METHANE MEASUREMENT GUIDELINES FOR MARGINAL CONVENTIONAL WELLS

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Table of Contents

Methane Measurement Guidelines for Marginal Conventional Wells

1. Purpose of the Guidelines

This document provides guidance and requirements for states and operators/well owners to measure methane emissions from marginal conventional wells (MCWs). As stated in the Funding Opportunity Announcement (FOA)-0003109, titled "Inflation Reduction Act (IRA)-Mitigating Emissions from Marginal Conventional Wells," Administrative and Legal Requirements Document (ALRD), these guidelines describe procedures for grant recipients to adequately measure and monitor methane emissions prior to and following the plugging and abandonment of any MCW (U.S. DOE et al., 2023). The measurements also verify that plugged wells are no longer emitting methane.

In 2023, in a separate but related program, guidelines for assessing methane emissions from orphaned wells were released to meet the Federal program reporting requirements for methane emissions reductions as described in Section 40601 (Orphaned Well Site Plugging, Remediation, and Restoration) of Title V (Methane Reduction Infrastructure) of the 2021 Bipartisan Infrastructure Law (BIL) (Public Law 117–158) (U.S. DOI et al., 2023). The Federal guidelines for the orphaned well program are to be continually reviewed for potential revision. While these guidelines for MCWs have been and will continue to be informed by the Federal guidelines for orphaned wells, there are significant differences in site equipment, characteristics, and expected average methane emission rates that warrant measurement approaches, protocols, and safety requirements specific to MCWs.

Given the variety of MCWs across the U.S., there is a need for multiple methodologies for the detection and measurement of methane emissions from MCW sites. Not every methodology presented here may be applicable to all well sites. These guidelines will be updated and refined as more comprehensive information becomes available. This may include suggested modifications to protocols as submitted to the authors of the guidelines by a grantee, contractor, or qualified measurement specialist. Additionally, emissions datasets will be reviewed to determine whether an emissions model can be developed for wells where measurement data is unavailable. Models may need to be specific to a geographic area, formation, or basin and consider geology, well age, depth, and type.

2. Introduction

There are more than 900,000 active oil and gas wells in the U.S. The majority of these wells are located onshore and target conventional reservoirs that trap hydrocarbons in high permeability formations below a sealing caprock. It is estimated that about 598,000 onshore conventional wells are marginally productive and potentially nearing their end of life (U.S. DOE et al., 2023). Marginal conventional wells (MCWs) are idle or producing onshore vertical or slightly deviated oil or natural gas wells (excludes highly deviated or horizontal wells) with a known owner/operator producing less than or equal to 15 barrels of oil equivalent per day (BOED) and/or 90 thousand cubic feet (Mcf) gas per day (1 BOE = 6 Mcf) over the prior 12 month period (U.S. DOE et al., 2023).

Estimates from 2019 indicate that oil and natural gas production from marginal wells (of which MCWs are a subset) contribute 6.2% and 5.8% of the national total from all wells, respectively (Environmental Defense Fund 2021). MCWs are concentrated in Appalachia, the Midwest, the Gulf Coast, the Rocky Mountains, and California—all regions that have a long and rich history of conventional oil and gas development (Figure 1). Nearly two-thirds (61.8%) of the MCW population are located in five states: Texas (30.2%), Pennsylvania (10.1%), Oklahoma (7.9%), West Virginia (7.7%), and California (6.0%). Sizeable MCW populations of more than 20,000 wells also exist in New Mexico (5.3%), Ohio (5.3%), Kansas (4.8%), Colorado (3.8%), Louisiana (3.4%), and Illinois (3.3%) (Figure 1).

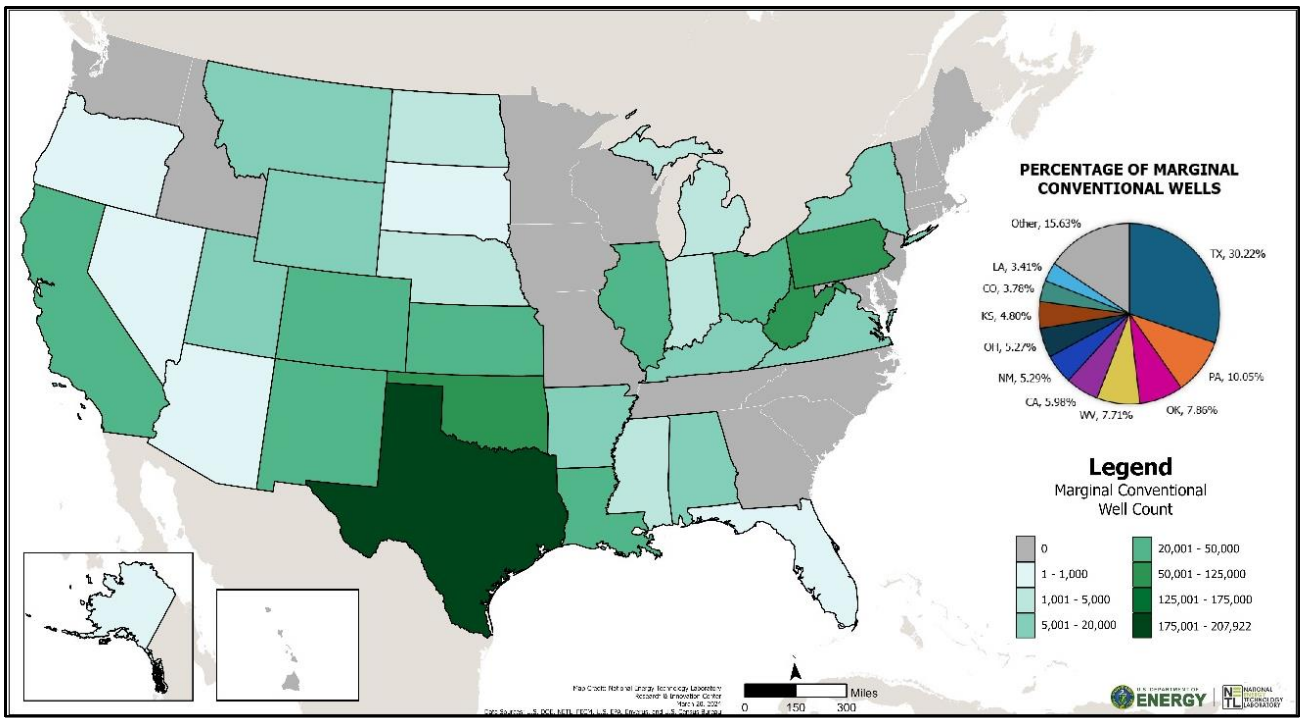

Figure 1: The number of MCWs aggregated per state in the U.S. (left) and the relative percentage of MCWs for each state (right) (calculated from Romeo et al., 2023, Enverus, and U.S. DOE et al., 2023).

Marginal oil and gas production in the U.S. contribute a large amount of methane emissions. One study estimated that marginal gas production is responsible for approximately 60% of the U.S. natural gas production emissions, while marginal oil production accounts for about 40% of the U.S. oil production emissions (Bowers, 2022).

Table 1: Relative Estimated Methane Emissions from Marginal and Nonmarginal Oil and Gas Production (Bowers, 2022)

	Approximate Well Count		Annual Production		Estimated Cumulative Methane Emissions			Average Population Emission Factors	
	Count	Share	boe/yr	Share	ton/yr	Tg/yr	Share	tons/yr/well	ton/MBOE
Natural Gas Production									
Marginal	420,000	78%	4.60E+08	7%	640,000 ±80,000	0.6 ±0.08	59% ±12%	1.5 ±0.2	1.4 ±0.2
Nonmarginal	120,000	22%	5.80E+09	93%	450,000 ±170,000	0.4 ±0.16	41% ±12%	3.7 ±1.4	0.077 ±0.030
Total Gas	540,000	100%	6.20E+09	100%	1,090,000 ±260,000	1 ±0.23	100%	2 ±0.5	0.18 ±0.04
Oil Production									
Marginal	363,000	80%	3.20E+08	8%	360,000 ±50,000	0.3 ±0.05	37% ±9%	1 ±0.1	1.1 ±0.2
Nonmarginal	88,000	20%	3.90E+09	92%	610,000 ±150,000	0.6 ±0.14	63% ±9%	7 ±1.7	0.16 ±0.04
Total Oil	451,000	100%	4.20E+09	100%	970,000 ±210,000	0.9 ±0.19	100%	2.2 ±0.5	0.23 ±0.05
Combined Oil and Gas Production									
Marginal	783,000	79%	7.70E+08	7%	1,000,000 ±140,000	0.9 ±0.13	49% ±11%	1.3 ±0.2	1.3 ±0.2
Nonmarginal	208,000	21%	9.60E+09	93%	1,060,000 ±320,000	1 ±0.29	51% ±11%	5.1 ±1.6	0.11 ±0.03
Total Oil & Gas	991,000	100%	1.00E+10	100%	2,060,000 ±460,000	1.9 ±0.42	100%	2.1 ±0.5	0.2 ±0.04

Emissions distributions from MCW sites are broad and vary by region and well type (petroleum versus natural gas) populations. On a macro-scale, the natural gas production and collection systems account for more methane emissions than petroleum systems (U.S. EPA, 2023). Heavy-tailed[1] distribution anomalies from high-emitting sites occur in either type of production site. The impact of the distribution skewness is significant, considering a fraction of sites (1–14%) can contribute ~50% or more to cumulative methane emissions from MCW sites (Lyon et al., 2016; Brandt et al., 2016; Omara et al., 2022). Furthermore, the data also suggest loss rates, or production-normalized emissions, from MCW sites increase as production declines. This results in disproportionally high emissions from ultra-low producing wells, which is why MCWs are being targeted for environmental mitigation (Omara et al., 2022). Abnormal site conditions, possibly caused by equipment malfunctions or failure, are the suspected cause of the disproportionally high emissions from high-emitting and ultra-low producing well sites. More wellsite equipment-specific emissions studies are needed to better understand the causes of these abnormal conditions (Alvarez et al., 2018).

Evidence suggests significant variations in emissions can occur over time; however, they happen stochastically and without clear seasonal or patterned trends (Deighton et al., 2022; Omara et al., 2022). Multiple factors (environmental and operational) can influence emissions from an MCW site, including atmospheric barometric pressure, operator-specific practices, and abnormal site conditions (Forde et al., 2019; Omara et al., 2022). Moreover, failure to monitor emissions coeval to one of these conditions may give an underestimated emissions result (Alvarez et al., 2018). Careful consideration of any suspected site-specific factors that can influence emissions is essential for accurate estimation of methane emission rate.

[1] A heavy-tailed distribution is a statistical distribution characterized by a higher probability of extreme values or outliers compared to a normal distribution. Heavy-tailed distributions are commonly observed from oil and natural gas emissions sources.

Generally, methane emissions can come from several sources common to all oil and gas well pads; however, certain emission scenarios are more common in MCW sites (Figure 2). Intentional vented emissions (designed as part of the production process) and unintentional leaks, also known as fugitive emissions, can occur at most components on a well site, such as wellheads, pneumatic devices, separators, dehydrators, compressors, and storage vessels (Omara et al., 2022). Fugitive emissions sources that are more prevalent in MCW sites are generally attributed to neglected maintenance on well infrastructure and correlate with deteriorated site conditions, such as corrosion-related integrity issues to subsurface casing, jacks, tanks, gathering lines, connections, and valves (Deighton et al., 2022).

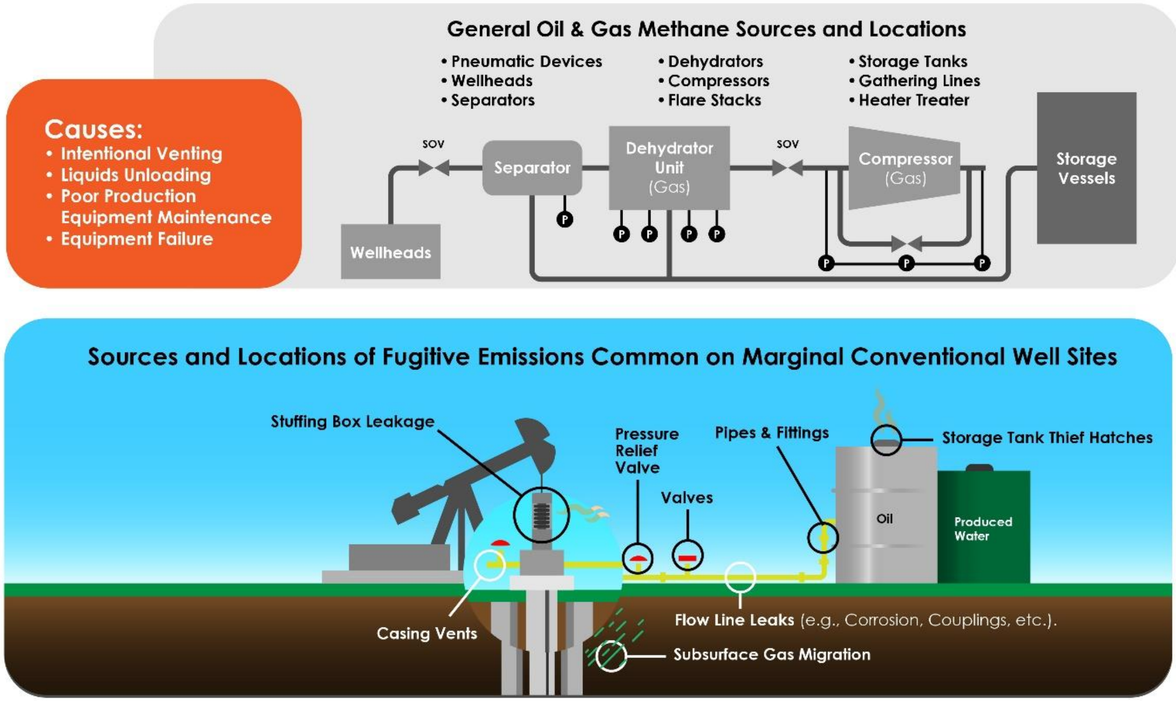

Figure 2: Schematic showing sources and locations of intentional and unintentional (fugitive) methane emissions on general (top) and MCW sites (bottom). Emissions on MCW sites can be combinations of intentional venting from shut-off valves (SOV), pneumatic devices[2] (P), and operating equipment, in addition to fugitive emissions from leaks.

In addition to methane, MCW sites can emit volatile organic compounds (VOCs), Hazardous Air Pollutants (HAPS) including benzene, toluene, ethylbenzene, and xylene (BTEX), and, in some cases, hydrogen sulfide (H_2S) (Deighton et al., 2022; El Hachem and Kang, 2022). Remediation of methane emissions through well site repair or plugging will also improve the overall environmental footprint from these other contaminants.

[2] Pneumatic devices are also referred to as process controllers and pneumatic controllers.

3. Purpose of the MERP-MCW Technical Assistance Program

The 2022 IRA amended the Clean Air Act by adding Section 136, "Methane Emissions and Waste Reduction Incentive Program for Petroleum and Natural Gas Systems" (also referred to as the Methane Emissions Reduction Program [MERP]) (codified at 42 U.S.C. 7436), which appropriated funds to the U.S. Environmental Protection Agency (EPA) for methane emissions mitigation and measurement at MCW sites. The U.S. Department of Energy (DOE) has partnered with the EPA to make a portion of these funds available to eligible states for the purpose of voluntary mitigation and measurement of methane emissions from MCW sites.

These activities are expected to result in methane and other greenhouse gas (GHG) emission reductions and to provide environmental benefits through the restoration completed as part of the well abandonment requirements for the wells. Results of these activities are also anticipated to mitigate legacy air pollution (through the reduction of associated non-GHG emissions) from oil and gas systems in low-income and disadvantaged communities and provide potential benefits to such communities, including improved ambient air quality, surface and groundwater quality, climate resiliency, and human health, as well as the creation of high-quality jobs.

The funding from the DE-FOA-0003109 has the following goals:

- Mitigate, to the maximum extent possible, methane and other GHG emissions by assisting the states and owner/operators to voluntarily identify and permanently plug MCWs;
- Measure methane emissions to provide a preliminary screening of emissions from MCW sites as a mechanism to inform plugging prioritization;
- Measure methane emissions from MCW sites prior to and following the plugging and abandonment to quantify mitigated emissions; and
- Support elements of environmental restoration required for full compliance with applicable state or Federal well plugging and abandonment standards and regulations.

Reference U.S. DOE et al., 2023 for more information on the MERP and associated MCW financial assistance.

4. Requirements for Methane Emissions Assessment

Grantees are required to measure methane emission rates prior to and following the plugging and abandonment of any MCW using applicable approaches described in these guidelines. Grantees must comply with all applicable state or Federal plugging and abandonment requirements. Facilities that report to the Greenhouse Gas Reporting Program (GHGRP) under Subpart W are required to follow the Subpart W quantification methodology (Code of Federal Regulations, 40 Part 98, 2024)[3] to quantify the methane mitigated from well plugging (see Section 5).

The purpose of pre-plugging measurements is to quantify mitigated methane. Quantitative approaches should have a minimum detection limit (MDL) of less than 100 grams/hour (g/h) and relatively high accuracy, so mitigated emission estimates are accurate. The purpose of post-plugging measurements is to verify the methane emissions are below detection, and qualitative approaches, such as optical gas imaging (OGI), can be used to confirm there are no emission sources.

[3] Rulemaking Notices for GHG Reporting | US EPA

Grantees are not required to use the methane emissions measurement approaches in this document for the purpose of screening MCWs to inform plugging prioritization. To make efficient use of time and resources, screening approaches are included in Appendix A as an option for grantees to consider when assessing and prioritizing wells for plugging. Although a 100 g/h detection limit is recommended, higher MDL approaches, including qualitative methods, can also be viable for identifying high emitters.

From Omara et al., 2022, approximately 80% of the 240 low production oil and natural gas well sites included in the study had methane emissions > 100 g/h, representing more than 99% of the cumulative emissions estimated from the sample set. Therefore, a methane detection limit of 100 g/h is low enough to achieve detection at the wells, for which methane emissions reduction is a priority, while allowing a variety of options for measurement methodologies, which range in detection limits, to be used. MDLs should be verified by references to peer-reviewed publications, instrument manufacturer specifications, and/or documented demonstrations of the standard operating procedures of the approach.

Because of the development of technologies and the rapid advancement of the measurement techniques, the methane emissions measurement protocols (Section 5) allow for the adoption of new approaches if they can be demonstrated to meet the guidelines outlined here.

4.1 Qualification of Measurement Specialist

Minimum requirements for a qualified measurement specialist are informed by U.S. DOI, et al., 2023. A measurement specialist refers to the contractor, partner, or state agency employee who will be conducting methane measurements at the site prior to and subsequent to plugging and remediating a well. A qualified measurement specialist should have completed all required safety training (e.g., H_2S, OSHA40/HAZWOPER) necessary to gain access to a site as well as a minimum of 20 hours of training specific to the equipment and methods described in these guidelines (Sections 5.1–5.3) and sufficient field experience such that measurements meet the data quality objectives of the methodological approaches. Measurement specialists should be familiar with the reference documents provided in these guidelines, particularly those relevant to the specific measurement instrumentation that is being used. The measurement specialist should be able to recognize and avoid/mitigate safety hazards related to the oil and gas well (Safety Considerations, Section 6), field conditions, weather variables, etc., to maintain personal safety. Measurement specialists are required to be aware of and evaluate all potential leak, flare, and vent points at an MCW site (some emission sources are depicted in Figure 2). The qualified measurement specialist should be prepared to submit data and results in a format that can be easily incorporated into the relevant agency database tool to assure consistent reporting.

4.2 Submission of Planned Measurement Instrumentation and Methodological Approaches

The specific measurement equipment and methods proposed by the contractor or qualified measurement specialist should be submitted for review by the NETL Federal Project Manager in advance of the field campaign in accordance with guidance within the Statement of Project Objectives (SOPO). The below additional criteria should also be included:

- The weather/environmental conditions, under which the method is effective, should be documented (i.e., wind speed, temperature, and cloud cover).
- MDLs for emissions measurements, resulting in a 'non-detect' classification, should be no more than 100 g/h with a 90% probability of detection.
- A quality assurance (QA)/quality control (QC) process is required where the contractor or qualified measurement specialist makes a second set of measurements at ~5% of randomly chosen wells to verify the precision of the selected methodology. These repeat measurements should be done on the same day because of possible longer-term, temporal variability in emission rates.

4.3 Data Reporting

Information about the methane emissions measurements will be shared on the public websites developed and maintained by the award recipients. In addition, the SOPO outlines public website reporting requirements related to well plugging and environmental restoration activities. The website will include the following information relevant to the methane emissions measurements:

- Wellhead location (decimal degrees, 5–7 decimal places, WGS84) and the American Petroleum Institute (API) number.
- Estimated annual reduction of methane emissions from each plugged well.
- Total estimated annual reduction of methane emissions from all plugged wells.

The estimated annual reduction of methane emitted is equal to a year of pre-plugging emissions (calculated assuming the pre-plugging measurement is constant over a year) minus a year of emissions from the post-plugged well (calculated assuming the post-plugging measurement is constant over a year). The website will be updated to include this data at a minimum of once per month in addition to the separate reporting requirements that are in the Quarterly Progress Report Template.

In addition to the reporting requirements in the public website and Quarterly Progress Report, during the field methane measurement campaign it is also recommended to document the following per well site:

- Date(s) and time(s) of the emissions measurements for pre-and post-plugging.
- Weather conditions at the time of measurements (temperature, barometric pressure, etc.).
- Name and affiliation of the qualified measurement specialist(s).
- Observations from the audio, visual, and olfactory (AVO) inspection.
- Description of the measurement approach, including instrumentation and calibration protocols.
- Well status (i.e., shut-in, idle, producing, etc.).
- Pre- and post-plugging well site description (listing of equipment on site; photographs recommended).

- Background methane concentration and how/when the measurement was taken.
- If conducted, a description of gas compositional analysis and/or soil gas surveys of the well site's surrounding area.
- A description and listing of the sources of emissions.
- Pre-plugging individual and aggregated methane emissions rate in g/h. If multiple measurements have been collected, either to characterize temporal variability or accuracy of the methodology, all results should be documented as well as the approach and results to arrive at an average emission rate.
- Date of plugging.
- Approach and results for post-plugging and verification/quantification of methane emissions reductions.
- Description of any attempts to characterize the variability and/or uncertainty in emission rate (i.e., repeated measurements at multiple date[s]/time[s], measurements for an extended time period, and measurements using multiple approaches).
- Abnormal site conditions (e.g., dilapidated equipment, open tank valves).
- Documentation of challenges and solutions.
- Future plans and goals (specific goals, strategies and anticipated outcomes for the MCW site).

5. Methane Emissions Measurement Approaches

The measurement approaches taken to quantify pre- and post-plugging emissions will vary depending on several factors, including whether the emissions data are already collected under Subpart W and desired performance metrics.

Under this guidance, facilities that report to the Greenhouse Gas Reporting Program under Subpart W are required to follow the Subpart W quantification methodology (Code of Federal Regulations, 40 Part 98, 2024) to quantify the methane mitigated from well plugging for the purposes of this program.

For all other facilities, this section describes methane emissions measurement approaches. These can be categorized into direct source emissions measurements, near-field measurements, and remote sensing. Selection criteria for which approach(es) should be used are dependent upon desired performance metrics, such as cost, areal coverage, time, and the skill required, as well as the MCW site characteristics (e.g., site configuration and status, number of potential leak/venting points, accessibility, access to electricity). Any selected measurement approach should have a current, accurate, and traceable calibration.

Due to the rapidly changing nature of technology and methods for measuring methane emissions from oil and natural gas wells, the methane emissions measurement protocol intentionally allows for novel approaches, subject to pre-approval (Section 4.2), so long as they meet the requirements outlined herein.

5.1 Direct Source Emissions Measurements

Direct source emissions measurement approaches require personnel to sample directly from potential emission locations using portable analytical systems capable of quantifying both the methane concentration and flow rate to determine the methane emission rate in mass/time (i.e., g/h). These approaches have the highest risk of personnel exposures to a combustible atmosphere and/or air toxics, and strict adherence to the safety considerations described in Section 6 is recommended.

5.1.1 High Flow Sampling

High flow sampling is a widely used approach for measurements of methane leakage, both in industrial settings (e.g., for maintenance or regulatory compliance), as well as with academic research studies (Allen et al., 2013; Pekney et al., 2018; Townsend-Small et al., 2016; Thoma et al., 2017). By introducing a focused vacuum at a high flow rate at potential leak points, the leakage is completely captured, and the methane concentration is analyzed by thermal conductivity, catalytic oxidation, tunable diode laser adsorption spectroscopy (TDLAS), cavity ringdown spectrometers (CRDS), or other scientific measurement principles. The multiplication of methane concentration and instrument flow rate yields the methane emission rate in mass/time (i.e., g/h). There are commercially available high flow samplers, as well as recently published open-source architecture, for the building of a high flow sampler from easily sourced components, platform-independent Python coding for all software, readily accessible sensor components, and the use of a commercial high-volume blower (Zimmerle et al., 2022). Various attachments (e.g., bags, funnels, and wands) are available for handling irregularly shaped components. Newer commercial systems have quantification limits on the order of 0.5 g/h with a reported accuracy better than ± 5%. Measurements typically take 5–10 minutes per leak point. To get an accurate methane emission rate measurement, it is critical to verify that the high flow sampler is fully capturing the emissions from the source location. An OGI camera can be used to visually verify emissions capture (more information about OGI in Appendix section A.2.1).

5.1.2 Flux Chambers

Static flux chambers are sealed containers with a fixed volume (V; m^3) that are placed over an identified leak. To calculate an emission rate (Q; g/h), the concentration of methane (C; g/m^3) within the container is measured over time (t; h):

$$Q = V\left(\frac{dC}{dt}\right)$$

Methane concentrations are determined by analyzing collected air samples from within the chamber at different points in time. The chambers do not require power, and the size of the chamber can be customized to fit the geometry of the leak. However, larger chambers may be more difficult to transport to remote locations and may be susceptible to displacement by high winds. Conversely, methane concentrations within smaller chambers may reach dangerous levels (> 5% v/v; lower explosive limit [LEL]) creating a potential hazard (Riddick et al., 2022).

Dynamic flux chambers are similar to static chambers in that a container of known volume (V; m^3) is placed over a leak. In this setup, however, air with a known methane concentration (C_{air}; g/m^3) at a known flow rate (q; m^3/h) is flushed through the chamber, thereby decreasing the potential development of a hazardous environment. The methane concentration within the chamber, measured either by a screening instrument or from collected air samples, should reach a steady state (C_{eq}; g/m^3) after a period of time, which can vary proportionally to the leak rate and size of the chamber, and the emission rate Q (g/h) can be calculated:

$$Q = q\left(C_{eq} - C_{air}\right)$$

This system requires greater logistical consideration given that a power source is needed to run both the pump for the air flow and a fan within the chamber to ensure that the system is well mixed. The accuracy of this method for quantifying methane emissions has been shown to be approximately ± 10% for controlled leaks of 40, 100, and 200 g/h (Riddick et al., 2022). This method of quantification requires the complete enclosure of the identified leak. Site specific characteristics, such as the presence of a connected pumpjack or other pipes/infrastructure on the wellhead, could limit the feasibility of this approach by requiring large enclosures.

5.1.3 Bag Sampling—Emission Rate Measurement

An alternative but similar approach to a rigid flux chamber method uses a flexible anti-static (i.e., Mylar) bag. This approach may be useful when leaks are difficult to capture because of irregular construction of the wellhead, multiple leak points identified at the wellhead, or difficulty isolating a leak. Bag sampling is conducted according to the EPA Protocol for Equipment Leak Emission Estimates (U.S. EPA, 1995). The method involves using flexible Mylar bags of various sizes to custom fit a containment around a potential leak source. The bag has an inlet port through which sweep air is introduced to the containment at a known flow rate (recommend from 5 L/minute up to 100 L/minute) and an exhaust port at which the concentration of methane is measured using a methane concentration analyzer once a steady value is achieved. With the known exhaust methane concentration and flow rate of sweep air, an emission rate is calculated as

$$Q = q(C_{out} - C_{in})$$

where Q is the emission rate in g/h, q is the flow rate (converted to m^3/h), and C_{out} and C_{in} are the concentration of methane (converted from parts per million [ppm] to g/m^3) in the air coming out of and going into the bag, respectively. The detection limit of this approach depends upon the analyzers selected for flow rate and methane concentration. An example of the application of this approach is described in Pekney et al., 2018.

5.1.4 Bag Sampling—Flow Rate Measurement

For the measurement of the leak flow rate only, anti-static bags of a known volume can be placed directly over a leak, and the amount of time it takes to fill the bag is recorded. The accuracy of the method is reported to be on the order of ± 10% (Heath Consultants Inc., 2023). This procedure requires a discrete leak point that can be completely sealed by the bag opening. This is a relatively inexpensive way to quantify a leak rate; however, chemical analysis of the leaking gas would be required to generate a methane emission rate. The material of the anti-static bag must be compatible with the sampled gas such that it would not affect the chemical analysis.

5.1.5 Methods that Couple Methane Concentration Measurements with Flow Rate Measurements

This methodology involves calculating an emission rate by combining data collected from two separate instruments: (1) to measure the flow rate and (2) to measure the gas concentration. One option for the flow rate measurement is the bag sampling approach described above, and some options for the measurement of methane concentration are described in Screening Approaches (Section A.1) in the Appendix. The multiplication of methane concentration and flow rate yields the methane emission rate in mass/time (i.e., g/h). The methane leak needs to be isolated and enclosed, such that there is a single discrete measurement location. The detection limit, accuracy, and sensitivity of this method can vary substantially based on the specific instruments that are deployed. Flow rates as low as 20 mL/minute and methane concentrations as low as 1 parts per billion (ppb) above the background are possible to quantify. Measurements can be collected quickly (minutes) with higher quality data obtained with longer collection times. Data from gas concentration instruments that only measure total hydrocarbon content may need to be adjusted based on the chemical composition of the gas being measured. An example of the application of this methodology is described in DiGiulio et al., 2023.

5.2 Near-Field Measurements

Near-field measurement approaches do not require personnel to sample directly from potential leak locations but instead position analytical instruments at some distance (meters to tens of meters) from the well site. Data can be collected from instruments that are either stationary in the downwind direction or mobile in a surveying platform. While plume dispersion introduces uncertainty in the methane emission rate estimation, these approaches have a lower risk of personnel exposures to a combustible atmosphere and/or air toxics as compared to direct source emissions measurements.

5.2.1 Ground-Based/Stationary Surveys Coupled with Gaussian Plume Dispersion Modeling

A point source Gaussian plume dispersion model is a most used atmospheric dispersion technique, whereby estimations of methane emission rates from point sources are made using downwind measurements of methane concentration, wind speed, direction measurements, and atmospheric stability classes that will be used to determine the plume width and height based on the distance from the source. A popular ground-based approach that uses Gaussian plume dispersion modeling is the EPA Other Test Method (OTM) 33A. This approach involves using a geospatial measurement of air pollution (GMAP) vehicle that is positioned directly downwind of the source to collect real-time methane concentration measurements that are combined with time-coupled, three-dimensional wind measurements to estimate mass emission rates (Thoma and Squier, 2014). In general, the GMAP vehicle is equipped with a high-performance methane concentration measurement system (methane analyzer), battery system, sampling port, 3D ultrasonic anemometer, weather station, and a high-resolution global positioning system (GPS). Based on the concentration measurement configuration and atmospheric conditions, the MDL of this approach can be as low as about 36 g/h. The approach is limited to day-time observations of near ground-level sources with relatively open terrain (few wind flow obstructions) with wind speeds > 1.0 m/s. The GMAP vehicle is positioned 20 to 150 meters (m) directly downwind of the source, and a series of 20-minute observations are conducted. The methane concentration and wind measurements are post-processed in an OTM 33A Gaussian plume dispersion model software, included with the method. The meteorological observations are used for plume reconstruction based on the distance from the source to the detector (GMAP vehicle) and the atmospheric stability class to determine plume width and height and then are combined with concentration measurements that input into the Gaussian plume dispersion equation, yielding an estimated emission rate in g/h. With proper operation, accuracies within +/- 70 g-CH_4/h can be achieved. For more information and publicly available resources, please refer to Thoma and Squier, 2014; Brantley et al., 2014; Edie et al., 2020; and Heltzel et al., 2020.

There are other Gaussian plume dispersion techniques combined with statistical approaches, such as the Markov chain Monte Carlo approach, that would yield a distribution of methane emission rate with uncertainty bounds as a function of methane concentration and wind speeds (Dubey et al., 2023). The Consortium Advancing Technologies for Assessment of Lost Oil and Gas Wells (CATALOG) Program is developing a publicly available version of this approach for orphaned wells. Although it is still under development, this methodology, when finalized, could also be applied to MCWs, assuming the well site is a point source. A detection limit and a quantification of uncertainty for this methodology have not yet been reported by CATALOG, but as it is designed for the assessment of orphaned wells that have a significantly lower average methane emission rate, satisfying the 100 g/h detection limit is expected.

5.2.2 Drone-Based Surveys/Assessments

Small uncrewed aircraft systems (sUAS), also referred to as drones, are useful in situations where accessibility is an issue, limiting vehicle-based surveys, such as EPA OTM 33A. The concentration measurements from drone-based methane sensors work based on a variety of principles, including but not limited to TDLAS, CRDS, etc. The concentration measurements, combined with wind sensor measurements on-board or on the ground, can be used in plume dispersion modeling to estimate methane emissions in g/h. Depending on the methane sensor configuration deployed in the field survey, the MDL may range from 0.01 ppm (CRDS) to 5 ppm (TDLAS). Data collection procedures are also affected by the configuration of the methane sensor. As an example, TDLAS sensors have the advantage of collecting data away from the methane plume, while open-path CRDS sensors require the sensing head to be in the plume to measure methane concentrations (Martinez, Miller, and Yalin, 2020). The detection limit for a drone-based survey varies, depending upon the methane sensor configuration, flight parameters, and weather conditions, but the detection limits reported in the literature are as low as 0.6–30 g/h (Atherton et al., 2017; Golston et al., 2018; Li et al., 2020; Subramanian et al,. 2015; von Fischer et al., 2017). Despite being very useful in areas with limited ground access, the effectiveness of the measurement campaign is dependent on a multitude of factors, including payload capacity, flight time (battery capacity), stability of the drone when flying in high winds (wind speed threshold), and so on. As a result, it is recommended that this method be used in conjunction with a demonstrated level of experience in drone operation and data analytics/modeling to accurately represent methane emissions from MCW sites. There are commercial services available that are qualified to perform drone measurements and data analytics to facilitate this approach. For more information and discussion on drone-based methane sensors and plume dispersion modeling, see Shaw et al., 2021.

5.3 Remote Sensing

Aircraft surveys provide a larger coverage of an area of interest with a resolution of up to 1 m, when typically flown at an altitude of ~3,000 m above ground level. A recent study has found, depending on the type of instrument on the aircraft, the MDL of the flight could be as low as 4.5 kg/h (Esparza et al., 2023). For low-altitude (hundreds of meters above ground level) surveys using Light Detection and Ranging (LiDAR), the MDL can be as low as 2 kg/h with 90% probability of detection (Kunkel et al., 2023).

In general, satellite-based methane sensors are used in large-scale, regional-scale, or basin-wide studies. Some examples include GHGSat, Sentinel-5P (TROPOMI), and Maxar Worldview-3. Due to the altitude at which these satellites orbit around the Earth, the resolution of their sensors is not adequate to detect relatively low emissions from MCW sites.

Therefore, <u>the use of data from aircraft surveys and satellites is not recommended as a methane emissions measurement approach for MCW sites at this time</u> due to the <u>current</u> detection limit not meeting the 100 g/h requirement. However, the sensitivity of these technologies is evolving rapidly. If these technologies can demonstrate that they meet the 100 g/hour detection limit in the future, these technologies could be reviewed by NETL, pursuant to Section 4.2 above. Furthermore, high- and low-altitude remote sensing could be used as a time efficient screening approach to identify high emitting MCW sites among a distribution of wells covering a larger area that could be missed otherwise using vehicle/sUAS-based approaches covering smaller areas. There are commercially available services that facilitate this approach.

6. Safety Considerations

MCW sites can vary substantially relative to location, accessibility, infrastructure type, and design, as well as risks. MCWs can be idle or active producing wells, and as such, site safety considerations are a critical aspect of working on these well sites. Active MCWs sites can carry risks to human health and the environment. In preparing to work with or around MCW sites, workers should first assure that site access authorization is obtained, and any company or site-specific safety considerations are followed. Some MCWs sites may require specific types of safety training (e.g., H_2S, OSHA40) to gain access to a site. Moreover, in some cases, well operators may require insurance or liability waivers for access to be allowed. Company or site-specific requirements for intrinsically safe instruments should be considered, particularly for direct source emissions measurement approaches. Method 21 requires that "the instrument shall be intrinsically safe for operation in explosive atmospheres, as defined by the National Electrical Code by the National Fire Prevention Association or other applicable regulatory code for operation in any explosive atmospheres that may be encountered in its use" (Code of Federal Regulations, U.S. EPA, 2017). When onsite, staff should have proper personal protective equipment that would, at a minimum, include a hard hat, safety glasses, fire retardant clothing, steel-toed boots, and relevant personal gas detection instrumentation. Moreover, site access should never be performed individually and should always be done in pairs (at least). Site requirements may include the presence of the main site operator, or someone designated by them. Workers should not make any attempts to open or close valves or otherwise attempt to manipulate or modify equipment. It is also recommended that workers effectively coordinate with operational personnel to understand the potential risks (e.g., high-pressure, H_2S, known leaks/vents, or other issues) and to also be fully aware of weather conditions to avoid increased risk situations. Site safety plans should be prepared prior to access to a well or group of wells and include relevant information about local emergency response plans prior to an emergency situation occurring.

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A. Appendix

A.1 Screening Approaches

To make efficient use of time and resources, an optional preliminary assessment of well sites to detect emissions may be adopted. Methane emissions measurements associated with screening may consider, but are not required to follow, the methane measurement guidelines for MCWs provided in this document. Screening techniques include measurements of methane concentration (in units, such as ppm or percent volume) collected around the well site to identify points at which the concentration significantly exceeds the background methane concentration of approximately 1.9 ppm[4] and optical gas imaging (OGI) for plume visualization (Lan, Thoning, and Dlugokencky, 2023). These screening techniques do not supply a methane emission rate but do provide a triaging of wells into the following categories:

- No emissions detected, no further investigation.
- Emitting at a low or moderate level, more comprehensive emission measurement may or may not be desired.
- High emitters, require a more comprehensive emission rate measurement.
- Well is high priority for plugging for other reasons, more comprehensive emission measurement may or may not be required.

This section describes instruments and approaches that provide a preliminary assessment of emissions at MCW sites.

One option for a recommended screening protocol follows the U.S. EPA Method 21 (Code of Federal Regulations, U.S. EPA, 2017), which describes the process to identify VOC leaks from process equipment. Using Method 21 is also feasible for vented sources in some instances. The method explicitly states that it "is intended to locate and classify leaks only and is not to be used as a direct measure of mass emission rate from individual sources." As such, after the application of the method, follow-up work would need to be done to quantify any identified sources of emissions using the technologies described in Methane Emissions Measurement Approaches (Section 5). The screening approaches discussed below are appropriate for leaks and vented emission sources.

Screening is conducted by directing the screening instrument to all potential emission points at an MCW site, allowing enough time at each point to achieve a steady reading. Due to the intermittent emissions observed at some wells, a 3–5-minute evaluation at each potential emission point is recommended. It is recommended that the following be recorded: the date(s) and time(s) of the screening, the name and affiliation of the qualified measurement specialist(s), the measurement approach, a well site description (listing of equipment on site, inclusion of photographs where practical), a description and listing of emission points, and the magnitude/description of each positive instrument response (emissions detection).

[4] While 1.9 ppm is the average background methane concentration, the actual value can vary substantially due to proximal sources and diurnal cycles. Site-specific methane background concentration should be documented.

Some evidence of leakage can be observed without analytical instruments. In some instances, emissions may be detected during AVO inspections. These types of inspections are occasionally employed for organic air pollutants other than methane; however, they also conform with EPA Method 21 (Code of Federal Regulations, U.S. EPA, 2017). Dead vegetation, oily deposits, and bubbles can all indicate the presence of a leak. However, not all leaks will have visible evidence; therefore, simple, visible observations are not recommended as a robust screening protocol for the purposes of this program.

The following subsections provide more details about specific instrumentation options for screening.

A.1.1 Methane Concentration Instrumentation

Commercially available, portable instruments for quickly measuring methane or methane-equivalent concentrations in ambient air range in cost from hundreds to tens of thousands of dollars with the instrument performance generally increasing with cost. On the lower range, LEL monitors, for example, are small hand-held, battery-powered devices that report the concentration of combustible gases in the air relative to the concentration where the gas becomes an explosion hazard (approximately 5% by volume). However, detection limits are ~100 ppm or greater.

Portable flame ionization detectors (FIDs) and infrared controlled interference polarization spectrometers are also capable of measuring 0–100% methane or methane-equivalent by volume with detection limits of approximately 0.5–1 ppm. LEL and FID monitors provide results for all combustible gases present and can report the total concentrations "as methane" depending on the instrument calibration. These two instruments are not specific only to methane but are appropriate as screening technology options, as FID and similar devices can be used to meet Method 21 equipment requirements.

CRDS and off-axis integrated cavity output spectrometers (OA-ICOS) can achieve sub-ppb detection limits but are at the highest range in cost. These high-precision instruments are typically used for more advanced quantification methods, such as OTM 33A.

A.1.2 Optical Gas Imaging Instrumentation

Although it is not a quantitative method, OGI provides a means to visualize leaks of natural gas by using its radiation absorption properties to produce an image in which the natural gas leak can clearly be distinguished. OGI is also a viable qualitative visual tool to confirm post-plugging methane emissions are not detected. Surveys with OGI cameras allow the user to view leaks at a distance with rapid spatial coverage. Detectability of a leak is related to the sensitivity of the camera, the size of the leak, distance from the source, experience of the camera operator, and environmental factors. OGI cameras have been used for years by the oil and gas industry to detect natural gas leaks. Although they provide a quick and safe method for leak detection and repair (LDAR), the cameras can be expensive, and typical OGI cameras do not provide quantitative emission rates. Depending on the type of OGI camera (e.g., cooled versus uncooled), the cost can range significantly. Proficiency in the use of these cameras require a well-trained, experienced operator to ensure present leaks are found.

Several environmental factors affect the monitoring approach: temperature (most important), wind speed, background methane concentrations, and the distance from the source. Additionally, several physical factors also affect leak detection, including the composition of the natural gas, the size of the leak release point, and the rate of the release. The methane leak plume detection on an OGI camera works best when there is a significant temperature difference between the gas released and the scene background. Several studies have attempted to quantify the detection limit of OGI cameras; however, it is important to bear in mind the detection limit of an OGI camera is dependent on the type of camera, environmental factors, physical factors, and the ability of the OGI operator. For example, one such study indicated that when the leak point and the ambient air have a temperature difference of 10°C or more, it yields an MDL of 10 g-CH_4/h at 25 m from the point of the leak using a passive infrared OGI camera (Ravikumar, Wang, and Brandt, 2017).

OGI provides an image that is useful for leak detection, but with hyperspectral imaging, the image is obtained along with the spectral signature for each pixel in the image that provides quantitative information of the leak. Quantitative OGI (QOGI) is an emerging technology, and several technology developers are attempting to use hyperspectral imaging and algorithms to identify and quantify natural gas leaks.

A.1.3 Column-Integrated Methane Concentration Instrumentation

Standoff laser-based, hand-held methane detectors can be used to identify leak points from a distance of up to 30 m. These instruments employ TDLAS to emit an infrared laser beam specific for methane detection that is analyzed after being reflected to the detector. Between the detector and reflection point, methane molecules absorb part of the laser energy proportional to the cumulative (column-integrated) methane concentration with units of ppm-m. The response time of these devices is rapid (0.1 seconds) with a typical sensitivity of 5 ppm-m at distances from 0 m to 30 m, which is more than an adequate performance for the purposes of this program. Unlike OGIs, hand-held methane detectors provide a non-visual approach to detect small leaks that could not be identified through imaging systems and are less affected by environmental factors, such as temperature and wind.