that were part of a larger component (e.g. valves) were counted separately. For example, a large valve that has three separate flanges (see **Figure C-4a**) would contribute three flanges to the total flanged connector count.

2.3.3 Valves

Examples of valves and counts are shown in **Figures C-5** to **C-8**. The function of a valve is to control flow and/or pressure through the line. The field sites had valves that could be operated manually, pneumatically, electronically, or a combination of these three mechanisms. Manual valves were categorized as those that require a person to physically turn a handle or wheel to open or close the valve (**Figures C-5** and **C-6**). Pneumatic valves were actuated (opened/closed, throttled) and controlled by pneumatic (e.g. instrument/fuel gas) means (**Figure C-7**). Electronic valves seen in this study could be controlled either electronically or manually (**Figure C-8**). Often pneumatic and electronic valves could also be controlled manually; but they were categorized as pneumatic/electronic not manual.

Manual Valve

- Manual valves were subdivided based on size and type. Valves that could be turned with one hand were classified as small, valves that could not easily be turned with one hand were classified as large.

- Small manual valves were identified as ball, needle, or gate valves (**Figure C-5**); large manual valves were identified as ball or gate valves (**Figure C-6**).
- Small manual valves located within pneumatic device loops were classified as individual valves and counted towards the total valve population. However, these valves were noted as being associated with a pneumatic device.

Pneumatic Valve

- In pneumatic valves, the size of the flow passage is controlled by a signal from the pneumatic controller.
- Pneumatic valves were identified by an instrument or fuel gas supply line, examples are shown in **Figure C-7**.
- Note that pneumatic valves were counted separately from pneumatic controllers and actuators, despite being part of the same pneumatic system. At the sites visited, the valve-portion of the pneumatic loop was not designed to vent (unlike actuators and controllers); therefore, any emissions coming from a pneumatic valve were classified as a leak.

Electronic Valve

- Electronic valves were present only at one site, and functioned as emergency shutdown valves (**Figure C-8**).

2.3.4 Pressure Relief Valves (PRV)

Examples of PRVs and component counts are shown on **Figure C-9**. The function of a PRV is to protect equipment from being subjected to pressures the equipment is not designed to handle. The PRV is designed to open when a certain pressure is exceeded, relieving the unsafe pressure. Many PRVs encountered in this study had a pipe or stack attached to their outlet side to route any emissions to a higher elevation (see **Figure C-9**). All components on pipes/stacks after PRVs are at atmospheric pressure and any emissions that appear to come from them are due to a malfunction (or activation) in the upstream PRV, therefore:

- Components on pipes/stacks following PRVs were **not** counted.
- Open pipes/stacks following PRVs were **not** categorized as open-ended lines (OEL).

2.3.5 Meters

Examples of meters are shown on **Figure C-10**. In this protocol, meters are defined as instruments that measure the rate or usage of an operational parameter, such as cumulative gas flow. Most meters in this study were identified by digital read-outs of parameters being measured.

- Meters were commonly found on gathering/discharge lines. For example, SCADA (supervisory control and data acquisition) systems at G&B stations typically have multiple meters associated with them.
- Small connections (threaded, compression) and valves connected to meters were counted individually, and therefore included in the site-wide count.
- Subdivision by meter type (e.g., ultrasonic, orifice) was not performed, however examples of types of meters encountered in this study are shown on **Figure C-10**.

2.3.6 Gauges

Examples of gauges are shown on **Figure C-11**. The purpose of a gauge is to instantaneously measure an operational parameter (e.g., pressure, temperature). Gauges do not provide information on the rate or usage of a parameter. At G&B stations, gauges can be analog (dial) or electronic, and usually measure pressure, temperature, or volume (level).

- For a gauge to be classified as leaking, the emissions had to come from the gauge itself (e.g., cracked glass, top of gauge), not the connectors that attached the gauge to pipes or equipment.
- Gauges were divided into categories based on type of measurement: pressure, temperature, level (i.e., site glass).
- Many pneumatic devices have gauges on the fuel gas line. These gauges were included in the site-wide count, but also identified as part of a pneumatic device.

2.3.7 Regulators

Examples of regulators and counts are shown on **Figure C-12**. For this study, regulators were defined as devices that reduce the inlet pressure of gas to smaller output pressure. At G&B stations regulators are commonly found on the fuel gas supply lines on pneumatic devices. These regulators reduce the fuel gas pressure to the required pneumatic device input.

- Many different types of pressure regulators were encountered during this study, some of which were designed to vent while others were not. If there was uncertainty on whether emissions from a regulator should be classified as a leak or vent, site operators were asked to confirm.
- Regulators were only classified as leaking or venting if the emission was confirmed to be sourced from the regulator (e.g. damaged seals, rusted/cracked housing, vent ports, etc.). Leaks from threaded or compression connections attaching tubing/pipe to the regulators did not qualify as a leak from a regulator.
- Many pneumatic devices have multiple regulators in series on their fuel/instrument gas lines. These regulators were counted individually and included in the site-wide count, but also identified as part of a pneumatic device.

2.3.8 Pneumatic Filters

Filters are commonly found on pneumatic devices to filter the instrument/fuel gas supplied to the device. Examples of filters are shown in **Figure C-13**. Like regulators, many different types of filters were encountered during this study. Most filters are designed to vent, but only when maintenance is required or a malfunction occurs in the pneumatic system. In most cases, emissions came from threaded connections attaching tubing to the filter, and not the filter body. In this situation, the leak was classified as a connector, as opposed to a leak from the filter.

2.3.9 Pneumatic Devices

Examples of pneumatic devices are shown on **Figure C-14**. 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. In other words, the energy of compressed gas in the actuator is converted into mechanical energy to reposition a valve.

Pneumatic components (controllers, actuators, EDSs) encountered in this study were all operated by compressed natural gas. All components (e.g., connectors, regulators, valves) within a pneumatic device loop were counted individually and added to the site-wide component count.

- Pneumatic devices were categorized by what was being controlled (pressure, level, flow) and venting frequency (intermittent or continuous).
  - Intermittent bleed vents were further divided by the venting action (snap or throttle)
  - Continuous bleed vents were identified as low (< 6 scf/hr) or high (>6 scf/hr) bleed based on measured emission rate
- Small components on the pneumatic device such as connectors, valves, regulators, gauges, filters, and PRVs were included in the site-wide count, but identified as part of a pneumatic device.
- As previously discussed, pneumatic device controllers (**Figure C-15**) and actuators (**Figure C-16**) were counted and measured separately, despite being part of the same pneumatic system. This is because actuators and controllers, even if in the same pneumatic loop, could have separate vents or leaks.
- Actuators are found on liquid lines for devices controlling level, and on gas lines for devices controlling flow/pressure.
- Emissions from pneumatic device controllers and actuators are classified as vents unless the component is malfunctioning (e.g., leak from valve stem of actuator, pneumatic device vent stuck open).

It should be noted that venting frequency and/or venting action could not be identified on all pneumatic devices in this study. This is due to a variety of factors, including the condition of the pneumatic device (missing labels, age), complexity of process equipment, or minimal observed venting rate or frequency. The following methods were used to identify the various pneumatic device characteristics:

- Check for a snap or throttle label inside the control box
- Observe device with FLIR optical imaging camera
- Listen for intermittent actuation
- Monitor emission rate with methane sensor/high flow, look for intermittent actuation
- Ask site operators
- Monitor pressure gauges on the control box. If the gauges are functioning properly, the pressure should occasionally drop to zero if snap acting, or the pressure should hover around a certain point if throttling. However, this is **not** a definitive way to identify venting action.
- Take note of make and model, check manufacturer specs

2.3.10 Compressor Vents

Examples of compressor vents are shown in **Figure C-17**. Compressors are designed to vent to prevent dangerous buildup of pressure in the rod housing of compressor throws. Compressor vents were divided into three categories: distance piece vents (DPV), rod packing vents (RPV), and pocket vents. These categories are discussed further below:

Distance Piece Vents

- DPVs vent from the top of compressor throws and are typically identified by a small section of open tubing or hose (see **Figure C-17**).
- All compressors measured in this study had one DPV for each throw (four DPVs per compressor). Although not encountered during this study, it should be noted that DPVs can also be manifolded together and routed to a separate venting or capture location.

Rod Packing Vents

- RPVs are piped from the bottom of a compressor's throw, often manifolded to RPVs from other throws, and typically routed to the lower front of the compressor skid where the emissions are vented (see **Figure C-17**). Like DPVs, the purpose of RPVs is to vent gas that escapes around rod packing seals from within a compressor throw.
- RPVs are also called Lower Packing Vents, since they allow liquids (e.g., condensation) to drain from the compressor throws to a sump below the compressor skid. Consequently, the effluent end of RPVs are typically routed down and to the front of the compressor skid.
- Emissions could not be measured from RPVs on individual compressor throws in this study; all RPVs were manifolded in some way and routed to a separate effluent vent location. At the four field sites, compressors had one or two RPV effluent vent locations (where measurements were collected), depending on how the compressor rod packing was piped. Compressors with all fours RPVs manifolded together had one effluent vent location. Compressors with two effluent vent locations had two RPVs manifolded and routed per effluent vent.

Pocket vents

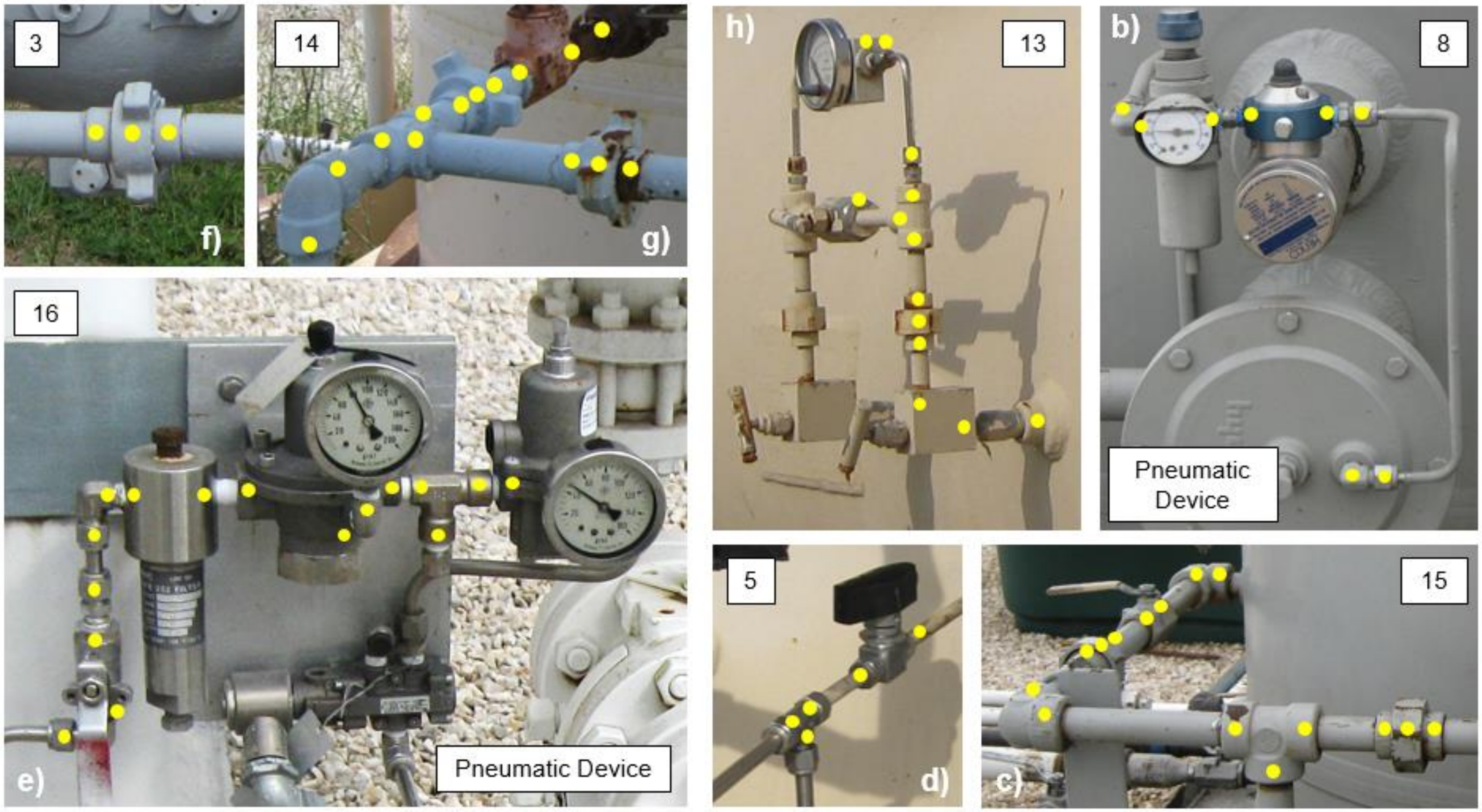
- Pocket vents are small vents located at the end of the compressor throws. They are typically identified as small tubing with a downward-facing open end (**Figure C-17**).
- Emissions from pocket vents were often not large enough to be visible with the FLIR (OGI) camera. This study measured four pocket vents in the first field campaign. Emissions from these vents were all less than 0.09 scf/hr. Therefore, pocket vents were not measured after Field Campaign 1.

In addition to classifying and counting compressor components, the following ancillary data was collected for each compressor, when possible:

- Compressor mode (operating, standby/pressurized, off)
- Inlet and discharge pressure
- Make, model, and horsepower
- Construction date
- Maintenance schedule
- Operating hours

CONNECTOR, OTHER (NON-FLANGED CONNECTOR)

These components connect piping or tubing together (e.g., Figures 1f and 1g), connect piping/tubing to other components (e.g., Figure 1b), or connect piping/tubing to equipment (e.g., Figure 1h, nest of components connected to a separator). This category includes all non-flanged connections, such as threaded (e.g., Figure 1c) and compression (e.g., Figure 1e) fittings.

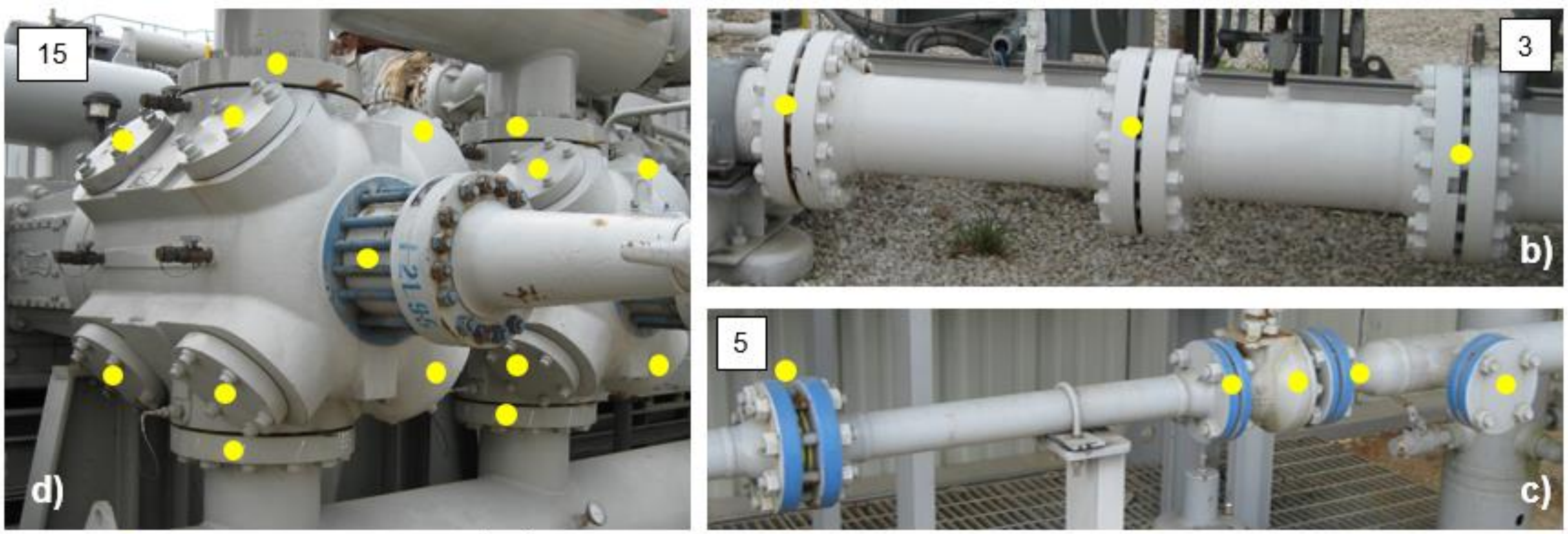


Notes: ● Components being counted [5] Total component count

Figure C-3*. Other connector examples*

CONNECTOR, FLANGED

These components connect lengths of pipe together (e.g., Figure 2b), connect other large components to pipes (e.g., valve in Figure 2a), or cap pieces of equipment (e.g., 2d) with a ring of bolts.

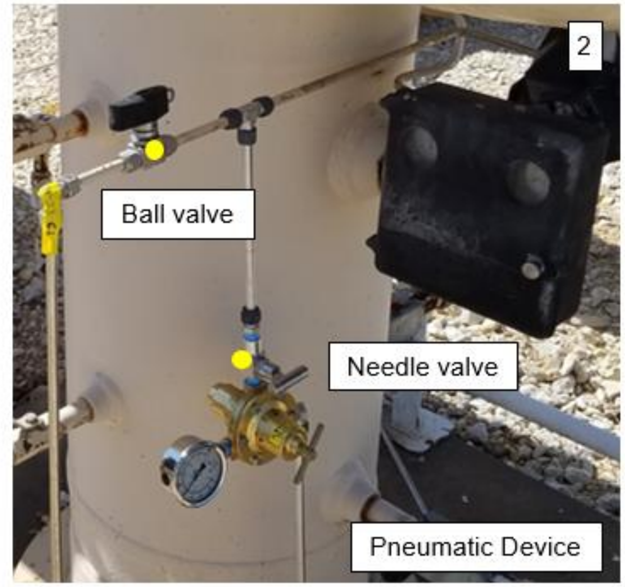


Notes: ● Components being counted 5 Total component count

***Figure C-4**. Flanged connector examples*

MANUAL VALVE, SMALL

The function of a valve is to control flow through the line. Small manual valves are subdivided into three categories: ball, needle, and gate valve. Other types of valves may also be present at G&B sites and can be classified as "other" or additional subcategories can be added. These valves are small enough to be turned with one hand.



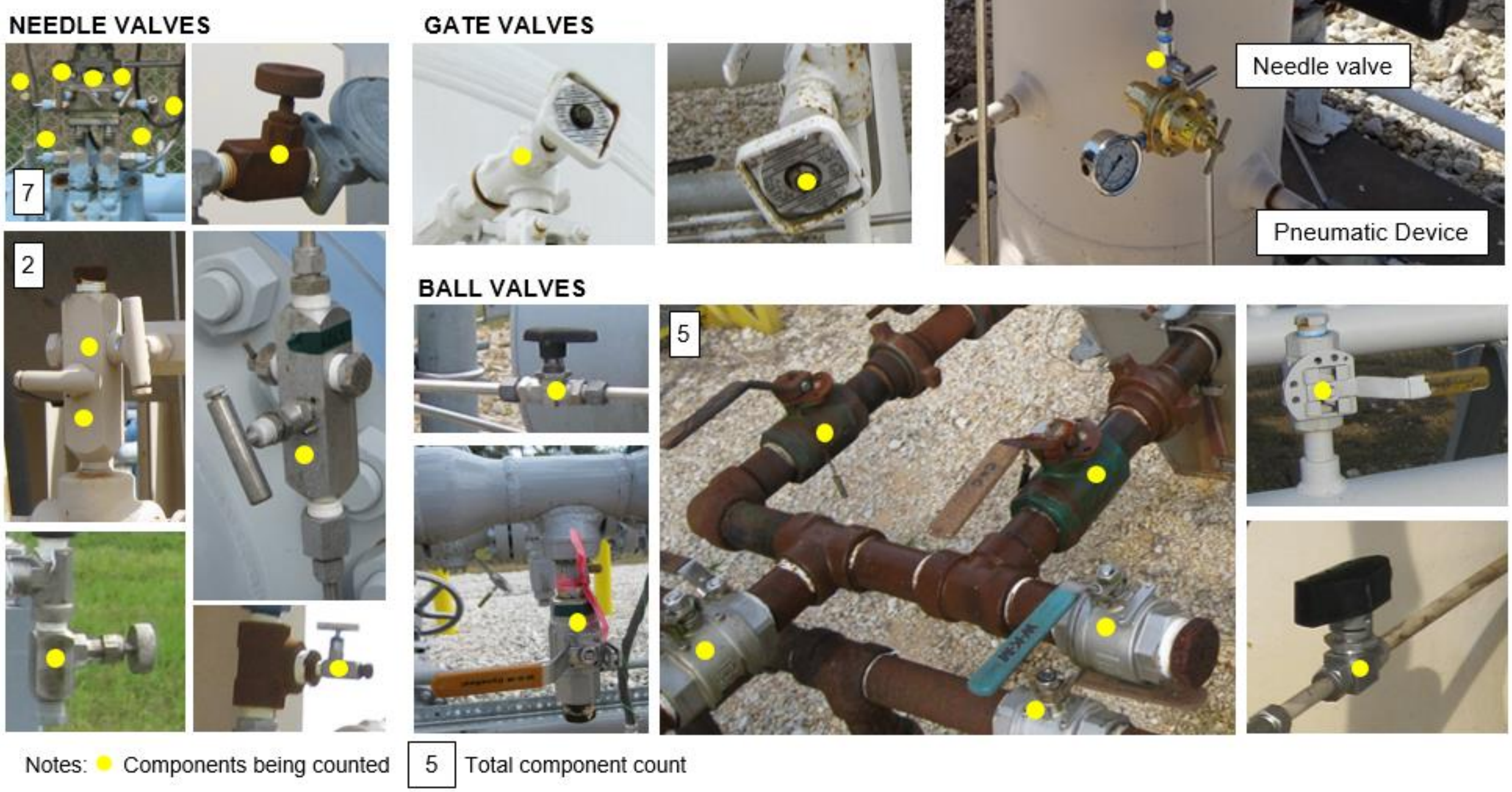


***Figure C-5**. Small manual valve examples*

MANUAL VALVE, LARGE

The function of a valve is to control flow through the line. Large manual valves are subdivided into two categories: ball and gate. These valves require two hands to turn and are usually connected to piping with flanged connectors.

Large ball valves may not have the handle attached, but can still be identified by the valve body.

GATE VALVES

ACTUATOR VALVE STEM

BALL VALVES

Notes: ● Components being counted ○ Valves with no handle attached [5] Total component count

Figure C-6. *Large manual valve examples*

PNEUMATIC VALVE – Emergency Shutdown (ESD)

The function of a valve is to control flow through the line. ESDs can usually be identified by a long, cylindrical valve with small tubing, connections, valves, regulators, and/or filters. These small components supply fuel gas, which is used to power the ESD actuator.

Figure C-7. *Pneumatic valve examples*

ELECTRONIC VALVE – Emergency shutdown (ESD)

The function of a valve is to control flow through the line. An electronic valve operates off of electricity instead of fuel gas. Notice there is conduit running into the valves in the photographs, but no ~½" fuel gas lines

The example valves are both electronic and big manual gate valves. These valves function as ESDs.

***Figure C-8**. Electronic valve examples*

PRESSURE RELIEF VALVE (PRV)

The function of a PRV is to protect equipment from being subjected to pressures the equipment was not designed to handle. The PRV is designed to open when a certain pressure is exceeded, relieving the excess/unsafe pressure. Any emissions coming from piping, valves, stacks, etc. following a PRV are considered to be emissions from a malfunctioning PRV.

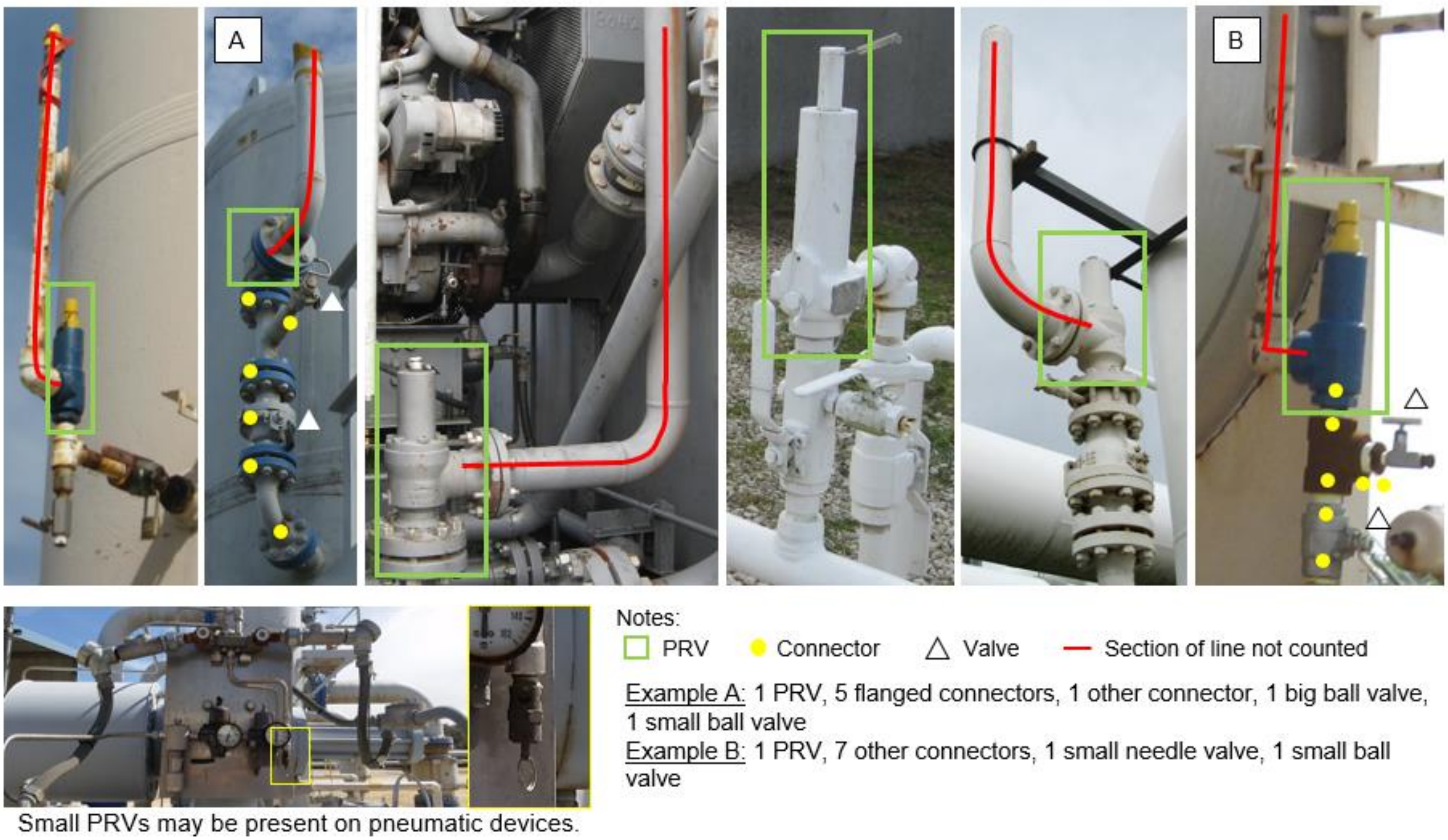


Figure C-9*. Pressure relief valve examples*

METER

Meters are defined as instruments that measure the rate or usage of an operational parameter, such as cumulative gas flow. Different types of flow meters include: orifice, venturi, annubar, and ultrasonic. Small needle valves and threaded connectors on meters were included in the site-wide component count.

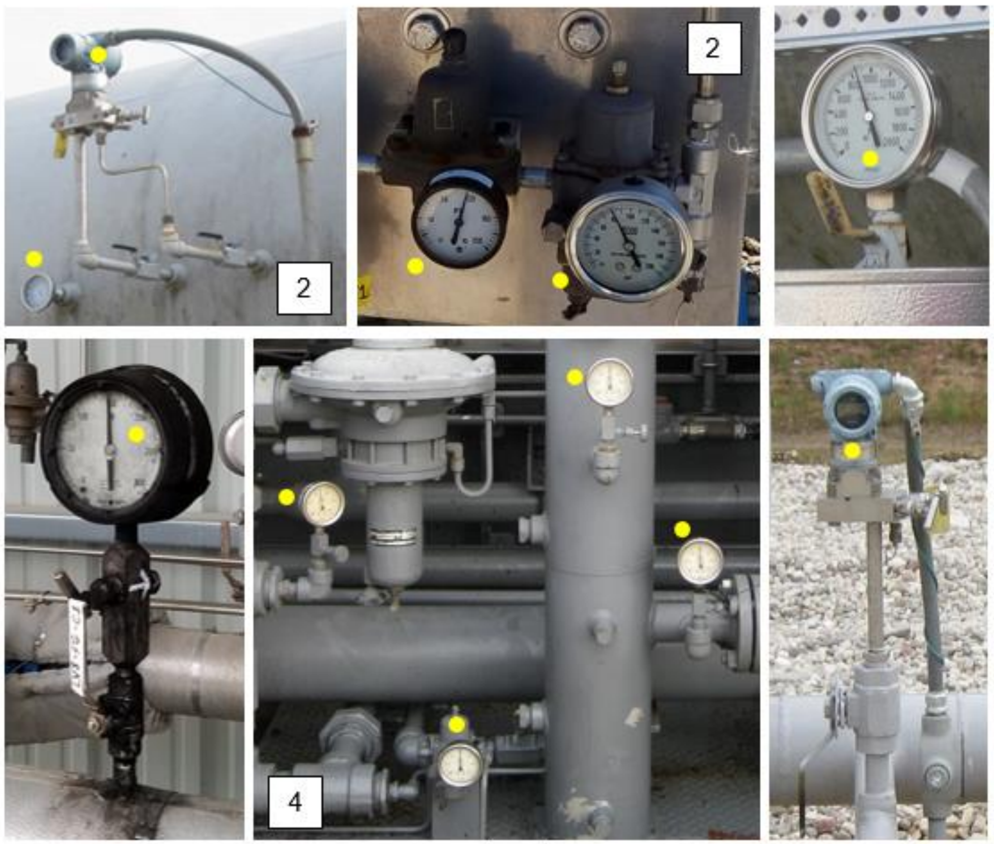
Note: Components being counted

Figure C-10. *Meter examples*

GAUGE

The purpose of a gauge is to instantaneously measure an operational parameter; gauges do not provide information on the rate or usage of a parameter . At G&B stations, gauges can be analog (dial) or electronic, and usually measure pressure, temperature, or volume (level).

PRESSURE AND TEMPERATURE



Notes: ● Components being counted [5] Total component count

LEVEL
(SITE GLASS)

Figure C-11. *Meter examples*

REGULATOR

The function of a regulator is to reduce inlet pressure to a selected outlet pressure.

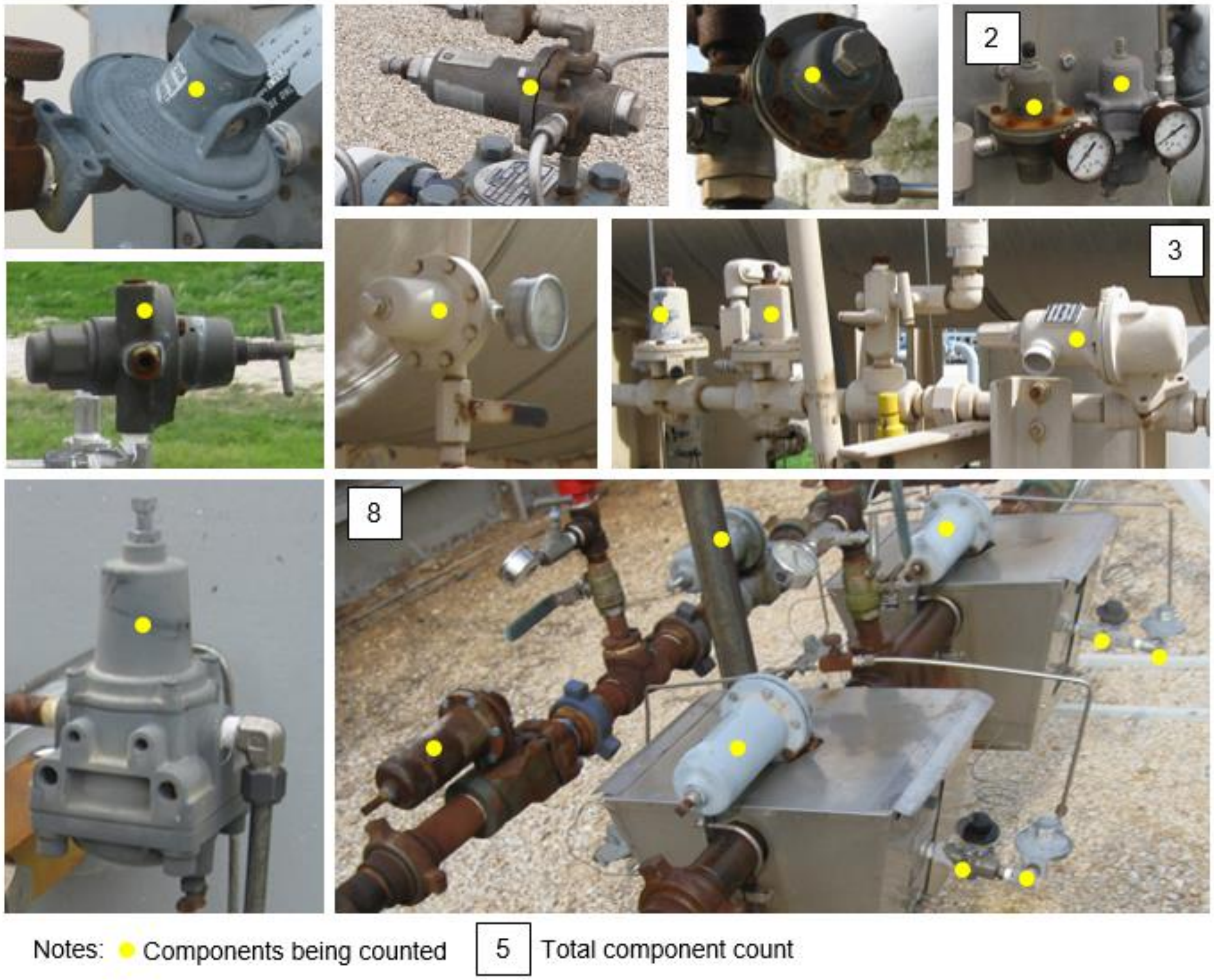


***Figure C-12**. Regulator examples*

FILTER

Filters are commonly found on pneumatic devices to filter the fuel gas supplied to the device.

Figure C-13. *Filter examples*

PNEUMATIC DEVICE

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 open or close a valve to achieve the desired system condition. The device actuates, or releases gas, to operate the valve.

***Figure C-14**. Pneumatic device examples*

PNEUMATIC DEVICE CONTROLLER

Pneumatic device controllers, such as the examples below, control the actuation of pneumatic devices. Controllers are supplied by fuel gas and also occasionally electricity. Controllers can be intermittent bleed with snap or throttle action, low continuous bleed (<6 scf/hr), or high continuous bleed (>6 scf/hr).

***Figure C-15**. Pneumatic device controller examples*

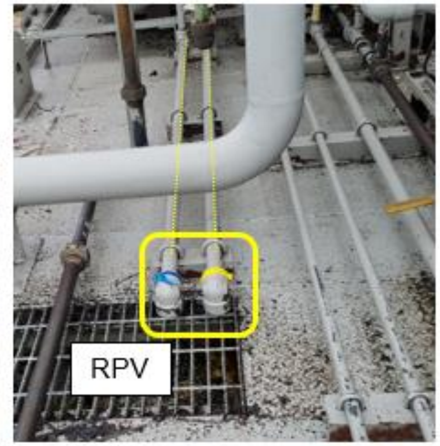
ACTUATOR

Actuators contain compressed gas, which is released when a signal is received from the pneumatic device controller, to operate a control valve when the component actuates.

Figure C-16*. Actuator examples*

COMPRESSOR VENTS

Compressors are designed to vent to prevent dangerous buildup of pressure. Compressor vents were divided into 3 categories for this protocol: distance piece vents (DPV), rod packing vents (RPV), and pocket vents. RPVs are piped from the bottom of the throw, follow the small tubing from the bottom of the throw to the vent.



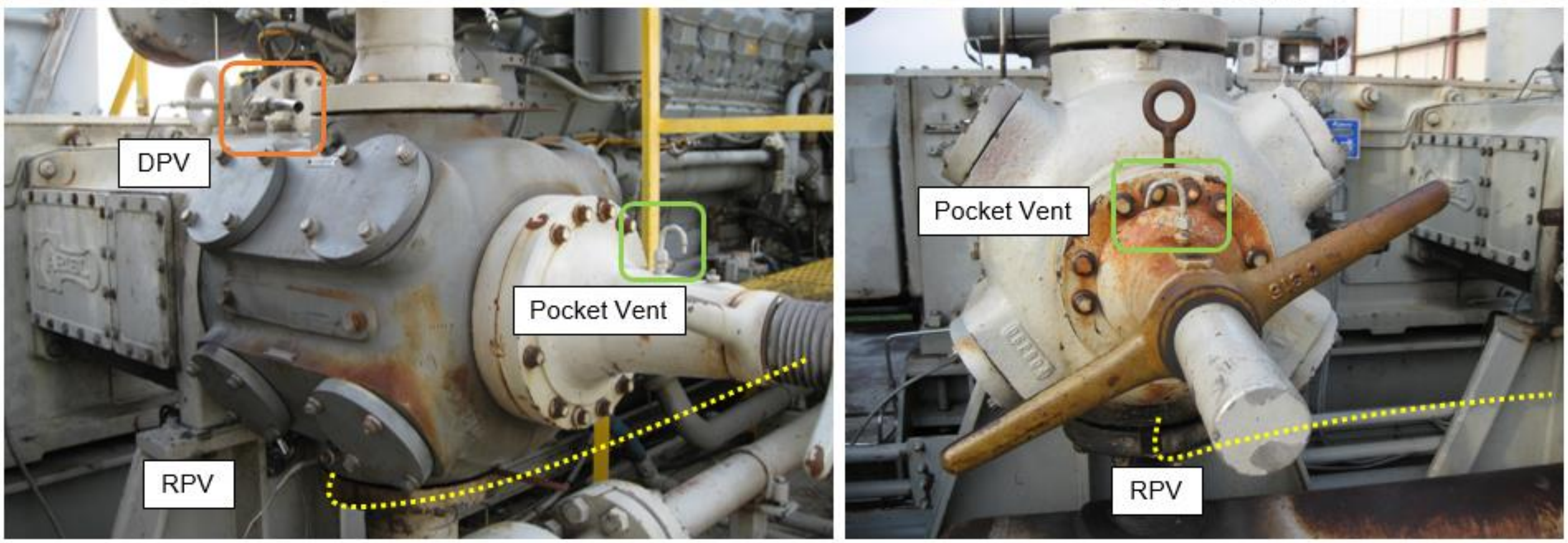


Figure C-17. *Compressor vent examples*

3.0 REFERENCES

U.S. EPA, 2016. Mandatory Greenhouse Gas Reporting Subpart W – Petroleum and Natural Gas Systems, 40 C.F.R. §98.232.

U.S. EPA, 2015. Mandatory Greenhouse Gas Reporting Subpart W – Petroleum and Natural Gas Systems, 40 C.F.R. §98.232.

APPENDIX D

OP-FTIR Spectrometry Procedures, Equipment and Specifications

APPENDIX D

OP-FTIR SPECTROMETRY PROCEDURES, EQUIPMENT, AND SPECIFICATIONS

1.0 BASIC PRINCIPLES OF OPEN-PATH SPECTROSCOPY

The RAM2000™ OP-FTIR was operated with a corner-cubed prismatic retro-reflector, oriented to accept prevailing winds through an open-air optical path. A beam of light spanning a range of wavelengths in the mid-infrared portion of the electromagnetic spectrum was propagated from the transmitter portion of the OP-FTIR instrument. Methane, ethane and carbon monoxide present in the air crossed the beam path, interfered with modulated infrared energy from a silicon carbide (SiC) glower source, became energetically excited by the resonant frequency of the source, and caused the beam to divest of relative energy.

The retro-reflector bent the source energy back to a mercury/cadmium/telluride detector in the OP-FTIR optics chamber, where a Michelson Interferometer achieved further modulation by splitting the returning beam of radiation into two paths, and recombined them in a way to generate an interference from the phase difference. The phase difference, and thus the interference, was dependent on the wavelengths present in the beam. In one of the paths, the radiation was reflected off a moving mirror, resulting in an intensity variation which was measured as a function of the path difference between the two mirrors. The result was an interferogram.

The interferogram obtained from a monochromatic beam was a simple cosine wave. The broadband interferogram was a sum of cosine waves (the Fourier series) for each spectral component as a function of mirror-beam-path separation. A spectrum (in optical frequency units) was obtained by performing a Fourier transform upon the interferogram. Interferograms were created at a chosen rate of 32 signal-averaged scans per one sample frame. Resultant absorbance spectra were compared to reference spectra using multi-component regression algorithms. Concentrations were path-averaged and path-integrated.

Compounds were identified and quantified via a computer-based spectral search involving sequential, compound-specific analyses and comparison to the system's internal reference spectra library. The most widely employed technique for analyzing FTIR spectral data is the multi-component classical least squares (CLS) technique. Any gaseous compound which absorbs the infrared (IR) region is a potential candidate for monitoring using this technology.

The Minimum Detect Levels (MDL) were algorithmically calculated values that defined the minimum methane concentration, within six sigma statistical confidence. Upon completion of a time-lapsed sampling session, all frames (samples) were averaged per analyte (methane/ethane/carbon monoxide) by the software. A mean MDL for each analyte was calculated based upon the full sampling session. According to the manufacturer, the range of detection limits for a 100-meter separation between the sensor and retroreflector was from 0.10 to 15 ppb for most infrared active chemicals.

Concentrations of analytes were reported only if the time-weighted mean concentration was found to be in excess of two times the software calculated mean MDL. The maximum detected concentration, observed at any given time during sampling history, was only reported if the maximum was found to be at least two times the software-calculated-mean MDL. As a result of these ultra conservative steps, the concentration values for methane (mean or max), were only reported if the results were beyond a 12 sigma statistical confidence range above the MDL. As a result, the possibility of having a false positive concentration was null.

2.0 OP-FTIR AND RETROREFLECTOR SET UP

The upwind and downwind locations were determined in relation to the physical properties of the compressors and gas gathering lines. The optical beam path between the OP-FTIR spectrometer and the retroreflector was oriented perpendicular to prevailing wind direction as much as possible.

Downwind setup locations for the OP-FTIR and retroreflector were restricted to areas that were free of traffic flow and were oriented such that the infrared beam was unobstructed by facility equipment or buildings. Each retroreflector array consisted of thirty-seven 2.5-inch hollow reflector cubes consisting of three mutually perpendicular mirrors that bend infrared light back to its exact point of origin and, as such, reduced the divergence of the beam on its return path back to the detector. The spectrometer was adjusted so that the siting scope (located between the spectrometer and telescope) displayed crosshairs at the upper left corner of the retroreflector mirror. A range finder or measuring wheel was used to measure the distance from the spectrometer to the retroreflector. The instruments required a round trip beam path for the measurement so it was necessary to multiply the distance by a factor of two.

Since the OP-FTIR system contained a liquid nitrogen cooling unit, liquid nitrogen was added to the spectrometer prior to measurement. Once the spectrometer system was engaged and the nitrogen cooling began, the OP-FTIR detector was allowed to cool for 20 minutes. Hotter ambient temperatures required a longer cooling time.

3.0 BACKGROUND (UPWIND) SAMPLING

Background or upwind samples were collected and evaluated to determine the possibility of upwind emitting sources contributing to emission levels at the study site. Upwind sampling locations were chosen as close to the sample area as possible and were free of wind obstacles to the extent possible. At least one-hour of upwind measurements was gathered at each location.

4.0 METEOROLOGICAL DATA TO SUPPORT EMISSION FLUX CALCULATIONS

A controlled stream of gas-phase SF_6 was released during OP-FTIR measurement periods. The OP-FTIR spectrometer detected and quantified the SF_6 plume along with methane and ethane (target compounds) to distinguish between thermogenic and biogenic methane sources. Since the SF_6 emission rate was known, the emission rate of other compounds were scaled based on the ratio of their concentrations to the measured SF_6 concentration.

Cylinders containing 99% pure SF_6 were utilized in conjunction with a 0-10 L min^{-1} mass flow controller to control the release of SF_6 from the cylinder. After the mass flow controller, the SF_6 traveled through a 50-m length of inert tubing to a tripod and was released from the end of the tubing at the tripod.

All meteorological measurements were collected at 6m above ground level concurrent with, and using the same instrumentation as, measurements collected for the high flow sampling program (See Appendix B) and all measurements were recorded with a Campbell Scientific CR1000 data logger.

Flow rates of the SF_6 mass flow controller used to release the tracer were checked at least monthly against a BIOS dry gas meter, and the dry gas meter was calibrated at least annually against a NIST-traceable standard.

APPENDIX E

Plume Visualization

APPENDIX E

PLUME VISUALIZATION

1.0 INTRODUCTION

A user-friendly data visualization tool was developed in Microsoft Excel to conservatively estimate the extent of the plume generated by measured emissions from compressors. An output table of results can be generated and used to create additional figures in other programs like Python.

2.0 PLUME VISUALIZATION MODEL

The Gaussian air dispersion model was used to visualize measured methane emission rates as methane plumes (**Equation D-1**). The Gaussian air dispersion model is a steady-state model; therefore, the resulting plume is a conservative visualization of the methane emissions measured in the field.

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \times \left[exp - \left(\frac{y^2}{2\sigma_y^2}\right)\right]\left[exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + exp\left(\frac{-(z=H)^2}{2\sigma_z^2}\right)\right] \quad \text{(Equation D-1)}$$

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 package calculates σ_y and σ_y, based on input parameters including date and time, site location, sky cover, and land surface cover. A screenshot of the main page of the tool is shown in **Figure D-1**. Up to three different emission sources can be input; the resulting plumes are calculated and plotted. A total plume is also generated, which sums individual plumes and plots a “total” plume.

2.1 Inputs

The user enters the following input data:

1. Source strength (mg/s); up to three sources. If the sources are emitting from different locations the distances between the sources can be input into the model. Source locations must be in x-y coordinate form, where the x-direction is parallel to the wind direction, and y-direction is horizontal to the wind direction.

2. Effective stack height (same for all sources)

3. Date (MM/DD/YY) and time (military) of emission.

4. Source location (latitude and longitude) and time zone. This information, along with date and time is used to calculate the solar elevation angle. The solar elevation angle is calculated using the NOAAA Solar Calculations (NOAA, 2010)

5. Sky cover. Based on options in a dropdown menu.

6. Landscape. Options include rural or urban.

7. Stability class. The Pasquill Stability Class is chosen from a dropdown menu. The tool is designed to help the user determine the stability class (see the next Section 2.2 Stability Class).

8. Wind speed (m/s) and height of wind speed measurement (m). If sky cover and wind speed are unknown, websites that have historical weather data such as Weather Underground may be useful.

9. Receptor height (m). The most conservative height is equal to the effective stack height

10. Plume grid spacing (delta X and Y) (m). The tool calculates plume concentrations for a set number of grid spaces; therefore, if a larger plume area is desired the delta X and/or delta Y values need to be increased

11. Initial X and Y coordinates (m). This is the starting location along the plume that the user wants to view. The default Initial Y is 0 m. Due to the equations used to calculate σ_y the Initial X must be greater than 0. The default value is 0.01 m

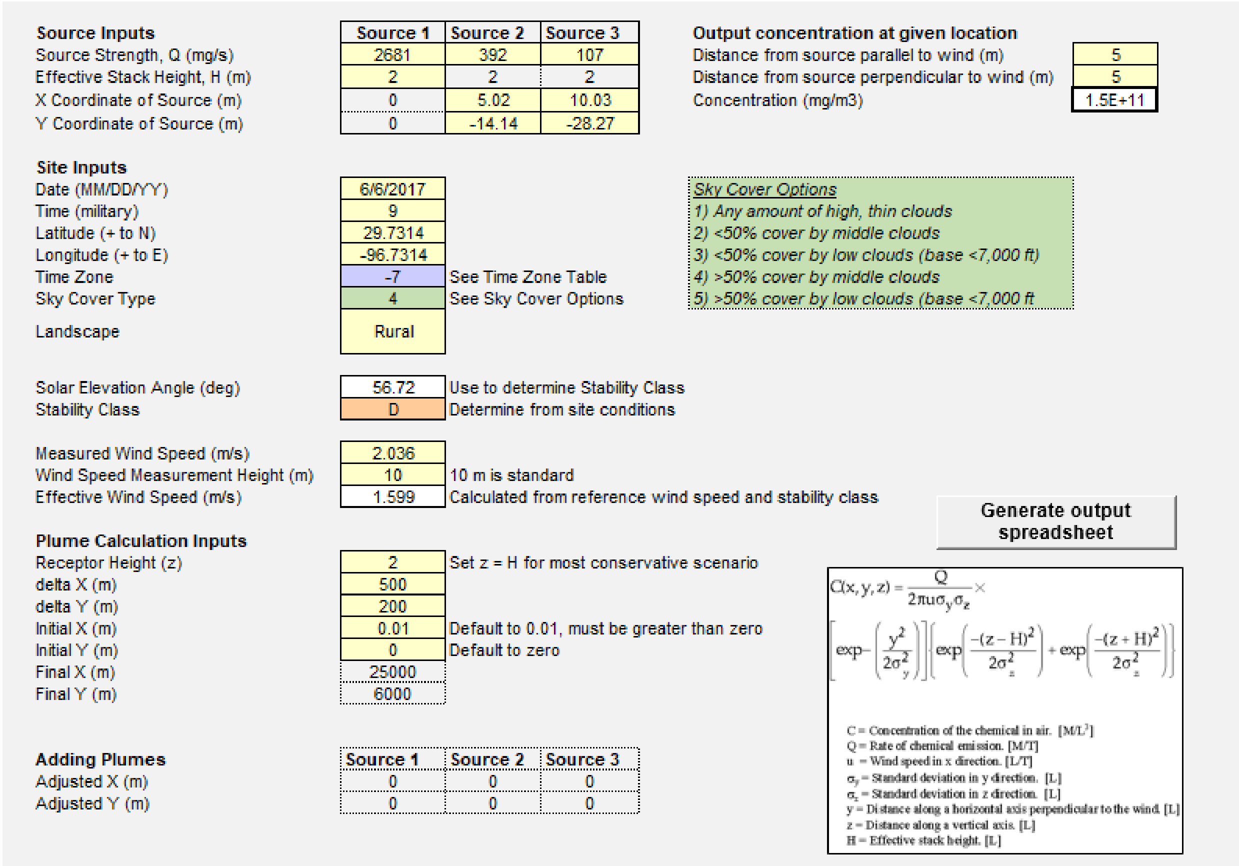


Figure D-1. *Screenshot of tool main page*

2.2 Stability Class

If needed, the visualization tool offers guidance for determining the atmospheric stability class based on the site conditions. The stability class guide is shown in **Figure D-2**.

1) Determine daytime insolation based on the solar elevation angle and sky cover. The solar elevation angle is calculated by the tool and output to the main page of the tool.

2) Find the atmospheric stability class based on the daytime insolation and surface wind speed. The surface wind speed is calculated by the tool based on the measured wind speed, wind speed measurement height, and landscape input by the user.

Determine Stability Class

1. Find Daytime Insolation

	Solar Elevation Angle (degrees)			
Sky Cover	> 60	≤60 but >35	≤35 but >15	Nighttime (≤15)
1) Any amount of high, thin clouds	strong	moderate	slight	*
2) <50% cover by middle clouds	strong	moderate	slight	*
3) <50% cover by low clouds	strong	moderate	slight	*
4) >50% cover by middle clouds	moderate	slight	slight	*
5) >50% cover by low cloud	slight	slight	slight	*

2. Find Atmospheric Stability Class

	Daytime Insolation			Nighttime *	
Surface wind speed at a height of 10 m (m/s)	Strong	Moderate	Slight	Thinly overcast or ≥4/8 low cloud cover	≤3/8 cloud colver
<2	A	B	B	F	F
2 to 3	B	B	C	E	F
3 to 5	B	C	C	D	E
5 to 6	C	D	D	D	D
>6	C	D	D	D	D

Notes:
Assume neutral class (D) for all overcast conditions
Night is defined as the period from one hour before sunset to one hour after sunrise

Figure D-2. *User guide to determine atmospheric stability class*

PLUME VISUALIZATION RESULTS

2.3 Output Concentration at a Given Location

The user can check the concentration of the final plume at any location in the generated figure. In the main page there is a location for the user to input a distance from the source in the x- and y-directions. The corresponding concentration is returned.

2.4 Total Plume Output

A screenshot of the Excel-calculated total plume for measured emissions from three compressors at Site 1, during Field Campaign 2 is shown in **Figure D-3**. Conditional formatting is used to color the plume based on methane concentration from grey at < 0.001 mg/m^3 (less than background concentrations) to dark red at > 100 mg/m^3.

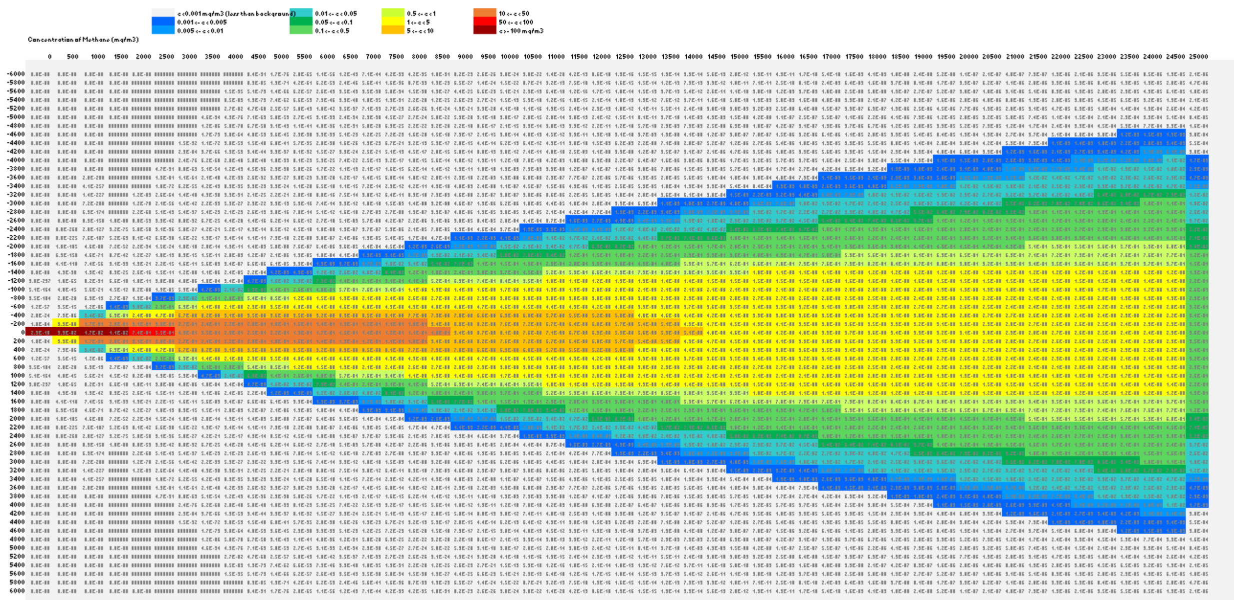


***Figure D-3**. Output figure - Estimated methane plume from compressor emissions, Site 1, Field Campaign 2, 9 am*

3.0 REFERENCES

NOAA, 2010. NOAA Solar Calculations

APPENDIX F

Emission Factors

APPENDIX F

EMISSION FACTORS

Emission factors (EF) were developed for the small number of sites (four) visited in this study. The EFs presented are not assumed to be nationally representative. Population EFs for leaking and venting components, respectively, are presented in **Tables F-1** and **F-2**. Leaker EFs are presented in **Table F-3**. EFs from USEPA Subpart W are provided for comparison. EF calculation details can be found in Section 2.4.3; the equations used to calculation EFs are repeated here.

$$Population\ EF_{i,leak} = \sum ER_{i,measured,leak} / N_{i,screened\ population}$$ **Equation 2-1**

$$Population\ EF_{i,vent} = Average(ER_{i,measured,vent})$$ **Equation 2-2**

$$Leaker\ EF_i = Average\left(ER_{i,measured,leak}\right)$$ **Equation 2-3**

Where:

$ER_{i,\ measured,\ vent}$ = Measured methane emission rate of leaking component type *i* (scf/hr)

$ER_{i,\ measured,\ vent}$ = Measured methane emission rate of venting component type *i* (scf/hr)

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

***Table F-1**. Population emission factors – Leaking components*

Component	EPA 2015 [a]	This Study		
	Pop. EF (scf/hr/comp)	Pop. EF (scf/hr/comp)	Component Population Count	Total Measured Emissions (scf/hr)
Valve	0.121	0.042	6,393	266
Connector	0.017	0.003	43,575	119
Open-Ended Line	0.031	-	-	0
Pressure Relief Valve	0.193	1.41	385	544

[a] From Table W-1A, USEPA Subpart W, 2015 update

***Table F-2**. Population emission factors – Venting components*

Component	EPA 2015 [a]	This Study		
	Pop. EF (scf/hr/comp)	Pop. EF (scf/hr/comp)	Sample Count	Stdev of Emission Rate (scf/hr)
Low Continuous Bleed Pneumatic Device Vents	1.39	3.6	8	1.60
High Continuous Bleed Pneumatic Device Vents	37.3	38.1	8	26.9
Intermittent Bleed Pneumatic Device Vents	13.5	12.8	85	23.9
Pneumatic Pump	13.3	8.8	3	4.88
Compressor Distance Piece Vent	-	30.3	80	51.2
Compressor Rod Packing Vent	-	165.1	28	242

[a] From Table W-1A, USEPA Subpart W, 2015 update

Table F-3. *Leaker emission factors*

Component	EPA 2016 [a] Leaker EF (scf/hr/comp)	This Study Leaker EF (scf/hr/comp)	Measurement Count	Stdev (scf/hr)
Valve	4.9	9.14	23	15.3
Flange	4.1	5.24	8	8.45
Connector (other)	1.3	3.21	24	6.65
Open-Ended Line	2.8	-	0	-
Pressure Relief Valve	4.5	68.0	8	145
Pump Seal	3.7	-	0	-
Other	4.5	3.53 [b]	14	6.17

[a] From Table W-1E, USEPA Subpart W, 2016 update
[b] Other category contains regulators, gauges, meters

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).

Table F-4. *Mass flow rates*

Measured emissions - kg CH_4/hr				
Field Campaign	Site 1	Site 2	Site 3	Site 4
1	36.2	12.5	9.25	11.2
2	11.5	3.89	3.11	5.52
3	5.69	14.1	8.58	18.5
4	6.67	8.13	4.19	20.6

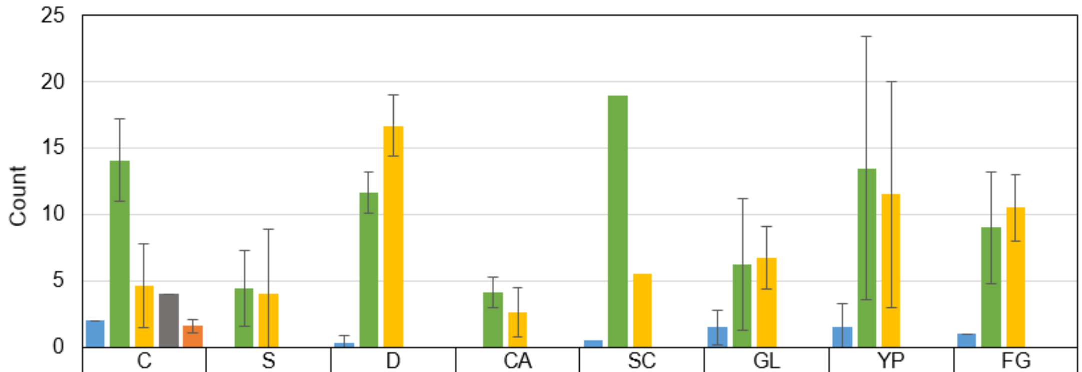
APPENDIX G

Additional Component Count Results

APPENDIX G

ADDITIONAL COMPONENT COUNT RESULTS

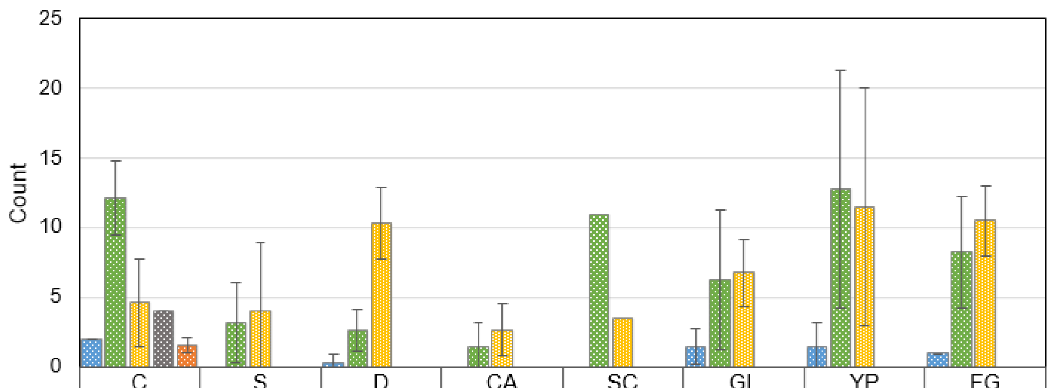
Component counts for component categories not presented in Section 3.1 (meters, gauges, regulators, DPVs and RPVs) are shown in **Figures G-1** and **G-2**.



	C	S	D	CA	SC	GL	YP	FG
Meter	2.0	0	0	0	0.5	1.5	1.5	1.0
Gauge	14	4.4	12	4.2	19	6.3	14	9.0
Regulator	4.7	4.0	17	2.7	5.5	6.8	12	11
DPV	4	0	0	0	0	0	0	0
RPV	1.6	0	0	0	0	0	0	0

Error bars are standard deviations. Abbreviations: DPV = distance piece vent, RPV = rod packing vent, C = compressor, S = separator, D = dehydrator, CA = coalescer, SC = slug catcher, GL = gathering line, YP = yard piping, FG = fuel gas skid

***Figure G-1**. Average component count by equipment type for additional component categories, including gas and liquid lines*



	C	S	D	CA	SC	GL	YP	FG
Meter	2.0	0	0	0	0.0	1.5	1.5	1.0
Gauge	12	3.2	3	1.5	11	6.3	13	8.3
Regulator	4.7	4.0	10	2.7	3.5	6.8	12	11
DPV	4	0	0	0	0	0	0	0
RPV	1.6	0	0	0	0	0	0	0

Error bars are standard deviations. Abbreviations: DPV = distance piece vent, RPV = rod packing vent, C = compressor, S = separator, D = dehydrator, CA = coalescer, SC = slug catcher, GL = gathering line, YP = yard piping, FG = fuel gas skid

***Figure G-2.** Average component count by equipment type for additional component categories, only gas lines*