DRAFT INTERIM REPORT **PRELIMINARY**

US DOE NETL Award Number DE-FE0031702

Quantification of Methane Emissions from Marginal (Low Production Rate) Oil and Natural Gas Wells

Issued: 18 November 2020

Prepared for: **U.S. Department of Energy**
National Energy Technology Laboratory

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TABLE OF CONTENTS

Tables

Figures

Appendices

Abbreviations and Acronyms

BOE .... Barrels of oil-equivalent
CSU .... Colorado State University
DOE .... Department of Energy
EPA .... Environmental Protection Agency
GSI .... GSI Environmental Inc.
LDAR .... Leak detection and repair
METEC .... Methane Emissions Technology Evaluation Center
MCFD .... Thousand cubic feet of gas per day
NETL .... National Energy Technology Laboratory
NSPS .... New Source Performance Standards
OGI .... Optical gas imaging
OTM .... Other Test Method
QA/QC .... Quality Assurance/Quality Control
scfh .... Standard cubic feet per hour

EXECUTIVE SUMMARY

Background

The U.S. Environmental Protection Agency's New Source Performance Standards (NSPS, 40 CFR Part 60, Subpart OOOOa) regulates fugitive emissions from new and modified oil and natural gas facilities. A rule amendment published on June 3, 2016, introduced and enacted controversial requirements for fugitive emissions monitoring at low-production oil and natural gas wells producing less than 15 barrels of oil equivalent (BOE) per day, also known as "marginal" wells in terms of their profitability to operators. In 2017, EPA granted a petition to reconsider those requirements and then fully rescinded them on September 14, 2020.

There are more than 1.1 million oil and natural gas wells in the U.S., of which about 770,000 (~70%) are considered marginal. There remains much debate among concerned stakeholders regarding whether marginal well sites should be subject to or exempt from fugitive emissions monitoring and associated details of the NSPS. Independent oil and gas producers contend that costly leak detection and repair (LDAR) requirements could affect all producers but will, in particular, affect small oil and gas operators of marginal wells located in 30 states, with an associated economic impact. Environmental interests suggest that marginal well operations could be responsible for over 50% of the methane emissions from oil and natural gas production nationwide and assert that frequent LDAR for these wells is critical to achieving needed reductions. Despite many points of disagreement, opposing stakeholders generally agree, however, that there is no substantial body of reliable, nationally representative data on marginal well emissions and associated activity factors, and there is a critical need for such data to support future decisions and rulemaking on this important issue.

Study Objective and Approach

The current project commenced in March 2019 under an Assistance Agreement with the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), with supplemental cost share being provided by oil and gas industry partners. The objective of this research is to measure methane emissions from marginal well sites at various basins across the United States. The goal is to collect and evaluate representative, defensible and repeatable data and draw quantifiable conclusions on the extent of emissions from marginal wells across oil and gas producing regions of the U.S., and to compare these results to published data available on the emissions from non-marginal wells. The scope of work primarily consists of the major tasks listed below, each described further in this Draft Interim Report.

- ***Data Source Status Assessment and Master Workplan*** (Complete, see Section 2.0): Key data gaps were identified based on a thorough review of published sources and partially addressed by information derived from a broad survey of oil and gas well operators. This information guided development of a master workplan to establish and document necessary site and technology selection criteria and the overall approach for field data collection, evaluation, and reporting.
    - *Literature Review.* The findings of 17 studies published between 2010 and 2019 indicate that site-level emissions measurements and "activity data" (i.e., related to operations) collected prior to the present study largely underrepresent and are not enough to accurately characterize emissions from the large population and wide diversity of marginal wells across the U.S.

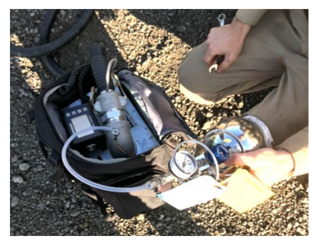
- *Blind Survey of Production Operators.* A confidential operator survey was conducted to gather representative information on the diversity of marginal and non-marginal oil and gas production site characteristics throughout the U.S. Survey questionnaires were widely disseminated to operators via multiple cooperating industry organizations. Responses representing over 86,000 sites across 29 basins in 23 states indicate that site characteristics most likely to relate to methane emissions include i) the main product generated at the site, ii) the production rate of oil and/or natural gas, iii) the "size" of the well pad defined in terms of the total site equipment count (wells, tanks, separators, etc.), and iv) the frequency of liquids unloading events. Figure 1, presented in Section 2.3, depicts the geographic distribution of 48 categories of sites representing the variability of these characteristics, based on operator survey responses.

- ***Regional Field Campaigns:*** Includes three 5-week field investigations, each performed in separate regions/basins. The ultimate objective of these campaigns includes capturing the variability and diversity of both physical and operational conditions, especially in areas with large numbers or a high density of marginal wells, or where marginal wells account for a large percentage of regional production.
  - *Field Campaign 1.* (Complete, see Section 3.0) Five weeks of field work were performed in October-December 2019 in the Appalachian, Illinois, and Forest City Basins, characterizing 116 discrete emissions detected among 233 sites. Figure 1 shows that the Appalachian is largely dominated by natural gas production, whereas oil production is predominant in the Illinois, and Forest City Basins. Site populations in other regions are much more diverse and not well represented by sites in the basins visited during Field Campaign 1.
  - *Field Campaign 2.* Originally planned for April-May 2020 in the Permian and Anadarko Basins, the Covid-19 pandemic and related travel and site access restrictions forced postponement of continued field work with a high degree of uncertainty. Two weeks of field work in the Upper Green River, Piceance, and Anadarko Basins were commenced on Oct 26, 2020. Tentative plans call for the remaining 3 weeks to be spent in the Permian and Palo Duro Basins in early 2021.
  - *Field Campaign 3.* Although included in the scope of work, federal funds have not yet been obligated to allow planning or execution of the final 5 weeks of field work, planned to include additional basins in the Rocky Mountains region, such as the Uintah and Denver-Julesburg Basins and, if possible, additional portions of the Permian and Anadarko Basin not reachable in Field Campaign 2. There is broad consensus among scientists with DOE, EPA, industry and environmental stakeholders that, due to the diversity and extensive geographic distribution of marginal wells across the U.S, there is a strong need for the full scope of the regional field campaigns to be carried out.

- ***Data Processing, Analysis and Reporting*** (see Section 4): Once qualified datasets from all regional field campaigns are fully developed, comprehensive exploratory and statistical data analyses will be performed to identify key groupings of sites in the studied regions and their distinguishing characteristics and emission profiles. Results will be applied to established site populations to i) extrapolate defensible estimates of total emissions from all producing well sites in each region/basin, ii) assess possible regional differences, and iii) if feasible, estimate comparable emissions in other oil and gas producing regions not included in this study. All activities, results and conclusions of the study will be summarized in a draft Comprehensive Report to be issued to NETL in September 2021.

- ***Technical Advisory Steering Committee*** (TASC, see Section 5): A full committee that includes representation from industry, regulators (including USEPA), non-government organizations, and academia, and a sub-committee comprised of industry representatives only were established and have convened on 3 occasions in order to provide input and feedback on key aspects of the project work scope.

Summary of Field Campaign 1



Employed Procedures: Field site selection and all field activities were performed in accordance with procedures detailed in the Regional Field Workplan (GSI, 2019b). Facilities were selected for measurement using geographically clustered, random sampling. All gas emissions were detected using an optical gas imaging camera and quantified, where possible, using a Bacharach Hi-Flow sampler in conjunction with gas composition-specific analyses. One emission was measured using the downwind tracer flux method.

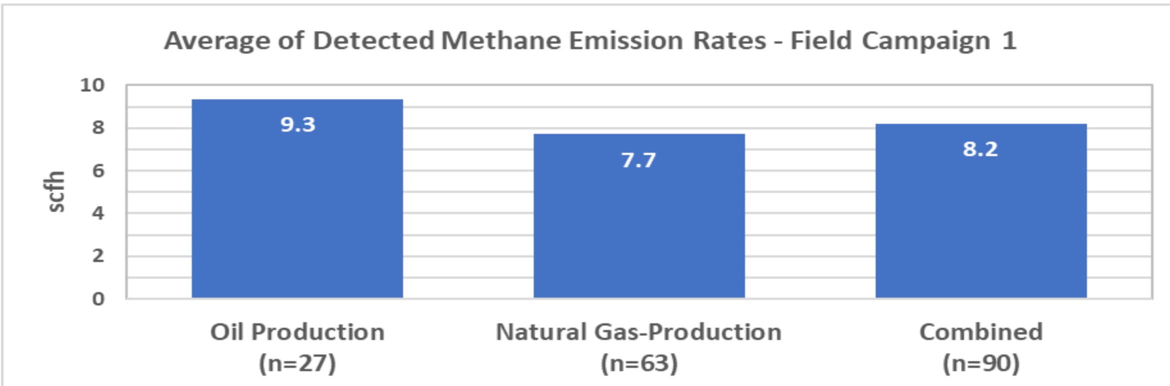
Visited Field Sites: Overall, 233 well sites were visited (146 natural gas sites and 87 oil sites), 228 of which exhibited marginal production at an average rate of 2.5 BOE per day of combined oil and natural gas (see Table 2 in Section 3.1). In the Appalachian Basin, 5 non-marginal sites producing 96 MCFD (16 BOE/day, "marginally non-marginal") to 4,000 MCFD (667 BOE/day) of dry gas were also visited. No non-marginal oil production sites were available in the visited regions. The relatively small size, low equipment counts, and ease of accessibility of most emission sources led to complete screening at all visited sites and complete measurements of most observed emissions. Besides emissions screening and measurements, detailed activity data, including major equipment counts and oil and gas production rates, were documented at each visited site.

Frequency of Detected Emissions: On a site-wide basis, no emissions were detected at approximately 65% of visited natural gas production sites and approximately 75% of visited oil production sites. Approximately 90% of the cumulative emissions detected in Field Campaign 1 are attributable to about 12% of the visited sites for both natural gas and oil production (see Figures 8 and 9 in Section 3.6).

Table 2, presented in Section 3.1, summarizes the frequency of detected emissions in terms of main product (i.e., at sites predominantly producing natural gas vs. oil) and type of equipment associated with each emission source. The frequency of detected emissions varied widely and exhibited no discernable patterns relative to observed equipment types or type of production.

Magnitude of Detected Emissions: Overall, emission rate measurements from Field Campaign 1 exhibit the long-tail behavior commonly observed in air emissions studies (see Figures 6 and 7 in Section 3.6). Approximately 90% of the observed emissions were less than 13 standard cubic feet per hour (scfh), and 95% of the observed emissions were less than 25 scfh. The top 10% of emission sources contributed 72% of the total emissions observed. The two largest emission sources, which alone accounted for 40% of the total measured emissions, correspond to an open hole in the wellhead casing of a marginal natural gas well (156 scfh) and the sucker rod packing on the pumpjack at a marginal oil well (137 scfh).

Tables 3 and 4, presented in Section 3 of this report, summarize the magnitude of measured methane emissions in terms of main product (sites predominantly producing natural gas vs. oil) and type of equipment or component associated with each emission source. Overall average measured methane emission rates are shown on the chart below.



Among natural gas sites, the average measured emission rate was 7.5 scfh (n=55) for sites with marginal production (≤15 BOE/d) vs. 9.0 scfh (n=8) at non-marginal production sites (>15 BOE/d). No site with non-marginal oil production was available to be measured in Field Campaign 1.

Preliminary Data Analyses: Figures 7 through 13, presented in Section 3.6, provide additional perspectives on the Field Campaign 1 dataset, including histograms of site-wide methane emissions and distributions of the emissions measurements categorized by equipment type and source component. Data analyses are ongoing and not complete. Therefore, the limited analysis and representations of data in this Draft Interim Report, and any interpretation of the same, should be considered preliminary.

Pending Comprehensive Data Evaluation

As described above, comprehensive exploratory and statistical data analyses will be performed on the fully developed datasets from all 3 regional field campaigns, as described in Section 4.0. It is important to recognize that the results presented here represent only a small fraction of the diversity of marginal well site characteristics present around the country, such as illustrated on Figure 1. Further investigation of sites exhibiting a broader range of product types, production rates, and site equipment counts in the remaining two field campaigns will provide more representative results and more meaningful conclusions upon completion of this project.

1.0 PROJECT OVERVIEW

1.1 Background

There are more than 1.1 million oil and natural gas wells in the U.S., of which about 770,000 (~70%) are considered "low production," producing less than 15 barrels of oil equivalent (BOE) per day. Production sites meeting this definition are also commonly referred to as "marginal" in terms of their profitability to operators. Similarly, wells producing less than 10 BOE per day are commonly referred to as "stripper wells". Marginal wells account for about 8 percent of total U.S. oil and gas production (IOGCC, 2016). Despite their production volume, some researchers suggest that these wells may be responsible for over 50% of the methane emissions from production operations but note that their sampling size (numbers of evaluated well sites) is too small to arrive at a firm conclusion on the relationship between production rates and methane emissions (Omara et al., 2018). Industry research has shown that costly leak detection and repair (LDAR) requirements could preclude continued production of many marginal wells, whose limited profitability already depends on the fluctuating oil and gas market (IOGCC, 2016; Bluestein, 2015).

1.1.1 Federal Regulation of Fugitive Emissions from Oil and Natural Gas Production

On June 3, 2016, the Environmental Protection Agency (EPA) published a final rule to amend the New Source Performance Standards (NSPS, 40 CFR Part 60, Subpart OOOOa) to reduce fugitive methane emissions from new and modified oil and natural gas facilities. This rule required semiannual leak monitoring at all production sites including marginal wells, which EPA had originally proposed to exempt during early rulemaking. In April 2017, EPA granted reconsideration on the applicability of the fugitive emissions requirements to low production well sites. Proposed rule changes were announced by EPA in October 2018 and August 2019.

On September 15, 2020, EPA published final technical amendments to the NSPS that rescinded fugitive monitoring requirements for marginal well sites and retained semiannual monitoring for non-marginal wells. The amended rule requires that a marginal well site either maintain its total production at or below 15 BOE per day or conduct semiannual monitoring. In a separate but related action, on September 14, 2020, EPA published final policy amendments to the NSPS that rescind all methane-specific requirements of the NSPS applicable to all sources in the oil and natural gas production and processing segments. Effective November 16, 2020, volatile organic compounds (VOC) became the only required emissions monitoring parameter for these sources.

Since EPA's September 2015 announcement of proposed NSPS amendments, there has been no shortage of debate regarding whether marginal well sites should be subject to or exempt from fugitive emissions regulation or associated details of the NSPS. For example, in its preamble to the 2016 rule, EPA cited an assumption that "low production well sites have similar equipment and components as sites that are not categorized as low production." In the preamble to the 2020 technical amendments, EPA cited "sufficient evidence that low production well sites are different than well sites with higher production." The latter is based on updates to the EPA "model plant" for low production well sites, by which assumed equipment types and component counts are used in conjunction with default EPA emission factors to estimate average site-level emissions. EPA indicated its updated model plant is based on fewer than 30 low production gas wells in a single basin. Many stakeholders on both sides of the policy debate have decried EPA's reliance on this data for nationwide rulemaking as "wholly inadequate" (Independent Producers, 2019) or "quintessentially arbitrary and capricious decision making" (Environmental Commenters, 2018). Considering that there are approximately 377,000 marginal gas wells and 394,000 marginal oil wells spread over 30 states, opposing stakeholders generally agree that there is no substantial body of reliable, nationally representative data on marginal well emissions and associated activity factors, and there is a critical need for such data to support future decisions and rulemaking on this important issue.

1.1.2 State vs. EPA Fugitive Emissions Monitoring Requirements

Current regulations in several states appear to incorporate federal NSPS requirements by reference. These include Kansas, Oklahoma, and West Virginia. In April 2018, during NSPS rulemaking, the EPA analyzed and summarized the requirements of various state fugitive emissions programs for well sites. They compared each state program's requirements to proposed revisions to the NSPS for the oil and natural gas sector (EPA, 2018). This analysis revealed many complexities and nuances of the state programs, which made them very difficult to compare qualitatively. While many differences were noted, EPA concluded that the fugitive emissions requirements related to monitoring, repair, and recordkeeping for California, Colorado, Ohio, Pennsylvania, Texas, and Utah were "equivalent" to those of the proposed NSPS amendments. EPA noted it was unable to determine the equivalency of requirements in Montana, New Mexico, North Dakota, and Wyoming.

In response to EPA's findings, analysts with the Environmental Defense Fund performed an independent comparison in addition to a quantitative analysis accounting for (among other factors) differences in the required timing to repair detected leaks, in order to assess the efficacy of state LDAR requirements to meet specified target methane emissions reductions relative to requirements of both the 2016 NSPS and 2018 proposed amendments. Based on their analysis, they concluded that the existing programs in California and Colorado would outperform the 2016 NSPS requirements in achieving methane reductions, and only these states plus Ohio would outperform requirements of the 2018 proposed amendments (McVay and Roberts, 2018).

1.2 Study Objective and Approach

The objective of the present study is to collect and evaluate representative, defensible, and repeatable data from marginal well sites and draw quantifiable conclusions on the extent of emissions from marginal wells across oil and gas producing regions of the U.S. Key questions include:

- How do marginal vs. non-marginal wells compare in terms of: production rates; type and quantity of equipment; frequency/timing of episodic high-emission events; equipment type/age/condition; absolute contribution to total emissions?
- How do site characteristics correlate with emissions?
- How significant are marginal well emissions?

To answer these questions, the scope of work of the present project (defined in the Statement of Project Objectives, last revised 22 Aug 2019) includes the major components listed below, each described further in subsequent sections of this Draft Interim Report.

- ***Data Source Status Assessment and Master Workplan*** (Complete, see Section 2)*:* Identified critical data gaps based on a thorough review of published sources and information derived from operator surveys; Established and documented necessary site and technology selection criteria and the overall approach for field data collection, evaluation and reporting.

- ***Regional Field Campaigns:*** Includes three 5-week field investigations, each performed in separate regions/basins. The ultimate objective of these campaigns includes capturing the variability and diversity of both physical and operational conditions, especially in areas with large numbers or a high density of marginal wells, or where marginal wells account for a large percentage of regional production.
  - *Field Campaign 1.* (Complete, see Section 3.0) Five weeks of field work were performed in October-December 2019 in the Appalachian, Illinois, and Forest City Basins, characterizing 120 discrete emissions detected among 233 sites.
  - *Field Campaign 2.* Originally planned for April-May 2020 in the Permian and Anadarko Basins, the Covid-19 pandemic and related travel and site access restrictions forced postponement of continued field work with a high degree of uncertainty. In efforts to safely and effectively advance project objectives as expeditiously as possible, throughout the summer of 2020 the project team, in coordination with NETL, actively monitored and pursued opportunities to access field sites in regions originally contemplated for Field Campaign 3. Two weeks of field work were commenced on October 26, 2020 and included sites in the Upper Green River, Piceance, and Anadarko Basins. Scheduling of the remaining 3 weeks remains on hold pending anticipated access to sites in the Permian and Palo Duro Basins in early 2021.
  - *Field Campaign 3.* Although included in the scope of work, federal funds have not yet been obligated to allow planning or execution of the final 5 weeks of field work, planned to include additional basins in the Rocky Mountains region, such as the Uintah and Denver-Julesburg Basins and, if possible, additional portions of the Permian and Anadarko Basin not reachable in Field Campaign 2. There is broad consensus among scientists with DOE, EPA, industry and environmental stakeholders that, due to the diversity and extensive geographic distribution of marginal wells across the U.S, there is a strong need for the full scope of the regional field campaigns to be carried out.
- ***Data Processing, Analysis and Reporting*** (see Section 4.0): Assess data and apply results to established site populations. All activities, results and conclusions of the study will be summarized in a draft Comprehensive Report to be issued to NETL in September 2021.
- ***Technical Advisory Steering Committee*** (see Section 5.0): Established and implemented in order to provide input and feedback on key aspects of the project work scope, the TASC is tiered, with a full committee that includes representation from industry, regulators (including USEPA), non-government organizations, and academia, and a sub-committee comprised of industry representatives only. Since inception of the project, the TASC has convened in April 2019, August 2019, and March 2020.

2.0 DATA SOURCE STATUS ASSESSMENT AND MASTER WORKPLAN

The Data Source Status Assessment Report and Master Workplan (GSI, 2019a) were issued to NETL as a single deliverable on September 30, 2019.

The Data Source Status Assessment involved the compilation, review, and analysis of existing available data regarding the frequency and magnitude of air emissions sources at both marginal and non-marginal oil and gas production well sites. Key activities under this task included performing a literature review to compile and review published, peer reviewed scientific articles to assess the quantity, quality, representativeness and usability to this study of data from previous studies; conducting a blind survey of oil and gas producing companies to collect available data on key site metrics; developing a GIS-enabled database of usable data from the literature and operator survey responses; and identifying gaps in the current understanding of emissions from marginal vs. non-marginal well sites.

The Master Workplan establishes and documents the overall study design needed to quantify methane emission rates and frequencies at representative populations of marginal oil and gas production sites. Field campaigns include two major components: i) a source survey to characterize the nature and frequency of key emission sources at a representative sample of well sites, and ii) a comprehensive emissions measurement program to quantify emissions from sufficient numbers of representative emitting sources. The key to this approach is a focused, statistically based selection of representative field sites included for screening and measurement. The Master Workplan details guidelines and procedures to meet needed levels of accuracy, representativeness and statistical rigor and ensure consistency among the collected data across different regions/basins.

2.1 Literature Review

Seventeen peer-reviewed papers published between 2010 and 2019 include evaluations of site-level emission measurements or estimates from approximately 9,000 production sites including approximately 25,000 wells spread across 13 major basins. Of this population, approximately 3,500 of the sites may be considered marginal and predominantly represent natural gas production, with very little representation of oil production. The major findings in the literature related to methane emissions from oil and natural gas production are summarized in the Data Source Status Assessment Report (GSI, 2019a) and point to the following major conclusions regarding emissions at oil and natural gas production sites:

- Site-level emissions measurements and activity data collected prior to the present study largely underrepresent low-producing wells and are not enough to accurately characterize emissions from the large population and wide diversity of marginal wells in the U.S.
- Key activity data and site-level characteristics associated with emissions, are especially needed, including operational data (e.g., liquids unloading type and frequency, frequency of unintended high-emission leak events, and leaked gas composition), equipment and component counts on per well basis.
- The most significant emissions sources appear to be vents and thief hatches associated with storage tanks, liquids unloading events, pneumatic controllers, and abnormal operating conditions.

2.2 Blind Survey of Production Operators

A confidential, blinded-data operator survey was conducted by the research team to gather representative information on the diversity of marginal and non-marginal oil and gas production site characteristics nationwide. The survey was designed and conducted in a manner consistent with the Paperwork Reduction Act of 1995 and the Office of Management and Budget requirements for information collection surveys. Key survey parameters included well location, site equipment counts, oil/gas production rates, and operational details.

Survey questionnaires were widely disseminated to operators throughout the United States by multiple cooperating industry organizations. The survey was designed to require a minimum of effort for operators to provide critical high-level information on marginal production sites, as needed to develop robust methane emissions measurement campaigns in multiple U.S. regions/basins and be able to extrapolate the findings of those campaigns across broader populations of production sites nationwide. In addition, operators were asked to provide information on non-marginal production sites, to the extent practical, for comparison with marginal well site characteristics.

The collected survey data helps to address data gaps identified by the literature review regarding site activity data for marginal well sites. Responses representing over 86,000 sites across 29 basins in 23 states indicate that site characteristics most likely to contribute to methane emissions include i) the main product generated at the site, ii) the production rate of oil and/or natural gas, iii) the “size” of the well pad defined in terms of the total site equipment count (wells, tanks, separators, etc.), and iv) frequency of liquids unloading events.

2.3 Emissions Source Characterization/Classification Criteria

Based on the variability of production site characteristics reported in operator survey responses, marginal well sites were classified according to parameters and categories as defined in Table 1. Using these criteria, each unique combination of parameter and category (e.g., dry gas site with production between 0-1 BOE/day/site and a medium well pad size) was assigned a different classification to assess the spatial distribution and variability of site characteristics.

Table 1. Marginal Well Classification Criteria

Parameter	Categories			
Main Product	Dry Gas	Wet Gas	Light Oil	Other*
Production Rate (BOE/day/site)	0-1	>1-4	>4-8	>8
Well Pad Size (Pieces of equipment)	Small (1)	Medium (2-3)	Large (4-5)	Extra-Large (>5)
Disposition of Associated Gas (oil wells)	Recovered	Vented	Combusted	Other/NA

* Other main products are coalbed methane and heavy oil, which represent a very small portion of the survey responses.

Figure 1 depicts the geographic distribution of 48 site categories represented in the results of the operator survey, where each color represents a unique category and similar (but distinct) colors visually represent more closely related categories. On this map one can see that marginal wells in the Appalachian and Arkansas Basins are largely dominated by natural gas production, whereas oil production is predominant in the upper Midwest. Other regions represented in the survey are characterized by much more diverse populations of marginal well sites representing both oil and gas production.

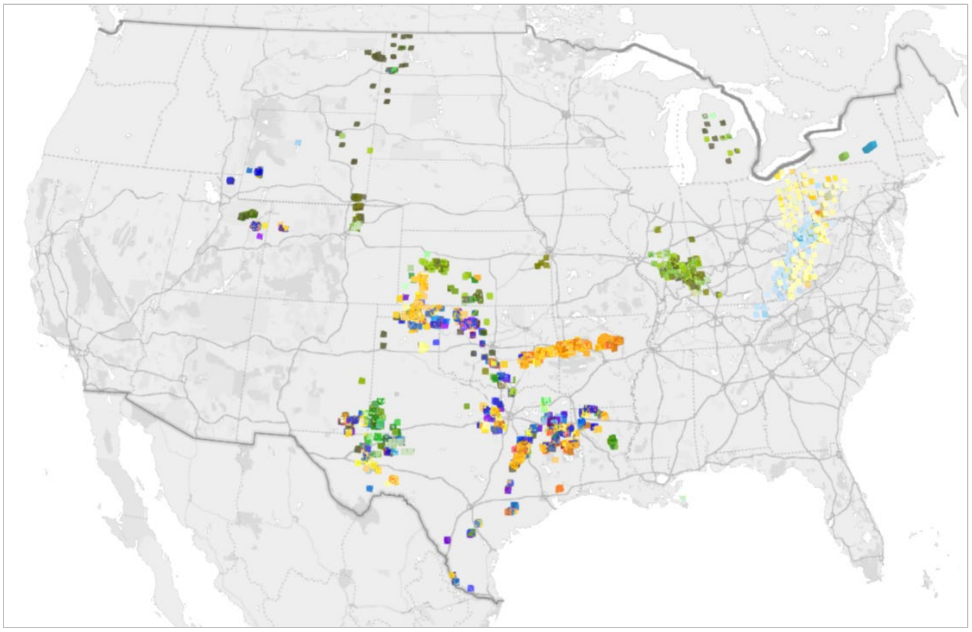


Figure 1. *Marginal well sites represented in operator survey results. Sites primarily producing dry gas are shown in colors ranging from yellow to red, wet gas sites range from purple to blue, and oil sites are in shades of green. Within each major product category, distinct colors represent differences in equipment count and production rate.*

2.4 Key Data Gaps Addressed

Key data gaps identified by the literature review included site activity data and methane emission measurements for representative populations of marginal oil and gas production sites. A new wealth of such data was collected by way of the operator survey, as detailed in the Data Source Status Assessment Report (GSI, 2019).

Most importantly, the regional field campaigns will provide a substantial body of data on the nature and magnitude of methane emissions across a diverse population of marginal oil and gas production sites located across the United States. In addition to methane emission screening and measurements, additional detailed activity data are being documented for each field site, including production data, gas-oil ratio, number of wells, equipment counts, gas composition, and general operations information, especially as pertinent to understanding individual emissions measurements.

3.0 REGIONAL FIELD CAMPAIGN 1

3.1 Field Campaign Overview

Regional Field Campaign 1 was performed between October 28 and December 13, 2019, including 25 days of emissions screening and measurements by scientists with GSI and the Colorado State University (CSU) Energy Institute using the METEC mobile laboratory (see https://energy.colostate.edu/metec/). Sampling in weeks 1 to 4 was conducted in the Appalachian Basin, and sampling in the Illinois and Forest City Basins was conducted in week 5 (see Figure 2). Field site selection and all field activities were performed in accordance with procedures detailed in the Regional Field Workplan (GSI, 2019b). Regulatory compliance was demonstrated through the issuance of all necessary permits and National Environmental Policy Act (NEPA) approval.

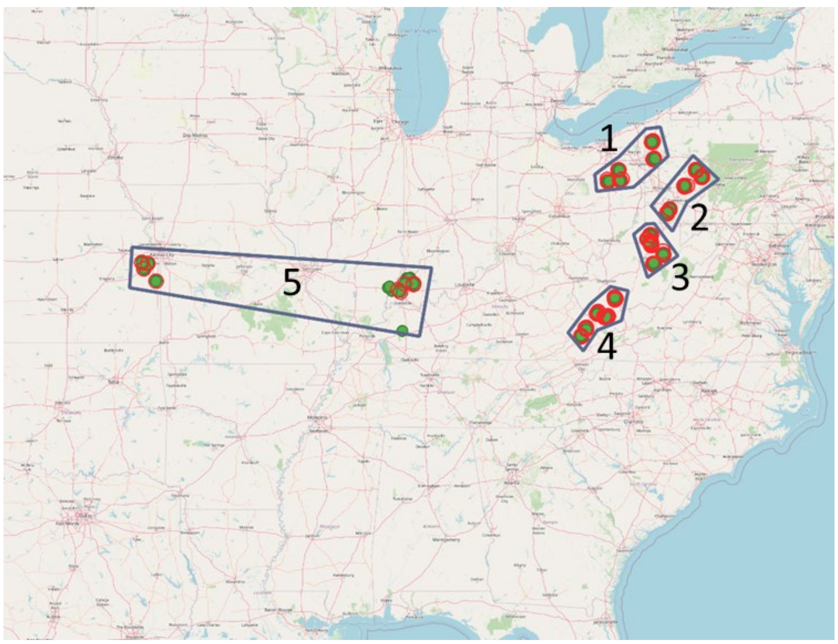


Figure 2. *Field campaign sampling clusters. Each of five measurement weeks occurred in the geographic regions highlighted (blue boxes). Shown within each box are sites that were available for measurement (green, filled circles) and sites that were measured (red, hollow circles).*

Overall, 233 well sites were visited, 228 of which were marginal with an average 2.5 BOE per day of combined oil and gas production. The relatively small size, low equipment counts, and ease of accessibility of most emission sources led to complete screening at all visited sites, and complete measurements of most observed emissions (i.e., a small percentage of emissions could not be not measured due to inaccessibility or equipment malfunction). Table 2 summarizes the frequency of detected emissions (116 discrete emissions in total) among observed equipment and site production types. These results exhibit large variability and no discernable patterns in the frequency of detected emissions relative to equipment type or produced product.

Eight emissions were quantified at 5 non-marginal well sites in the Appalachian Basin producing dry natural gas from 96 MCFD (16 BOE/day, “marginally non-marginal”) to 4,000 MCFD (667 BOE/day). We did not find opportunities to visit a non-marginal oil production site in any of the visited regions or any additional non-marginal gas production sites in the Illinois and Forest City Basins. We intend to collect data from more non-marginal oil and gas wells during subsequent field campaigns, especially targeting "marginally non-marginal" conventional wells producing in the range of 15-50 BOE/day, in contrast to much higher producing unconventional wells.

Table 2. Summary of observed equipment and detected emissions

	Natural Gas Sites (n=146)			Light Oil Sites (n=87)		
Equipment Category	#Equipment Observed	#Emissions Detected	Emission frequency	#Equipment Observed	#Emissions Detected	Emission frequency
Wellheads	165	32	19%	97	13	13%
Meters	157	3	2%	7	2	29%
Compressors	4	3	75%	2	0	0%
Separators	130	4	12%	28	4	14%
Dehydrators	1	0	0%	0	0	-
Tanks	157	-	-	68	-	-
Thief hatches	-	4	3%	-	8	12%
Vents	-	16	10%	-	14	21%
Yard piping	-	3	-	-	0	-

For purposes of this study, the precise definition and classification of an oil or natural gas production "site" can be subjective. During the course of Field Campaign 1, some locations where multiple wells were not located on the same well pad but were within close proximity (e.g. 20 wells within a 100-acre area) and shared a common tank battery, were designated as a single site. For purposes of data analysis, such wells were subsequently reclassified and counted separately due to large similarity of their characteristics with many other well-only sites visited during the field campaign.

3.2 Field Site Selection

Facilities were selected for measurement using geographically clustered, random sampling. Prior to embarking on the field campaign, target clusters of candidate sites were selected from region-wide lists made available by participating well operators (host operators). While actual field sites were chosen at random, the initial selection of candidate site clusters was iterative and, to the extent practical, sought to reasonably represent the larger regional and national populations of marginal production sites, maximize the number of facilities visited, and minimize potential biases.

In each region, a complete list of candidate sites in selected clusters for each operator was provided. Each day of sampling was dedicated to a specific cluster of sites with a specific operator. Daily short lists of target field sites were then chosen at random by the field team, no more than a day in advance of being visited, for emissions screening and measurement. This tiered and randomized approach to site selection sought to ensure the integrity of the study results by providing minimal advance notice to operators as to which sites would be visited.

For clusters with more sites than could be visited in a day, the following strategy was used. Sites were randomly selected and rank-ordered as "A", "B", or "C"-sites, which correspond to red, green, and blue dots , respectively, as shown in Figure 3. Note that the cluster of sites in Figure 3 appears as a single green dot in Figure 2. A-sites were the preferred sites to be visited, then B-sites. C-sites were generally not visited. In rare cases, exceptions were made to this strategy for logistical reasons. For example, if there was time to visit one more site in a day and the next A-site on the list was an hour drive away, a nearby B-site would be visited oppurtunistically to maximum the number of site visits for that day. For clusters with fewer sites, all sites within the cluster were screened.

Figure 3. *Daily site selection example. "A", "B", and "C"-sites (red, green, and blue dots, respectively) were chosen at random for measurement. Measured sites are noted with red circles.*

3.3 Emissions Screening and Measurement

The field investigation team was equipped with a variety of equipment and instrumentation, deployed using various methods, to detect and quantify methane emissions typical of oil and gas operations. Optimal screening and measurement methods were chosen at each site to best capture emissions, considering site-specific circumstances, instrumentation or method limitations, and operator safety.

In Field Campaign 1, all gas emissions were detected using an Opgal "Eye-C-Gas" 2.0 optical gas imaging (OGI) camera and quantified, where possible, using a Bacharach Hi-Flow sampler (BHFS), as shown in Figure 4. Summa canister samples of the gas were collected during 68 of 95 of the BHFS measurements for analysis by a third-party laboratory, as needed to determine the composition of sampled gas streams. Gas composition-specific data were used to determine the methane component of emissions measured with the high-flow method. Details of the procedure to derive corrected whole gas, methane, and VOC emission rates relative to BHFS instrument readings in the field are provided in Appendix A.

Additionally, with the METEC mobile laboratory, downwind techniques were available to quantify emissions not suitable for direct measurement with the BHFS, such as due to inaccessibility, high magnitude, or gas composition (see Figure 4). Downwind measurements were used only once during Field Campaign 1, where the tracer flux ratio method was utilized to measure an emission from a tank battery where the H_2S content of the field gas presented a safety concern and prevented an attempt at direct measurement.

Figure 4. *Emissions were identified using optical gas imaging (OGI) and quantified using the BHFS.*

Figure 5. *Setting up for a downwind tracer-flux measurement of a tank battery. Downwind sampling methods were employed only once during Field Campaign 1.*

A total of 24 emissions detected at 15 sites were not successfully measured. Due to a malfunction of the BHFS, which occurred over two days of sampling before it was identified and corrected, measurements of 17 emissions observed at 9 sites cannot be accurately quantified. At 5 other sites, 6 detected emissions could not be measured due to either i) being inaccessible and too small to measure with downwind techniques, ii) BHFS malfunction due to extreme weather (too cold for batteries), or iii) in one case, operator interference (an open valve was closed before we could measure). All emissions that were identified but not measured are noted and flagged in the field data measurement results. Based on OGI recordings of the emission sources and general observations of the site and equipment operations, these emissions appeared to be "typical" and are expected to fall within the distribution of other observed and measured emissions from comparable emission sources, as characterized in this study.

3.4 Site Activity Data Collection

Detailed activity data was documented at each visited site, including oil and gas production rates, major equipment counts, and a general functional description of site processes and activities. Additional data pertinent to understanding any individual measurement, including weather and operating conditions at the time of sampling, was also recorded to the extent available.

During each site visit, the host operator representative (usually the site pumper) escorting the sampling team was "interviewed" to characterize the nature and representativeness of conditions observed during the visit versus at other times, i.e., the expected variability in site conditions with respect to the potential for site emissions. In follow up to the field campaign, each host operator was requested to provide additional available site data, such as time series of well production data, reports of previous emissions monitoring or measurement efforts, etc. These data have yet to be fully collected and will be compiled and analyzed comprehensively with the results of field campaigns 2 and 3.

3.5 Emissions Measurement Results

In accordance with the Regional Field Workplan (GSI, 2019b), all field data were compiled and validated per applicable quality assurance/quality control (QA/QC) procedures and assessed for usability for further analysis. Tables 3 and 4 summarize the results of qualified methane emissions measurements for Field Campaign 1 in terms of major equipment type and component type, respectively.

Table 3. Equipment-Specific Methane Emissions

	Natural Gas Sites		*Light Oil Sites*		*All Sites*	
Equipment Category	**#Emissions Measured**	**Avg. Methane Rate (scfh)**	**#Emissions Measured**	**Avg. Methane Rate (scfh)**	**#Emissions Measured**	**Avg. Methane Rate (scfh)**
Wellhead	27	8.6	8	23.7	35	12.1
Meter	3	2.0	2	0.5	5	1.4
Compressor	3	5.6	0	-	3	5.6
Separator	12	1.7	1	9.2	13	2.3
Tank						
Thief hatches	3	28.6	7	2.0	10	10.0
Vents	12	8.3	9	4.3	21	6.6
Yard piping	3	8.6	0	-	3	8.6
Total	***63***	***7.7***	***27***	***9.3***	***90***	***8.2***
Total marginal	*55*	*7.5*	*27*	*9.3*	*82*	*8.1*
Total non-marginal	*8*	*9.0*	*0*	*-*	*8*	*9.0*

Table 4. Component -Specific Methane Emissions

	Natural Gas Sites		Light Oil Sites		All Sites	
Component Category	**#Emissions Measured**	**Avg. Methane Rate (scfh)**	**#Emissions Measured**	**Avg. Methane Rate (scfh)**	**#Emissions Measured**	**Avg. Methane Rate (scfh)**
Connector-flanged	1	12.3	0	-	1	12.3
Connector-other	14	3.1	0	-	14	3.1
Meter	3	2.0	1	0.3	4	1.5
Other	15	13.7	7	23.9	22	16.9
PRV	3	3.3	0	-	3	3.3
Regulator	1	1.1	0	-	1	1.1
Valve	10	2.0	2	11.5	12	3.6

3.6 Preliminary Analysis of Field Campaign 1 Results

Field data was collected during Field Campaign 1 from a limited area representing only a small fraction of marginal well classifications identified in the Data Source Status Assessment (see Section 2.0). Data analysis is ongoing; therefore, the limited analysis and representations of Field Campaign 1 results presented here should be considered preliminary. Further investigation of sites exhibiting a broader range of product types, production rates, and site equipment counts in the remaining field campaigns and subsequent comprehensive data analyses will provide more representative results and more meaningful conclusions (See section 4.0).

Overall, the emission rate measurements from Field Campaign 1 exhibit the long-tail behavior commonly observed in air emissions studies. As shown in Figure 6, 90% of the observed emissions were less than 13 scfh, and 95% of the observed emissions were less than 25 scfh. However, the top 10% of emission sources contribute 72% of the total emissions observed.

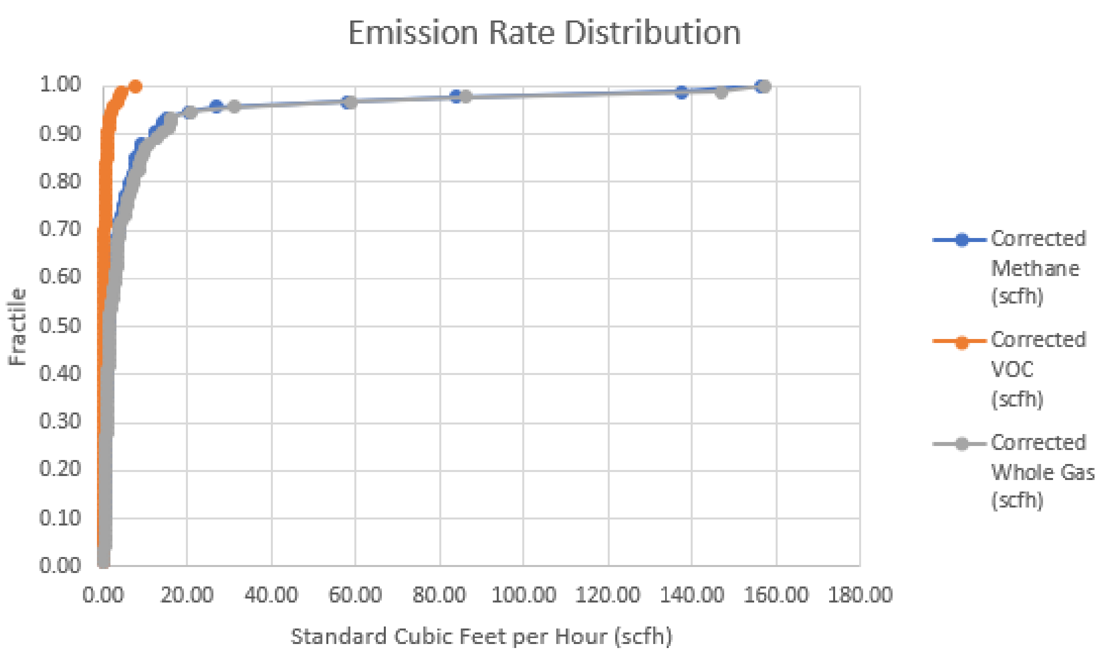


Figure 6. *Long-tail behavior is observed in emission rate results. Few of the emitters contribute most of the emissions.*

Figures 7 through 13 provide additional perspectives on the Field Campaign 1 dataset. In order to embody the full dataset, Figures 7 to 9 account for the 24 detected emissions that could not be measured with placeholder values equal to the overall average emission rate for the corresponding equipment type, as reported in Table 3.

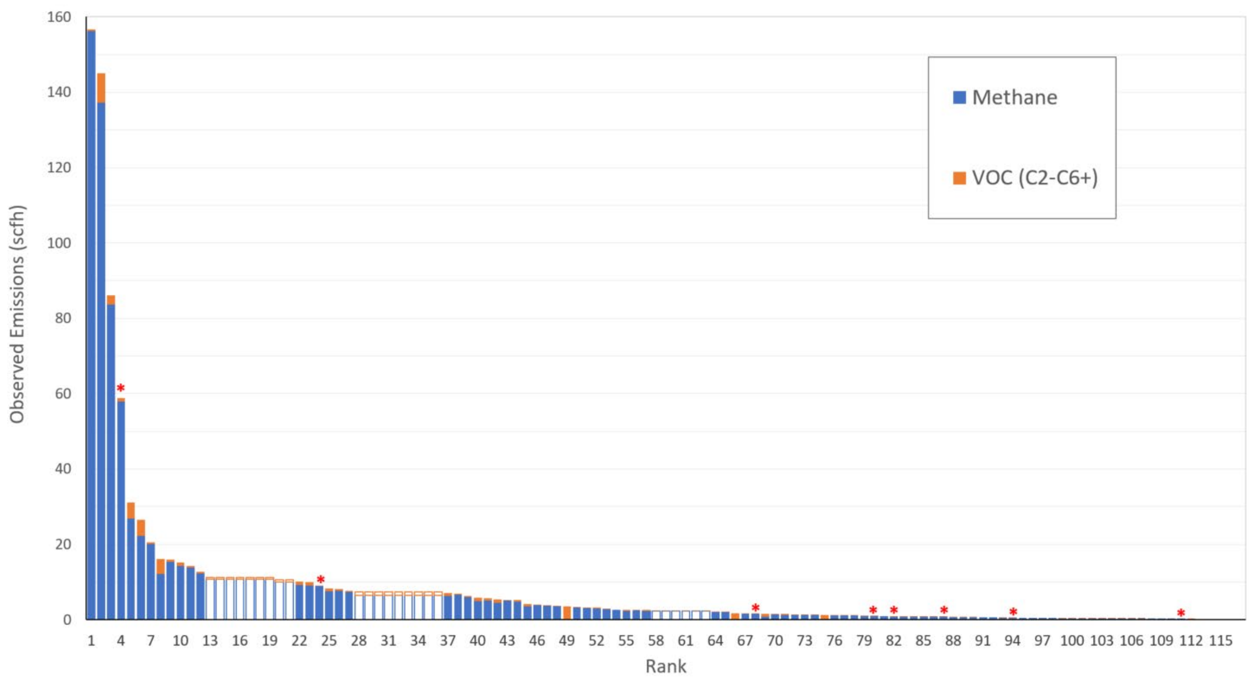


Figure 7. *All detected emissions (n=116) ranked from largest to smallest, including detected but unmeasured emissions (n=24) represented by unfilled placeholder columns showing the average emission for the corresponding equipment type (wellhead, tank thief hatch, tank vent, or separator; see Table 3). A red asterisk denotes each of the 8 emissions measured at non-marginal natural gas well sites.*

Although natural gas sites were classified as producing either dry or wet gas (greater or less than 85% methane), preliminary analyses indicate no significant difference between the distributions of emissions in these categories. Therefore, both wet and dry gas are included in natural gas production site counts. Figures 8 and 9 compare the distributions of emissions between natural production gas sites (n=146) and oil production sites (n=87). General observations to date include that no emissions were detected at approximately 65% of visited gas sites and approximately 75% of visited oil sites. On a site-wide basis, approximately 90% of the cumulative emissions detected in Field Campaign 1 are attributable to about 12% of the visited sites for both natural gas and oil production.

The two largest emission sources, which alone accounted for 40% of the total measured emissions, correspond to an open hole in the wellhead casing of a marginal natural gas well (156 scfh) and the sucker rod packing on the pumpjack at a marginal oil well (137 scfh). In both cases, these represent significant outliers for the "wellhead" equipment type and "other" component type, as shown on Figures 10 and 11.

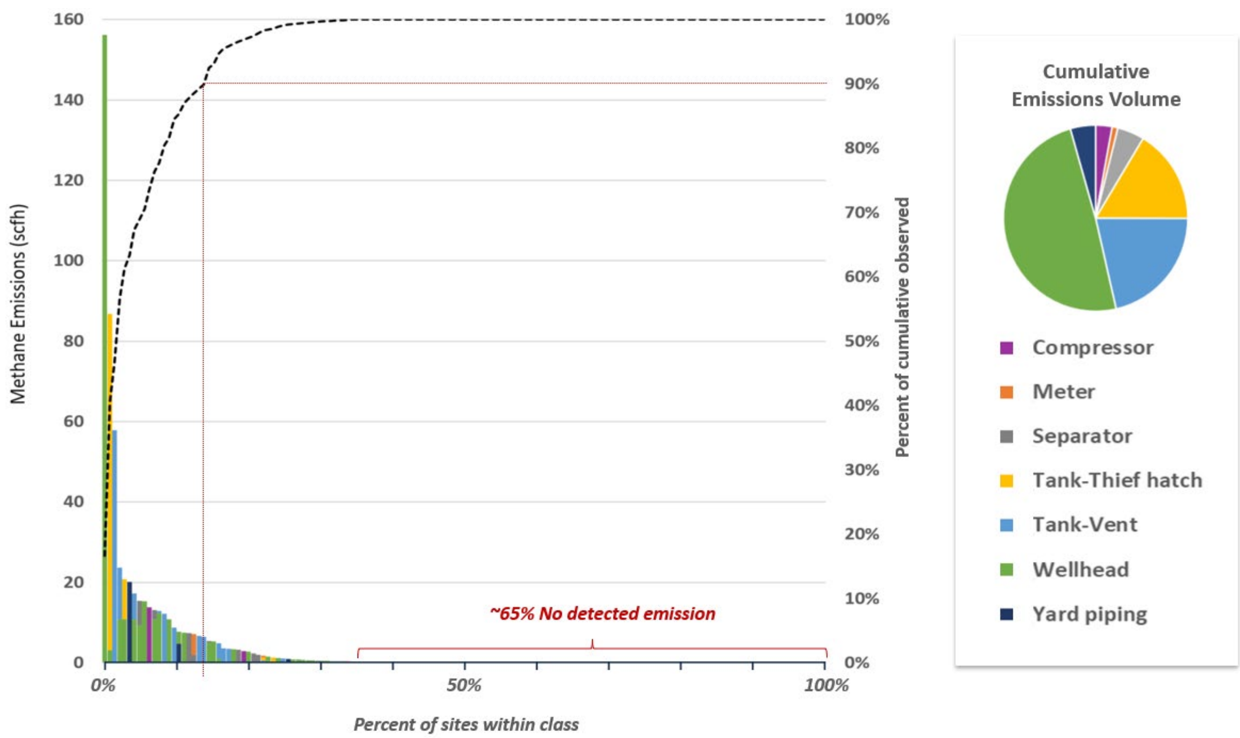


Figure 8. *Site-wide methane emissions - Natural gas production sites (n=146)*

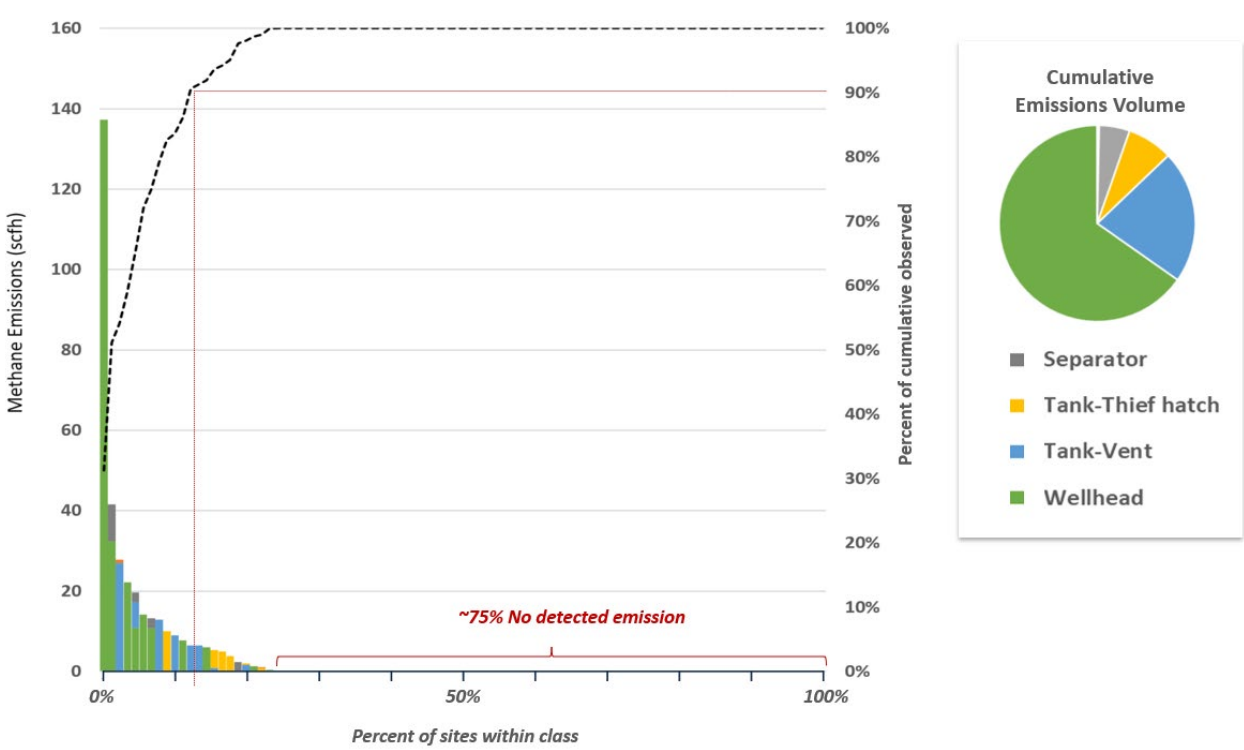


Figure 9. *Site-wide methane emissions - Oil production sites (n=87)*

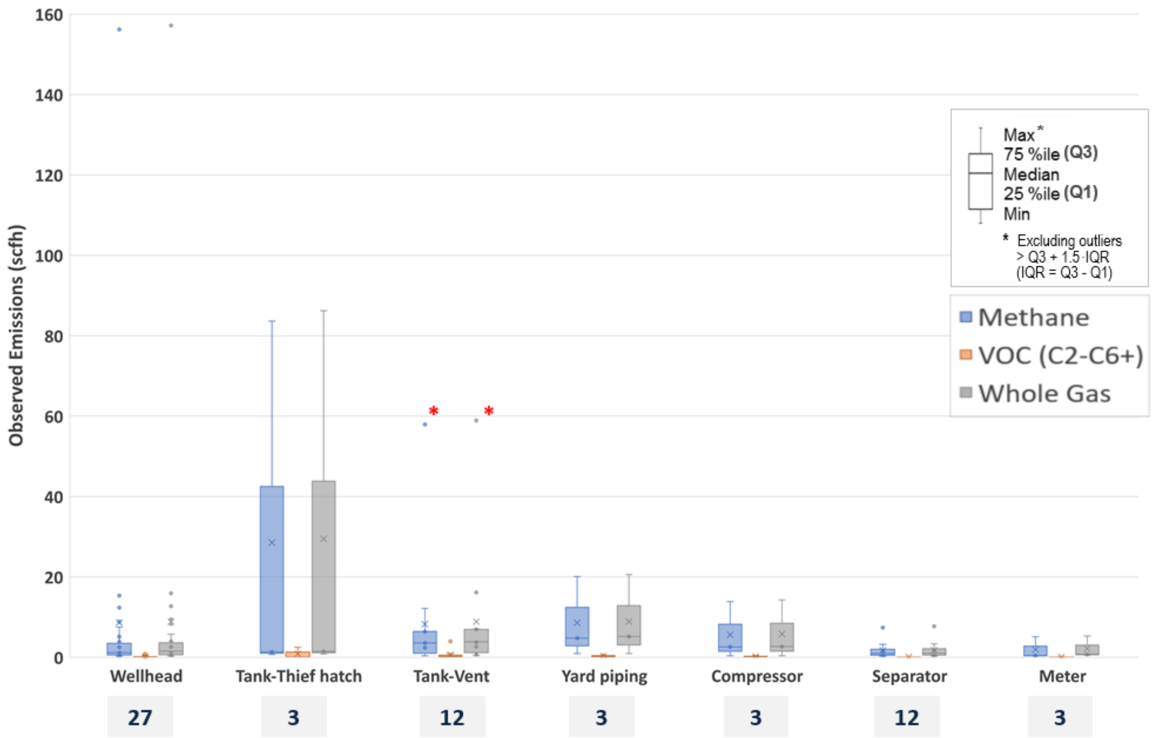


Figure 10. *Distribution of emissions by major equipment type - Natural gas production sites. A red asterisk denotes measurements at non-marginal well sites.*

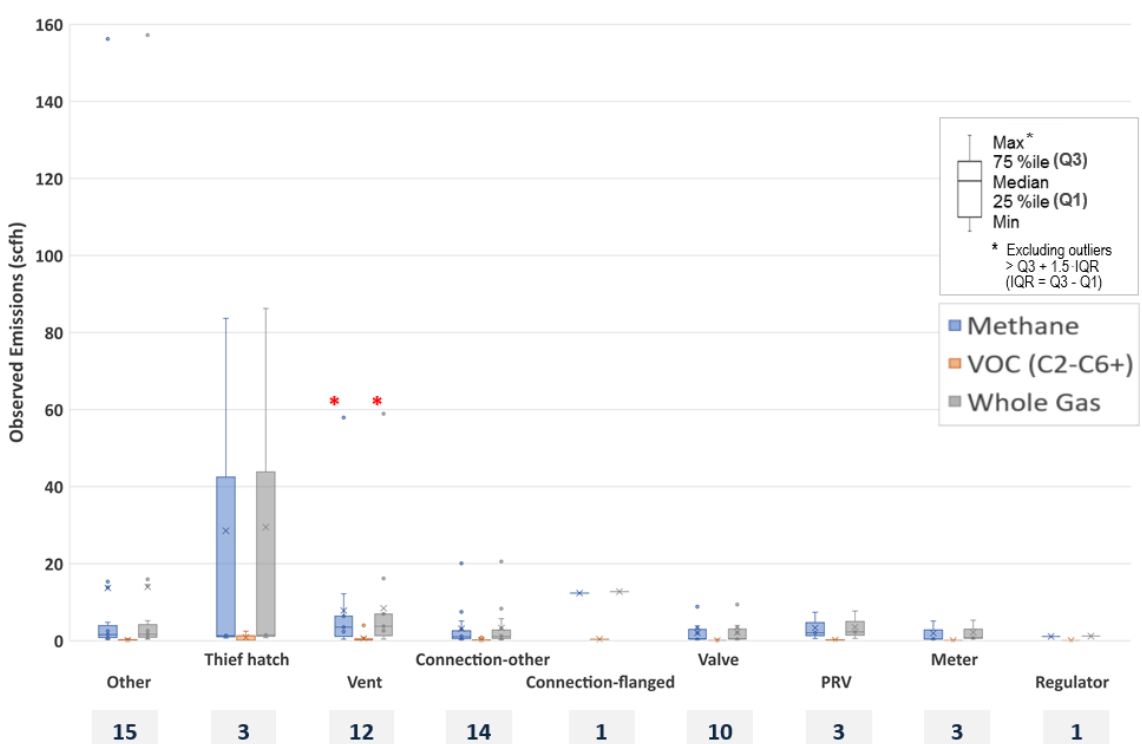


Figure 11. *Distribution of emissions by component - Natural gas production sites. A red asterisk denotes measurements at non-marginal well sites.*

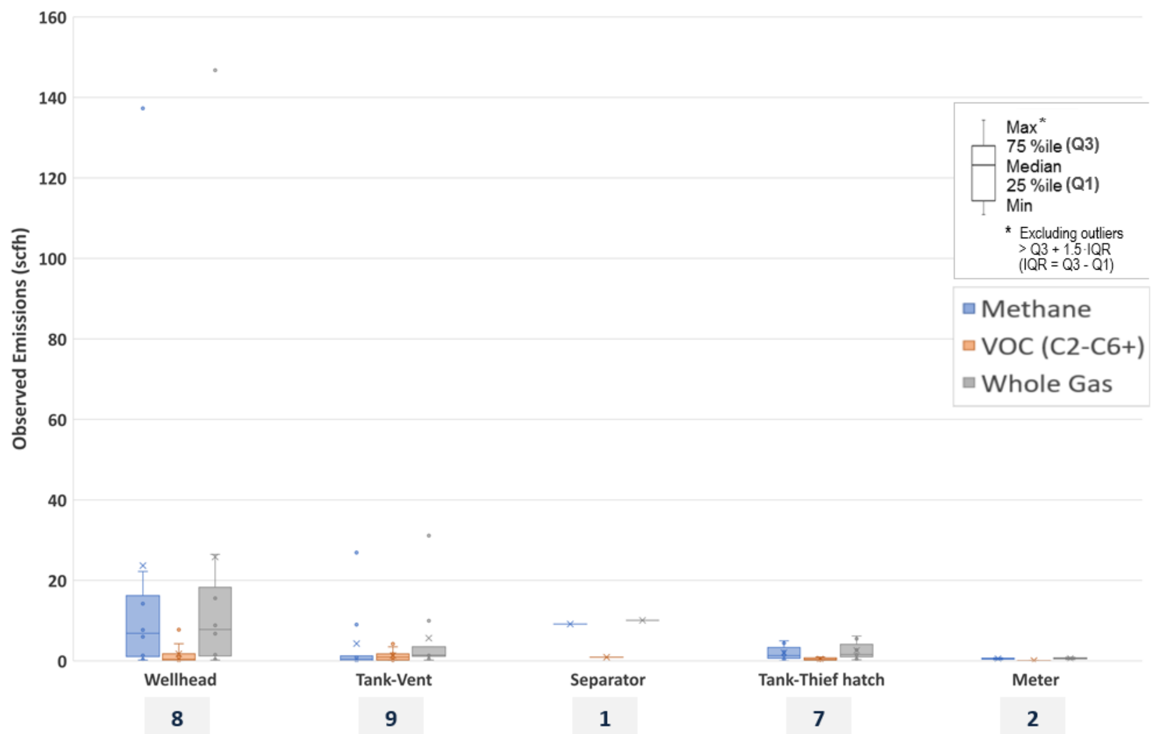


Figure 12. *Distribution of emissions by major equipment type - Oil production sites.*

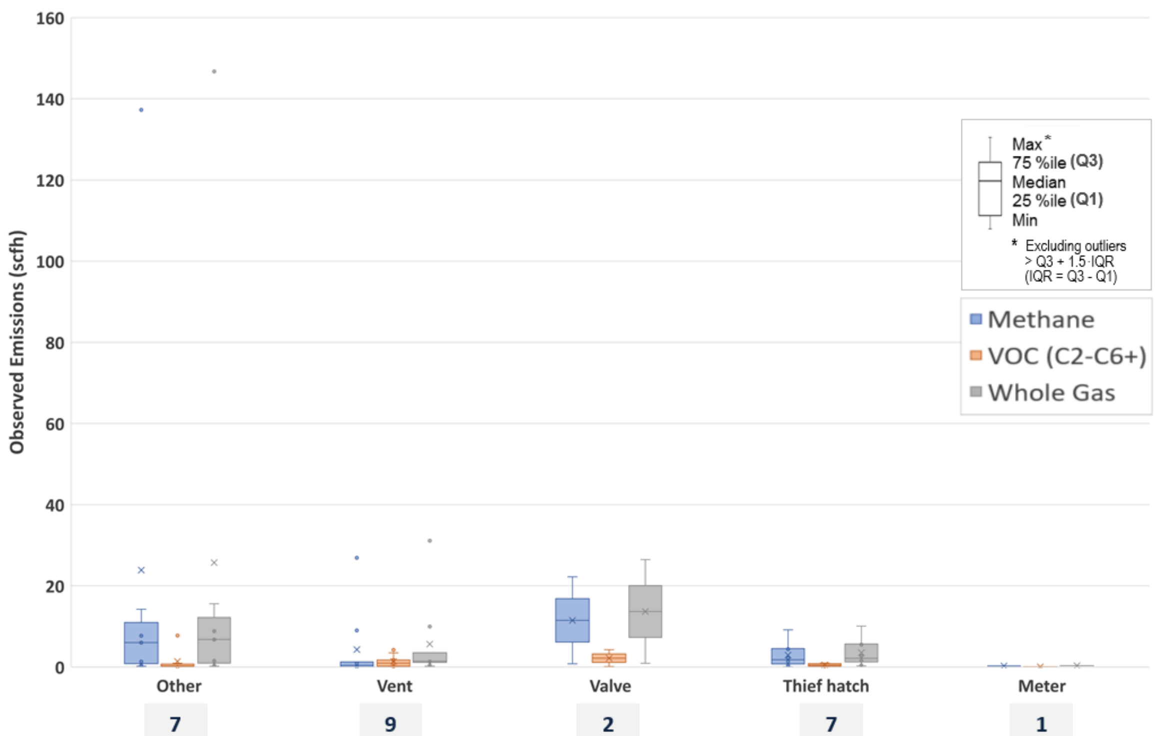


Figure 13. *Distribution of emissions by component - Oil production sites.*

4.0 COMPREHENSIVE DATA PROCESSING, ANALYSIS AND REPORTING

Once qualified datasets from all regional field campaigns are fully developed, comprehensive exploratory and statistical data analyses will be performed to identify key groupings of sites in the studied regions and their distinguishing characteristics and emission profiles. Figure 14 presents a conceptual example of planned analyses by which the initial site classification criteria defined in Section 2.3 may be reevaluated, and representative emission profiles will be developed for and compared among key marginal and non-marginal well site populations.

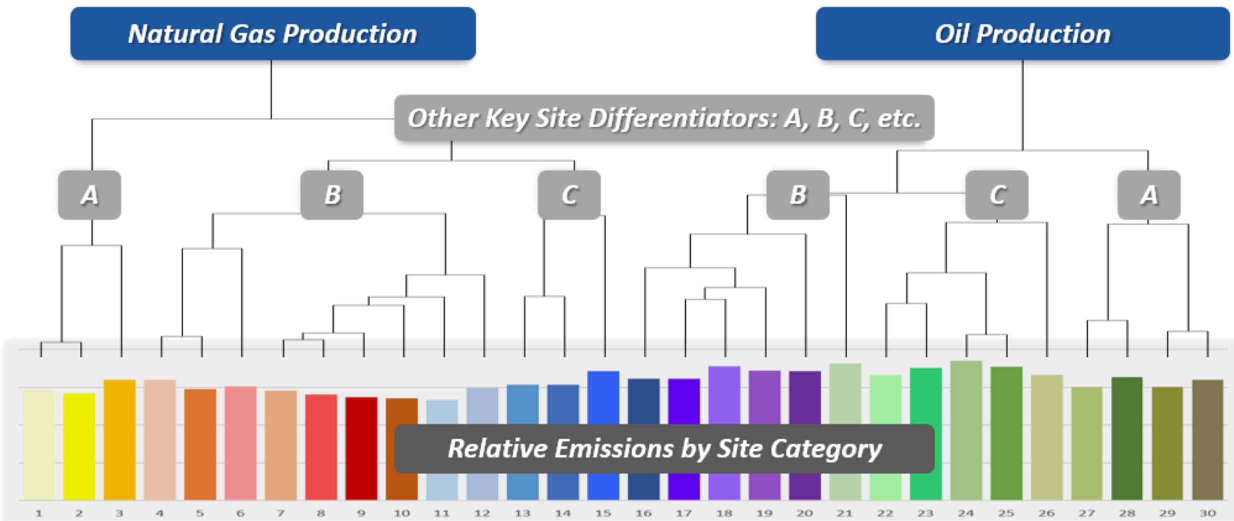


Figure 14. *Conceptual example of data analysis to develop representative emission profiles for distinct site populations, such as shown in Figure 1. Besides product type, other key differentiators may include "size" (equipment count), production rate, and other factors as determined through further analysis.*

The data and results will be synthesized for further spatial analysis and representation, as necessary. The combined results, including operator-provided activity data, frequency of emissions from key sources, and the magnitude of such emissions based on measurements collected at representative fractions of each type of emitting source, will be used to extrapolate defensible estimates of total emissions from all producing well sites in each region/basin. Additionally, actual region-wide counts and total emissions will be estimated and compared to assess possible regional differences and further, extrapolate the study results to estimate well site emissions in other oil and gas producing regions not included in this study.

In September 2021, the study will conclude with submittal of a draft Comprehensive Project Report to DOE/NETL (and supplemental funding sponsors) and meetings to discuss the key findings and conclusions. The report will summarize the scope/objectives, data collection procedures, and results of the regional field investigations, compare marginal well site emissions among different regions of the U.S., and contrast these findings with published data for both marginal and non-marginal well sites.

5.0 TECHNICAL ADVISORY STEERING COMMITTEE

There has been a high level of interest and participation on this project from industry and regulatory stakeholders concerned with quantification of methane emissions from marginal oil and gas wells. A Technical Advisory Steering Committee (TASC) was established and implemented in order to provide input and feedback on key aspects of the project work scope. The TASC is tiered, with a full committee that includes representation from industry, regulators, non-government organizations, and academia, and a sub-committee comprised of industry representatives only. Since the start of the project, the TASC has convened on three occasions as follows:

- ***April 2019:*** Four calls covering identical topics were held to introduce the project, discuss the preliminary literature review, planning of the operator data survey, and proposed field strategy.
- ***August 2019:*** Four calls covering identical topics were held to discuss the results and findings of the Data Source Status Assessment Report and draft Master Workplan, including site selection criteria for the upcoming field investigations. The research team incorporated extensive TASC feedback in preparation of the *Regional Workplan* for Field Campaign 1.
- ***March 2020:*** Two calls covering identical topics were held on March 12, 2020, to discuss preliminary results and findings from Field Campaign 1 and plans for Field Campaign 2.

The industry sub-committee played a major role during the initial data assessment and master workplan development. Subsequently, the full TASC has been enlisted to ensure site selection, regional workplans, measurement technologies, and data measurement and analysis approaches are adequately addressed to meet stakeholder requirements and strict quality assurance/quality control (QA/QC) standards.

Routine engagement and open communication with the TASC has provided an excellent opportunity for the GSI project team to inform key stakeholders of project plans and findings and for TASC participants to increase project efficiency by providing real-time feedback on sampling protocols, data analysis, and interpretation of findings.

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APPENDIX A

High Flow Sampler Measurement Correction to Account for Whole Gas Composition

APPENDIX A
High Flow Sampler Measurement Correction to Account for Whole Gas Composition

The Bacharach Hi-Flow sampler (BHFS) makes two critical measurements in order to report a resultant emission rate: 1) volumetric flow of the air and emission source being drawn through the device, and 2) the concentration of the emission source. Several steps were taken to ensure measurement quality of BHFS results. First, the bulk flow through the instrument was tested using a laminar flow element (LFE) and was confirmed to fall within the manufacturer's stated accuracy (5% of indicated). Volumetric flow rates were corrected to standard condition using daily average temperatures and pressures from nearby weather stations. Next, the concentration measurements were evaluated.

The BHFS uses a pellistor-based, catalytic oxidation sensor that is used in two modes: catalytic-oxidation (cat-ox) for emission rates less than 5%, and thermal conductivity detector (TCD) for emission rates greater than 5%. The operating mode of the sensor in the BHFS was noted during measurements in the field campaign; 87 measurements were made in cat-ox mode, and 8 measurements were made in TCD mode.

The sensor in the BHFS was calibrated daily, however the calibration was made on standard cylinders containing only methane. In a controlled environment, the BHFS could be calibrated on the actual gas being measured and the whole gas response would then be appropriate for that gas composition. In lieu of calibrating for all potential gases to be encountered in the field, Summa canister samples were taken at the inlet of the BHFS for 68 of the 95 measurements. Canisters were sent to a third-party laboratory for gas composition analysis. Reported gas compositions were then used to calculate an "expected" BHFS whole gas response relative to methane for the actual gas composition measured and the sensor mode during the measurement. Recorded field responses were then compared to calculated "expected" responses for verification. Field and laboratory results show reasonable agreement in aggregate for both the TCD and the cat-ox mode, as shown in Figures A.1 and A.2, respectively.

These results indicate that the BHFS measurements were reasonable and that future BHFS measurements made by the instrument calibrated on methane can be response-corrected by knowing the composition of the measured gas and the active sensor mode during the measurement. By taking a canister sample to get a representative gas composition for each measured emission, methane and VOC emission rates can be evaluated directly for those specific emission sources, and indirectly evaluated from the BHFS-reported whole gas results corrected by the recorded gas composition and sensor mode. Therefore, wherever multiple emissions were related to a common gas source, only one canister sample was needed to correct all related BHFS measurements.

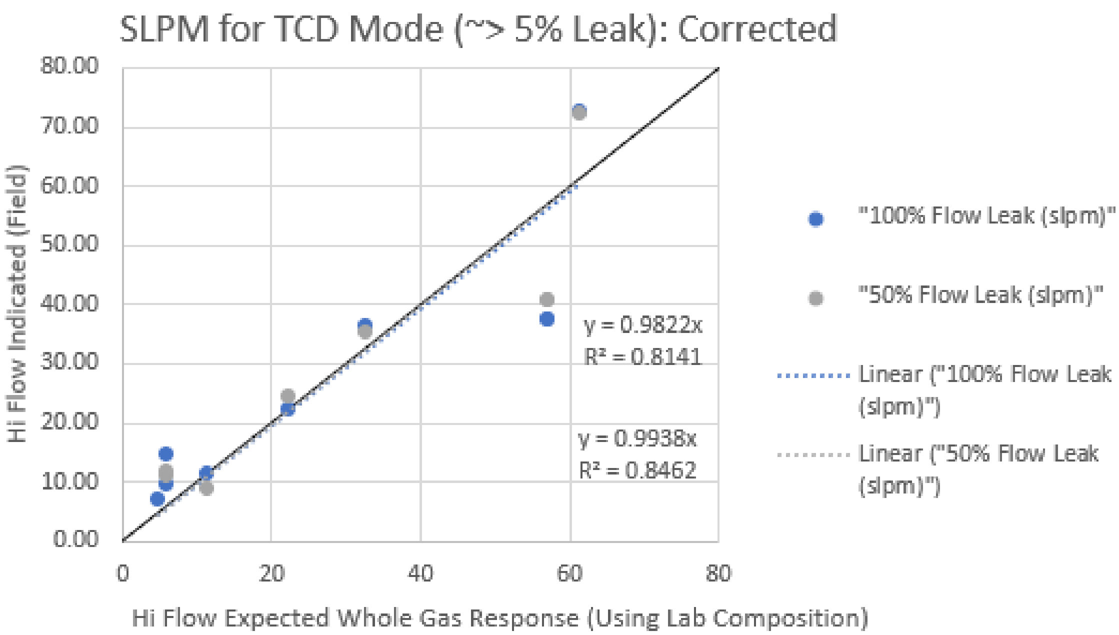

Figure A.1. *BHFS expected whole gas response compared to actual response for measurements made in thermal conductivity mode.*

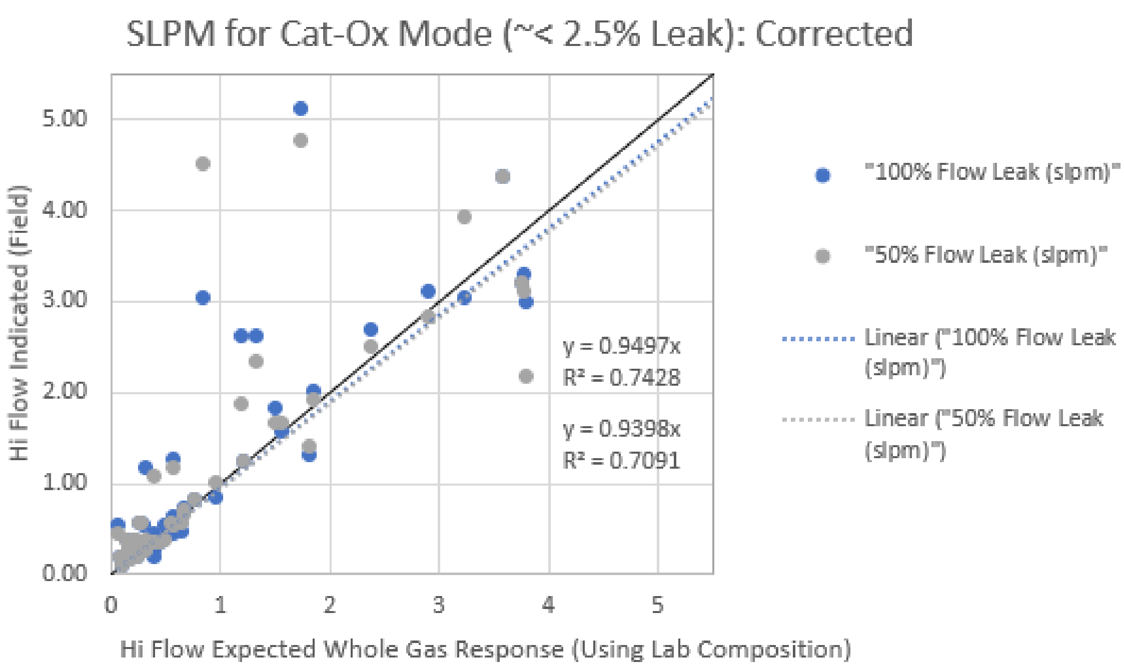

Figure A.2. *BHFS expected whole gas response compared to actual response for measurements made in catalytic-oxidation mode.*