Methane Emissions from Gathering and Boosting Compressor Stations in the U.S.:
Supporting Volume 3:
Emission Factors, Station Estimates, and National Emissions
October 2019 Revision

Daniel Zimmerle[1], Timothy Vaughn[1], Benjamin Luck[1], Terri Lauderdale[2], Kindal Keen[2], Matthew Harrison[3], Anthony Marchese[1], Laurie Williams[4], and David Allen[5]

[1]Energy Institute at Colorado State University
[2]AECOM
[3]SLR Consulting
[4]Fort Lewis College
[5]University of Texas, Austin, TX, USA

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S3-1 Field Campaign

This section provides an overview of the field campaign for the entire project and the data collected in the field campaign data and during the analysis phase of the project.

Accompanying data files:
All data tables referenced in this report are provided in the file *DataTable.xlsx*. Sheet names are given as needed throughout the document in italics; for example, a listing of partner data can be found in *D10 Partner Site Data*.

Throughout this volume we refer to a single compressor station as a "station" and reserve the term "facility" to refer to all operations by one company in one basin, in keeping with the EPA's Greenhouse Gas Reporting Program's definition of a *gathering and boosting facility*.

S3-1.1 Sampling Plan

Prior to the field campaign, partners provided lists of their stations along with basic information about the stations, including the location, number of compressors, a simple classification of the site type, and whether the station handled primarily *wet* or *dry* gas. In the context of this study, wet gas is defined as gas with less than 95% methane content. The partner data gathered is in sheet *D10 Partner Site Data*. Each partner was assigned an arbitrary letter ID, "A" thorugh "I".

The field campaign was conducted using geographically-clustered random sampling. The sampling procedure was as follows:

1. Basins where partners operated were selected to be representative of the mix of USA production basins.
2. In each basin, one or more partners were selected that had substantial operations in the basin. Field campaign weeks were dispersed such that each partner provided site access and support for a total of 2-3 weeks during the campaign.
3. Within the basin, for each week scheduled in the basin, one partner was selected as the host for that week.
4. For each campaign week, five random stations were selected from the partner's stations within the basin. These five stations were organized geographically to minimize travel time between stations, typically completed in the evening or overnight. These stations were designated the "primary" stations for each day.
5. For each selected station, 3-5 nearby stations were identified using distance calculations, and ordered by distance. These secondary stations were measured in predetermined order if work was completed at the first station in less than a day.
6. Key characteristics of all selected stations for all campaign weeks were checked against the characteristics of all partner stations to assure a representative sample. The primary parameters checked were:

   (a) The type of station: compression, dehydrating, treating, and other station types.
   (b) The size of the station; the number of compressor engines was utilized as a surrogate for size.
   (c) Whether the station handled wet or dry gas.

   Note that geographical diversity was assured by the selection of basins.

7. The above plan was shared with the host partner, who reviewed the site selection for any major issues. If a station was under major repairs, the station was excluded for safety reasons and its likely lack of pressurization, which could lead to unrepresentative emissions. Stations with high H_2S gas, where special breathing equipment was required, were also excluded from the field campaign.

8. Driving distances between stations were checked after selection, and if these differed substantially from the predetermined order, the order of the stations was changed to minimize travel time between stations.

The above plan was designed to maximize the number of stations measured during the campaign, while still measuring the appropriate mix of stations. The resulting diversity of stations selected for the field campaign matched the diversity of partner stations to within ±12% on these selected categories. Figure S3-1 overlays selected regions to the county level and measured stations for the entire field campaign. Counties are colored by gas production, illustrating that the campaign measured a diversity of production rates, including, importantly, the highest producing counties in the USA.

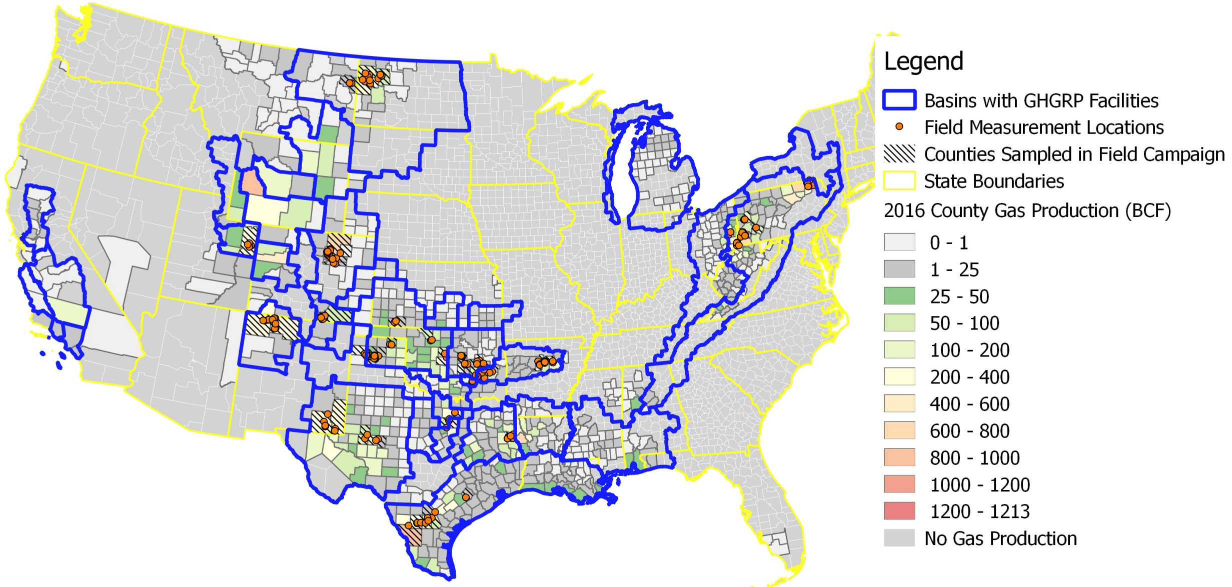

Figure S3-1: Map showing locations measured during the field campaign. Blue outlines indicate AAPG basins used for GHGRP reporting. Gas production is taken from DrillingInfo™data.

Field teams measured the primary station and then moved on to secondary stations, in preplanned order, each day. The number of stations measured varied by day - on some days only the primary station was measured, while on others the team completed all selected stations and moved on to the next day's stations. The speed of measurement depended primarily upon the complexity of the station, although weather, road conditions, and distance between stations were also factors. Typically, teams measured 1-5 stations per day (except for 2 days where eight or more small stations were measured). The resulting mix of measured stations differed from the original station list and mix developed during campaign planning. However, the station mix closely aligns with the field campaign design. Figure S3-2 illustrates the mix of stations measured in the field campaign compared with the all stations in the partner population.

Two measurement teams were deployed for the field campaign. Both teams were equipped with one or more optical gas imaging (OGI) cameras for detecting emissions, a high flow sampler and other equipment for measuring emissions (see Section S3-1.3). In addition, Team 1 was equipped with six gas meters for long-term recording of pneumatic controller emissions (see Luck et al.[1]) and a set of equipment for measuring methane entrained in engine exhaust, a major source of emissions for gathering stations (see Vaughn et al.[2]). Team 1 completed 11 weeks of measurement while Team 2 completed 8 weeks.

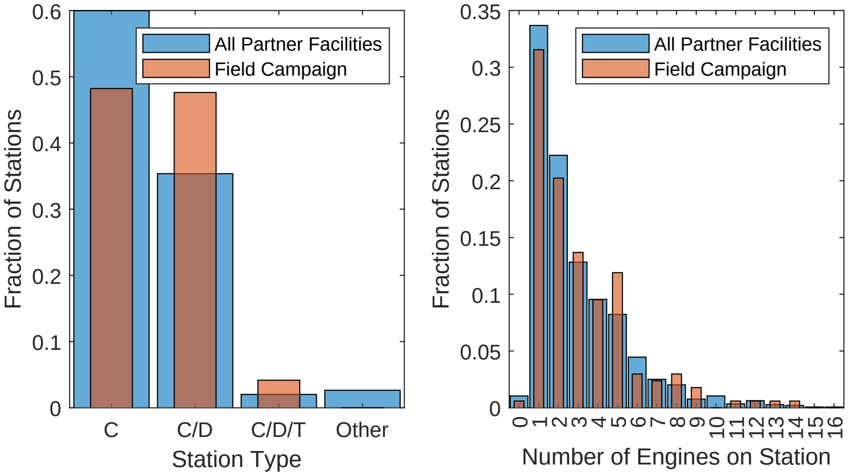

Figure S3-2: Mix of station types in the field campaign. Stations are classified by the type of major equipment on the station, where *C* indicates compression, *D* indicates dehydration, *T* indicates acid gas removal (treating). *Other* includes stations with no compressors.

For each measurement day, emissions detection and measurements were completed on *units* of *major equipment*, including: compressors, dehydrators, acid gas removal (AGRU, also known as *treaters*) skids, station separators, atmospheric tanks, and yard piping. While all types of tanks would have been measured, field teams encountered only atmospheric tanks - i.e. tanks kept at near atmospheric pressure, and typically vented to the atmosphere directly or through a combustion device (e.g. a flare) or a vapor recovery unit (a small compressor that compresses gas and injects it into the sales or fuel system on the station).

Yard piping was broken into sections for ease of processing, and each section was recorded, screened and measured as a unit. While all stations have at least one yard piping unit, some stations had several. Typical units of yard piping include fuel gas systems, station inlet and outlet headers, meter runs, and pig launchers and receivers. In addition, measurement teams occasionally divided yard piping into arbitrarily numbered subsets for ease of measurement. Measurement categories are further defined in Section S3-1.5. The measurement team selected units to screen with OGI, and, time permitting, measured any leaks found on the unit. Both screening data and measurements were recorded *only if the entire unit was screened and/or measured.* Regardless of how yard piping was divided into subsets at a station, yard piping is considered screened measured for a station only if all subsets of yard piping at that station were screened and measured.

On each measurement day, the team screened equipment with an OGI camera and measured emissions as found. When all major equipment units at a station were measured, the team would move to a nearby station on the selected list and continue measuring. Similarly, measurement teams would count components on major equipment units for use as activity data. As with measurement data, counts were recorded only if all components on the unit were counted. For identical skid-based equipment, the count on one skid was applied to all identical skids on the station.

It is important to note that the sampling of equipment for counting and measurement was independent; a particular unit of major equipment may have been counted but not measured, or measured but not counted. Component types counted are described in S3-1.5. Field protocols are included in the appendices: *Appendix D Field Protocol.pdf* covers overall field measurement and counting protocol, *Appendix E Component Counting Protocol.pdf* provides instructions for component counting, and *Appendix F HiFlow Sampler Reach Protocol.pdf* provides for methods for reaching high emission locations.

Data was accumulated into two tables, *D8 Measurements* for all OGI detections and measurements, and *D9 Equipment* for all major equipment records and component counts. Tables are tied together by a major equipment ID consisting of a station identifier (randomly assigned integer in [1,3000]), equipment type, and an equipment ID. Additional qualifying fields provide more detail on the type of equipment.

During the field campaign, field teams made 229 measurements of pneumatic controllers (PCs) using the same methods as utilized for other emission sources (see Section S3-1.3). While these measurements last a few minutes, long duration measurements of PCs are required to adequately characterize emissions, and the measurement protocol did not distinguish between normal and abnormal operation of the controllers. Therefore, these measurements *are not* included in the measurement data set.

In addition, gas flow meters were installed at stations to measure PC emissions over an extended period [1]. These measurements could provide updated emissions factors for PCs, but due to a measurement error, additional corrections were made to some recordings and some recordings were discarded. To void any potential bias in the sample, this study instead utilizes emission factors from the GHGRP for all PC emissions.

S3-1.2 Additional Data from Longitudinal Compressor Study

Coincident with the field campaign for this study, GSI Environmental, Inc., completed a longitudinal* study of four compressor stations in southeast Texas. During campaign planning, the teams from both studies coordinated sampling methods and data collection. Following GSI's campaign, GSI provided their measurement data to CSU for inclusion in the CSU study.

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[*] A longitudinal study looks at a, typically smaller, study population multiple times. The main study presented here is "latitudinal" - it looked at a larger sample population one time; i.e. a snapshot in time.

The GSI study focused on multiple measurements of the compressor stations over a one year period. Therefore, each compressor station was visited several times, screened with OGI, and measured using the high flow method. Since each unit was measured multiple times, potentially finding different emission locations or different emission rates at the previously identified locations, multiple emission measurements at any emission location were averaged before inclusion in the study data set to avoid unduly weighting these four stations relative to the other stations in the study. The impact of including this data is shown in Table S3-1. For reference (not used in the study), the impact of including all measurements without averaging is included in Table S3-2.

Stations included from the GSI study were assigned station IDs 3001 to 3004 in the study data sets and are assigned a partner ID code of "J".

Table S3-1: Categories Impacted by Additional GSI Data

Category[1]	Meas. Count	Added Meas. Count	No GSI Data	With GSI Data	Relative Difference In Mean
Compressor PRV	33	2	17.8	21.2	20% [17% to 21%]
Non-compressor PRV	20	3	9.18	10.8	18% [15% to 21%]
Compressor Rod Packing Vent	353	37	26.2	28	7.6% [6% to 7.9%]
Non-compressor Regulator	37	6	7.76	8.05	3.3% [2.7% to 3.9%]
Compressor Connector Flanged	39	2	11.8	12.1	3% [2.7% to 3.5%]
Compressor Valve	38	1	40.5	41.2	2.1% [1.9% to 2.5%]
Compressor Blowdown Vent	29	1	21.8	21.5	-2% [-5.8% to -0.12%]
All Pump	11	1	36.6	35.6	-3.7% [-7.8% to -1.8%]
Compressor Regulator	34	3	14.5	13.8	-4.4% [-4.9% to -3.9%]
Non-compressor Valve	86	13	8.39	7.88	-6.1% [-9.2% to -3%]
Compressor Connector Threaded	98	9	15.8	14.6	-7.3% [-9.9% to -6%]
All Other	36	6	27	24.1	-10% [-12% to -8.6%]
Compressor Pocket Vent	19	4	9.45	7.82	-17% [-19% to -16%]
Non-compressor Connector Flanged	25	6	9.7	7.92	-18% [-20% to -17%]

[1] Categories with more than 1% change shown

Table S3-2: Categories Impacted by Non-Averaged GSI Data

Category[1]	Meas. Count	Added Meas. Count	Without GSI Data	With GSI Data	Relative Difference In Mean
Compressor PRV	33	5	17.8	31.6	80% [73% to 82%]
Non-compressor PRV	20	3	9.18	10.8	17% [14% to 21%]
Compressor Rod Packing Vent	353	80	26.2	27.9	7.4% [4.7% to 8.9%]
Compressor Valve	38	2	40.5	41.8	4.2% [3.5% to 4.5%]
Compressor Connector Flanged	39	3	11.8	12.2	3.3% [2.9% to 3.7%]
Non-compressor Regulator	37	7	7.76	8.02	2.8% [2.3% to 3.5%]
Non-compressor Connector Threaded	71	15	5.72	5.68	-1% [-1.8% to -0.48%]
Compressor Blowdown Vent	29	1	21.8	21.3	-2% [-6.9% to 0.41%]
All Pump	11	1	36.6	35.7	-3.5% [-7.7% to -2.1%]
Compressor Regulator	34	3	14.5	13.9	-4.3% [-4.9% to -3.8%]
Non-compressor Valve	86	21	8.39	7.97	-4.9% [-9.4% to -0.52%]
Compressor Connector Threaded	98	9	15.8	14.7	-7.5% [-9.4% to -6.1%]
Compressor Pocket Vent	19	4	9.45	7.8	-17% [-19% to -16%]
All Other	36	12	27	22	-17% [-21% to -15%]
Non-compressor Connector Flanged	25	7	9.7	7.68	-21% [-22% to -19%]

[1] Categories with more than 1% change shown

S3-1.3 Measurement Equipment

Leaks were detected utilizing infrared gas cameras, commonly known as *optical gas imaging* or *OGI*. Both Opgal EyeCGas and FLIR GF320 cameras were used. The detection threshold of these cameras is an active research area. Ravikumar et al. [3] suggest a 90% detection efficacy of $\epsilon = 1.845d^{1.925}$, where d is the observation distance from the camera to the leak location. For this study, we estimate a typical observation distance of 1.5 m, leading to an estimated 90% detection threshold of 0.21 scfh methane.

The primary instrument used to measure fugitive and vented emissions was the Bacharach Hi Flow sampler (BHFS). Several authors have expressed concerns about the operation of the instrument [4, 5, 6]. However a recent report by EPA Inspector General [7] indicates that the instrument provides effective measurements provided that use procedures, spelled out in the instrument's user manual [8] are followed correctly.

A total of 1153 emission locations were measured using the BHFS. For each measurement, 1-4 measurement attempts (i.e. repeat measurements) were made resulting in 2142 total attempts; 844 emission locations had at least two measurement attempts to quantify emissions. In 301 measurement attempts (14% of all attempts), emissions were detected by OGI, but produced a zero emission reading when measured using the high flow instrument. For 103 emission locations, all measurement attempts returned readings of zero.

Given the time delay between the OGI screen and high flow measurement, the emissions may have stopped due to a variety of reasons, including changes in site operation or intermittent equipment operation. However, it is also possible that emissions seen during the OGI screen persisted, but the emission rate was below the lower detection limit (LDL) of the high flow instrument. To assess the instrument's LDL, a controlled release test was performed, with natural gas releases (approximately 85% methane) from 0 to 0.5 scfh, with the instrument having a 100% detection rate of the emissions at 0.5 scfh. A logistic regression was performed to establish the LDL, as shown in Figure S3-3, of 0.204 scfh. To estimate uncertainty in high flow measurements, a relative accuracy of ±10% was assumed (normally distributed errors, 90% confidence interval). This data is included in the data tables, in sheet *D1 HiFlowLDL*.

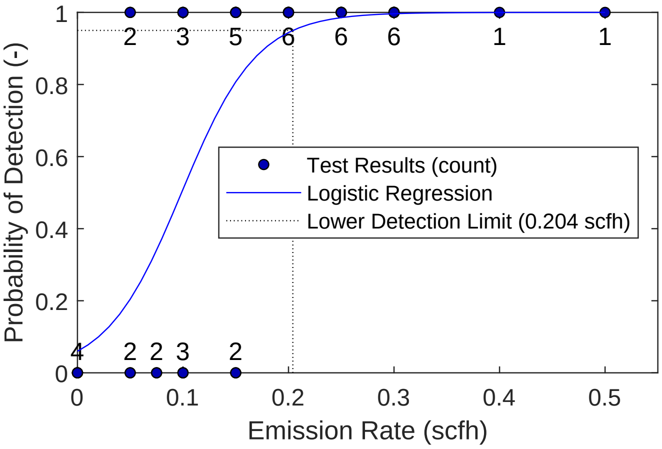

Figure S3-3: Data and logistic regression utilized to develop a lower detection limit (LDL) for one of the Bacharach High Flow samplers utilized in the study. Points represent test conditions performed in outdoor laboratory tests using compressed natural gas. Point labels indicate the number of non-sequential test cases with either detections (y=1) or non-detection (y=0). The logistic regression and computed lower detection limit at 95% confidence level are also shown.

The BHFS must be corrected for gas composition. These corrections were developed by testing after the field campaign, and are instrument-specific. Six BHFS instruments were utilized in the field campaign. Three of these units were returned to METEC post-campaign to develop corrections: one unit owned by CSU (‘CSU’ - 544 measurements) and two owned by UT Austin (‘UTBlack’ - 64 measurements and ‘UTBlue’ - 7 measurements). The other units were not available after the campaign; one had been stolen during the campaign (the unit id’d as ‘AECOM’) and the other two were used by partner company personnel and were not available post-campaign. Of the unavailable units only the AECOM unit had been utilized for a large number of measurement attempts (478).

While several authors provide BHFS corrections they utilized for various studies, most corrections were developed by limited testing – typically one or two gas compositions fed directly to the BHFS sensor. In contrast, the corrections presented here use specialized equipment at METEC to vary both flow rate and methane composition over a wide range by mixing methane, ethane and propane using mass flow controllers. This system is capable of controlled emission rates of 1-100 slpm. Resulting emissions were introduced directly into the intake of the instruments. Therefore, the resulting corrections include all instrument subsystems, including flow measurement and sensor behavior. All test data is provided in the data tables, in sheet *D6 BHFS Test Data*.

The resulting test data is shown in Figure S3-4 for all three available BHFS instruments. The data clearly indicates a dependence on both gas composition, as indicated in the BHFS manual, and *also* on indicated flow rate (i.e. the flow rate reported on the instrument screen), which is not mentioned in the BHFS manual. The flow rate dependence could be due to variation in the flow rate sensor (an orifice plate sensor), the concentration sensor, or could be a software artifact.

Data was collected over a multi-month period, when METEC and staff were available and weather conditions supported outdoor use of the equipment. Gas compositions used in testing mirror those seen in the field. The BHFS senses gas concentration using a single pellistor sensor operating in two modes, a catalytic oxidation (CatOx) mode which operates up to a gas concentration of approximately 5%, and a thermal conductivity mode for gas concentration above ≈5%. The active sensor is noted by observing the number of digits displayed to the right of the decimal point on the gas composition reading: CatOx - 2 digits, TCD - 1 digit [9]. Switching between modes *does not* occur at exactly 5%, and the switching concentration is dependent on the whether input gas is going from low-to-high or high-to-low concentration. Ranges observed in testing at METEC are noted in the titles of the Figure S3-4. The UTBlue unit produced unstable readings near the switch-over point; therefore, the testing team left a gap in the flow rates when collecting test data.

Additional unusual measurement behaviors were observed during testing. Over multiple days of data collection, the testing team saw substantial changes in indicated emissions for the same emission rate, likely due to changes in calibration; the instrument was calibrated before each testing session. As per the instrument manual, each BHFS was calibrated at two points, 2.5% methane in nitrogen and 100% methane. These two calibration points represent single-point calibrations for each of the sensor's active modes - 2.5% for CatOx and 100% for TCD. In field conditions, the sensor is not operated at 100% methane, as this would violate the "high flow" assumption This experience indicates that day-to-day variations in calibration may be substantial, and daily calibration – the procedure recommended to avoid sensor transition failure – may actually contribute to uncharacterized measurement uncertainty. Additional investigation is recommended for future projects.

Testing was done in sets, where each set of emissions had an approximately constant flow rate but a series of different methane fractions. A set was included only if the linear regression across methane fractions (concentrations) for a chosen flow rate had $R^2 \geq 0.5$.

Experimentation indicated that a curve fit parameterized on both indicated flow rate and methane fraction produced high R^2 values and produced an easily implemented correction curve. For the CatOx sensor, the form of this correction equation constrains the output (actual flow) to be zero when the indicated flow is zero, since the CatOx mode is utilized for low emission rates. The form of the correction equation for the TCD mode does not require this constraint, and the simplest surface form (bi-linear) was used for the TCD mode.

Since the active sensor is not known in the field data - gas concentration was noted without noting the number of digits on the display (the display behavior was not known at the time of the field campaign) - there exists a gas concentration region where the instrument may be in either sensor mode. In these cases *both* corrections are applied, and the resulting data shows a corresponding increase in uncertainty. When the measurement instrument was not available for testing at METEC, the correction for all three of the available instruments was applied, which resulted in up to six estimates of actual gas flow if the gas concentration was in the transition region of all three instruments.

Parametric values for the resulting corrections are shown in Table S3-3 for CatOx mode and Table S3-4 for TCD mode. Figures S3-5 to S3-7 show the correction curves and test data. Finally, Figures S3-9 and S3-8 compare the three corrections on one plot.

Table S3-3: Corrections for BHFS in CatOx Sensor Mode

$\hat{g} = a_1 g + b_1 g\phi + c_1 g^2 \phi$
where:
$\hat{g}$ is the actual flow rate (slpm)
g is BHFS indicated flow rate (slpm)
ϕ is methane mixing ratio (-)

	CSU		**UTBlack**		**UTBlue**	
Coefficient Name	Coefficient Value	Confidence Interval	Coefficient Value	Confidence Interval	Coefficient Value	Confidence Interval
a_1	0.935	±0.041	0.747	±0.042	0.736	±0.042
b_1	0.238	±0.057	0.311	±0.064	0.127	±0.062
c_1	0.0142	±0.0042	-0.0113	±0.006	0.0118	±0.0056
R^2	1		0.99		0.99	

Table S3-4: Corrections for BHFS in TCD Sensor Mode

$\hat{g} = a_1 g + b_1 \phi + c_1 g\phi$
where:
$\hat{g}$ is the actual flow rate (slpm)
g is BHFS indicated flow rate (slpm)
ϕ is methane mixing ratio (-)

	CSU		**UTBlack**		**UTBlue**	
Coefficient Name	Coefficient Value	Confidence Interval	Coefficient Value	Confidence Interval	Coefficient Value	Confidence Interval
a_1	2.48	±0.097	1.6	±0.16	1.86	±0.16
b_1	-2.07	±1.3	-15.9	±4.1	8.46	±2.1
c_1	-1.47	±0.11	-0.637	±0.17	-1.3	±0.17
R^2	0.99		0.84		0.89	

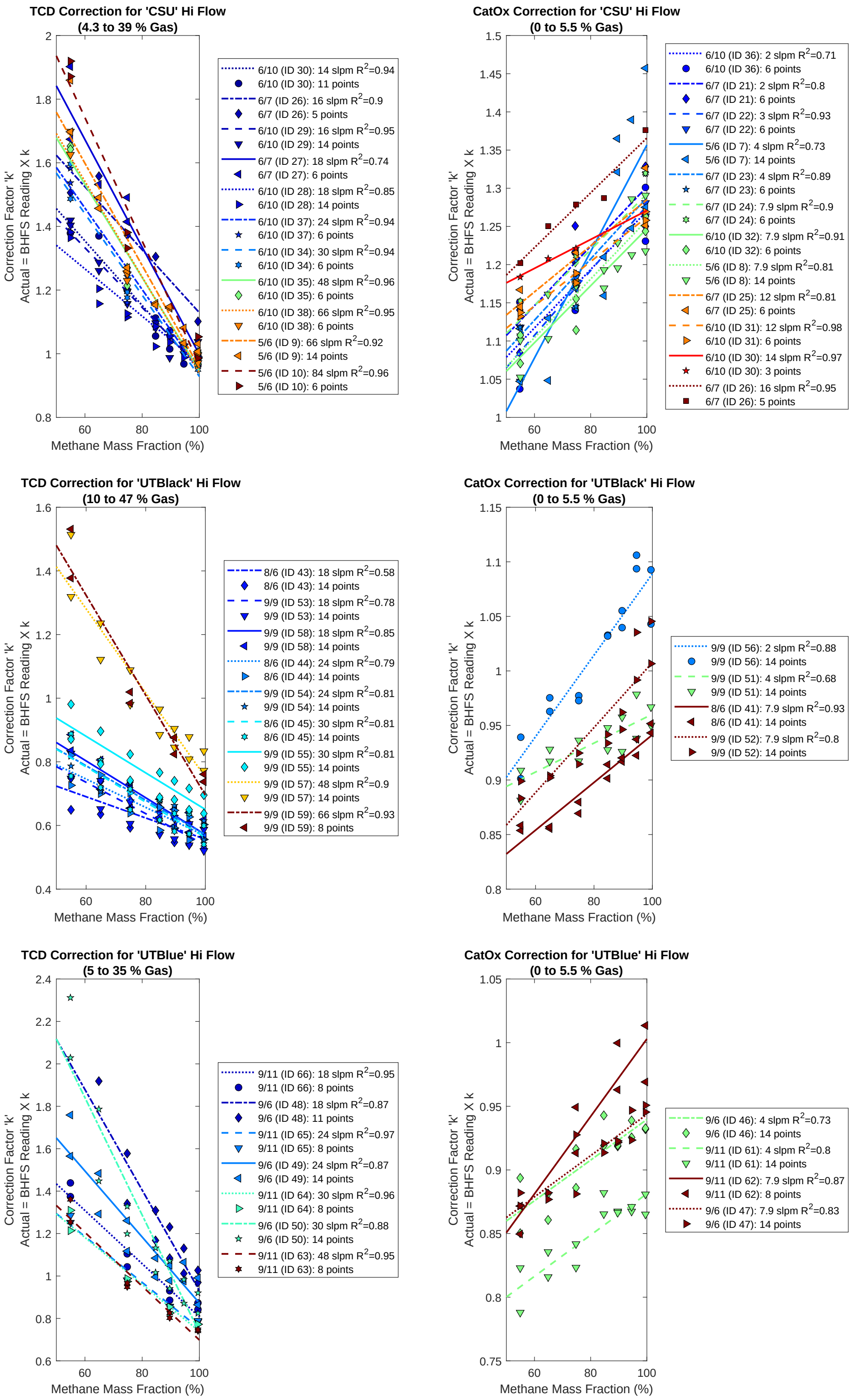

Figure S3-4: Summary of calibration data utilized to develop the gas composition and flow rate correction for the BHFS instruments. Left side of each plot includes all data for when the instrument utilized its sensor in thermal conductivity (TCD) mode; right plot provides the data when the instrument used the same sensor in catalytic oxidation (CatOx) mode.

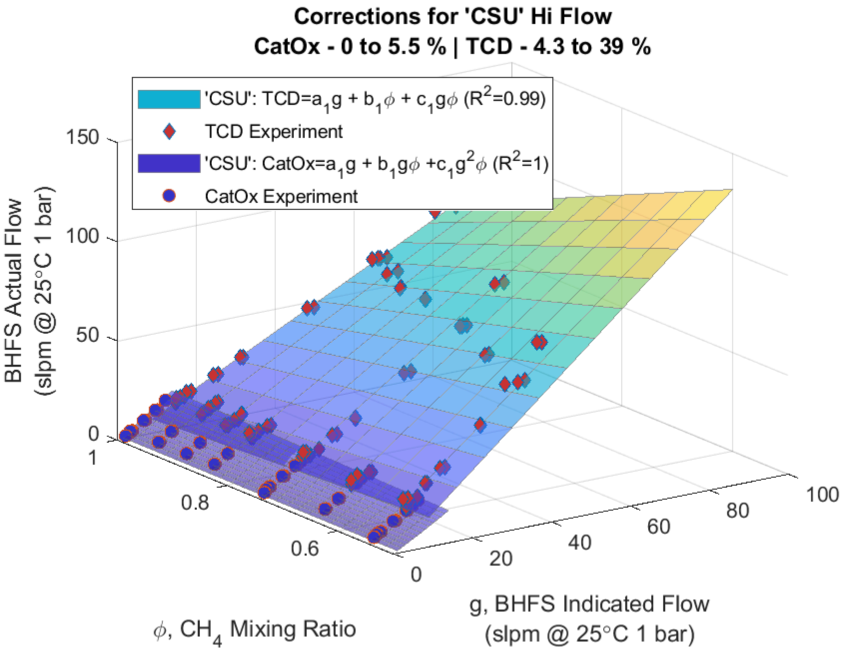

Figure S3-5: Correction surfaces for the CSU BHFS instrument. Standard conditions are 1 atm / 25°C

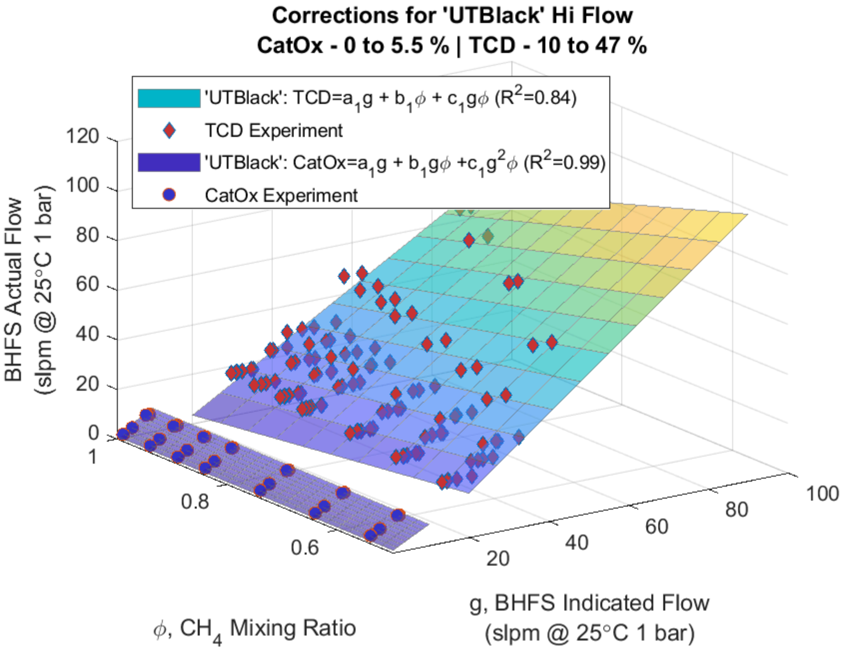

Figure S3-6: Correction for the UT Black BHFS instrument. Standard conditions are 1 atm / 25°C

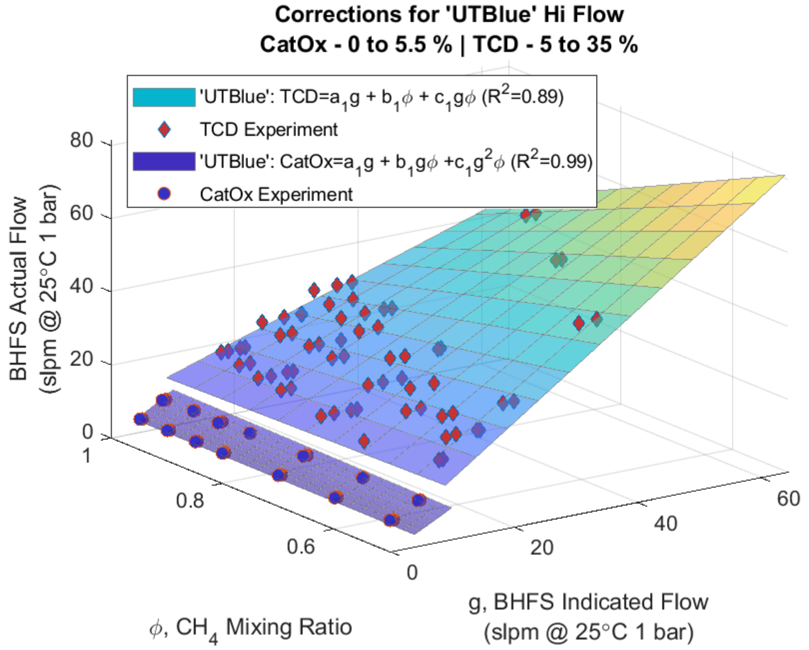

Figure S3-7: Correction for the UT Black BHFS instrument. Standard conditions are 1 atm / 25°C

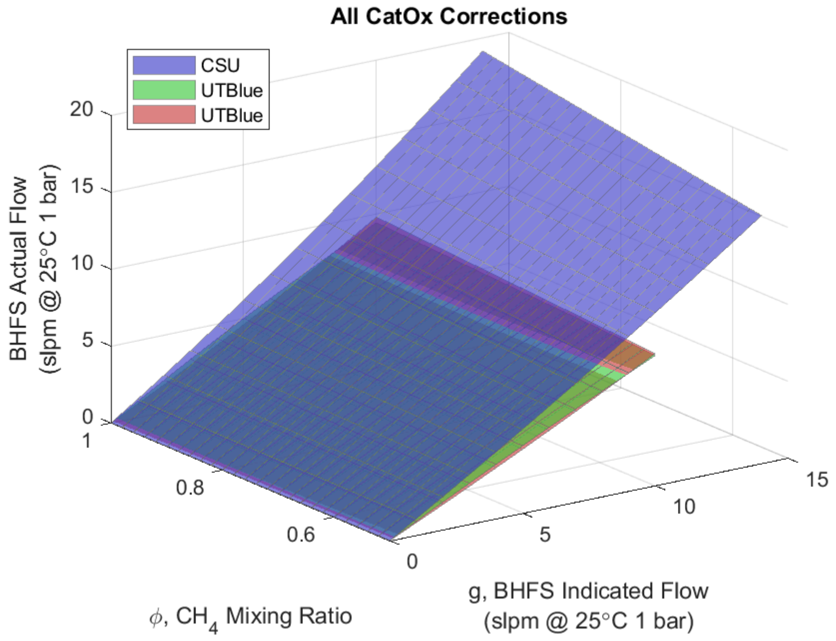

Figure S3-8: Comparison of correction curves for all three BHFS instruments operating in CatOx mode. Standard conditions are 1 atm / 25°C

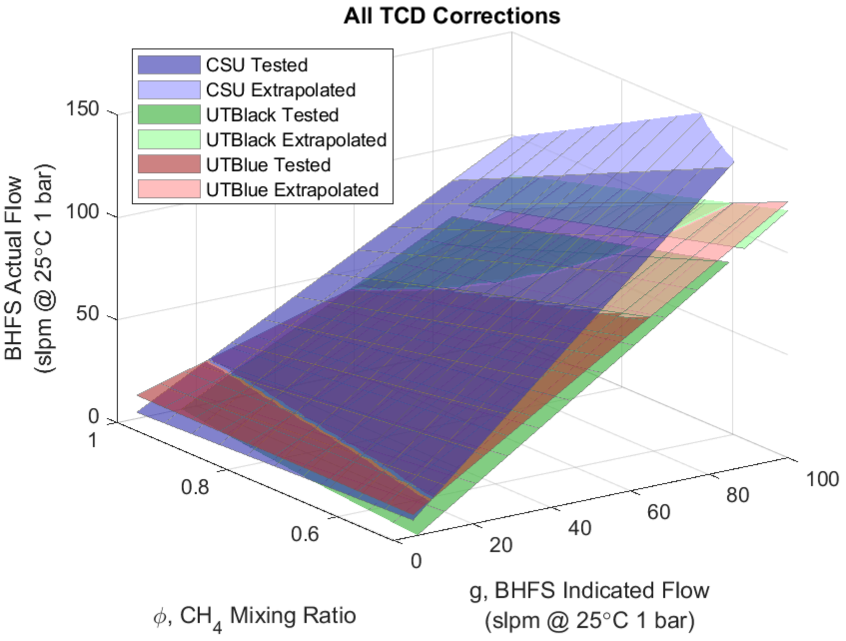

Figure S3-9: Comparison of correction curves for all three BHFS instruments operating in TCD mode. Standard conditions are 1 atm / 25°C

S3-1.4 Bag Measurements

During the field campaign, 4 measurements were made using a bag [10] when the field team judged that the emission was too large for the BHFS. Bag measurements use a $3ft^3$ bag to capture the gas while another operator times how long the emission took to fill the bag. Since few bag measurements were used, and bag measurements have not been tested for accuracy in field conditions, measurement errors were modeled using a normal distribution and a 90% confidence interval of ±20%.

S3-1.5 Measurement Data Summary

This chapter provides an overview of the measurement data categorized by the type of major equipment on which the measurement was made, and the component which was measured. Not all component types occur, or were measured, on all types of major equipment. For component emission factors, there are insufficient measurements to develop emission factors for each component type on each type of major equipment. Therefore, emission factors are divided into three major categories:

Compressor: includes components on the compressor skid and associated compressor driver, typically a natural-gas fueled engine or turbine, or an electric motor. See Table S3-5.

Tank: includes all major venting sources on atmospheric tanks; no pressurized tanks were encountered in the field campaign. To simplify the analysis, 3 measurements of minor tank components are included in the *Non-compressor* category. See Table S3-7.

Non-compressor: includes components not associated with either tanks or compressors. See Table S3-6.

The counts listed in the tables include all emissions identified, whether or not they could be successfully measured.

In addition, one measurement made on a dehydrator still vent was eliminated from the analysis, as it was the only measurement of its type. See Section S3-5 for how dehydrator vents were modeled at the station and national levels.

In general, a major equipment unit is identified by the flange or valve which connects the unit to the other equipment at the station. The *compressor* and *tank* categories consist of only one type of major equipment, compressors and tanks, respectively. The *non-compressor* category includes three major equipment types: acid gas removal units (AGRUs), dehydrators, and separators, as well as components on yard piping. Separators in this category include only those separators which are not mounted on the skid of other equipment. For example, an interstage separator on a compressor skid is included in the compressor component counts.

All remaining equipment that is not in one of the above major equipment categories is classified as *yard piping*. During the field campaign, in-line heaters were counted separately, but since only four units were encountered across all stations, these units are counted as yard piping in all subsequent analysis. Yard piping configuration varies between stations, but often includes suction and discharge headers, pig launchers and receivers, fuel gas conditioning and metering equipment, meter runs, and other miscellaneous support equipment. Yard piping accounts for 69% of non-compressor measurements.

Table S3-5: Compressor Measurement Count

	Major Equipment Type	
Component Type	**Compressor**	**Total**
Blowdown Vent	109	**109**
Common Multi-Unit Vent	23	**23**
Common Single-Unit Vent	49	**49**
Connector Flanged	48	**48**
Connector Threaded	127	**127**
Other	38	**38**
PRV	200	**200**
Pocket Vent	28	**28**
Regulator	37	**37**
Rod Packing Vent	530	**530**
Starter Vent	66	**66**
Valve	42	**42**
Total	**1297**	**1297**

Table S3-6: Non-compressor Measurement Count

	Major Equipment Type				
Component Type	**AGRU**	**Dehydrator**	**Separator**	**YardPiping**	**Total**
Common Station Vent	0	0	0	20	**20**
Connector Flanged	0	0	5	28	**33**
Connector Threaded	1	18	12	56	**87**
OEL	2	3	2	20	**27**
Other	0	4	3	17	**24**
PRV	0	44	28	93	**165**
Pump	0	0	0	15	**15**
Regulator	0	15	4	28	**47**
Valve	2	6	17	101	**126**
Total	**5**	**90**	**71**	**378**	**544**

Table S3-7: Tank Measurement Count

	Major Equipment Type	
Component Type	**Tank**	**Total**
Common Multi-Unit Vent	22	**22**
Common Single-Unit Vent	79	**79**
Thief Hatch	120	**120**
Total	**221**	**221**

S3-1.6 Measurement Quality Indicators

As part of the quality assurance procedure post-campaign, field entries were classified to indicate the quality of the measurement. Based on these classifications, emission measurements were either included in emission factors, excluded, or estimated from available information.

Emission locations which were detected using the OGI camera and measured successfully with high flow instrument or bag are marked as "Measured." All other measurement entries indicate some type of question or problem with the measurement process.

Two measurement quality indicators indicate that a measurement was attempted, but was unsuccessful. In general, these emission locations are likely to have higher emissions than other locations that were successfully measured.

Value	**Description**
Exceeded Capacity	Measurement exceeded the upper measurement capacity of the high flow instrument, including two cases: (1) OGI detected where the team attempted to measure, but emissions exceeded capacity of the high flow instrument and a bag would not work, and (2) a measurement was not attempted due to the size of the emission observed by the OGI camera operator and/or safety concerns related to measuring a larger leak. A model was developed to estimate these emissions when calculating major equipment emission factors and station emissions; see Section S3-4.2.
Incomplete capture	Field team could not achieve a sufficiently tight seal to capture all emissions with the high flow instrument. Incomplete captures were identified by observing the measurement process with an OGI camera during measurement – if the camera operator noted emissions that were not captured by the measurement instrument, the measurement was marked as incomplete in field notes. In 11 of 23 cases, the camera operator also estimated the fraction of emissions captured by the instrument. These estimates were utilized to estimate total emissions; see Section S3-2.5.

Additionally, there are five measurement quality indicators that identify cases where emissions could not be measured due to issues unrelated to the size of the emissions:

Value	**Description**
Inaccessible	Emission locations were identified as inaccessible for one of three reasons: (1) Emissions were detected with OGI, but could not be safely accessed by the measurement team; (2) Prior to the protocol change on July 26^{th} emission points that should have been measured and could have been safely measured but had no OGI detect were identified as inaccessible, and (3) one case when the OGI camera was not available for detection
Safety	Nearby equipment that was too hot to safely access or personal gas monitor alarmed near the emission location.
Cannot Measure	Measurement conditions were incompatible with the instrumentation available for reasons other than inaccessibility or safety. Examples include conditions when emissions had significant entrained oil vapor, such as a crankcase vent, or when measuring would disrupt the operation of site equipment.
Weather	Too windy to complete measurement.
Other	Includes observed emissions that were fixed before they could be measured and emissions that were not measured due to time constraints

Finally, one measurement quality indicator, *OGI non-detect*, denotes measurements made on leak sources where there was no prior OGI camera detection of emissions. Prior to July 26^{th} the protocol was to measure all compressor and station vents, tank thief hatches and vents, as well as several other components, even if the OGI screen did not detect emissions. Teams made 429 measurements in this category, resulting in 1 non-zero measurement (0.23%). Note: The non-zero measurement was a made on a compressor (Station 744, Compressor 1202).

These measurements validated that OGI was detecting measurable emissions nearly 100% of the time on these key component categories. Therefore, after July 26^{th}, OGI non-detects in these categories were not generally measured. Table S3-8 summarizes all measurements in this category. Note that some unmeasured OGI non-detects are included in the field data tables where field comments or other information were collected and deemed useful to subsequent practitioners. These measurements are summarized in Table S3-8.

Table S3-8: Measurements where no Emissions were Detected with OGI

Measurement Location	Count of OGI Detections		Fraction Non-Zero
	No Emissions Measured	Non-Zero Emissions Measured)	
Blowdown Vent	68	0	0%
Common Multi-Unit Vent	2	0	0%
Common Single-Unit Vent	39	0	0%
Common Station Vent	1	0	0%
Connector Threaded	1	0	0%
OEL	1	0	0%
PRV	199	0	0%
Pocket Vent	1	0	0%
Rod Packing Vent	56	1	1.8%
Starter Vent	32	0	0%
Thief Hatch	25	0	0%
Valve	3	0	0%
Total	428	1	0.23%

In 88 cases, or 7.8% of all emission locations, an OGI detect was followed by one or more measurement attempts that all indicated zero emissions. Two cases are possible: First, the emission rate may be below the lower detection limit of the measurement instrument. Second, the emission rate may have changed between the OGI detect and the attempted measurement. Counts of these measurements are summarized in Table S3-9. Locations where more than 10% of measurements returned zero are noted as bold text in the table.

Table S3-9: OGI Detections with Zero Measurements

Measurement Location	Total Measurements	Number of Zero Measurements	Zero Fraction
Compressor Blowdown Vent	29	2	6.9%
Compressor Common Multi-Unit Vent	**13**	**2**	**15%**
Compressor Common Single-Unit Vent	23	0	0%
Compressor Connector Flanged	39	2	5.1%
Compressor Connector Threaded	98	9	9.2%
Compressor Other	23	2	8.7%
Compressor PRV	**33**	**5**	**15%**
Compressor Pocket Vent	19	1	5.3%
Compressor Regulator	34	1	2.9%
Compressor Rod Packing Vent	352	8	2.3%
Compressor Starter Vent	**20**	**3**	**15%**
Compressor Valve	37	2	5.4%
Non-compressor Common Station Vent	6	0	0%
Non-compressor Connector Flanged	25	1	4%
Non-compressor Connector Threaded	71	6	8.5%
Non-compressor OEL	**23**	**3**	**13%**
Non-compressor Other	13	0	0%
Non-compressor PRV	**20**	**9**	**45%**
Non-compressor Pump	11	0	0%
Non-compressor Regulator	37	3	8.1%
Non-compressor Valve	**86**	**22**	**26%**
Tank Common Multi-Unit Vent	14	0	0%
Tank Common Single-Unit Vent	**42**	**5**	**12%**
Tank Thief Hatch	65	2	3.1%
Total	1133	88	7.8%

S3-1.7 Gas Types and Units

All measurement equipment quantified whole gas emission rates, which were later corrected by temperature and barometric pressure to standard conditions of 60 °F and one atmosphere and are presnted in *standard cubic feet per hour*, (scfh).

Station gas composition was utilized to estimate the methane emission rate. Since gas composition varies within a station, whole gas emission factors are recommended for vented and fugitive emissions when using leaker, average, and major equipment emission factors. For methane emissions, the conversion from scfh to mass flow units is 19.2 g/scf.

Throughout this analysis, gas types are identified by coded names:

Value	Description
WholeGas	Emission rate is in mass flow of the entire gas stream, uncorrected for composition.
CH4	Methane-only fraction of the emission rate, using the appropriate gas compositions.

S3-1.8 Comparison Emission Factors

Emission factors developed here are compared with emissions factors utilized by the Greenhouse Gas Reporting Program (GHGRP), which in turn are derived from a 1996 GRI/EPA study [11] of methane emissions in the oil and gas supply chain. The GRI/EPA focused on well sites; at the time gathering and boosting (G&B) was not considered as a separate supply chain segment. (The GRI/EPA study recognized the following supply chain segments: Onshore Production, Offshore Production, Gas Processing, Transmission, Storage, and Customer Meter Sets.)

Emission factors were developed from measurements on 12 eastern, and 13 western production (i.e. well) sites. The study surveyed 1 well site with gathering compressors in the eastern area (2 compressors), and 13 well sites with gathering compressors in the western U.S. (61 compressors). Gathering compressors hosted on well sites such as those likely visited by the measurement teams during the GRI/EPA study, are typically smaller than those surveyed in this study.

The GRI/EPA study utilized a flame ionization detector (FID) to screen for leaks (this study used OGI) and used one of two methods to quantify emissions:

1. Apply EPA's correlation equation [12] to estimate the emission rate based on concentration measured by the FID.
2. Quantify with high flow method, similar to the approach utilized in this study.

The GRI/EPA study gathered component counts by major equipment at each site visited using a method similar to this study (see Table S3-10). Average factors for the equipment sample are tabulated in Table S3-11.

To calculate national activity factors, the study estimated 129 small gathering compressors in the Eastern US, none at G&B stations (all were estimated to be at well sites, a type of compressor *not* included in this study). In the Western US, the study estimated 16,915 small gathering compressors (found on well sites), and 96 large gathering compressors on 12 large G&B stations.

Table S3-10: EPA/GRI Volume 8, Table 1:Default Average Component Counts for Major Onshore Natural Gas Production Equipment and Onshore Petroleum and Natural Gas Gathering and Boosting Equipment[1]

Major Equipment	Valves	Connectors	Open-ended Lines	Pressure Relief Valves	Compressor Seals
Eastern U.S.					
Wellheads	8	38	0.5	0	Not reported
Separators	1	6	0	0	
Meters/piping	12	45	0	0	
Gathering Compressors	12	57	0	0	
In-line heaters	14	65	2	1	
Dehydrators	24	90	2	2	
Western U.S.[2]					
Wellheads	11 (30%)	36 (20%)	1 (28%)	0	0
Separators	34 (44%)	106 (38%)	6 (94%)	2 (68%)	0
Meters/piping	14 (31%)	51 (47%)	1 (113%)	1 (150%)	0
Gathering Compressors	73 (102%)	179 (51%)	3 (50%)	4 (84%)	4 (69%)
In-line heaters	14 (49%)	65 (70%)	2 (66%)	1 (89%)	0
Dehydrators	24 (31%)	90 (37%)	2 (69%)	2 (53%)	0

[1] [13, Table 1]

[2] Values in parentheses represent the 90% confidence interval. Confidence intervals were not reported for Eastern U.S. component counts.

Table S3-11: EPA/GRI Volume 8, Table 2: Average Component Emission Factors[1]

Component Type	Total Count of Components Screened	Component Emission Factor (scfh CH_4)	Component Emission Factor (scfh whole gas)	Confidence Interval[2] (CH_4)
Eastern U.S.				
Valves	4,200	0.021	0.027	29%
Connectors	18,639	0.003	0.004	20%
Open-ended Lines	260	0.048	0.062	54%
Pressure Relief Valves	92	0.032	0.041	88%
Western U.S.				
Valves	6,059	0.095	0.122	10%
Connectors	32,513	0.013	0.017	9%
Open-ended Lines	1,051	0.025	0.032	33%
Pressure Relief Valves	448	0.152	0.195	37%
Compressor Seals	40	0.271	0.347	72%

[1] [13, Table 2].

[2] Confidence interval provided for methane emission factors but not for whole gas factors.

Comparison factors for major equipment emission factors are taken from EPG GHGRP and EPA GHGI, and are shown in Table S3-12.

Table S3-12: Comparison Factors for Major Equipment Units

	EPA GHGI 2016[1]		EPA GHGRP 2017 (East)[2]		EPA GHGRP 2017 (West)[3]	
Equipment Type	Whole Gas (scfh whole gas)	Methane (scfh CH_4)	Whole Gas (scfh whole gas)	Methane (scfh CH_4)[3]	Whole Gas (scfh whole gas)	Methane (scfh CH_4)[3]
Compressors	14.5	11.9	0.5	0.41	12.7	9.83
Dehydrators	3.41	2.80	1.1	0.91	4.87	3.69
Separators	2.84	2.33	0.05	0.04	6.49	5.01
Meters & Piping [4]	1.50	1.23	0.46	0.38	2.78	2.12
In-line Heaters	1.77	1.46	0.73	0.60	3.05	2.34

[1] GHGI emission factors are from April, 2018, Table 3.6-2 for wellpad equipment[14, Table 3.6-2].
[2] EPA GHGRP emission factors taken from *Subpart W Calculation Tool for RY16 and Later.xlsx*, sheet '(r) Population Factors-4'[15].
[3] Whole gas emission factors are converted to methane using an average methane fraction of 0.821 from GHGI Table 3.6-3.
[4] Activity data for the meters/piping emission factor is the number of meters in the facility, as per U.S. Code of Federal Regulations 98.233(r)(2)(i)(A).

Leaker emission factors computed here are also compared with measurements from a study of transmission and storage stations. Data used for comparison is the "CDFMaster.xlsx" data file from Zimmerle et. al [16], using only measurements taken from transmission stations. Comparison data is summarized in Table S3-13. For emissions from open-ended lines ("OEL"), measurements from compressor and non-compressor tables were combined into one emission factor. To convert from methane to whole gas, the paper assumes a methane mass fraction of 0.95.

Table S3-13: Whole gas leaker emission factors from transmission and storage study

Leaker Emission Factor	Sheet in T&S Data File	Measurement Count	Emission Factor (scfh Whole gas)
Compressor Connector Flanged	CC Connector	145	21.2 [0.07 to 120]
Compressor Connector Threaded	CC Connector	145	21.2 [0.07 to 120]
Compressor Valve	CC Valve	139	12.2 [0.564 to 86.8]
Compressor PRV	Other	93	22.6 [0.585 to 298]
Non-compressor PRV	Other	93	22.6 [0.585 to 298]
All Other	Other	93	22.6 [0.585 to 298]
Non-compressor Connector Flanged	NC Connector	218	9.87 [0.0616 to 58.4]
Non-compressor Valve	NC Valve	134	12 [0 to 56.3]
Non-compressor Connector Threaded	NC Valve	134	12 [0 to 56.3]
Compressor Rod Packing Vent	RecipRodPack_OP	34	219 [0 to 1.81×10^3]
Compressor Blowdown Vent	BD_ALL	379	76.4 [0 to 494]
All OEL	CC OEL and NC OEL	153	143 [0 to 1.71×10^3]

[1] Activity factor from GHGRP for eastern and western regions.

S3-2 Component Leaker Emission Factors

Leaker emission factors for component categories, represent the distribution of emission rates expected from a source category when emissions are detected during an OGI screen or using a similar screening method. In general, leaker factors are utilized by screening equipment with a leak detection method, and each detected leak is estimated using the appropriate leaker emission factor.

For some component categories, choices must be made on how to group measurements into emission factors. Sections S3-2.1-S3-2.3 discuss key categories where grouping decisions were made. To compare sub-categories of an emission factor, we utilized 2-sample Kolmogrov-Smirnov test (MatLab `kstest2()`) with a statistical significance of 0.95 to detect differences between sub-categories of emissions. For example, one might test whether a valve has the same leak rate on dehydrators as in yard piping.

S3-2.1 Tank Vent Emission Factor Categories

This section describes the development of emissions factors for atmospheric tanks. For the 180 stations in the field campaign, 168 stations had one or more atmospheric-pressure tanks on the station. A total of 403 atmospheric tanks were identified in the field campaign, and 251 were screened and measured. The remaining 12 stations had no tanks.

Measurements were made on two tank locations – thief hatches and other vents (commonly called *Enardo* valves, a type of pressure relief valve or “PRV”). In some cases, measurements were taken on vents attached to a common header across multiple tanks.

This study identifies three source locations for tank emissions:

Thief Hatch: Large access port, typically on the top of the tank. Most thief hatches are equipped with a hatch cover that will open if pressure in the tank exceeds a preset limit. On some tanks, thief hatch may indicate an open hole in the top of the tank with no cover. The number of thief hatches per tank was not counted during the field campaign. Although it is common to have only one thief hatch per tank, 4 tanks measured in the field campaign had more than one measurement per tank, indicating the presence of more than one thief hatch.

Common Single-Unit Vent: A vent location, likely equipped with one or more pressure relief valves, that combines one or more openings in the tank, typically not including the thief hatch. While vent configurations vary widely, it is not unusual that multiple ports or vents in a tank will be combined into a header and routed to atmosphere through a single open-ended line. Common single-tank vents were not counted during the field campaign. However, tanks typically have ports in addition to a thief hatch, and it is reasonable to assume at least one single-tank vent per tank, although some may be plumbed together with vents from other tanks into a common multi-tank vent.

Common Multi-Unit Vent: A vent location that combines vents from multiple tanks into a single emission location. Vent locations are similar to those in the common single-unit vent. Common multi-tank vents were not counted during the field campaign, and the number of such vents and the ports connected to each is difficult to estimate.

Due to their configuration, safely accessing tank emission locations may be difficult if significant emissions are present. During the field campaign, 85 measurements were attempted, and 68 attempts resulted in successful measurements (80%). Of the 50 measurements of common single-tank vents attempted, 84% were successful. As with other sources, successful measurements are utilized in emission factors and estimates are utilized where sources were identified but could not be measured.

Comparing emission sources from individual tanks, both thief hatches and common single tank vents exhibit a similar emission distribution. However, since the activity data for each location is different, and since sufficient data exists for two strong emission factors, both leaker emission factors are provided. Multi-tank vents are significantly larger than single tank vents, warranting separate emission factors. Unfortunately, the number of measurements for multi-tank vents is small, leading to increased uncertainty for that emission factor.

S3-2.2 Compressor Vent Categories and Operating Modes

This section considers how to group emissions measurements for compressors into emission factors, considering the operating state of the compressor, the type of compressor, and the type of compressor driver. In particular, it considers whether separate emission factors are needed – and can be provided – for different operating modes.

Figure S3-10 provides a visual depiction of the common compressor sources on a cutaway view of a single compressor cylinder, and defines principal components of the cylinder. The handling of rod packing vents (RPVs) varies between compressor installations. In some installations, RPVs are connected to a single header and routed to a vent location. In others, RPVs are vented individually at the compressor or through short lengths of tubing. Since emissions from the dog house originate with emissions through rod packing, emissions from dog house vents are included in rod packing emissions. The pocket, and associated pocket vent, sets the compression ratio of the compressor cylinder. While rod packing is designed to emit in regular operation, the pocket vent should not have emissions during normal operation.

Compressors may be in three operating states or *modes*:

Abbreviation	**Description**
NOP	Pressurized but not operating (“not operating pressurized”)
NOD	Depressurized and not operating (“not operating depressurized”)
OP	Pressurized and operating (“operating”)

Similarly to other measurement campaigns [17, 18], most compressors were operating when measured during this field campaign. During the campaign, field teams screened 465 compressors utilizing OGI and measured 454 compressors, some of which had no OGI detect and no emissions measured. OGI detect occurred on 319 compressor units and was measured using high-flow or bag methods. Of the measured compressors, 83% of the compressors were operating at the time of measurement, and 87% of compressor-related measurements were made while the compresor was operating. (See Tables S3-14 and S3-15)

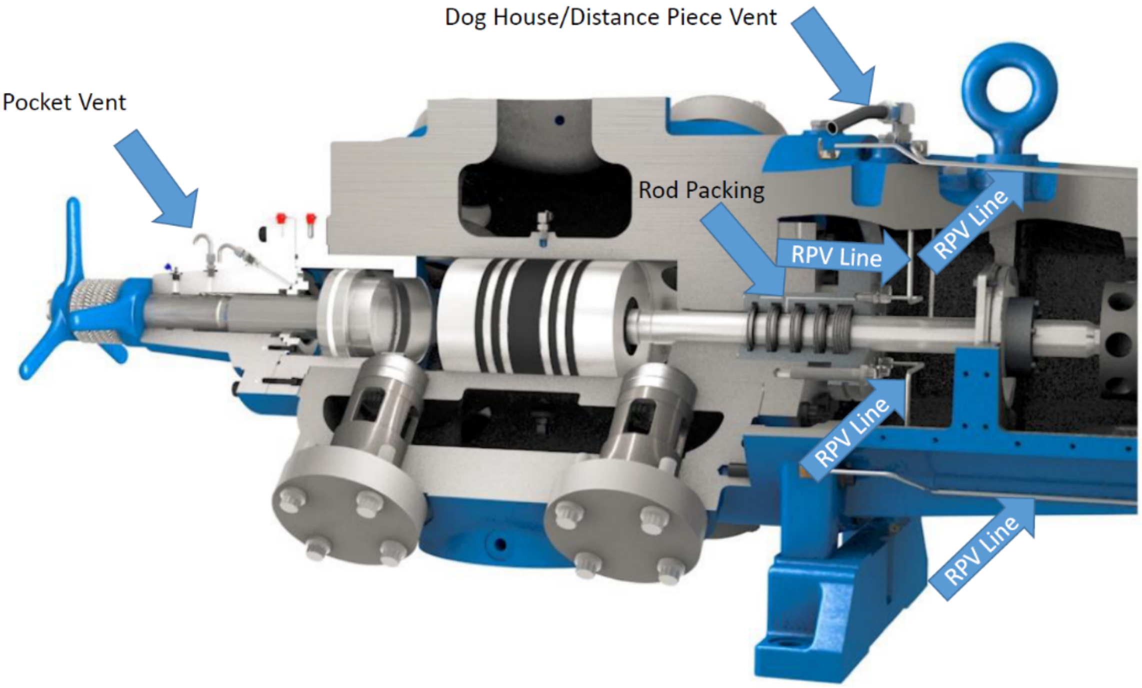

Figure S3-10: Components of compressor cylinder. RPV refers to *rod packing vent*, the vent location for gas which is emitted through the *rod packing seal.* When operating, rod packing vents are expected to emit some gas. The *dog house*, or *distance piece*, contains the straight section of the cylinder rod between the rod packing housing and the crank case of the compressor (not shown). For this study, emissions from dog house vents are considered to rod packing emissions, as the gas has passed through the rod packing and into the dog house area. The pocket vent allows gas to be pushed out of the cylinder when adjusting the compression ratio of the cylinder; in normal operation the pocket vent should not emit any gas.

Image: https://www.arielcorp.com/Technical-Papers/Compressor-Emissions-Reduction-Technology/

Table S3-14: Compressor Operating Mode Summary for Measured Compressors

	Operating Mode				
Compressor Type	**NOD**	**NOP**	**OP**	**Total**	**Fraction**
Centrifugal	5	2	7	**14**	*3.1%*
Reciprocating	31	36	336	**403**	*89%*
Screw	2	0	35	**37**	*8.1%*
Total	**38**	**38**	**378**	**454**	*100%*
Fraction	*8.4%*	*8.4%*	*83%*	*100%*	

Table S3-15: Count of Measurements Made on Compressors, by Operating Mode

	Operating Mode					
Measurement Type	**NA**	**NOD**	**NOP**	**OP**	**Total**	**Fraction**
Component	0	5	17	264	**286**	*36%*
Vent	41	14	27	431	**513**	*64%*
Total	**41**	**19**	**44**	**695**	**799**	*100%*
Fraction	*5.1%*	*2.4%*	*5.5%*	*87%*	*100%*	

Due to the small number of both units and measurements in NOD and NOP modes, all emission factors are calculated utilizing all measurements in all modes to create emission factors which are not mode-specific. This method effectively combines all operating modes into one emission factor, which is representative of aggregate emissions, provided it is applied to fleets of gathering compressors which have similar, high, utilization rates, as the rates seen in this study.

Notwithstanding the above, it should be noted that for sources where some emission measurements were made in NOP and NOD modes, significant differences were seen relative to operating mode measurements. Examples are provided in Tables S3-16 and S3-17 for two common compressor vents. Therefore, if future data suggests a change in compressor utilization patterns, additional measurements should be made in those NOD and NOP modes to develop separate emission factors. (*KS Test* in the table indicates results of a *Kolmogrov-Smirnoff 2-sided test of similarity*, at the 95% confidence level.)

Table S3-16: Measurement Comparison by Operating Mode for Blowdown Vent

Category	Sub-Category	Count	KS Test	Min	Mean	Max	Mean Ratio	Bootstrap CI
Blowdown Vent		30		0.136	10.8	103		0.14 to 82.76
Blowdown Vent	NOD	3	Passed	3.75	41.4	103	3.81	3.75 to 102.85
Blowdown Vent	NOP	7	Passed	0.166	6.77	22.5	0.62	0.17 to 22.47
Blowdown Vent	OP	20	Passed	0.136	7.7	22.3	0.71	0.14 to 22.26

Table S3-17: Measurement Comparison by Operating Mode for Rod Packing Vent

Category	Sub-Category	Count	KS Test	Min	Mean	Max	Mean Ratio	Bootstrap CI
Rod Packing Vent		393		0.111	23.6	717		0.14 to 163.99
Rod Packing Vent	NOD	7	Passed	4.21	11.5	21.3	0.49	4.21 to 21.28
Rod Packing Vent	NOP	17	Passed	0.115	23.1	113	0.98	0.12 to 113.20
Rod Packing Vent	OP	369	Passed	0.111	23.9	717	1.01	0.14 to 167.94

As shown in Table S3-18, 89% of compressors are of the reciprocating type, followed by screw compressors (8.1%) and a small number of centrifugal compressors (3.1%). 93% of reciprocating compressors are driven by reciprocating engines, typically 4-stroke lean- or rich-burn engines, as shown in Table S3-19. Other compressor types are more often driven by electric or turbine drives. As with the operating mode, few measurements were made on centrifugal or screw compressors (about 4.1%). Therefore, only one emission factor is developed, including all compressor types, and – as with the discussion on operating mode – the result should be applicable provided the mix of compressors does not change substantially from the mix seen in this study.

Table S3-18: Compressor Driver Type by Compressor Type for Measured Compressors

	Compressor Type				
Compressor Driver	**Centrifugal**	**Reciprocating**	**Screw**	**Total**	**Fraction**
Electric Motor	0	1	12	**13**	*2.9%*
Reciprocating Engine	6	402	25	**433**	*95%*
Turbine	8	0	0	**8**	*1.8%*
Total	**14**	**403**	**37**	**454**	*100%*
Fraction	*3.1%*	*89%*	*8.1%*	*100%*	

Compressor are equipped with several vent locations designed to emit gas during certain compressor operations. For example, a blowdown vent is utilized to depressurize a compressor, typically to release pressurized gas in the compressor to atmosphere. When not being utilized to depressurize

Table S3-19: Compressor Driver Type Summary for Measured Compressors

	Operating Mode				
Compressor Driver	**NOD**	**NOP**	**OP**	**Total**	**Fraction**
4-Stroke Lean Burn	18	22	260	**300**	*66%*
4-Stroke Rich Burn	17	15	101	**133**	*29%*
Electric Motor	0	0	13	**13**	*2.9%*
Turbine	3	1	4	**8**	*1.8%*
Total	**38**	**38**	**378**	**454**	*100%*
Fraction	*8.4%*	*8.4%*	*83%*	*100%*	

a compressor, a blowdown vent should emit no gas and any observed emissions are due to leakage through the blowdown valve. In this study emissions blowdown vents, starter vents and pocket vents were not measured during defined venting operations. Therefore emissions reported from these three categories in this study are leaks.

In contrast, when the compressor is operating, rod packing seals are designed to emit some gas, and any observed emissions are technically *venting*, i.e. planned emissions, although on some compressors, rod packing may be emitting more than the manufacturer's specifications. When the compressor is not operating (NOP or NOD modes), emissions should be zero, and any measured emissions are considered leaks.

Comparing the four compressor vent locations encountered during the field study, we find that a separate emission factor is required for each vent location, but insufficient data exists to split emission factors by *both* vent type and operating mode. Therefore separate emission factors are developed for each vent location.

S3-2.3 Component Categories for Flanged and Threaded Connectors

During the field campaign, connectors were classified as flanged or threaded connectors. The comparisons of leaker emission factors (whole gas), below, indicates that all connectors on compressor equipment have statistically similar emissions (Figure S3-11), while connectors on non-compressor equipment have statistically different emissions (Figure S3-12). No explanation of this behavior is available. For consistency, emission factors are separated by connector type for both compressor and non-compressor equipment.

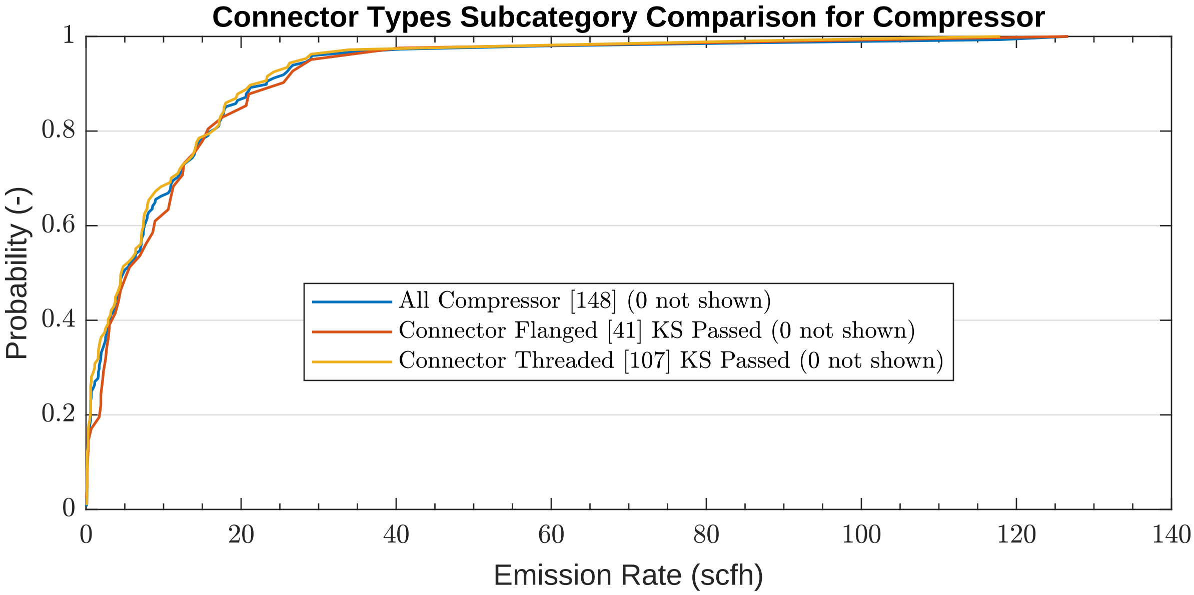

Figure S3-11: Connector Types Subcategory Comparison for Compressor

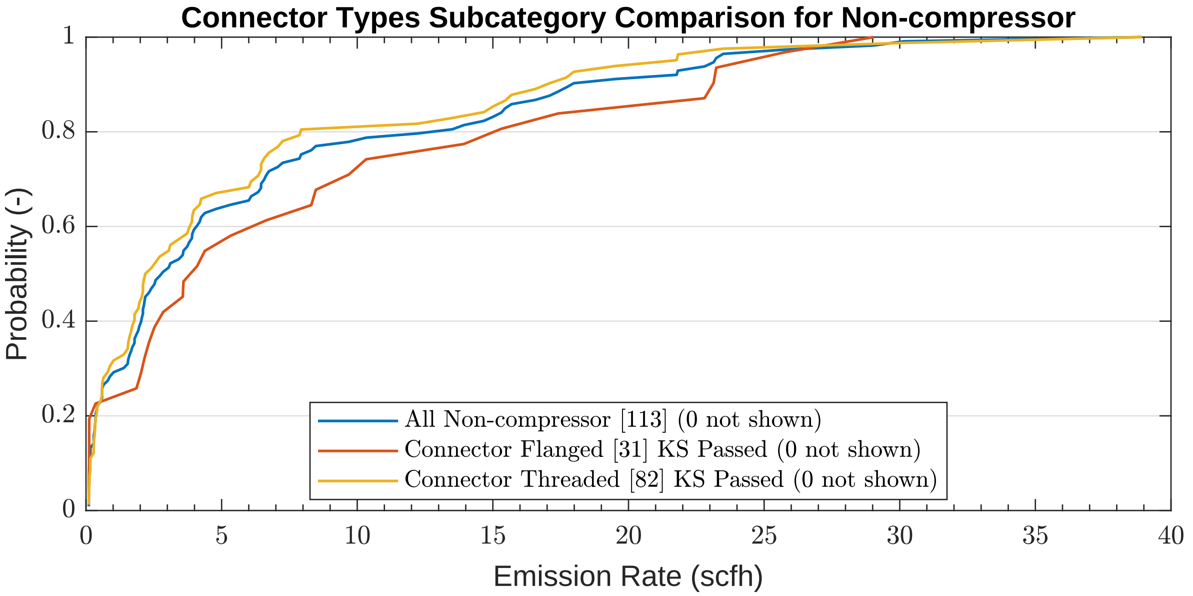

Figure S3-12: Connector Types Subcategory Comparison for Non-compressor

S3-2.4 Use of Measurement Quality Indicators in Leaker Emission Factors

Table S3-20 summarizes the use of measurement quality indicators in development of leaker emission factors. Measurement quality indicators which were not included in leaker emission factors were excluded for one or both of two factors: First, insufficient information existed to estimate emissions for any given emission point. Second, for these categories, there is no indication that the unmeasured emissions were unrepresented by measurements that *were* completed – i.e. there is no evidence they were systematically higher or lower than other successful measurements. In practice, detected emissions which were successfully measured (measurement quality indicator of "Measured") and measurement attempts with "Incomplete Capture" were included in the leaker emission factors.

Table S3-20: Measurement Quality Indicators For Leaker Factors

Measurement Quality Indicator	Included in Leaker Emission Factor	Measurement Made (possibly incomplete)[3]	Estimated Emissions Included in Leaker Emission Factor
Measured	✓	✓	✗
Incomplete Capture	✓	✓[1]	✓
Exceeded Capacity	✗	✗	✗[4]
Inaccessible	✗	✗	✗
Safety	✗	✗	✗
Cannot Measure	✗	✗	✗
Weather	✗	✗	✗
Other	✗	✗	✗
OGI Non-detect[2]	N/A	N/A	N/A
Multi-component vents	✓[5]	✓	✗

[1] Field teams estimated the fraction of emissions captured in 11 of 23 measurements. Mean fraction estimated, and range of estimates, is 56% [30% to 90%].

[2] Some measurements of vents were made prior to July 26th for vents with no OGI emissions detection. These measurements are not included in leaker factors since leaker factors are only applicable for emission points with OGI detections.

[3] Incomplete measurements are classified as *Incomplete Capture*. See description in text.

[4] *Exceeded Capacity* measurements are included in major equipment emission factors but not in leaker or population emission factors.

[5] Separate emission factors are developed for multi-component emission locations, seperate from single-component emission locations.

In a few cases, attempts to measure emissions exceeded the capacity of the measurement equipment. Including these large emitters in leaker emission factors tends to distort individual factors. For example, one "Exceeded Capacity" measurement occurred on compressor flanged connectors but zero on compressor threaded connectors, while for non-compressor connectors, it situation was reversed. Therefore, all "Exceeded Capacity" measurements are excluded from leaker emission factors but are included in emission factors for major equipment (Section S3-4).

S3-2.5 Estimation of “Incomplete Capture” Measurements

For “Incomplete Capture”, emissions are estimated from the measured value divided by the fraction captured when noted by the observer with an OGI camera who watched the measurement. Where field notes do not indicate a fraction captured, the fraction is estimated using boostrap methods from the distribution of all such estimates made during the field campaign. A histogram of these estimates is shown in Figure S3-13. The mean value of these estimates is 56% [41% to 73%] indicating that, on average, actual emissions were approximately twice the measured value. The impact of this adjustment is tabulated in Table S3-21. All measurement records for incomplete capture as summarized in data table *D7 IncompleteCaptures*.

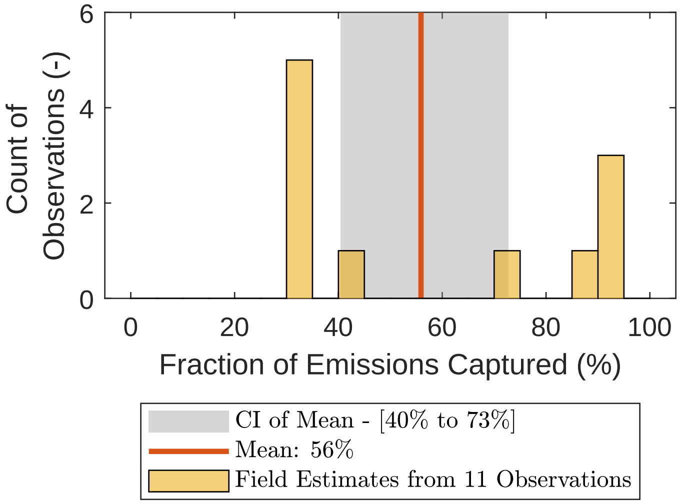

Figure S3-13: Estimated Fraction of Emissions Captured For Incomplete Capture

Table S3-21: Impact of Incomplete Capture Adjustment on Leaker Emission Factors

Category[1]	Without Adjustments	With Adjustments	Relative Difference In Mean
Compressor Blowdown Vent	10.8	21.1	95% [38% to 228%]
Station Common Station Vent	53	85.3	62% [41% to 104%]
All Pump	23.3	35.5	51% [21% to 101%]
Tank Common Single-Unit Vent	32.6	48.3	49% [26% to 101%]
Compressor Connector Threaded	9.83	14.6	49% [30% to 83%]
Compressor PRV	16.2	21.3	31% [14% to 75%]
Compressor Rod Packing Vent	23.8	28	18% [11% to 41%]
Compressor Valve	37.4	41.2	10% [6.2% to 18%]
All Other	23.2	24.1	3.3% [3.1% to 3.7%]
Compressor Connector Flanged	11.9	12.2	2.4% [1.9% to 3%]
Non-compressor Connector Flanged	8.07	7.9	-1.9% [-2.2% to -1.6%]

[1] Categories with more than 1% change shown

S3-2.6 Leaker Emission Factor Tables

Table S3-23 compares emission factors developed here to GHGRP emission factors and to similar emission factors for transmission [16] for those categories that have comparable emission factors. Abbreviations used in the table are:

- *Comp* - indicates emission factors for component in compressor service.
- *NC* - indicates non-compressor service.
- *Reg.* - abbreviates “regulator”.
- *Conn.* - abbreviates “connector”.

The complete set of leaker emission factors for whole gas are summarized in Table S3-24 and data table *D21 Leaker Whole Gas EF*. Component categories where there were less than 15 measurements are indicated by italics in the tables, and should be utilized with caution. Appendix B contains detailed plots and activity data tables for all leaker emission factors.

In addition to the component categories in the tables, no leaks were detected on 2 component categories, although a substantial number of components in each category were counted during the field campaign. No emission factors are possible for this set of components, although screening results indicate emissions are lower than other categories with detected and measured emissions. A summary of the component counts are in Table S3-22. Note that a full list of component counts, by major equipment type, is included in the *DataTable.xlsx*.

Table S3-22: Component Categories with No OGI Detections or Measurements

Component Category	Number of Components Counted
Gauge	1859
Meter	618

Table S3-23: Component Leaker Factor Comparison

Component[1]	Emission Factor (scfh whole gas)	GHGRP[2] Emission Factor	Ratio Study to GHGRP	Transmission[3] Emission Factor	Ratio Study to Transmission
All OEL	5.58 [+67%/-51%]	2.8	1.99	143 [+1093%/-100%]	0.044 [0.016 to 0.1]
All Other	24 [+67%/-49%]			22.6 [+1218%/-97%]	1.1 [0.43 to 2.5]
Comp Blowdown Vent	21.3 [+150%/-70%]			76.4 [+546%/-100%]	0.15 [0.066 to 0.28]
Comp Conn. Flange	12.2 [+57%/-40%]	4.1	2.98	21.2 [+465%/-100%]	0.77 [0.21 to 2]
NC Conn. Flange	7.88 [+42%/-36%]	4.1	1.92	9.87 [+491%/-99%]	0.84 [0.47 to 1.4]
Comp Conn. Thread	14.5 [+52%/-38%]	1.3	11.2	21.2 [+465%/-100%]	0.64 [0.19 to 1.5]
NC Conn. Thread	5.77 [+31%/-28%]	1.3	4.44	12 [+368%/-100%]	0.5 [0.29 to 0.78]
Comp PRV	21.2 [+82%/-57%]	4.5	4.71	22.6 [+1218%/-97%]	0.8 [0.29 to 1.8]
NC PRV	10.8 [+123%/-80%]	4.5	2.41	22.6 [+1218%/-97%]	0.53 [0.092 to 1.4]
Comp Reg.	13.9 [+38%/-32%]	4.5	3.09		
NC Reg.	8.01 [+33%/-30%]	4.5	1.78		
Comp Rod Packing Vent	28.2 [+37%/-24%]			219 [+728%/-100%]	0.12 [0.059 to 0.23]
Comp Valve	41.1 [+109%/-64%]	4.9	8.39	12.2 [+613%/-95%]	3.3 [0.91 to 8.2]
NC Valve	7.89 [+46%/-37%]	4.9	1.61	12 [+368%/-100%]	0.68 [0.38 to 1.1]

[1] Abbreviations: "Comp" = Compressor service; "NC" = non-compressor service; "Conn." = connector; "Reg." = regulator.

[2] [**?**, Table W-1E]

[3] [16, Data File CDFMaster.xlsx]

Table S3-24: Whole Gas Leaker Emission Factors

Component	Number Measured	Number Simulated	Emission Factor (scfh whole gas)	Confidence Interval (scfh whole gas)	Fraction of Emissions Due to Largest 5% of Emitters
Non-compressor service					
Connector Flanged	31	1	7.88	[+42%/-36%]	18%
Connector Threaded	82	0	5.77	[+31%/-28%]	25%
PRV	23	0	10.8	[+123%/-80%]	54%
Regulator	43	0	8.01	[+33%/-30%]	18%
Valve	99	0	7.89	[+46%/-37%]	38%
Compressor service					
Connector Flanged	41	1	12.2	[+57%/-40%]	33%
Connector Threaded	107	5	14.5	[+52%/-38%]	47%
PRV	35	1	21.2	[+82%/-57%]	43%
Regulator	37	0	13.9	[+38%/-32%]	21%
Valve	39	1	41.1	[+109%/-64%]	58%
Common Multi-Unit Vent	13	0	66	[+86%/-71%]	
Common Single-Unit Vent	23	0	76	[+52%/-45%]	20%
Blowdown Vent	30	1	21.3	[+150%/-70%]	59%
Pocket Vent	23	0	7.81	[+80%/-61%]	34%
Rod Packing Vent	390	7	28.2	[+37%/-24%]	46%
Starter Vent	21	0	296	[+193%/-96%]	86%
Rod Packing Vent (OP)	366	7	28.5	[+35%/-24%]	47%
Rod Packing Vent (NOP)	17	0	23	[+65%/-49%]	
Rod Packing Vent (NOD)	7	0	11.5	[+42%/-37%]	
Tank service					
Common Multi-Unit Vent	15	0	119	[+90%/-68%]	
Common Single-Unit Vent	42	2	48.4	[+86%/-58%]	45%
Thief Hatch	65	0	30.1	[+54%/-41%]	41%
Other					
OEL	23	0	5.58	[+67%/-51%]	31%
Other	42	1	24	[+67%/-49%]	44%
Pump	12	2	35.5	[+74%/-53%]	

S3-3 Component Average Activity and Emission Factors

Average emission factors (also known as *population* emission factors) provide distributions of emissions for a population of components. Average factors are typically utilized by counting all components within a population and multiplying the count of components with the appropriate emission factor. Unlike leaker factors, Section S3-2, no screening for leaks is required.

S3-3.1 Methodology for Average Emission Factors

This section describes the methods utilized to develop average emission factors. The same calculation method is also utilized to develop major equipment emission factors, Section S3-4.

During the field campaign, major equipment units (Table S3-25) were screened utilizing optical gas imaging (OGI). Average emission factors are calculated by (1) adding estimates or measurements for all detected emissions, (2) estimating the total number of components screened – the *activity basis* for the emission factor, and (3) dividing the emissions estimate by the activity estimate. The emission estimate must include an estimate for all detected emissions, and the activity estimate must include an estimate for all components screened.

Components were counted on a subset of major equipment. Considering one component category c there is a set $\{n_{c,e}\}$ containing $N_{c,e}$ units of major equipment of type e for which components were counted, producing a distribution of component counts for that type of major equipment, $D_{c,e}$, where each element of the distribution is the count on one piece of major equipment.

Table S3-25: Major Equipment Types

Type	Total	OGI Screen	Measured
AGRU	14	8	8
Compressor	541	465	435
Dehydrator	154	132	123
Separator	372	336	326
Tank	403	339	251
YardPiping	876	815	805

There is a also a set $\{m_{c,e}\}$ containing $M_{c,e}$ units of major equipment which were screened and measured. These units may or may not have been subjected to component counts. Any OGI detections on the screened units are noted, producing a set of $\{E_{c,e}\}$ emission detections. As per the discussion of quality indicators (Section S3-1.6), some, but not all detections were successfully measured. For population (and major equipment) emission factors, we estimate all detected but unmeasured emissions except for the large emitter quality indicator, as described in Section S3-3.2. Therefore $\{E\}$ has a non-zero estimate for all detected emissions. Other screened components, where there was no OGI detect, are assumed to have zero emissions, following common practice for development of population emission factors.

To develop an component count estimate for emission factor f_c, we cycle through the $\{m_{c,e}\}$ pieces of major equipment which were screened and measured for the emission factor and estimate a component count for each. Since not all measured equipment was counted, this includes two terms – actual component counts when available, ($\{\hat{n}_{c,e}\} = \{m_{c,e}\} \cap_e \{n_{c,e}\}$), and estimated component counts when not available. The component count estimate is:

$$D_c^{(j)} = \sum_{e\in f}\left[\sum_{e\in\{\hat{n}_{c,e}\}} D_{c,e} + \sum_{i=\hat{N}_{c,e}+1}^{M_{c,e}} \mathrm{draw}(D_{c,e})\right] : j = 1..N_j \tag{1}$$

where the operator draw(d) draws a sample from distribution d. The sampling operation is completed N_j times to develop a distribution of component counts, $D_c = \{D_c^{(j)} : j = 1...N_j\}$. For this analysis $N_j = 5000$. Distribution D_c represents a component count estimate for all equipment which was screened for component type c and therefore is the total component population for f_c.

Total emissions associated with these components can also be summed, using the same uncertainty models as described for leaker emissions factors in Section S3-2.4:

$$E_c^{(j)} = \sum_{e\in f}\sum_{e\in\{E_{c,e}\}} E_{c,e} : j = 1..N_j \tag{2}$$

where replicates $1..N_j$ account for measurement and estimation uncertainty.

Finally, the emission factor distribution for the component f_c is:

$$f_c^j = \frac{E_c^{(j)}}{D_c^{(j)}} : j = 1..N_j \tag{3}$$

S3-3.2 Estimation of Detected but Unmeasured Emissions

Average emission factors must include estimates for all detected emissions, since component counts are included for all screened and measured units. Table S3-26 summarizes how each measurement quality indicator was incorporated into simulated emissions. Additional notes:

- When incorporating a measurement into the emission factor, either a completed measurement (column 2 in table) or drawing from a leaker emission factor (column 3 in table), measurement uncertainty is also applied to the emission rate.
- If an "Exceeded Capacity" indicator is encountered on a unit of major equipment, that unit is not included in average emission factor calculation. This guarantees that all detected emissions are included in the average emission factor calculation.
- For the two tank emission categories (thief hatches and common single-unit-vents) and one compressor emission category (common single-unit vents), activity counts were not completed during the field campaign. For these emission factors we assume there is one hatch or vent per unit (tank or compressor). This assumption reduces the component count, and increases the emission factor, in these categories.

  For example, of 251 tanks screened and measured in the field campaign, 81 had thief hatch emissions and 4 of those tanks had emissions reported on more than one thief hatch. Assuming the frequency of multiple measurements is approximately equal to the frequency of multiple thief hatches in the total population, the assumption of one thief hatch per tank increases the average emission factor by 4.9%. Using the same analysis, the assumption increases the tank and compressor single unit vent average emission factor by 14% and 3.1%, respectively.

Table S3-26: Measurement Quality Indicator For Average Emission Factors

Measurement Quality Indicator	Measurement Included in Factor	Estimated from Leaker Emission Factor for Component[1]	Estimated using Alternative Algorithm
Measured	✓		
Incomplete Capture			✓[2]
Exceeded Capacity			✖[3]
Inaccessible		✓	
Safety		✓	
Cannot Measure		✓	
Weather		✓	
Other		✓	
OGI Non-detect			✓[4]
Single-unit vents			✖[5]
Multi-unit vents			✖[5]

[1] Estimate made by identifying the component type for each identified emission source, and then drawing an emission rate from the leaker emissions distribution for that component type.

[2] *Incomplete Capture* emissions are included in average factors using same algorithm as utilized for leaker factors.

[3] Emissions for *Exceeded Capacity* are not included in average emission factors, but are included in major equipment emission factors.

[4] OGI non-detects are included, as are other non-detects, as "no detected emissions" when calculating average emission factors.

[5] Single-unit vents, which combine emissions from multiple components, and multi-unit vents, which combine emissions from multiple equipment units, are not included in average emission factors, but are included in major equipment emission factors and station estimates.

S3-3.3 Average Emission Factor Results

Table S3-27 summarizes the population (average) emission factors. Columns in the tables are:

Column Header	**Description**
Category	Emission factor category name.
Activity Basis	Which components were counted to create the average emission factor.
Mean Population	The mean number of units which were screened with OGI during the field had they been emitting.
Emission Factor	Mean value of the emission factor (scfh)
Confidence Interval	Empirical 95% confidence interval taken from the replicates in Eqn. 3 without bootstrapping
GHGRP East & West	Where possible, data is compared with emission factors from the *GHGRP*. For average factors, GHGRP provides seperate factors for the eastern and western USA, see Section S3-1.8.

Activity factors for all component and major equipment categories are given the data file *D12 Components Per Unit*. Data for emission factors are in the data file *D22 Average Whole Gas EF*. The additional data file *AvgFactor.xlsx* contains detailed data for all average factors, in the form of histograms of the simulated results.

Since many of the average factor distributions are highly skewed, detailed distributions for whole gas average factors are provided in the accompanying data files *AvgFactors.xlsx*.

Table S3-27: Whole Gas Average Emission Factors

Component	Activity Basis	Mean Population	Emission Factor (scfh WholeGas)	Confidence Interval (scfh WholeGas)
Non-compressor service				
Connector Flanged	Counted Components	12,290	0.0213	[+17%/-14%]
Connector Threaded	Counted Components	38,696	0.0127	[+12%/-11%]
PRV	Counted Components	1,067	0.279	[+50%/-22%]
Regulator	Counted Components	608	0.626	[+23%/-19%]
Valve	Counted Components	9,981	0.091	[+28%/-23%]
Compressor service				
Connector Flanged	Counted Components	30,964	0.0186	[+25%/-14%]
Connector Threaded	Counted Components	60,419	0.0308	[+31%/-20%]
PRV	Counted Components	1,698	0.54	[+44%/-25%]
Regulator	Counted Components	658	0.781	[+15%/-14%]
Valve	Counted Components	10,204	0.169	[+38%/-18%]
Common Multi-Unit Vent	One per Station	140	7.2	[+36%/-23%]
Common Single-Unit Vent	One per Compressor	433	4.19	[+22%/-14%]
Blowdown Vent	One per Compressor	416	0.614	[+126%/-22%]
Pocket Vent	Compressor Cylinders	1,506	0.135	[+30%/-17%]
Rod Packing Vent	One per Compressor	412	27.7	[+25%/-11%]
Starter Vent	One per Compressor	426	16.7	[+78%/-31%]
Rod Packing Vent (OP)	One per Compressor	431	25.2	[+25%/-11%]
Rod Packing Vent (NOP)	One per Compressor	435	1.14	[+39%/-28%]
Rod Packing Vent (NOD)	One per Compressor	434	0.15	[+18%/-20%]
Tank service				
Common Multi-Unit Vent	One per Station	127	15.9	[+40%/-27%]
Common Single-Unit Vent	One per Tank	246	5.35	[+33%/-17%]
Thief Hatch	One per Tank	240	8.05	[+9.4%/-9.3%]
Other				
OEL	Counted Components	476	0.294	[+30%/-21%]

Tables S3-28 and S3-29 compare the component average emission factors to emission factors utilized in the GHGRP for whole gas and methane, respectively. Different average emission factors are utilized by the GHGRP for eastern and western regions of the USA, as described in Section S3-1.8.

To compute ratios, the confidence interval provided with GHGRP emission factors was assumed to be a 90% confidence interval on lognormally distributed data with a relative mean of $m = 1.0$ and a relative standard deviation of $s = CI/1.645$, since $z_\alpha/2 = 1.645$ for a 90% CI. Since some GHGRP emission factors have high uncertainty (CIs as high as 88%), the ratios are highly uncertain as well.

Table S3-28: Comparison of Whole Gas Average Emission Factors to GHGRP Factors

Category	Emission Factor (scfh)	**Eastern Region** GHGRP EF (scfh)	**Eastern Region** Ratio of Study to GHGRP EF	**Western Region** GHGRP EF (scfh)	**Western Region** Ratio of Study to GHGRP EF
Compressor Connector Flanged	0.0186 [+25%/-14%]	0.003	6.28 [4.65 to 8.53]	0.017	1.1 [0.902 to 1.4]
Non-compressor Connector Flanged	0.0213 [+17%/-14%]	0.003	7.2 [5.41 to 9.47]	0.017	1.26 [1.04 to 1.5]
Compressor Connector Threaded	0.0308 [+31%/-20%]	0.003	10.4 [7.45 to 14.7]	0.017	1.82 [1.42 to 2.43]
Non-compressor Connector Threaded	0.0127 [+12%/-11%]	0.003	4.3 [3.28 to 5.54]	0.017	0.75 [0.639 to 0.878]
Compressor PRV	0.54 [+44%/-25%]	0.04	17.4 [5.21 to 42.8]	0.193	2.93 [1.63 to 4.95]
Non-compressor PRV	0.279 [+50%/-22%]	0.04	9.01 [2.82 to 22.5]	0.193	1.52 [0.871 to 2.64]
Compressor Valve	0.169 [+38%/-18%]	0.027	6.46 [4.27 to 9.78]	0.121	1.4 [1.1 to 1.95]
Non-compressor Valve	0.091 [+28%/-23%]	0.027	3.48 [2.21 to 5.16]	0.121	0.755 [0.564 to 0.991]
Compressor Rod Packing Vent	27.7 [+25%/-11%]	1.3	21.8 [15.2 to 30.8]	1.3	21.9 [15.3 to 31.2]
All OEL	0.294 [+30%/-21%]	0.061	5.32 [2.6 to 9.76]	0.031	9.92 [6.03 to 15.6]
Compressor Rod Packing Vent (OP)	25.2 [+25%/-11%]	1.3	19.8 [13.9 to 28.3]	1.3	19.8 [13.9 to 28.1]
Compressor Rod Packing Vent (NOP)	1.14 [+39%/-28%]	1.3	0.895 [0.556 to 1.37]	1.3	0.895 [0.558 to 1.4]
Compressor Rod Packing Vent (NOD)	0.15 [+18%/-20%]	1.3	0.119 [0.0814 to 0.165]	1.3	0.118 [0.0807 to 0.167]

Table S3-29: Comparison of Methane Average Emission Factors to GHGRP Factors

		Eastern Region		**Western Region**	
Category	Emission Factor (scfh)	GHGRP EF (scfh)	Ratio of Study to GHGRP EF	GHGRP EF (scfh)	Ratio of Study to GHGRP EF
Compressor Connector Flanged	0.014 [+23%/-14%]	0.00234	6.04 [4.51 to 8.22]	0.0133	1.06 [0.873 to 1.32]
Non-compressor Connector Flanged	0.0174 [+16%/-14%]	0.00234	7.54 [5.6 to 9.93]	0.0133	1.31 [1.09 to 1.58]
Compressor Connector Threaded	0.0254 [+29%/-19%]	0.00234	11 [7.91 to 15.4]	0.0133	1.92 [1.51 to 2.52]
Non-compressor Connector Threaded	0.0108 [+13%/-11%]	0.00234	4.7 [3.58 to 6.07]	0.0133	0.819 [0.702 to 0.967]
Compressor PRV	0.459 [+51%/-28%]	0.0312	18.9 [5.81 to 46.3]	0.151	3.21 [1.81 to 5.69]
Non-compressor PRV	0.243 [+48%/-22%]	0.0312	10.1 [3.14 to 25.3]	0.151	1.7 [0.959 to 2.94]
Compressor Valve	0.15 [+46%/-18%]	0.0211	7.36 [4.81 to 11.4]	0.0944	1.6 [1.26 to 2.34]
Non-compressor Valve	0.0772 [+28%/-24%]	0.0211	3.78 [2.44 to 5.68]	0.0944	0.821 [0.605 to 1.07]
Compressor Rod Packing Vent	24.3 [+26%/-11%]	1.02	24.5 [17.3 to 35.8]	1.02	24.4 [17 to 35.1]
All OEL	0.238 [+31%/-21%]	0.0476	5.56 [2.64 to 10.5]	0.0242	10.2 [6.35 to 15.9]
Compressor Rod Packing Vent (OP)	22.1 [+25%/-12%]	1.02	22.2 [15.6 to 31.8]	1.02	22.4 [15.4 to 32.3]
Compressor Rod Packing Vent (NOP)	0.988 [+40%/-29%]	1.02	0.997 [0.611 to 1.56]	1.02	0.993 [0.615 to 1.54]
Compressor Rod Packing Vent (NOD)	0.117 [+17%/-22%]	1.02	0.118 [0.0804 to 0.166]	1.02	0.118 [0.0798 to 0.165]

S3-3.4 Component Counts for Average Emission Factors

Component counts (i.e. component activity factors) for each major equipment type are given in Tables S3-30 - S3-35. Where available, activity factors are compared to component counts used in the GHGRP for the Eastern and Western EPA regions.

Table S3-30: Component Counts for AGRU

Component	Activity Basis	Units Counted	Component Count (-)	East[1] Component Count	Ratio East to Study	West[1] Component Count	Ratio West to Study
Connector Flanged	Unit	7	53 [+36%/-100%]				
Connector Threaded	Unit	7	128 [+154%/-58%]				
Gauge	Unit	7	6 [+150%/-100%]				
Meter	Unit	7	0.857 [+600%/-100%]				
OEL	Unit	7	0.571 [+425%/-100%]				
PRV	Unit	7	5 [+100%/-40%]				
Pneumatic Controller	Unit	4	0				
Regulator	Unit	7	1 [+600%/-100%]				
Valve	Unit	7	50.1 [+70%/-30%]				

[1] Activity factor from GHGRP for eastern and western regions.

Table S3-31: Component Counts for Compressor

Component	Activity Basis	Units Counted	Component Count (-)	East[1] Component Count	Ratio East to Study	West[1] Component Count	Ratio West to Study
Connector[2]	Unit	286	211 [+109%/-83%]	57	0.27	179	0.846
Connector Flanged	Unit	286	71.6 [+137%/-97%]				
Connector Threaded	Unit	286	140 [+160%/-80%]				
Gauge	Unit	286	3.31 [+385%/-100%]				
Meter	Unit	286	1.43 [+1923%/-100%]				
OEL	Unit	283	0.622 [+865%/-100%]	0	0	3	4.82
PRV	Unit	286	3.93 [+78%/-100%]	0	0	4	1.02
Pneumatic Controller	Unit	130	3.18 [+57%/-69%]				
Regulator	Unit	286	1.52 [+294%/-100%]				
Valve	Unit	286	23.6 [+133%/-100%]	12	0.508	73	3.09

[1] Activity factor from GHGRP for eastern and western regions.
[2] Includes both flanged and threaded connectors to compare to GHGRP activity factor.

Table S3-32: Component Counts for Dehydrator

Component	Activity Basis	Units Counted	Component Count (-)	East[1] Component Count	Ratio East to Study	West[1] Component Count	Ratio West to Study
Connector[2]	Unit	63	149 [+134%/-75%]	90	0.605	90	0.605
Connector Flanged	Unit	63	21.2 [+238%/-100%]				
Connector Threaded	Unit	63	128 [+154%/-85%]				
Gauge	Unit	63	3.9 [+310%/-100%]				
Meter	Unit	63	0.222 [+800%/-100%]				
OEL	Unit	63	0.46 [+552%/-100%]	2	4.34	2	4.34
PRV	Unit	63	2.54 [+133%/-100%]	2	0.788	2	0.788
Pneumatic Controller	Unit	31	3.23 [+176%/-69%]				
Regulator	Unit	63	3.19 [+242%/-100%]				
Valve	Unit	63	23.1 [+155%/-100%]	24	1.04	24	1.04

[1] Activity factor from GHGRP for eastern and western regions.

[2] Includes both flanged and threaded connectors to compare to GHGRP activity factor.

Table S3-33: Component Counts for Separator

Component	Activity Basis	Units Counted	Component Count (-)	East[1] Component Count	Ratio East to Study	West[1] Component Count	Ratio West to Study
Connector[2]	Unit	184	47.9 [+284%/-83%]	6	0.125	106	2.21
Connector Flanged	Unit	184	16.6 [+297%/-100%]				
Connector Threaded	Unit	184	31.3 [+285%/-96%]				
Gauge	Unit	184	0.766 [+552%/-100%]				
Meter	Unit	184	0.0598 [+1573%/-100%]				
OEL	Unit	182	0.225 [+788%/-100%]	0	0	6	26.6
PRV	Unit	184	1.2 [+151%/-100%]	0	0	2	1.67
Pneumatic Controller	Unit	80	1.93 [+160%/-48%]				
Regulator	Unit	184	0.25 [+1060%/-100%]				
Valve	Unit	184	11.3 [+217%/-100%]	1	0.0882	34	3

[1] Activity factor from GHGRP for eastern and western regions.

[2] Includes both flanged and threaded connectors to compare to GHGRP activity factor.

Table S3-34: Component Counts for Tank

Component	Activity Basis	Units Counted	Component Count (-)	East[1] Component Count	Ratio East to Study	West[1] Component Count	Ratio West to Study
Connector Flanged	Unit	54	4.44 [+585%/-100%]				
Connector Threaded	Unit	54	35.4 [+382%/-88%]				
Gauge	Unit	54	1.48 [+383%/-100%]				
Meter	Unit	54	0				
OEL	Unit	54	0.278 [+980%/-100%]				
PRV	Unit	54	1.63 [+244%/-100%]				
Pneumatic Controller	Unit	32	0				
Regulator	Unit	54	0.37 [+710%/-100%]				
Valve	Unit	54	5.13 [+829%/-100%]				

[1] Activity factor from GHGRP for eastern and western regions.

Table S3-35: Component Counts for Yard Piping

Component	Activity Basis	Units Counted	Component Count (-)	East[1] Component Count	Ratio East to Study	West[1] Component Count	Ratio West to Study
Connector[2]	Station	43	266 [+316%/-93%]	45	0.169	51	0.192
Connector Flanged	Station	43	85.7 [+302%/-95%]				
Connector Threaded	Station	43	180 [+333%/-92%]				
Gauge	Station	43	4 [+561%/-100%]				
Meter	Station	43	1.51 [+287%/-100%]				
OEL	Station	42	0.881 [+661%/-100%]	0	0	1	1.14
PRV	Station	43	2.58 [+353%/-100%]	0	0	1	0.387
Pneumatic Controller	Station	17	5.06 [+177%/-100%]				
Regulator	Station	43	2.19 [+396%/-100%]				
Valve	Station	43	61.8 [+317%/-96%]	12	0.194	14	0.227

[1] Activity factor from GHGRP for eastern and western regions.
[2] Includes both flanged and threaded connectors to compare to GHGRP activity factor.

S3-4 Emission Factors for Major Equipment

This section provides the emission factors for units of major equipment, such as compressors or separators. To develop emission factors, each unit of equipment was identified by its station ID, equipment type, and equipment identifier. For example, station 123 could have a compressor identified as "*station 123, compressor, unit 1*" and a separator identified as "*station 123, separator, unit 1*". In the data tables, sheet *D9 Equipment*, each unit of major equipment is represented by one line of data.

S3-4.1 Major Equipment Modeling Methods

A unit may have been screened with OGI and may also have been measured. If a unit is marked as screened, the entire unit was screened with an OGI camera, and if a unit is marked as measured, an attempt was made to measure all detected emissions on the unit. To develop emission factors, only units which were both screened and measured are included in the emission factor. For these units, all successful measurements are combined with estimates for all detected but unmeasured sources, using the same process as defined for *component average emission factors*, described in Section S3-3, with the following additions:

Common single-unit vent: these emission locations include emissions that all originate on a single major equipment unit, and all measured emissions are included in the total emissions for that unit.

Common multi-unit vent: these emission locations require additional handling, since these sources include emissions from multiple major equipment units. Multi-unit vents occur on both *compressors* and *tanks*. Emissions from these sources may originate with one, some, or all of the units combined into the multi-unit vent. Therefore, for an individual unit, emissions from one of these sources may range from zero to the 100% of emissions, and it is important to capture this range of uncertainty in the resulting per-unit emission factor(s).

Therefore, to handle multi-unit vents, emissions were first simulated as described in Section S3-3, producing a series of Monte Carlo estimates for the emissions. The emissions were then divided by a random number of "emitting units", uniformly distributed between zero and the number of units connected to the multi-unit vent. This method replicates the full range of emissions for an individual unit, while assuming that, in the mean, one half of the connected units are responsible for the emissions. For example, if four compressors were connected to a common vent, the algorithm would estimate that, on average, two compressors are responsible for all of the emissions at any given time, with a range of emissions from any one unit from zero to the full emission rate of the multi-unit vent.

Yard piping: When measured during the field campaign yard piping was divided into arbitrary sub-units that were convenient for field teams. Therefore, a single station may have multiple yard piping equipment identifiers, all combining into a single yard piping "unit" for a station. Only stations where *all* yard piping was screened and measured are utilized to develop yard piping emission factors.

Pneumatic controllers: As per standard practice in the GHGRP and GHGI, pneumatic controller emissions *are not* combined into the emissions from major equipment. Instead, the count of pneumatic controllers, and their emissions, are tracked as a separate line item at the *station* for station estimates (see Section S3-5) or the *basin* for national estimates (see Section S3-6).

Exhaust methane: Also following the practice of the GHGRP and GHGI, emissions of methane entrained in the combustion exhaust of the compressor driver (commonly known as *combustion slip*) *are not* included in compressor emission factors. Combustion slip is tracked as separate methane source line(s) in the GHGI, and included in separate reporting fields for GHGRP and national model.

Vented emissions: Vented emissions include gas released from blowdowns or engine starters, and gas escaping through rod packing seals or centrifugal compressor seals. Blowdowns are typically associated with compressors and yard piping, but may also be occur on most other major equipment groups. Gas engine starters utilize gas pressure to crank compressor drivers during start up, and apply only to compressors. As in the GHGI, blowdowns and starting gas emissions are represented by a separate category ("blowdown stacks") and *are not* included in the major equipment emission factors. Emissions from rod packing and compressor seals *are* including in the compressor emission factor.

Compressors and compressor drivers: All fugitive and vented emissions from the compressor skid are included in the *compressor* emission factor. This includes fugitive emissions on the compressor, compressor driver, and any auxiliary equipment attached to the skid.

While this study updates combustion slip and rod packing estimates, it does not update blowdown or engine starter emission factors, which were not measured, or centrifugal compressor seal emissions, which were encountered in too low a frequency to be statistically valid.

Dehydrator and AGRU vents: Some methane may be present in dehydrator still vents and combustion stacks for heaters on AGRUs. This study develops no new emission factors for these sources. Dehydrator vents are included in station and national emission estimates using GHGRP estimation methods; AGRU emissions are not estimated by GHGRP and not included.

Flares: Few flares were encountered during the field campaign and no fugitive emissions (leaks) were measured on gas supply lines for these units. No new emission factors are provided by this study. Methane released in combustion exhaust of the flare is estimated for national emissions using GHGRP methods.

S3-4.2 Large Emitters

Major equipment emission factors include estimates of all emissions on every unit that was measured. The majority of emission locations are handled as described in Section S3-3. The handling of the remaining measurement classification, "Exceeded Capacity", is described here.

For measurement attempts that exceeded the capacity of the available measurement methods, there are no direct measurements of emissions. In most cases, the field team estimated that emissions would exceed the capacity of available instruments *or* observed emissions were too large to safely attempt a measurement. In the data tables, this type of emitter is marked as "Exceeded Capacity", and is referred to in the text as a *large emitter*.

Table S3-36 provides the number of large emitter sources by station divided into compressors, tanks and all other equipment. Two stations had two large emitters; the remainder had one. Table S3-37 shows the same data, divided by component type. Common vents at the station yard piping, compressors, and tank batteries are the most frequent locations for EC sources.

While large emitters occurred on several component categories, these events are so rare that it does not make sense to include an estimate of emissions in any one component category where a similar (rare) event may occur – but was not observed – in another, similar, category. For example, as per Table S3-37, including large emitter emissions in Compressor/Flanged Connector, but not in Compressor/Threaded Connector would indicate the former emits far larger emissions than the latter, which is unlikely true in general. Similarly a large emitter was encountered on Non-Compressor/Threaded Connector, but not on Non-Compressor/Flanged Connector. Therefore, emissions estimates for large emitters are not included in component average emission factors, but are estimated in the major equipment emission factors, and since major equipment emission factors are the basis of station and national emission estimates, this treatment carries through to those estimates as well.

Table S3-36: Facilities with Exceeded Capacity Measurements

Study ID	Number of Sources Compressor	Other Station	Tank	Total
7	0	0	1	1
11	1	0	1	2
19	0	1	0	1
570	1	0	0	1
1404	0	1	0	1
1564	1	0	0	1
1644	0	0	1	1
1731	0	0	1	1
2686	1	0	0	1
2736	0	0	1	1
2856	0	0	1	1
3001	1	1	0	2
Total	5	3	6	14

Table S3-37: Components with Exceeded Capacity Measurements

	Number of Sources							
	Compressor		Non-Compressor		Tank		Total	
Component	EC Count	Meas. Count	EC Count	Meas. Count	EC Count	Meas. Count	EC Count	Meas. Count
Common Multi-Unit Vent	2	23			3	22	5	45
Common Single-Unit Vent	1	49			2	79	3	128
Common Station Vent			2	20			2	20
Connector Flanged	1	48					1	81
Connector Threaded			1	87			1	214
Rod Packing Vent	1	530					1	530
Thief Hatch					1	120	1	120
Total	5	777	3	140	6	221	14	1138

For this study, no method was available to measure emissions when they exceeded the capacity of the high flow instrument and a bag would not work for either safety or mechanical reasons. It is therefore necessary to approximate these emissions utilizing data from other studies. Two recent studies performed on compressor stations provide some insight into emission rates; the frequency at which large emitters occur is taken directly from observations during the field campaign.

The first study performed component level measurements on transmission and storage (T&S) stations, paired with downwind tracer flux measurements, and accumulated additional measurements made by partners utilizing similar equipment and methods [16]. Component measurements for this study included measurements made at higher emission rates than was measurable during the current study. We utilize large measurements from the T&S study to provide information about large emitters sizes for this study, but *do not* use the super-emitter category identified in that study. To convert from kg/h methane to whole gas, we utilize the assumed methane content of 0.95 by mass; a typical assumption for transmission systems.

The second study performed both component level and downwind measurements on gathering compressor stations in the Fayetteville shale play [17]. Since the study utilized similar measurement equipment as this study, component measurements were not made above the range of the high flow instrument. However, the study isolated two large emitters on tanks using downwind methods which were too large to measure with onsite instruments - 606 [± 278] and 140 [± 64.2] kg/h methane. The larger of these measurements was confirmed by three aircraft measurements that estimated similar emission rates. To convert from kg/h methane to whole gas, we utilize an estimated methane content of 0.97 by mass.

These measurements were utilized to estimate emission rates for large emitters that could not be measured in the field campaign:

Rod Packing: The T&S study included 9 rod packing vent measurements that exceeded the high flow device capacity (data file sheet *D14 Rodpacking from T&S*). For use these measurements are fit to a lognormal distribution, shown in Figure S3-14, as an example of the fitting method utilized here.

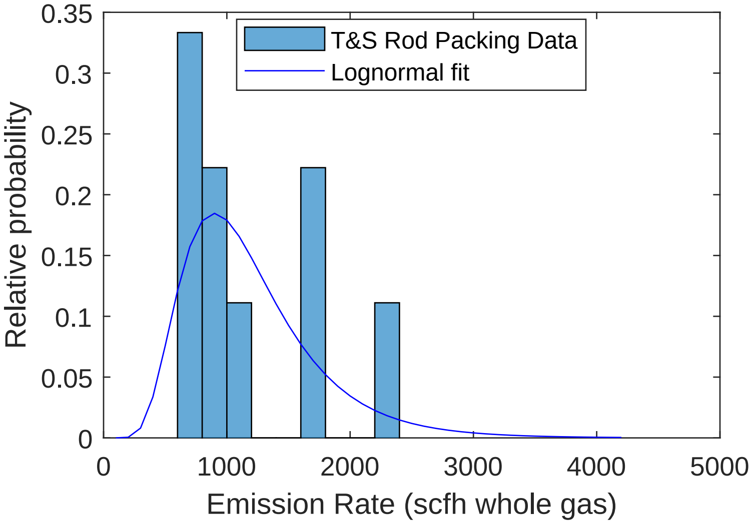

Figure S3-14: Data for rod packing emissions from the T&S study that exceeded the high flow capacity, and resulting lognormal fit to the data.

Common Single-Unit Vents* and *Thief Hatch: Following a similar method, 15 measurements from isolation valves from the T&S study were utilized to model all single-unit vents and thief hatch emitters (data file sheet *D15 Vents from T&S*).

***Common Multi-Unit Vents* and *Common Station Vent*:** For these vents we assume emissions will range across both the T&S isolation valve data as well as the additional measurements made during the Fayetteville study. These measurements were concatenated into a single measurement set and fit to a lognormal distribution, with twice the weight given to the Fayetteville measurements to balance the influence of data from both sources.

***Connectors*:** Large emissions from connectors are, by their nature, smaller than the other large emitters described above. These leaks were modeled using a triangular distribution centered on the BHFS upper measurement limit (600scfh whole gas) with an offset of ±20%. This method provides an estimate in line with observations, a mean at the maximum reading of the BHFS, and bounded tails.

Resulting emission factors are summarized in Table S3-38.

Table S3-38: Summary of Emission Factors for Large Emitters

	Source Data		**Lognormal Model**		
Component	Count	Mean & Confidence Interval (scfh whole gas)	μ Parameter	σ Parameter	Mean & Confidence Interval (scfh whole gas)
Rod Packing	9	1,188 [656 to 2,298]	6.99	0.438	1195 [461 to 2561]
Common Single-Unit Vent Thief Hatch	15	2,483 [724 to 9,439]	7.42	0.856	2416 [313 to 8970]
Common Multi-Unit Vent Common Station Vent	19	5,210 [724 to 32,539]	7.83	1.17	4965 [255 to 24750]

The large emitter model impacts the three major equipment emission factors where large emitters occur (see Table S3-37). As has been found in other studies, large emitters occur infrequently, but account for a large fraction of total emissions. The impact is shown in Table S3-39.

Table S3-39: Impact of Large Emitter Model on Emission Factors

Major Equipment Type	Fraction of Samples Larger than Maximum of Reference Model[1]	Fraction of Samples Larger Than CI of Reference Model[2]	Emissions Increase Due to Large Emitter Model[3]
Compressors	0.0033%	4.5%	70%
Tanks	0.46%	3.3%	74%
Yard Piping	0.95%	3.8%	83%

[1] Fraction of the time emission estimates exceed the largest emission estimate from the reference distribution that does not contain the large emitter model.

[2] Fraction of the time emission estimates exceed the upper 95% confidence interval of the reference distribution that does not contain the large emitter model..

[3] Increase in mean emissions due to the large emitter model.

S3-4.3 Major Equipment Results

Table S3-40 compares study emission factors for major equipment to similar emission factors from the GHGI and GHGRP. Since confidence intervals are not available for some emission factors, the ratio of mean values is utilized for all comparisons.

Table S3-40: Major Equipment Factor Comparison

Component[1]	Emission Factor (scfh whole gas)	GHGI[2] Emission Factor	Ratio Study to GHGI	GHGRP East[3] Emission Factor	Mean Ratio Study to GHGRP East	GHGRP West[3] Emission Factor	Mean Ratio Study to GHGRP West
AGRU	4.04 [+451%/-95%]						
Compressor	110 [+542%/-100%]	14.5	7.58	0.5	220	12.7	8.63
Dehydrator	3.41 [+894%/-94%]	3.41	1	1.11	3.07	4.87	0.7
Separator	0.647 [+1188%/-68%]	2.84	0.228	0.05	12.9	6.49	0.0998
Tank	39.3 [+560%/-99%]						
YardPiping	86.3 [+190%/-100%]	1.5	57.5	0.46	188	2.78	31

[1] Abbreviations: "Comp" = Compressor; "AGRU" = Acid gas removal unit;
[2] [14, Table 3.6-2]
[3] [**?**]

Emission factors are summarized below in Table S3-41 for whole gas and Table S3-42 for methane. Column headers are:

Column Header	**Description**
Category	name of the emission factor.
Activity Basis and Mean Population	the unit definition ("activity basis") and number of units screened ("mean population") used to develop the emission factor. Only units where all detected emissions could be estimated are included in the population.
Emission Factor	emission factor (mean of per-unit emissions), and upper and lower 95% confidence intervals. Since emission factors are developed utilizing Monte Carlo methods, these values are equivalent to a bootstrap mean and confidence interval of the emission factor.
Identified Emission Sources per Unit	mean number of emission sources identified, on a per-unit basis, the fraction of major equipment units in each category with *no* emissions detected, and the maximum number of emission sources found on one unit.

Appendix C Major Factors provides overview plots of each emission factor. Since many major equipment units were screened with OGI and no leaks were found, units with no detected fugitive emissions are plotted on the logarithmic plots at a low, non-zero value, to make counts of these units visible.

Table S3-41: Major Equipment Whole Gas Emission Factors

Category	Activity Basis	Mean Population	Emission Factor (scfh whole gas)	Confidence Interval (scfh whole gas)	Mean Sources per Unit	Fraction of Units with No Sources	Maximum Sources per Unit
AGRU[1]	Unit	8	4.04	[+264%/-99%]	0.5	63%	2
Compressor	Unit	435	110	[+78%/-44%]	2.69	20%	18
Dehydrator	Unit	124	3.41	[+76%/-59%]	0.532	74%	6
Separator	Unit	326	0.647	[+78%/-53%]	0.153	90%	6
Tank	Tank	251	39.3	[+130%/-62%]	0.793	44%	4
YardPiping	Station	157	86.3	[+265%/-80%]	1.9	48%	17

[1] Emission factor is based upon few measurements and is unlikely to be robust.

Table S3-42: Major Equipment Methane Emission Factors

Category	Activity Basis	Mean Population	Emission Factor (scfh CH_4)	Confidence Interval (scfh CH_4)	Mean Sources per Unit	Fraction of Units with No Sources	Maximum Sources per Unit
AGRU[1]	Unit	8	3.61	[+274%/-99%]	0.5	63%	2
Compressor	Unit	435	94.4	[+77%/-46%]	2.69	20%	18
Dehydrator	Unit	124	2.95	[+77%/-59%]	0.532	74%	6
Separator	Unit	326	0.545	[+79%/-54%]	0.153	90%	6
Tank	Tank	251	33.6	[+120%/-61%]	0.793	44%	4
YardPiping	Station	157	74.4	[+238%/-80%]	1.9	48%	17

[1] Emission factor is based upon few measurements and is unlikely to be robust.

S3-5 Station Emission Estimates

Estimates of complete station emissions were assembled for the 180 stations in the field campaign (including the four stations from the GSI longitudinal study, see Section S3-1). Handling of each type of emissions is briefly discussed below.

Vented and Fugitive Emissions: For each unit of major equipment emissions, a unit may be screened and measured, or not measured. For units that were screened and measured, actual measurements are utilized and bootstrapped for uncertainty using the same method as in Section S3-4. If a major equipment unit was not measured, emissions are drawn from the appropriate major equipment emission factor for that unit. Following simulation, emissions are accumulated by major equipment group (compressors, tanks, yard piping, etc.).

Pneumatic Controllers: Counts of PCs were taken from major equipment unit data if the unit was counted. For units where components were not counted, values were drawn from the activity factor for "PCs per unit" (see data tables, sheet *D12 Components Per Unit*) for the appropriate unit type (compressors, tanks, dehydrators, etc.). During the field campaign, the number of pneumatic controllers was counted, but the type of controller (i.e. bleed type) was not determined and recorded. To calculate pneumatic emissions, the mix of high/low/intermittent bleed pneumatic controllers was taken from reports to the GHGRP:

1. If the partner indicated that the station was on instrument air, the pneumatic controller count was assumed to be zero *for the purposes of calculating emissions.* This assumes that all controllers on the station are connected to instrument air.
2. If a station was in a basin where the partner reported to the GHGRP, the pneumatic controller mix was taken from the partner's GHGRP reports for the basin. This assumes that the ratio of controllers is the same for every station in the basin.
3. When a station *was not* in a basin where the partner reported to the GHGRP, the pneumatic controller mix was taken from the mean of all GHGRP reports in that basin.

Results of this analysis are provided in data table *D13 Pneumatic Controller Mix.*

Emissions were estimated utilizing whole gas emission factors from the GHGI for low (1.39 scfh), high (37.3 scfh), and intermittent bleed (13.5 scfh) devices. Uncertainty was assumed to be 20% at a 95% confidence level.

Compressor Exhaust: Methane entrained in compressor exhaust, often known as "combustion slip" or "methane slip", was developed in Vaughn et al. [2] for all stations in the field study.

Large Emitters: For stations with large emitters, these sources were modeled as in the major equipment emission factor description (Section S3-4). Where equipment was not measured, major equipment emission factors were utilized, including the (low probability) impact of large emitters.

Dehydrator Vent Emissions: Methane released from dehydrator vents was estimated using emissions reported to the GHGRP, divided into "small" dehydrators with throughput <0.4 MMscfd, and "large" dehydrators with throughput >0.4 MMscfd.

For large dehydrators, each unit is reported separately to the GHGRP. For small dehydrators, all units combined into a single estimate for each GHGRP report. Total emission rate in both case was estimated by summing vented methane and methane emitted from flared emissions. Resulting distributions are summarized in table S3-43. The data pulled from GHGRP tables are included in data tables *D2 GHGRP Large Dehy* and *D3 GHGRP Small Dehy.*

If throughput was known for the station, per-dehydrator throughput was estimated by dividing station throughput by the number of dehydrators. If throughput was not known, the distribution for large dehydrators was utilized. Using the large/small selection, the emissions were drawn from the appropriate distribution. Due to the size of stations with dehydrators in the field campaign, only 1 station utilized the small dehydrator distribution to compute emissions.

Table S3-43: Summary of GHGRP Data for Dehydrators

Dehydrator Size (rated throughput)	Records in GHGRP	Emission Rate ($kg \cdot h^{-1}$	Emission Rate Units
Large (>0.4 MMscfd) [1]	2921	1.88 [0 to 17.2]	$kg \cdot h^{-1} unit^{-1} CH_4$
Small (< 0.4 MMscfd) [2]	104	0.188 [0 to 0.331]	$kg \cdot h^{-1} report^{-1} CH_4$

[1] GHGRP Subpart W, reporting year 2017, Table W_DEHYDRATORS_LARGE [19, Table E.3].

[2] GGHRP Subpart W, reporting year 2017, Table W_DEHYDRATORS_SMALL [19, Table E.1].

Flare Emissions: During the field campaign, field teams noted when flares were connected to tanks to combust vented emissions. These flares may also have been used for other waste gas at the station. No measurements were made of flare emissions. To estimate emissions at stations, we utilize data from GHGRP reports [19, Table N.1], and included in the data tables in sheet *D5 GHGRP Flare Stacks.* For reporting year 2017, the table contains 4318 flares for gathering and boosting, of which 23% are reported as having zero emissions. For the field campaign 10 of 180 stations had flares. To estimate flare emissions, the following process was used:

- If no flares were noted on any tank during the field campaign, we assume there is no flare at the station, and flaring emissions are zero. If a flare is noted on *any* tank, then we assume there is one flare on the station.
- If the partner reported flares to the GHGRP gathering and boosting sector (In Table N.1, field `INDUSTRY_SEGMENT` is equal to *"Onshore petroleum and natural gas gathering and boosting [98.230(a)(9)]"*) emissions from these flares were randomly sampled to estimate flaring emissions.
- If the partner did not report flares to GHGRP as noted above (even through a flare was observed during the field campaign), emissions were estimated from all flares reported in the basin.

It should be noted that GHGRP reports contain a small number of flares with large emissions, which occurred in basins and/or company combinations that were not sampled in the campaign, and thus not used in the analysis process indicated above. The largest 1% of flares have emissions greater than 4.9 $kg \cdot h^{-1}$ methane, and account for 37% of total emissions reported to the GHGRP. Therefore, emissions from these larger flares appear in the national model, but are not applicable to the stations measured in this study.

Throughput Normalized Emissions: Throughput was not available for all stations. Where available, throughput normalized emissions were computed by:

1. Converting throughput from the provided units to mass units ($kg \cdot h^{-1}$) using the gas composition from the station, or, if none was available, an average gas composition for all stations.
2. Dividing estimated emissions by throughput.

S3-5.1 Station Results

Selected elements of the station emission estimates are summarized in Table S3-44 with stations listed in order of increasing emissions. Detailed results are provided in the data files *D23 Station Emissions*.

Table S3-44: Station Emissions

Facility ID	Facility Type[1]	Large Emitter Count	Number Comp.	Number Elec. Comp.[2]	Instr. Air[3]	Emissions ($kg \cdot h^{-1} CH_4$)	Thruput ($kg \cdot h^{-1} CH_4$)	Thruput Normalized Emissions
2364	C	0	1	1	NR	0.00386 [+79%/-79%]	19.6	0.02%
165	C	0	1	1	NR	0.00582 [+65%/-66%]	91.3	0.0064%
2586	C	0	1	1	NR	0.00585 [+65%/-65%]	84.7	0.0069%
2285	C	0	1	1	NR	0.00587 [+64%/-65%]	22.8	0.026%
83	C	0	1	1	NR	0.00588 [+64%/-65%]	81.5	0.0072%
1437	C	0	1	1	NR	0.00592 [+62%/-63%]	97.8	0.0061%
2407	C	0	1	1	NR	0.00772 [+57%/-56%]	84.7	0.0091%
2420	C	0	1	1	NR	0.00787 [+54%/-57%]	61.9	0.013%
2956	C	0	1	1	NR	0.00791 [+56%/-55%]	554	0.0014%
1487	C	0	1	0	No	0.00981 [+50%/-50%]	0	
202	C	0	1	1	NR	0.0117 [+46%/-45%]	313	0.0037%
119	C	0	1	0	NR	0.0328 [+611%/-85%]	31.3	0.1%
85	C	0	1	0	NR	0.0367 [+500%/-78%]	30	0.12%
1510	C	0	1	0	NR	0.0476 [+264%/-86%]	116	0.041%
1442	C	0	1	0	NR	0.0525 [+573%/-81%]		
2685	C	0	1	1	Yes	0.114 [+21%/-18%]		
39	C	0	2	0	NR	0.115 [+288%/-69%]		
1161	C	0	1	1	NR	0.161 [+43%/-38%]		
14	C	0	1	0	No	0.251 [+77%/-33%]		
1643	C	0	1	0	No	0.321 [+90%/-20%]	79.2	0.41%
244	C	0	1	0	NR	0.404 [+548%/-97%]	65.8	0.61%
1846	C	0	1	1	NR	0.405 [+384%/-97%]	228	0.18%
1834	C	0	2	0	Yes	0.573 [+242%/-47%]	843	0.068%
1080	C/T	0	3	0	Yes	1.01 [+313%/-46%]	4.67×10^3	0.022%
2485	C	0	1	0	Yes	1.05 [+12%/-11%]	0	
2607	C	0	1	0	No	1.07 [+73%/-44%]	634	0.17%
504	C	0	1	0	No	1.48 [+276%/-80%]	1.27×10^3	0.12%
1171	C	0	1	0	No	1.66 [+54%/-39%]	210	0.79%
1306	C	0	1	0	No	1.7 [+176%/-80%]	196	0.87%
1488	C	0	3	0	Yes	1.85 [+179%/-55%]		
1610	C	0	1	0	Yes	2.29 [+123%/-77%]		
719	C	0	1	0	No	2.29 [+46%/-28%]	267	0.86%
1308	C	0	1	0	No	2.29 [+235%/-54%]		
315	C	0	1	0	No	2.34 [+65%/-20%]	44.7×10^3	0.0052%
481	C	0	1	0	No	2.54 [+79%/-61%]	0	
2259	C/D	0	2	0	Yes	2.75 [+549%/-88%]	1.63×10^3	0.17%
1291	C	0	2	0	No	2.76 [+181%/-48%]	1.6×10^3	0.17%
2297	C	0	3	0	No	2.97 [+17%/-17%]	2.59×10^3	0.11%
2742	C	0	2	0	Yes	3.1 [+202%/-72%]	3.57×10^3	0.087%
1120	C/D	0	1	0	Yes	3.12 [+562%/-80%]	2×10^3	0.16%
788	C/D	0	5	0	Yes	3.18 [+476%/-85%]	6.01×10^3	0.053%
2188	C	0	1	0	No	3.19 [+172%/-53%]	1.17×10^3	0.27%
895	C	0	1	0	No	3.19 [+55%/-43%]		
1830	C	0	1	0	No	3.22 [+36%/-24%]	246	1.3%
268	C/D	0	1	0	Yes	3.34 [+456%/-64%]		
1165	C	0	3	0	No	3.39 [+54%/-35%]	7.82×10^3	0.043%

Table S3-44 continued

Facility ID	Facility Type[1]	Large Emitter Count	Number Comp.	Number Elec. Comp.[2]	Instr. Air[3]	Emissions $(kg \cdot h^{-1} CH_4)$	Thruput $(kg \cdot h^{-1} CH_4)$	Thruput Normalized Emissions
1652	C/D	0	2	0	Yes	3.42 [+456%/-64%]	550	0.62%
1756	C	0	2	0	No	3.5 [+157%/-47%]	1.29×10^3	0.27%
1860	C	0	2	0	No	3.54 [+97%/-45%]	991	0.36%
2474	C	0	1	0	No	3.58 [+245%/-76%]	352	1%
556	C	0	1	0	No	3.62 [+173%/-60%]	2.54×10^3	0.14%
2973	C/D	0	4	0	Yes	3.64 [+403%/-86%]	15.6×10^3	0.023%
2773	C/D	0	2	0	Yes	3.83 [+446%/-71%]	4.98×10^3	0.077%
2927	C/D	0	5	0	Yes	3.86 [+392%/-76%]	5.98×10^3	0.065%
2990	C	0	2	0	No	3.89 [+68%/-52%]	970	0.4%
2057	C/D	0	1	0	Yes	3.98 [+352%/-68%]	1.03×10^3	0.39%
704	C	0	2	0	Yes	3.99 [+456%/-81%]	1.47×10^3	0.27%
2964	C	0	3	0	Yes	4.38 [+220%/-67%]	5.2×10^3	0.084%
1141	C/D	0	2	0	Yes	4.62 [+465%/-85%]	2.25×10^3	0.2%
640	C/D	0	2	0	No	5.02 [+326%/-67%]	857	0.59%
1525	C	0	1	0	No	5.31 [+38%/-23%]	10.7×10^3	0.049%
2552	C/D	0	2	0	Yes	5.33 [+272%/-49%]		
952	C	0	2	0	No	5.34 [+113%/-40%]	5.85×10^3	0.091%
1681	C	0	2	0	No	5.4 [+114%/-37%]	9.97×10^3	0.054%
1779	C/D	0	1	0	No	5.74 [+273%/-50%]	469	1.2%
136	C	0	3	0	No	5.86 [+53%/-40%]	2.21×10^3	0.27%
2516	C	0	2	0	No	5.94 [+99%/-35%]	10.1×10^3	0.059%
2214	C	0	2	0	No	6 [+102%/-35%]	3.21×10^3	0.19%
492	C	0	2	0	Yes	6.02 [+101%/-34%]	5.43×10^3	0.11%
2785	C	0	4	0	Yes	6.06 [+130%/-31%]	2.93×10^3	0.21%
2783	C/D	0	1	0	No	6.53 [+247%/-59%]	549	1.2%
1011	C	0	1	0	No	6.61 [+29%/-20%]	483	1.4%
1536	C	0	1	0	No	6.76 [+456%/-84%]	587	1.2%
7	C	1	3	0	Yes	6.88 [+82%/-72%]	1.3×10^3	0.53%
1592	C/D/T	0	1	0	No	7.25 [+223%/-53%]	1.31×10^3	0.55%
1660	C	0	4	0	Yes	7.29 [+402%/-92%]	3.87×10^3	0.19%
2228	C	0	2	0	No	7.49 [+383%/-75%]	596	1.3%
216	C	0	2	0	No	7.5 [+82%/-30%]	2.41×10^3	0.31%
1633	C/D	0	5	0	Yes	7.57 [+256%/-58%]	6.82×10^3	0.11%
1914	C	0	2	0	No	7.7 [+45%/-36%]	775	0.99%
1644	C/D	1	5	0	Yes	7.73 [+338%/-62%]	3.97×10^3	0.19%
94	C/D	0	1	0	No	7.76 [+190%/-51%]	822	0.94%
1418	C	0	5	0	Yes	7.88 [+250%/-54%]	10.1×10^3	0.078%
2963	C/D	0	2	0	No	8.37 [+169%/-46%]	2.1×10^3	0.4%
621	C/D	0	2	0	Yes	8.6 [+487%/-89%]	4.02×10^3	0.21%
2744	C	0	1	0	Yes	8.75 [+124%/-35%]	738	1.2%
19	C/D	1	2	0	Yes	8.75 [+334%/-66%]	10.7×10^3	0.082%
1661	C	0	1	0	No	8.96 [+61%/-27%]	1.16×10^3	0.77%
1451	C/D	0	1	0	Yes	9.08 [+169%/-48%]	5.47×10^3	0.17%
2376	C	0	4	0	No	9.46 [+25%/-16%]	57.1×10^3	0.017%
2469	C/D	0	1	0	No	9.57 [+156%/-38%]	980	0.98%
1937	C/D/T	0	1	0	No	10.7 [+146%/-58%]		

Table S3-44 continued

Facility ID	Facility Type[1]	Large Emitter Count	Number Comp.	Number Elec. Comp.[2]	Instr. Air[3]	Emissions ($kg \cdot h^{-1} CH_4$)	Thruput ($kg \cdot h^{-1} CH_4$)	Thruput Normalized Emissions
791	C	0	2	0	No	11.2 [+192%/-52%]	1.47×10^3	0.76%
200	C	0	4	0	No	11.3 [+161%/-58%]	2.41×10^3	0.47%
765	C	0	2	0	No	11.5 [+47%/-33%]	4.61×10^3	0.25%
1235	C/D	0	5	0	Yes	11.7 [+186%/-50%]	15.4×10^3	0.076%
2736	C	1	4	0	Yes	11.8 [+588%/-90%]		
772	C	0	3	0	No	12.2 [+81%/-21%]	11.8×10^3	0.1%
247	C/D	0	3	0	No	13.4 [+112%/-38%]	727	1.8%
1702	C/D	0	3	0	No	13.7 [+170%/-40%]	7.46×10^3	0.18%
1315	C/D	0	4	0	Yes	13.8 [+182%/-51%]	13.5×10^3	0.1%
360	C/D	0	3	0	Yes	14.8 [+217%/-57%]		
40	C/D	0	1	0	No	15 [+111%/-50%]	4.88×10^3	0.31%
2268	C/D	0	5	0	Yes	15 [+169%/-41%]	19×10^3	0.079%
2291	C	0	1	0	No	15.1 [+35%/-24%]	919	1.6%
1167	C	0	6	0	No	15.1 [+380%/-54%]	952	1.6%
2416	C/D	0	3	0	Yes	16.4 [+168%/-66%]	9.27×10^3	0.18%
2603	C/D	0	3	0	Yes	16.6 [+292%/-66%]	19.5×10^3	0.085%
1566	C/D	0	3	0	No	17 [+334%/-58%]	9.76×10^3	0.17%
2307	C/D	0	1	0	Yes	17.3 [+91%/-30%]	644	2.7%
2451	C/D	0	2	0	No	17.4 [+308%/-65%]	3.57×10^3	0.49%
699	C/D	0	5	0	No	17.5 [+100%/-29%]	12.2×10^3	0.14%
2116	C/D	0	3	0	No	17.6 [+127%/-43%]	7.56×10^3	0.23%
1875	C/D	0	1	0	No	17.8 [+252%/-53%]	852	2.1%
3004	C	0	3	0	No	18.3 [+46%/-19%]		
206	C/D	0	5	0	Yes	19.9 [+151%/-63%]	21.1×10^3	0.094%
17	C/D/T	0	2	0	No	20.1 [+121%/-49%]	6.02×10^3	0.33%
235	C/D	0	5	0	Yes	20.2 [+75%/-37%]	24.9×10^3	0.081%
3003	C/D	0	2	0	No	21.9 [+71%/-23%]		
430	C/D	0	2	0	No	22.2 [+203%/-48%]	2.74×10^3	0.81%
2691	C/D	0	1	0	No	23.1 [+77%/-37%]	2.44×10^3	0.95%
2491	C	0	2	0	No	23.5 [+32%/-32%]	6.81×10^3	0.34%
1895	C/D	0	3	0	No	23.8 [+124%/-42%]	17.9×10^3	0.13%
1738	C/D	0	3	0	Yes	24 [+115%/-38%]	7.49×10^3	0.32%
744	C/D	0	3	0	No	24 [+321%/-59%]	6.26×10^3	0.38%
634	C/D	0	2	0	No	24.1 [+132%/-45%]	11×10^3	0.22%
117	C	0	7	0	No	25.2 [+369%/-68%]	5.48×10^3	0.46%
251	C/D	0	2	0	No	25.5 [+374%/-43%]	16×10^3	0.16%
1292	C/D	0	12	0	Yes	25.8 [+126%/-31%]	75.6×10^3	0.034%
1825	C/D	0	4	0	Yes	26.2 [+73%/-33%]	22.8×10^3	0.11%
2149	C/D	0	4	0	No	29.2 [+283%/-55%]	4.91×10^3	0.59%
3002	C/D	0	4	0	No	29.3 [+51%/-19%]		
604	C/D	0	2	0	No	29.6 [+89%/-31%]	7.88×10^3	0.38%
2186	C/D	0	3	0	No	30.2 [+66%/-30%]	10.9×10^3	0.28%
2048	C/D	0	3	0	Yes	30.9 [+315%/-53%]	41.3×10^3	0.075%
509	C	0	1	0	No	32.1 [+97%/-32%]	2.73×10^3	1.2%
512	C/D/T	0	3	0	Yes	32.1 [+150%/-37%]	13.2×10^3	0.24%
252	C/D	0	6	0	Yes	32.3 [+93%/-33%]	33.8×10^3	0.095%

Table S3-44 continued

Facility ID	Facility Type[1]	Large Emitter Count	Number Comp.	Number Elec. Comp.[2]	Instr. Air[3]	Emissions ($kg \cdot h^{-1} CH_4$)	Thruput ($kg \cdot h^{-1} CH_4$)	Thruput Normalized Emissions
1945	C/D	0	2	0	No	33.9 [+77%/-31%]	3.88×10^3	0.87%
1262	C/D/T	0	4	0	Yes	34.1 [+138%/-46%]	3.16×10^3	1.1%
2610	C/D	0	2	0	No	34.5 [+113%/-36%]	4.96×10^3	0.7%
2833	C/D	0	3	0	No	34.9 [+141%/-39%]	11.2×10^3	0.31%
2494	C/D	0	5	0	Yes	35.2 [+91%/-30%]	202×10^3	0.017%
691	C/D/T	0	4	0	Yes	35.8 [+300%/-58%]	20.5×10^3	0.18%
818	C	0	2	0	No	35.9 [+19%/-20%]	35.3×10^3	0.1%
55	C/D	0	4	0	No	36.7 [+83%/-35%]	11.3×10^3	0.32%
1505	C/D	0	4	0	No	38 [+82%/-30%]		
2827	C/D	0	4	0	No	39.7 [+47%/-22%]	5.06×10^3	0.79%
789	C/D	0	5	0	No	40.1 [+113%/-31%]	18.5×10^3	0.22%
2947	C/D	0	6	0	Yes	40.3 [+88%/-29%]	39.1×10^3	0.1%
2874	C	0	4	0	Yes	41.4 [+37%/-25%]	12.7×10^3	0.33%
2686	C/D	1	5	0	Yes	42 [+121%/-31%]	27.1×10^3	0.16%
1564	C/D	1	7	0	No	42.1 [+215%/-47%]	22.6×10^3	0.19%
1126	C/D	0	5	0	Yes	44.3 [+238%/-56%]	10.9×10^3	0.4%
2551	C/D	0	4	0	Yes	44.7 [+51%/-28%]	27.9×10^3	0.16%
1873	C/D/T	0	4	0	Yes	45.3 [+223%/-46%]	22.5×10^3	0.2%
333	C/D	0	6	0	Yes	47.1 [+36%/-20%]	42.3×10^3	0.11%
2064	C/D	0	2	0	No	49.5 [+112%/-39%]	8.53×10^3	0.58%
570	C/D	1	3	0	No	51.2 [+36%/-18%]	8.71×10^3	0.59%
1731	C/D	1	2	0	No	51.8 [+208%/-70%]	430	12%
790	C/D	0	6	0	No	52.4 [+54%/-23%]	18.4×10^3	0.29%
2856	C/D/T	1	5	0	Yes	52.6 [+150%/-37%]	27.5×10^3	0.19%
2557	C/D	0	5	0	No	53.8 [+61%/-24%]	24.2×10^3	0.22%
2575	C/D/T	0	5	0	No	55.8 [+106%/-28%]	19.2×10^3	0.29%
1618	C/D	0	6	0	No	59.6 [+66%/-26%]	24.6×10^3	0.24%
1496	C/D	0	5	0	No	60.7 [+38%/-20%]	22.5×10^3	0.27%
1461	C/D	0	11	0	Yes	71.9 [+35%/-24%]	58.6×10^3	0.12%
2588	C/D	0	5	0	No	72.6 [+60%/-26%]	18×10^3	0.4%
441	C/D	0	6	0	Yes	74.9 [+44%/-24%]	61.3×10^3	0.12%
660	C/D	0	12	0	No	76.6 [+113%/-25%]	14.4×10^3	0.53%
1785	C/D	0	10	0	Yes	79.8 [+82%/-24%]	57.6×10^3	0.14%
66	C	0	12	0	No	80.4 [+19%/-18%]	73×10^3	0.11%
123	C/D	0	7	0	No	81.6 [+106%/-26%]	30.6×10^3	0.27%
1259	C/D	0	8	0	Yes	85.7 [+118%/-31%]	126×10^3	0.068%
2643	C/D/T	0	9	0	Yes	90 [+66%/-29%]	42.4×10^3	0.21%
705	C/D	0	9	0	No	97.3 [+126%/-33%]		
11	C/D	2	5	0	No	127 [+96%/-36%]	19.6×10^3	0.65%
2073	C/D	0	8	0	No	224 [+38%/-17%]	8.23×10^3	2.7%
1404	C/D	1	2	0	Yes	272 [+214%/-71%]	121×10^3	0.22%
3001	C	2	4	0	No	437 [+162%/-65%]		

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[1] Abbreviations: “C” = Compression; “D” = Dehydration; “T” = Treating;

[2] Number of compressors driven by electric drivers

[3] Indicates if instrument air was used for pneumatically actuated valves. NR = “not recorded”

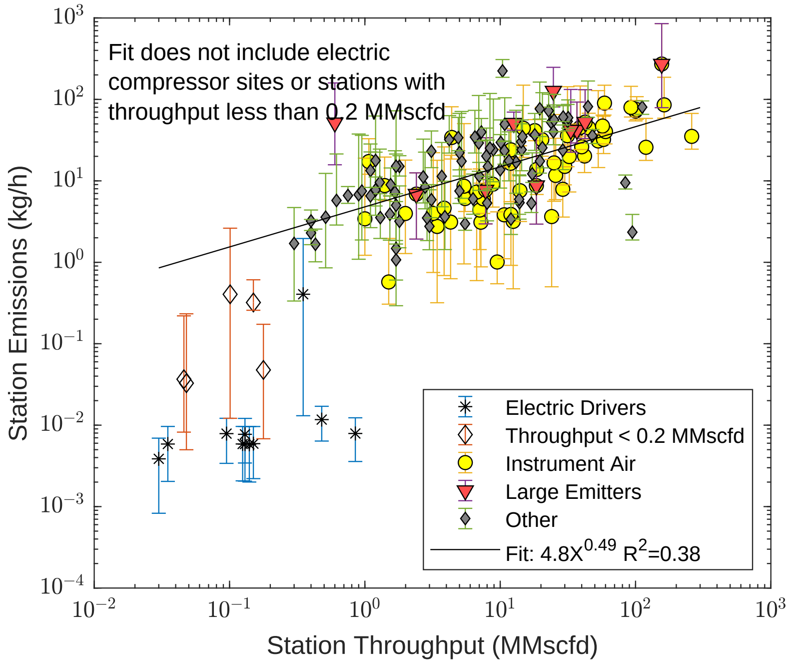


Figure S3-15: Emission rate as a function of throughput for the 157 stations in the field campaign where throughput data was available. Key characteristics of each station are indicated by point shape, including stations with all electric compressor drivers, stations where gas pneumatics and associated actuators are powered by instrument air, and stations with large emitters. Fit does not include 5 stations with throughput below 0.2 MMscfd or 11 small, all-electric, stations.

S3-6 National Emission Estimate

This section describes methods utilized to estimate national emissions. Section S3-6.1 discusses methods utilized to estimate the number of stations, which is used to estimate yard piping emissions, and major equipment units not included in GHGRP reports for the gathering and boosting sector. Section S3-6.2 describes the method utilized to scale activity data from GHGRP reports to a national estimate.

S3-6.1 Estimating Counts not Provided by GHGRP Reports

In general, the national emissions were estimated by utilizing major equipment counts from GHGRP reports for the gathering and boosting segment. However, as shown in Table S3-45, there are two categories where major equipment counts are not available – yard piping and separators. These must be estimated from other data.

Table S3-45: Activity Basis For National Model

Major Equipment Type	Counts in GHGRP Reports	Estimated from Station Count	Estimated from Other Ratio
AGRU	✓		
Compressors	✓[1]		
Dehydrator	✓[2]		
Separator			✓[3]
Tank	✓[4]		
Yard Piping		✓	
Pneumatic Controllers	✓		
Combustion Slip	✓[5]		

[1] Count of all compressors, including centrifugal and reciprocating.

[2] Count of large and small dehydrators combined.

[3] Ratio of separators-per-compressor developed from partner data and applied to combined compressor count for each GHGRP report.

[4] Count of large and small tanks combined.

[5] Since run hours and engine type are not known, the study assumed that mix seen in partner stations is representative of the mix of compressors in GHGRP.

Station Count Estimate: The number of gathering stations is not included in the GHGRP reports for the gathering and boosting sector. Since the emission factor for yard piping utilizes a *per-station* activity driver, the number of stations must be estimated at the basin or national level. While stations sizes vary widely (from 1 to 16), mean station size is substantially less variable, with 1.8 to 4.4 compressors per station across basins (considering only basins where partner companies had at least 25 stations). Using this data, a distribution of "compressors per station" was developed for each basin where sufficient partner data was available. This ratio is then used to estimate station count from the number of compressors in GHGRP reports.

Partners provided station information associated with 72 GHGRP reports. One partner provided station information by AAPG basin, but reported to the GHGRP using three separate reports, one for each operating company in the basin. In this case, all counts reported in the basin were combined for comparison purposes.

The ratio of compressors-per-station varies widely between basins and GHGRP reports, particularly for basins with few GHGRP reporters, and typically lower gas production. Therefore a separate ratio was developed for each basin where there were at least 100 partner compressors in the basin. To develop these estimates, an inverse Monte Carlo method must be used – identifying the number of stations required to account for reported compressor stations, rather than estimating the number of compressors given a number of stations.

In each basin there are S_p partner stations, each with a defined compressor count, $\{C_k, k = 1..S_p\}$. We also know that N_g compressors were reported to the GHGRP in that basin by partner and non-partner operators. We generate compressor populations by randomly selecting stations from $\{C\}$ and adding the compressor count:

$$\left[\sum_{i=1}^{S_j} draw(\{C\}, 1)\right] - N_g \leq \max(\{C\}) \tag{4}$$

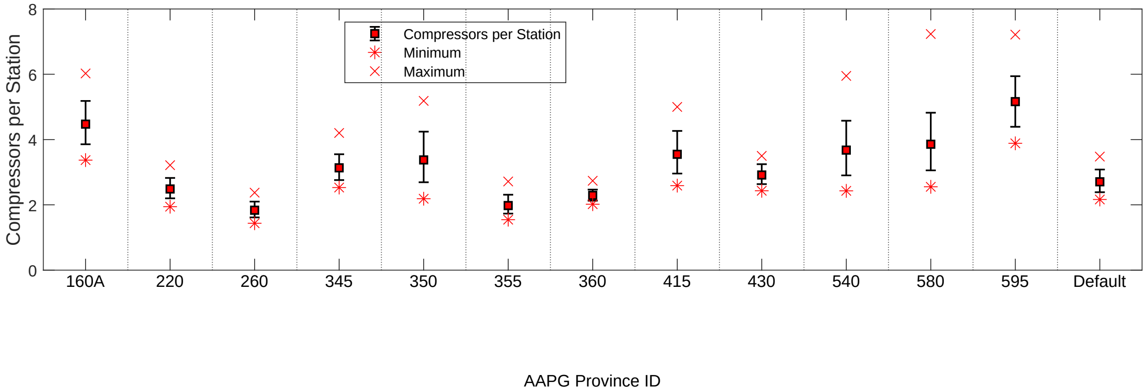
The unknown in this equation is S_j, the number of stations for Monte Carlo replicate j required to produce N_g reported compressors. The above equation is solved 5000 times to develop a distribution of station counts, $\{N\}$, each of which produces N_g total reported compressors. A distribution of compressors per station, $\{P\}$ is then developed by dividing the reported compressor count by the simulated station count:

$$\{P_j\} = \frac{N_g}{S_j}, j = 1..5000 \tag{5}$$

The resulting ratios are shown in Figure S3-16. For AAPG basins with less than 100 compressors, the station count was estimated utilizing a ratio developed using all partner data in all basins, and labeled as "Default" in the figure. The resulting estimate of station count is shown in Figure S3-20 and provide in data table *D17 Compressors per Station.*

Basin 545 has one GHGRP report with 18 tanks and no reported compressors. For this basin, the station count is estimated using the number of tanks encountered in the field campaign. This results in an estimate of 0.6 [0 to 1] stations per tank.

Separator Count Estimate: Similarly, the ratio of separators-per-compressor was developed to estimate the number of separators for each basin with GHGRP reports. Since a separator count was not included in site information provided by the partners (Section S3-1), this ratio was estimated from data collected on the 180 stations visited during the field campaign. Scaling factors were developed for each basin where the field campaign measured a minimum of 5 stations. In each basin, the count of separators and compressors for each station was bootstrapped, producing a distribution of ratios for each basin. All data not used in the per-basin factors was utilized to create a default distribution for all other basins. Results are shown in Figure S3-17 and in data table *D18 Separators per Compressor.*



Compressors	482	418	273	458	140	201	1,002	145	581	119	217	101	487
Stations	108	169	151	145	42	101	439	41	200	33	57	20	181

Figure S3-16: The ratio of compressors per station developed from partner data to estimate the station count for each AAPG basin. For each of the basins listed, partner data included more than 100 stations and a basin-specific ratio was developed. Partner data from outside the listed basins was used ot develop a default factor for use in all other basins.

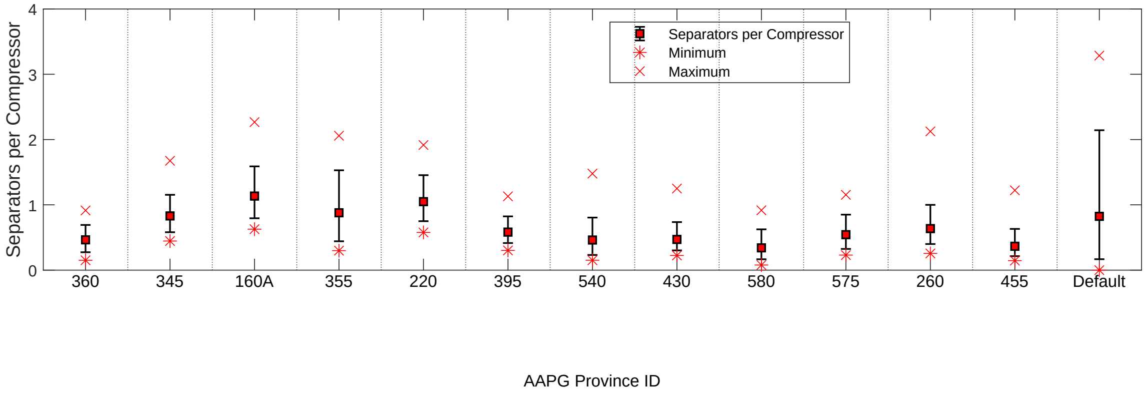
As with the station count for the basin with no reported compressors (basin 545), we estimated the separator count from the count of tanks and separators encountered in the field campaign, i.e. 1.1 [0 to 3] separators per tank.

Methane in Combustion Exhaust: Combustion slip (unburned methane entrained in combustion exhaust) is taken directly from Vaughn et al. [2], where a distribution of estimates was developed for each basin. Briefly, the model estimates the mix of compressor drivers for each basin using a combination of data from the GHGRP and data collected in the field campaign of this study. The model also estimates the typical load on compressors and average run time per year. The mix of driver types overall, and the mix of engine types for engine-driven units, varies substantially between basins. As a result, the combustion slip per compressor unit varies substantially between basins. Data from that paper is repeated in the data table *D19 Combustion Slip By Basin.*

Dehydrator Vent Emissions: Reported emissions for dehydrator vents (still or reboiler vents) were utilized directly from data reported to the GHGRP and then scaled to national estimates as discussed below. Large dehydrators ($\geq$ 0.4 MMscfd throughput) are reported with one record per unit [19, Table E.3]. Small dehydrators ($<$ 0.4 MMscfd throughput) are aggregated and reported as a single record for each basin [19, Table E.1].

Flaring Emissions: Flares are reported individually to the GHGRP [19, Table N.1] by estimating the quantity of gas sent to the flare and the methane combustion efficiency (typically 98%). GHGRP reports were used directly and scaled to national estimates as discussed below.

Blowdowns: Equipment blowdowns are reported as a count of blowdowns in several categories with estimated blowdown volumes [19, Table I.1 and Table I.2]. This data is included in the data tables in sheet *D4 GHGRP Blowdown Stacks.* Emissions from pipelines were excluded from this simulation, since this study focuses on station emissions.



Compressors	46	65	95	34	37	42	50	33	32	29	31	32	15
Separators	21	53	106	27	38	24	22	15	10	15	19	11	11

Figure S3-17: The ratio of separators per compressor developed from stations sampled in the field campaign. Basin-specific factors are developed for all basins where at least 5 were sampled in the field campaign. All data not used for basin-specific factors was utilized to develop the default factor for use in other basins.

S3-6.2 Scaling from GHGRP Reports to National Estimate

Gathering and boosting operations are reported to GHGRP if emissions from any operator's operation in a basin exceeds the reporting threshold of 25,000 metric tonnes of CO_2 equivalent emissions. Smaller operators in any basin, and small operations in basins with little gas production do not exceed this threshold and are not reported. Therefore, in addition to stations and equipment represented by the GHGRP reports, there are additional stations and equipment which are not reported to the GHGRP. No external information exists to directly scale GHGRP reports to national estimates. Therefore, to estimate the amount of non-reported equipment, we utilize a surrogate model developed from the production sector.

The DrillingInfo database [20] tracks the total natural gas production in the USA at a detailed level. GHGRP reports for the production sector (subject ot the same reporting threshold as G&B) include natural gas production equipment and production rate of oil and gas for all production operations, by basin. The national model assumed that the ratio between reported and non-reported gas production is a good estimate of the ratio between reported and non-reported gathering stations and equipment, and used this ratio to scale up GHGRP reported equipment counts and associated emissions to a national estimate. In general, we utilize the ratio:

$$f_1 = \sum_{i \in \{N\}} g_i / \sum_{i \in \{N\}} d_i \tag{6}$$

where d_i is the gas production from DrillingInfo, and g_i is the gas production reported to the GHGRP production sector, for basin i, and N is the set of all basins with GHGRP reports. Any equipment count, station count, or emission estimate in basin i, can be scaled using this factor to account for operations not reported to the GHGRP by applying $X_i = x_i/f_1$.

Starting with reporting year 2017 GHGRP data[19], we apply the following filters:

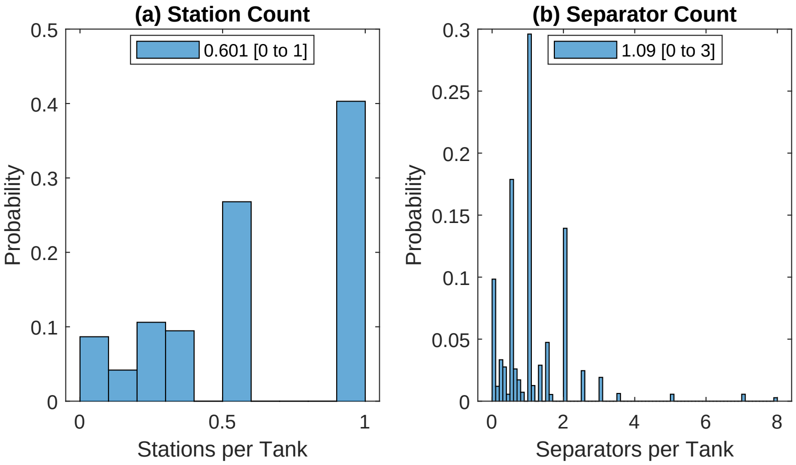


Figure S3-18: For basins with no reported compressors, station and separator count were estimated from reported tank count. Panel (a) shows the distribution of stations per tank, while panel (b) shows the distribution of separators per tank. Distributions are shown with no bootstrapping. Data can be extracted from data table *D9 Equipment*.

- GHGRP basin 210 has an known error where production is more than 250% of the DrillingInfo data, likely due to an erroneous report by one company; data from this basin was not utilized.
- To concentrate our analysis on gas-producing facilities, we eliminate any GHGRP basin where less than 50% of gas produced from wells is sold. This filter removes 6 basins accounting for 0.89% of GHGRP-reported gas production.

Starting with 65 basins that have non-zero DrillingInfo production data, 38 of those basins have GHGRP reports and 32 remain after all filters are applied; i.e. $N = 32$. These 32 basins produce 88% of gas production in the USA (DrillingInfo numbers). For currently available data $f_1 = 90\%$. All data is summarized in data table *D16 Production Ratio.*

In addition, the ratio d_i/g_i varies substantially between basins, particularly for basins with lower gas production and/or few GHGRP reports. Therefore, we modify Eqn. 6 to weight the probability of each basin by the gas production from DrillingInfo in each basin, and use the one ratio (with uncertainty) to scale all basins. This is performed by resampling $\{N\}$ so that each basin is represented proportionally to its gas production, and recomputing f:

$$f_w = \sum_{i \in \{\hat{N}\}} g_i / \sum_{i \in \{\hat{N}\}} d_i \tag{7}$$

where $\hat{N}$ is the proportionally up-sampled set of basins. Eqn. 6 is applicable in any basin with one or more GHGRP reports. For currently available data f_w =0.936 [0.907 to 0.957], meaning that this study estimate that approximately 94% of gathering station infrastructure is reported to the GHGRP. Initial and weighted distributions are shown in S3-19.

In addition, there are 27 basins with no production GHGRP reports but some DrillingInfo production. To account for this production, after scaling all basins by f_w, the total is additionally scaled to account for G&B operations outside basins with GHGRP reports. This factor is:

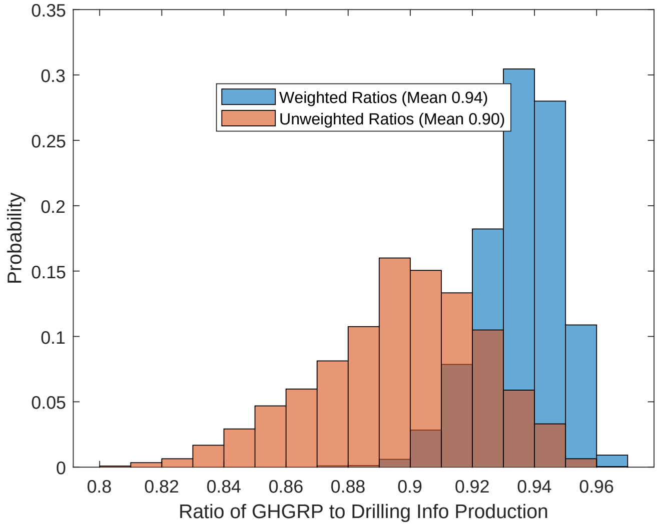


Figure S3-19: Scaling factor developed by comparing DrillingInfo™with gas production numbers from the GHGRP production [19, Table AA.1.i] at the basin level. Unweighted ratios reflect the input data after filtering (Eqn. 6), while weighted ratios reflect a weighted bootstrap of the input data (Eqn. 7).

$$f_o = \sum_{j \in \{M\}} d_j / \sum_{k \in \{M+N\}} d_k \tag{8}$$

where $\{M\}$ is the set of basins with no GHGRP reports. These basins constitute a small portion of USA gas production and $f_o = 0.63\%$.

Finally, results for station counts or emission estimates in each basin are scaled using f_w and total national emissions are scaled by $(1 + f_o)$ to estimate national emissions:

$$X = (1 + f_o) \sum_{i \in \{N\}} \frac{x_i}{f_w} \tag{9}$$

where x_i is a station count or emission estimate and X is the national estimate of that parameter. In practice both x_i and f_w are distributions and the division $\frac{x_i}{f_w}$ is accomplished using Monte Carlo methods.

Using these ratios and the ratio of compressors-per-station developed in Section S3-6.1, a national station count estimate was developed as shown in Figure S3-20. Initial scaling from GHGRP reports resulted estimate of 5,683 [5,447 to 5,926] stations, and the application of $(1+f_o)/f_w$ results in a national estimate of 6,111 [5,852 to 6,377] stations, including 6,075 [5,817 to 6,339] stations within basins with GHGRP reports and 36 [34 to 37] in other basins.

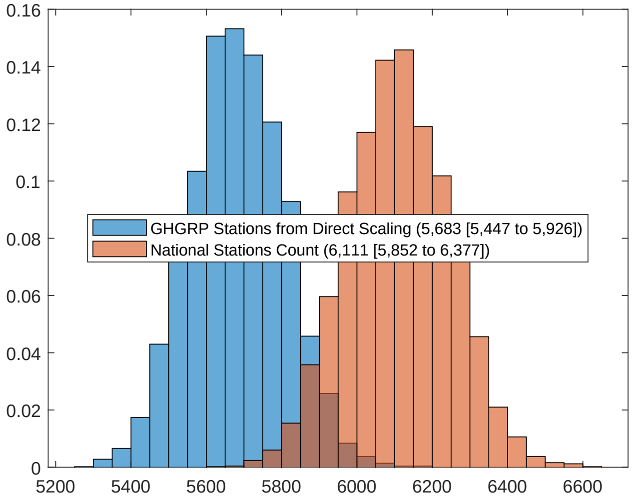


Figure S3-20: Estimated national station count. The initial estimate is made by estimating station count from compressor count, by basin, using ratios in Figure S3-16. The resulting estimate is scaled to a national estimate utilizing the gas production ratio between DrillingInfo and GHGRP production reports.

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