Final Report

CHOPS Associated and Vent Gas Measurement

Prepared for PTAC

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Disclaimer

Abstract:

This is the final report of a project to evaluate associated and vent gas measurement in the CHOPS (cold heavy oil production with sand) sector in Alberta and Saskatchewan. This project starts off with a review of the gaps in CHOPS gas measurement. Next, SRC completed field-testing at CHOPS sites to assess methodologies for measuring associated gas, vent gas and methane emissions from casing gas. Then SRC field-tested various methodologies and technologies for measuring CHOPS tank vent gas. The field-testing indicates that measurement of CHOPS gas, venting, and methane emissions will improve with direct measurement methodologies. SRC provides recommendations to address two key issues related to methane emissions which are measurement accuracy and a perceived gap between reported venting and regional emissions.

Acknowledgment

Project funding is from the Saskatchewan Ministry of Energy Resources and Innovation Saskatchewan and PTAC (Petroleum Technology Alliance of Canada).

SRC is sincerely grateful for the incredible technical and operations expertise and assistance provided by producer volunteers during multiple rounds of field testing.

EXECUTIVE SUMMARY

In 2020, regulatory changes were made to the methods of measuring and reporting associated and vent gas from cold heavy oil production with sand (CHOPS). The objective of this project is to provide recommendations on practical and cost-effective associated and vent gas measurement methods to address two key issues related to methane emissions:

- Measurement accuracy
- A perceived gap between reported venting and regional emissions measurement.

A review of past reports on CHOPS methane measurement and reporting indicates that there are three main gaps which possibly result in discrepancy between actual and reported emissions:

Gap 1: Inaccurate measurement of casing gas venting with GOR (gas to oil ratio) methodology.
Gap 2: Inaccurate measurement of tank venting.
Gap 3: Absence of measurement of other methane emission sources.

This project involves two phases of field-testing, designed to evaluate the first two gaps. The key finding of the Phase 1 field-testing is that *the accuracy of measurement of casing gas venting (methane emissions) improves with direct measurement*. Phase 2 testing indicates that *methane detection and screening may be a vital component of methane measurement accuracy*. Phase 2 testing also shows that venting (methane emissions) from CHOPS tanks can be directly measured by a number of flow meters. Direct measurement can be used to develop company/site tank emission factors or to complete periodic testing. Gap 3 was not addressed in this project. To ensure that improvements to casing gas and tank venting measurements will improve overall site emission accuracy, Gap 3 emissions would also need to be investigated.

CHOPS site designs are changing as the sector transitions to new methane targets. Producers may improve methane measurement further by using multiple measurement methodologies and technologies and reconciling the results.

This project is funded by the Saskatchewan Ministry of Energy and Resources and PTAC. The project includes six tasks, as indicated:

1. Scan studies and regulations on CHOPS gas measurement and reporting (Section 2).
2. Establish a technical advisory committee.
3. Assess CHOPS gas measurement methodologies and technologies (Section 3).
4. Field-test gas measurement methodologies and technologies (Section 4).
5. Analyze and report findings (Section 5).
6. Make recommendations for CHOPS gas measurement and reporting (Section 6).

Recommendations:

Future investigations:

1. Study all CHOPS sector methane emissions; collect data with both equipment-level and aerial methodologies and technologies. If the casing and tank vents are the main sources of methane emissions in the CHOPS sector, it will make sense to improve measurement of these sources. This study will also show whether foamy oil flow leads to high tank venting at new sites. Alternatively, use data from existing producer direct measurement surveys of all methane emissions sources.

2. Evaluate accuracy improvements to vent and methane measurement from reconciling surveys with multiple methodologies and technologies including aerial surveys.

3. Evaluate periodic and continuous methane detection and screening technologies for managing methane at CHOPS sites.

4. Evaluate the option of flow meters with IoT (internet of things) technology moved from site to site to collect several hourly rate tests of vented casing gas per year, per site. This option may reduce safety risks and costs associated with frequent measurement.

The accuracy of gas and methane measurement in the CHOPS sector improves with the following:

1. Measure all CHOPS site methane emission sources. Use more accurate measurement means for sources or sites contributing more to the overall methane inventory.

2. At CHOPS sites, use direct measurement of casing venting with continuous meters or **24**-hour hourly rate testing rather than GOR testing methodology or GOR estimates. At sites where it is difficult to test hourly rate of the vented casing gas, complete hourly rate testing of the other casing streams.

3. Measure CHOPS tank venting from low emission tanks with *published*, *field* or *company*-specific emission factors developed from direct measurement data (diaphragm, positive displacement, or turbine meters with gas analysis) rather than the Vasquez-Beggs correlation or GIS analysis. If overall methane inventories indicate that low-emitting tanks are a very small percentage of CHOPS sector methane, then published emission factors would suffice until larger methane sources are mitigated.

4. For CHOPS tanks with moderate to high venting, use *site*-specific emission factors or periodic, direct measurement to measure tank methane emissions. Periodic testing is appropriate for sites where casing gas routinely vents via the tank.

5. Install continuous detection (inexpensive flow meters) on tank or casing vents where infrequent, high emissions are a possibility (foamy oil or gas conservation equipment failures).

6. Consider CHOPS tanks designed for easy access for direct measurement of tank venting.

7. Increase measurement accuracy of all methane emission sources (including casing gas venting) by using multiple measurement methodologies and technologies (including aerial surveys) and reconciling the results.

8. Further increase methane measurement accuracy by increasing the frequency of measurement surveys. Comparisons of emission inventories from low to high frequencies will provide indication of the relative benefit of increasing frequency.

Acronyms, Definitions and Units of Measurement

Acronyms:

AB	Alberta
AER	Alberta Energy Regulator
BS&W	Basic sediment and water, the percentage by volume of sand and water in the produced liquid from a CHOPS well.
C4+	Refers to any hydrocarbon components larger than propane and propene.
CAPP	Canadian Association of Petroleum Producers
CHOPS	Cold heavy oil production with sand
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
GC	Gas Chromatograph
GHG	Greenhouse gas
GIS	Gas in solution
GOR	Gas-to-oil ratio (standard m^3 gas/m^3 oil)
IoT	Internet of things technology
PD	Positive displacement meter
PTAC	Petroleum Technology Alliance Canada
PVT	Pressure, volume, and temperature measurement
P_w	Average m^3 oil produced in a day for the most recent month
QOGI	Quantitative optical gas imaging
SCADA	Supervisory control and data acquisition
SK	Saskatchewan

SRC Saskatchewan Research Council

Definitions:	
Associated gas	gas produced in association with oil production at oil wells, commonly known as solution gas; it includes produced gas that is vented, flared, or used as fuel.
Bottom-up measurement	Refers to directly measuring methane emissions or vented gas at the source with meters or hand-held devices.
fugitive emission	Unintentional releases of hydrocarbons to the atmosphere.
$GOR_{associated\ gas}$	GOR value determined based on the total casing gas where some of the associated gas may be vented, flared, gathered, or used as fuel.
$GOR_{Non\text{-}fuel\ gas}$	GOR value determined based on the casing gas that is vented, flared, or gathered (does not include casing gas used as fuel).
$GOR_{Reservoir}$	GOR value of the gas and oil in the reservoir which may not equal the associated gas GOR of the gas and oil produced at the wellhead.
$GOR_{Vent\ gas}$	GOR value determined based on the vented casing gas.
Non-Fuel	The term non-fuel gas is used in this report to evaluate sites where casing gas is used as fuel but without gas gathering and combustors. Non-fuel gas equals the total casing gas subtracting casing gas used as fuel.
Overall vent gas	In Alberta this is all routine and non-routine vent gas.
Produced gas	Synonymous with associated gas.
Raw gas	Mixtures of methane, paraffinic hydrocarbons, nitrogen, carbon dioxide, hydrogen sulphide, helium, and minor impurities recovered or recoverable from a well, which are gaseous at measurement conditions.
Solution gas	Associated gas
Standard gas conditions	101.325 kPa, 15°C
Top-down measurement	Refers to directly measuring methane emissions or vented gas using equipment mounted to drones, airplanes, helicopters, satellites.

Total casing gas	All the gas reaching the well surface via the casing annulus.
Vent gas	Un-combusted gas that is released to atmosphere. In Saskatchewan vent gas includes fugitive emissions. In Alberta vent gas excludes fugitives and it is synonymous with overall vent gas.
Vented casing gas	Casing gas vented to atmosphere from a valve on the casing gas piping.

Units of Measure:

^oC	degrees Celsius
d	day
kg	kilogram
kPa	kiloPascal
h	hours
m	meters
10^3 m^3	Thousands of cubic meters of gas; where gas volume is at standard conditions of 101.325 kPa, 15^oC

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1. INTRODUCTION

1.1 Project Description

Current methods of estimating gas production and atmospheric venting volumes associated with CHOPS (cold heavy oil production with sand) production in Alberta and Saskatchewan have been scrutinized for their level of effectiveness and accuracy. Canada has ongoing targets to reduce emissions of the greenhouse gas (GHG) methane. Recent site and regional level surveys of methane emissions near CHOPS sites suggest that the actual vented gas volumes are higher than the reported values of vented gas. These, along with previous studies on CHOPS gas measurement may have prompted changes to federal and provincial regulations governing the reporting of gas volumes from CHOPS wells. The Ministry of Energy and Resources of the Government of Saskatchewan and the Petroleum Technology Alliance Canada (PTAC) contracted the Saskatchewan Research Council (SRC) to investigate cost-effective methods of accurately measuring associated gas and vented volumes from CHOPS wells.

1.2 Project Objectives and Scope

The objective of the project is to provide recommendations to the Saskatchewan government and PTAC on associated gas and vented gas measurement methods to address two key issues:

- Measurement accuracy;
- A perceived gap between reported venting and regional methane emissions measurement.

This project focuses on methane from heavy oil wells in Saskatchewan and Alberta that use non-thermal (cold), primary and secondary recovery methods, with sand influx, known as cold heavy oil production with sand (CHOPS).

The project scope begins with a review of industry, government, and academic studies on CHOPS wells, and applicable regulations. As well, the scope includes an assessment of current and alternate gas measurement methodologies and technologies. Field testing evaluates current and alternate methodologies and technologies. The results of the field testing are used to identify best practices and to make recommendations for the reporting of gas and venting volumes at CHOPS wells.

The project scope is divided into six tasks, as follows:

Task 1 – Scan studies and regulations on CHOPS gas measurement and reporting:

This task includes a review of several government, industry, and academic studies which were completed in the past couple of decades, and which investigate gas and methane emissions measurement at CHOPS wells. Section 2 of this report contains a review of these studies along with a survey of current federal, Saskatchewan and Alberta regulations related to gas measurement and reporting, and methane emissions reductions at CHOPS sites.

Task 2 - Establish a technical advisory committee:

A technical advisory committee is established to gather input on other relevant CHOPS data, current and alternate technologies and methodologies, and a field-testing program. In addition, producer representatives on the committee provide site assistance with field testing. Committee membership includes the Ministry of Saskatchewan, PTAC, SRC, Environment and Climate Change Canada, the Alberta Energy Regulator (AER), and CHOPS industry representatives. The results of this task support Tasks 3, 4, 5, and 6.

Task 3 – Assess CHOPS gas measurement methodologies and technologies:

This task assesses the merits and disadvantages of both current and alternate methodologies and technologies for measuring and reporting associated and vent gas and methane emissions at CHOPS sites. This review is summarized in section 3 of this report. Section 3 includes an analysis of the main gaps in gas measurement and proposes a field-testing program to address these gaps.

Task 4 – Field test gas measurement technologies and methodologies:

As detailed in section 4 of this report, current and alternate methodologies and technologies are field tested. The field test is divided into multiple phases. Phase 1 focuses on methodologies to measure associated and vent gas from CHOPS well casings. Phase 2, on the other hand, focuses on methodologies and technologies to measure associated gas and venting from CHOPS oil production tanks.

Task 5 - Analyze and report findings:

The data from the field-testing program is analyzed and presented in section 5 of this report. Alternate methodologies and technologies are compared to assess their accuracy.

Task 6 - Make recommendations for CHOPS gas measurement and reporting:

Section 6 of this report provides conclusions and recommendations for future associated and vent gas and methane emissions measurement and reporting.

1.3 Project Background

For many years, the Saskatchewan and Alberta governments have required oil producers to report gas production from their wells, along with volumes of gas vented, flared, and combusted as fuel. These volumes are reported publicly. The original purpose of this gas reporting was to manage oil and gas resource development. With rising concerns with GHG emissions, provincial gas reporting has served a dual purpose by also providing information for GHG emission management. Provincially reported gas volumes have been used to provide CHOPS site and equipment-level information on GHG emissions in Canada's national inventory of greenhouse gas sources and sinks to the United Nations Framework Convention on Climate Change (Government of Canada, 2021). Furthermore, associated and vent gas measurement and reporting support GHG emission reduction programs within individual CHOPS companies. Knowledge of the actual associated and vented gas is also important for new regulations that attempt to set targets for methane emissions from the oil and gas industry.

Emissions of methane, which is a greenhouse gas, are not directly measured and reported from CHOPS sites in Saskatchewan. Instead, producers measure and report vent gas. The gas is assigned a product type; product types include gas (which is natural gas), helium, nitrogen, hydrogen, and carbon dioxide (Government of Saskatchewan, 2020a). The gas that vents from CHOPS sites is almost exclusively reported as gas (natural gas), and it typically contains over 93 to 96% by volume of methane (Clearstone Engineering, 2019).

In Alberta, producers measure, and report gas (synonymous with *raw gas*) and it refers to mixtures of methane, paraffinic hydrocarbons, nitrogen, carbon dioxide, hydrogen sulphide, helium, and minor impurities recovered or recoverable from a well, which are gaseous at measurement conditions (Province of Alberta, 2021). In addition, Alberta CHOPS producers now directly report methane emissions to the Alberta Regulator (AER, 2021).

This project will help to quantify and manage methane emissions and vent gas in the CHOPS sector. Although the methane emitted from a given CHOPS vent source is not exactly equal to the reported vent gas volume from the source, they are inferred from one another; methane emissions of a particular vent source are the product of the reported vent gas volume and the volume percentage of methane in the gas. In addition, vent gas may contain carbon dioxide or gas may be combusted as fuel or flared at CHOPS sites, resulting in carbon dioxide and other GHG emissions. While carbon dioxide has a much lower global warming potential than methane, methane emission measurement, reporting and mitigation programs may impact the management of carbon dioxide and other greenhouse gases.

Often in the past, measurement technologies of associated and vent gas streams have involved volumetric rate measurement of the entire gas stream in piping before it vents to atmosphere. On the other hand, new site and regional measurement technologies can measure the volumetric or mass flows of methane in the atmosphere.

1.4 About SRC

The Saskatchewan Research Council (SRC) is Saskatchewan's leading provider of applied research, development, and demonstration (RD&D) and technology commercialization. Saskatchewan Research Council's Energy Division provides Smart Science Solutions™ to clients in the areas of applied R&D, scale-up, demonstration and commercialization across all sectors. The Energy Division is well-positioned to participate in all forms of energy production, conversion, and conservation leading towards the goal of significant economic and positive environmental impacts for Saskatchewan.

CeDER is a Saskatchewan-based test and validation platform managed and led by SRC that provides real-world testing, demonstration and validation of emissions measurement, reduction, capture, and conversion technologies. Designed to accelerate industry adoption of practical and economic technologies, CeDER offers independent, industry-recognized, third-party validation.

SRC's CeDER mobile facilities are modular, meaning that the instrumentation and equipment required for each project can be mobilized as needed. This mobile capability has been designed to be flexible and to provide a wide range of testing for diverse technology scenarios. Wireless data acquisition systems allow us to use industry standard instrumentation on-site.

CeDER's trailers can be deployed to test technologies in the field at full- or pre-commercial scales and can be moved easily between locations. While SRC's home base is in Saskatchewan, it operates in field locations across Canada.

2. Scan of Studies and Regulations on CHOPS Gas Measurement and Reporting

The following is a scan of past studies and regulations on the CHOPS industry, focusing on associated and vent gas and methane emissions sources, characteristics, measurement, and reporting. The scan is divided into background information, describing features of CHOPS sites, current regulations on gas and methane at CHOPS sites, and a summary of challenges with measurement and reporting.

2.1 Background on CHOPS Production

Industry, government, and academic studies, as well as government regulations, reveal the complicated aspects of measuring and reporting associated gas, vent gas and methane emissions from CHOPS production in Alberta and Saskatchewan. Section 2.1 contains an overview of CHOPS production, the differences between CHOPS industry emissions and those from conventional oil, gas and emission terminology, the emission sources at CHOPS wells, and the gas flow regimes during CHOPS production.

2.1.1 Description of CHOPS Production

In a CHOPS reservoir, oil, gas, and water reside in a layer of sand. Reservoirs are usually shallow, 300 to 900 m deep, and have low pressures, less than 4000 kPa (Clearstone Engineering, 2019). When a CHOPS well is produced, the oil, water, sand, and gas mixture flows into the production line. As this process occurs, a continuously growing and collapsing network of wormholes starts to develop in the sand layer (**Fig. 1**). Often there is a high amount of sand in the production mixture early in the life of the well, and then the amount of sand reduces as the well ages. The oil typically has a high density and viscosity, and it is termed heavy oil or crude bitumen. Gas from CHOPS reservoirs is high in methane (Clearstone Engineering, 2019). Over a third of CHOPS wells in Saskatchewan and Alberta are in single-well batteries, while the remainder are grouped with several others in multi-well batteries. Multi-well batteries typically contain two to five wells. Most new CHOPS sites have multiple wells (New Paradigm Engineering, 2017). In Alberta, in 2018, there were 2466 CHOPS sites with 6630 wells (Clearstone, 2019). In addition, new sites often employ horizontal and directional wells which achieve higher oil production, while older sites usually have vertical wells. There is sometimes lower sand production from horizontal wells.

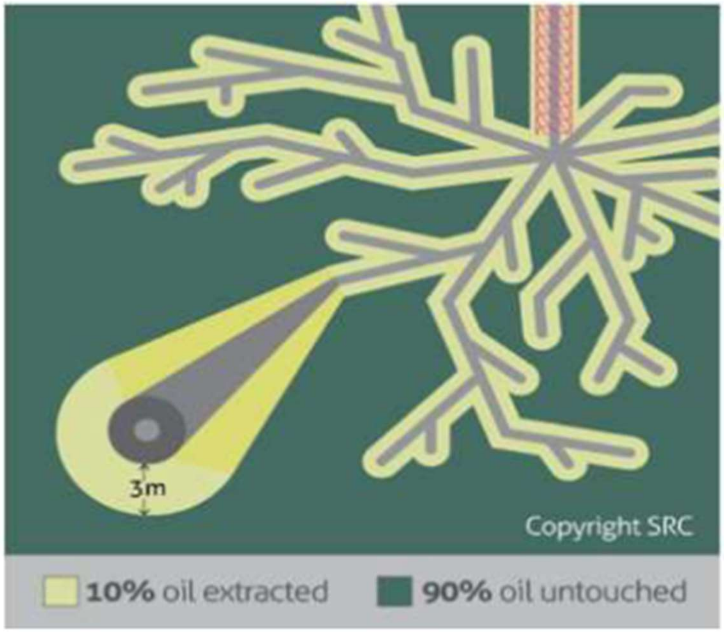


Fig. 1 — Wormhole development in sand layer of reservoir during oil production from a CHOPS well.

2.1.2 Vent Gas and Emissions from CHOPS Versus Conventional Oil Production

CHOPS wells often result in more gas vented to atmosphere than conventional oil wells for two reasons. The first reason is that the annular space between the well casing and the emulsion production line of the well is not sealed from the oil reservoir and this annular space is controlled at relatively low pressures. Thus, the down-hole area often behaves as a separator for the oil and gas in the reservoir. Some of this gas travels directly up the annular space of the casing to the wellhead. A great deal of this casing gas is conserved or flared rather than directly vented to atmosphere, but it is difficult to install conservation equipment and infrastructure for all the casing gas, at all CHOPS wells.

The second reason is that the oil is very viscous, containing gas, sand, and water. As a result, it is difficult to collect the oil at large, multi-well batteries, where gas in the produced oil can be more easily conserved. Rather than pumping this complex, multi-phase mixture to larger batteries, the oil is separated from the sand and gas in on-site production tanks. The oil and water are then trucked from the production tanks to processing batteries on a daily to weekly basis (Fig. 2). Furthermore, it is challenging to separate the gas from the oil in separators upstream of the production tanks. Gas produced with the oil line includes gas that enters the emulsion production line, gas that is dissolved in the oil, and gas that is trapped in the oil as bubbles or gas slugs. This gas typically vents to atmosphere from the tank because it is both costly to install and difficult to operate vapour recovery equipment on all CHOPS tanks to conserve the gas. In spite of the sand, horizontal drilling has recently proven to be successful in the CHOPS sector. Horizontal drilling makes it easier to install multi-well pads of greater than 3 wells at CHOPS sites.

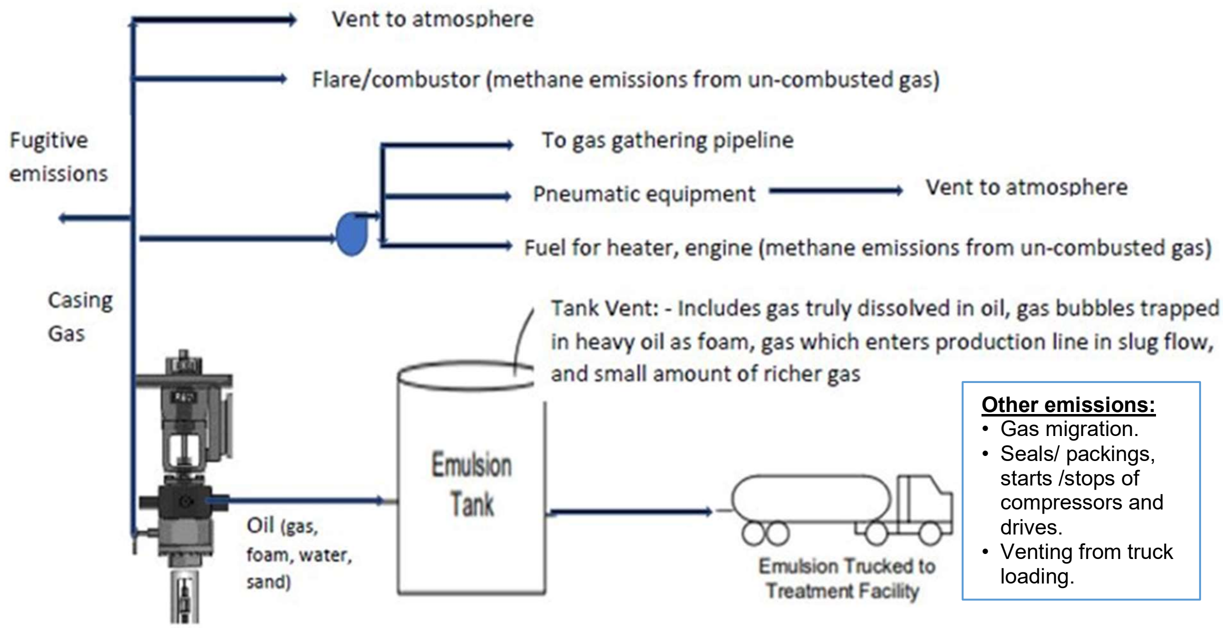


Fig. 2 — Flow diagram of a single-well CHOPS site.

2.1.3 Definitions of Emissions, Associated Gas, and Vent Gas

As explained in Section 1.1, the gas measured and reported at CHOPS sites is mostly methane. For clarity in this report, the terms *associated gas* and *vent gas* will follow the definitions of Saskatchewan Directive PNG 017 (Government of Saskatchewan, 2020a). PNG 017 defines *associated gas* as gas produced in association with oil production at oil wells, commonly known as *solution gas*; it includes *produced gas* that is captured, vented, flared, or used as fuel. *Produced gas* is not explicitly defined in PNG 017 but it is implied by this definition to be equal to *associated gas*. This report will use the term *associated gas* in place of *produced gas*. In Alberta regulations, the terms *produced gas* and *gas production* are not defined but are equivalent to the Saskatchewan definition of associated gas (AER, 2020a). This report will not use the Alberta terms *non-associated gas* (gas produced from a gas pool that is not associated with the oil or bitumen reservoirs or with production) and *solution gas* (volatile hydrocarbons that are dissolved in solution with produced oil or bitumen).

In this report, *associated gas* includes both the gas from the casing and the gas produced in the emulsion production line. There are multiple sources of associated gas that reach the surface of a CHOPS well. Associated gas can be gas from a reserve adjacent to the oil in the reservoir which flows into the reservoir and reaches the surface via the well casing or production line. Also, associated gas may be gas from oil, which is produced at the well, which separates from the oil while within the reservoir and reaches the surface via either the well casing or the production line. Often CHOPS wells produce only 5 to 15% of the oil in the reservoir (**Fig. 1**). Associated gas can originate from oil that does not get produced, while still within the reservoir, and travels to the well casing or production line. Finally, associated gas includes gas which is dissolved in the oil or exists as bubbles or gas slugs trapped in the oil, which reaches the surface via the production line.

Vent gas is un-combusted gas that is released to atmosphere (AER, 2020a and Government of Saskatchewan, 2020a). In Saskatchewan vent gas includes *fugitive emissions*. In Alberta, the AER defines *overall vent gas* as vent gas excluding fugitive emissions (AER, 2021). In both Saskatchewan and Alberta *fugitive* emissions are defined as unintentional releases of hydrocarbons to the atmosphere. Some publications on CHOPS production refer to all the gas that enters the annular space of the casing and reaches the surface as *vent gas* because it is the gas venting from the downhole area before liquid enters the production tubing. Instead, in this report, all gas reaching the surface via the casing will be termed *total casing gas* and in general, any portion of this gas will be termed *casing gas*.

2.1.4 Stream Balance at CHOPS Sites

Associated gas at CHOPS wells can reach the surface by either coming up with the produced oil or by flowing up the casing. The associated gas is mostly methane, but includes other gases such as carbon dioxide, ethane, and propane. At the surface, the casing gas can be continuously vented to atmosphere from a vent valve, combusted in an engine to power equipment such as pumps or combusted in oil tank heaters. At a minority of CHOPS sites, casing gas is used to mechanically power pneumatic equipment and then vented to atmosphere. At some sites, the casing gas is collected in gas gathering lines, or incinerated in a flare, incinerator, enclosed combustor, or catalytic combustor. The combustion efficiencies of on-site heaters, drives, flares, and combustors can vary, and the site emissions can include un-combusted gas.

CHOPS associated gas, which reaches the surface via the emulsion production line, is normally vented from the on-site, fixed-roof, oil production (emulsion) tanks to atmosphere, except in rare situations where vapour recovery systems have been installed on the tanks. The gas in the produced oil can be bubbles within the oil which form foam, gas truly dissolved in the oil, or slugs of gas. The production tanks are normally heated to speed up the breakdown of the foam and the dissolution of gas from the oil. While the composition of the associated gas from a CHOPS reservoir does not change much over time, the compositions of the tank vents vary significantly, daily. The atmospheric tanks draw in air after the oil and water are removed from the tank, and then the air vents out the tank as it fills. In addition, water in the oil and some of the volatile species in the oil evaporate in the heated tank and combine with the other vent gases.

Site emissions include gas vented from the oil and water transport trucks during loading or liquids recirculation. In addition, on-site drives, heaters, flares, and combustors convert hydrocarbon gases carbon dioxide. Some of the associated gas at CHOPS sites may also escape as fugitive emissions from either the casing gas or the production lines. Furthermore, a particular CHOPS site may have fugitive emissions from equipment containing purchased natural gas and propane, or from casing gas that is collected at neighboring sites and transported into the site for fuel use. There is also irregular atmospheric venting of associated gas from the site or neighboring sites during emergencies, well completions, well testing, well workover and other maintenance activities, unlit flares or combustors, and the release of pressure relief valves. In addition, gas vents from compressor seals, packings, crankcases, and the start and stops of compressors and drives, online analyzers, blowdown venting from solid desiccant dehydrators, pig traps and pigging operations, and in rare cases, glycol dehydrators. Some gas from the reservoir can migrate through the ground to the surface. Table 1 helps to explain the sources of gas emissions at a CHOPS site.

Table 1 — Material Balance of Associated Gas and Other Gas Streams at a CHOPS Site

Gas Source	Gas Emission
Associated Gas of the Well (mostly methane, and may contain carbon dioxide)	
1. Gas in production line	Emulsion tank vent
	Fugitive emissions from production lines and equipment
2. Casing Gas	Gas vented to atmosphere at atmospheric vent valve on casing piping or tank
	Gas recovered to gas gathering pipeline (gas product or used at other sites as fuel)
	Un-combusted gas from flare/combustor
	Un-combusted gas from drives, heaters
	Gas driving pneumatic equipment, vented to atmosphere after use
	Gas venting from analyzers, desiccant dehydrators, glycol dehydrators, seal/packing /crankcases/start/stops compressor, drives, venting during emergencies (including blowdowns, relief valve venting), maintenance (including well completion, workover testing), pigging operations.
	Fugitive emissions from casing lines and equipment
Other Emissions Sources	
3. Gas in empty trucks	Gas venting from trucks while loading water or oil into trucks on site (Natural gas)
4. Atmosphere	Air which enters emulsion tank and then vents as the tank fills
5. Reservoir	Water and components in the oil which flash in the emulsion tank and then vent
6. Gas/propane from other sites	Fugitive emissions from on-site propane supplies or gas piped from other sites (propane or natural gas). Gas venting during emergencies (including blowdowns), maintenance (including well completion, workover testing), pigging operations.
7. Combustion	Carbon dioxide emissions from drives, heaters, flares, combustors
8. Reservoir	Gas migration and surface casing vent flow from the reservoir through the ground, to surface near the well.

2.1.5 CHOPS Flow Regimes

The flowrates of gas in the casing annulus or the production line are variable (New Paradigm Engineering, 2004). A possible reason for this variation is that typically only 5 to 15% of the oil in the reservoir is produced with CHOPS wells, but there is gas in all the oil in the reservoir. Gas from oil that *is not* produced, can migrate to either the production line or the casing, and then be produced from the casing or production line, along with the gas from oil that *is* produced. The downhole area behaves as a separator for both categories of oil, and the overall pressure balance for the liquid and gas product streams, affects gas flowrate in the casing. Another cause of variation in gas volumes can be variations in the gas-liquid-solid flow regimes both in the reservoir wormholes and in the production line. Depending on the flow regime, there may be intermittent flow of gas in the casing or production line. Two examples of gas-liquid-solid flow regimes include foamy oil and gas slugging (**Fig. 3**). In foamy oil, the gas exists as bubbles trapped in the viscous oil. In gas slugging, there are large pockets of gas which may inhabit the entire cross section of a wormhole, or line. In addition, there can be varying gas-liquid flow regimes in the casing.

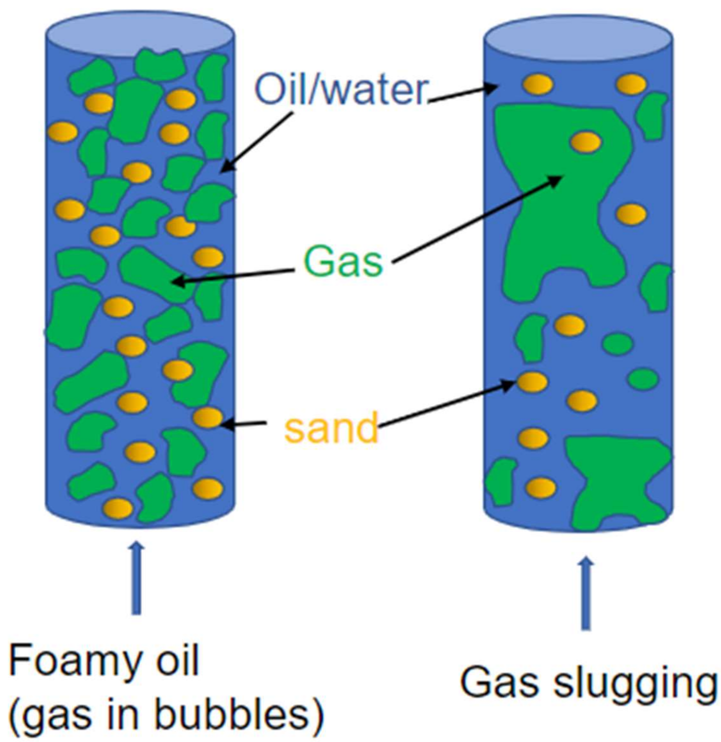


Fig. 3 — Multi-phase flow regimes which exist in reservoir wormholes and well production line.

Oil production also varies over the life of a CHOPS well. Often CHOPS wells only produce for 5 to 10 years. Although features vary from well to well, there exists a trend that oil production is highest in the early life of the well, which may be only a few months or a year. As a result, a large proportion of the associated gas is produced in the early life of the well. And at this time, gas flowrates from the oil production tank vents may be high due to foamy oil. Gas from the tank vents may be quite low for older wells, but some wells may continue to have pockets of gas entering the production line. In addition, there may be variation in gas flowrates in the casing or production line between types of wells (vertical, horizontal, and directional wells).

2.2 Regulatory CHOPS Gas and Methane Measurement, Reporting and Mitigation

The following section illustrates the rapid changes to regulatory CHOPS gas and methane measurement and reporting and GHG mitigation. It explains that the methodologies for measuring certain gas volumes are regulated while other vent/methane emission volumes can be determined by various methodologies. This section also explores some of the challenges with measurement and reporting, where many of the challenges involve the GOR methodology.

2.2.1 Introduction to Gas and Methane Regulations

The Alberta Energy Regulator (AER) and the Government of Saskatchewan regulate the CHOPS industry in their respective provinces. In addition, the Canadian government regulates greenhouse gas (GHG) emissions and mitigation, supported by recent provincial regulations and equivalency agreements. Both provinces have directives called *Measurement Requirements of Oil and Gas Operations*, Directives 017 and PNG017 in Alberta and Saskatchewan, respectively (AER, 2020a; Government of Saskatchewan, 2020a). These directives require that each month, CHOPS producers report oil production and associated gas volumes to the Petrinex accounting system for provincial regulators. Petrinex is a system jointly governed by the Alberta, British Columbia, Manitoba, and Saskatchewan governments, and industry, represented by the Canadian Association of Petroleum Producers and the Explorers and Producers Association of Canada (Johnson et al., 2017). As part of the monthly reports, the producers report associated gas that is flared, vented (vent gas), consumed as fuel (fuel gas), and gathered. In Alberta, producers also determine the mass of methane in vent gas and fugitive emissions and then report these as methane emissions (AER, 2020a). **Fig. 4** shows how different gas sources and emissions are reported.

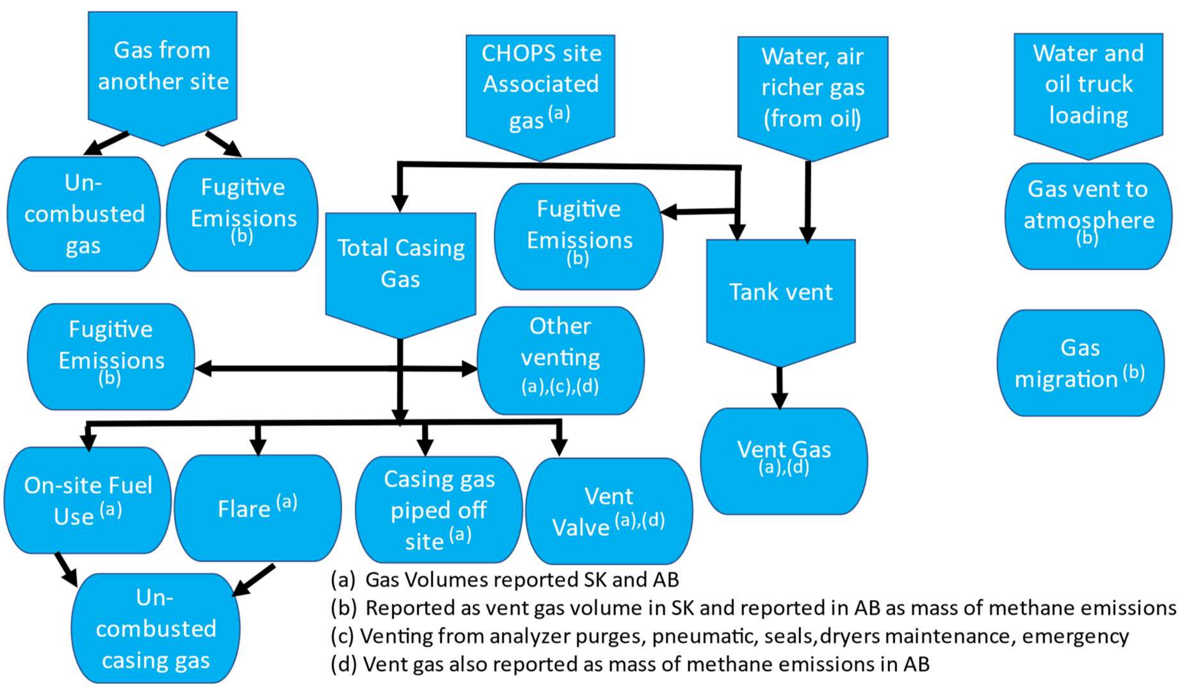


Fig. 4 — Regulatory associated gas, vent gas and methane emissions reporting requirements

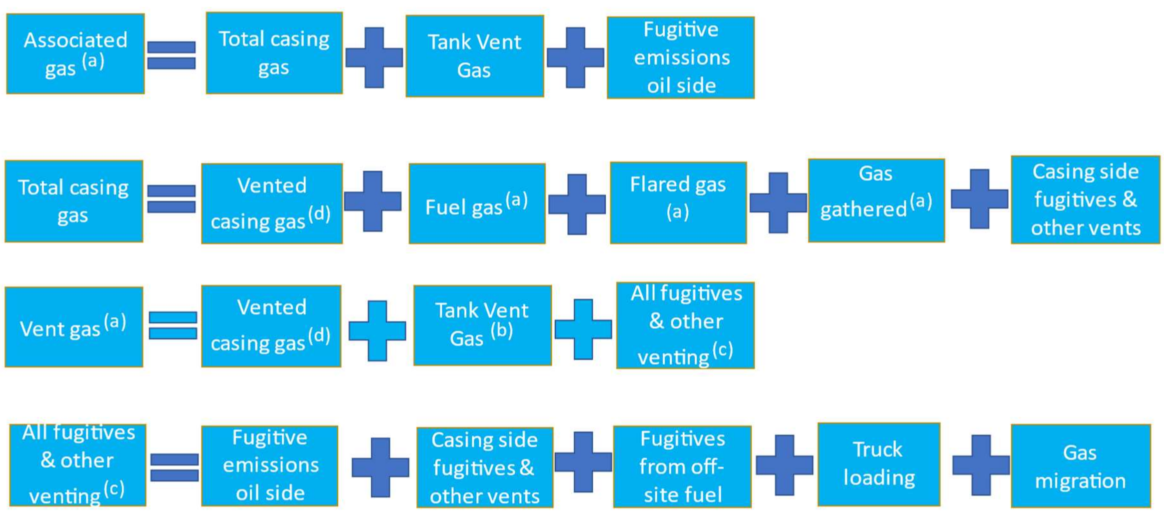
In the past, the dominant sources of methane emissions at CHOPS sites were venting excess casing gas via a vent valve to atmosphere, followed by tank vents, and in previous years these were the only vent gas sources reported for regulations. There is now more casing gas conservation at CHOPS sites and there are many other sources of vent gas and methane (**Table 1**). In 2019, Saskatchewan Directive PNG 017 (2020a) updated the definition of vent gas to include venting from online gas analyzers, solid desiccant dehydrators, pig trap operations, pneumatic devices, compressor seals, blowdowns for emergency or maintenance, well testing, completions and workovers, glycol dehydration equipment, engine and turbine starts, liquid loading of tank trucks, and fugitive emissions. Alberta Directives 017 and 060 (AER 2020a and AER 2021) are similar with the key differences that fugitive emissions and venting during liquid loading/unloading of tank trucks are excluded from the definition of vent gas and these volumes are reported directly as methane emissions. In both provinces, gas migration is included with fugitive emissions (AER 2021 and Government of Saskatchewan 2019).

The Government of Canada (2021) submitted Canada's national inventory of greenhouse gas sources and sinks to the United Nations Framework Convention on Climate Change for the years 1990 to 2019. In these inventories, all GHG emissions from the upstream oil and gas industry are termed fugitive emissions, and include venting, equipment leaks, formation CO_2 venting, storage losses, loading/unloading losses, accidental releases. Venting is sub-divided into reported and unreported venting, and it can include methane and carbon dioxide. In the 2010 to 2019 inventories, reported venting fuel and flaring emission volumes are sourced directly from Petrinex system for Alberta for the 2010 to 2019 inventory years for all oil and gas wells. The fuel and flared amounts are used to determine additional carbon dioxide and other GHG emissions. In these years, the reported vent gas at CHOPS sites mainly included routine venting from the casing side vent valves and the oil production tank vents. All other types of emissions, as well as all of Saskatchewan's flaring and venting emissions, are based on three studies completed for the inventory years 2000, 2005, and 2011, by Clearstone Engineering Ltd. (Government of Canada, 2021). Saskatchewan's reported flaring and venting volumes from the oil and gas industry are an important source of information in the Clearstone inventories, but Alberta activity data and published emission factors are used for several unreported emissions sources (Government of Canada, 2021).

2.2.2 Measuring and Reporting Gas and Methane at CHOPS Sites

In the past, the monthly volume of associated gas from a CHOPS well was reported as the sum of associated gas from the casing side and from the tank vent; and vent gas was reported as the sum of vent valve casing gas and tank vent gas. Now other vent sources (such as compressor seal and pneumatic vents) in Saskatchewan, are included in these volumes. In Alberta, producers report the mass of methane emissions from most CHOPS sources, including fugitive emissions. CHOPS vent gas and fugitive emission reporting continues to be mostly bottom-up. Rutherford et al. (2021) explain that in bottom-up surveys, emissions per component (source) or activity are measured or estimated at the components, while top-down surveys involve the entire site or multiple sites via technology mounted on aircraft, satellites, or weather stations.

Measuring the CHOPS gas flared, vented, and used for fuel is complex and the complexity has increased by expanding the inclusion of other vent gas sources (Alberta and Saskatchewan) and methane emissions (Alberta). In a few cases, there are continuous meters on all the casing gas streams which provide some of these volumes each month. In the rest of the sites, periodic gas-to oil ratio (GOR) or hourly rate tests are conducted to determine various casing gas stream volumes. Neither continuous metering nor GOR/hourly rate testing accounts for all vent gas sources and methane emissions. These other sources and emissions need to be metered or estimated and then carefully included with the information from continuous meters and GOR/hourly rate testing for either vent gas or methane emissions reporting. **Fig. 5** illustrates the relationships between some of the values which require regulatory reporting. The methodology for metering/estimating each source is explained further in the following sections.



(a) Regulatory reporting Saskatchewan and Alberta
(b) Assuming atmospheric oil production tank without vapour recovery
(c) Includes other casing gas vents (pneumatic, seals, dryers). Reported as vent gas (Sask) and reported separately (Alberta).
(d) Routine venting from vent valve

Fig. 5 — Relationships between gas streams.

2.2.2.1 Measuring and Reporting Tank Vent Gas

When there is no vapour recovery on the oil production tanks, CHOPS tanks vent to atmosphere. Few tanks have continuous meters on the vents. Directives 017 and PNG 017, allow the tank vent gas volumes to be estimated or metered by other means. The Saskatchewan Directive PNG 017 suggests using a test separator to determine the amount of associated gas in the produced oil. The highly viscous CHOPS oil often traps gas, and it is impractical to use separators for testing CHOPS production. Most CHOPS producers do not use test separators. Directive PNG 017 also offers the option of finding the gas in solution (GIS) value, to determine tank vent gas. Here, the GIS is found at least once in the site's life by taking a sample from the emulsion production line and conducting either PVT analysis or flash liberation analysis on the multi-phase sample. Saskatchewan Guideline PNG 035 (2019) also suggests using the Vasquez-Beggs bubble-point pressure correlation to estimate flashing losses from hydrocarbon tanks, along with estimates of breathing and working losses.

Similarly, Alberta Directive 017 suggests tank venting at heavy crude oil batteries can be determined from a test separator, GIS sampling, or methods listed under the *CAPP Guide for Estimation of Flaring and Venting Volumes from Upstream Oil and Gas Facilities.* An old version of the guide suggests that vent volumes for heavy oil production tanks can be estimated using the Vasquez-Beggs correlation or Standing correlation (CAPP, 2002). The CAPP guide does not discuss the estimation of breathing and working losses from the oil production tanks. Many CHOPS producers, in both provinces, use the Vasquez-Beggs correlation.

2.2.2.2 Continuous Metering of Casing Gas Streams

Both the Alberta and Saskatchewan directives require that if a CHOPS well associated gas, flared gas, gathered gas, or vented gas stream has a flowrate greater than 2000 standard $m^{3/}$day, then the gas stream must be metered. And if the annual average fuel gas consumption is greater than 500 m^3/day then fuel gas must be metered. Directives 17 and PNG 017 lay out the precise details of how to meter these streams, depending on the number of wells, flowrates of various gas streams, and types of equipment. Metered values can be used to help determine total casing gas, vented casing gas, associated gas, fuel, flared, and vent gas volumes but need to be considered along with measurements of other vent gas sources.

2.2.2.3 GOR Testing to Determine Casing Gas Volumes

When gas streams are not continuously metered on the casing side of a CHOPS well, monthly gas volumes (associated gas, fuel, flared, and vent gas volume) may be partially estimated with the help of gas to oil ratio (GOR) and hourly rate (Alberta only) testing. GOR and hourly rate at a CHOPS site must be tested periodically depending on the associated gas volumes at the site. In Alberta, the frequency of GOR or hourly rate test is once every 3 years if the gas rate is less than 100 m^3/d, annual if the gas rate is 100 to 1000 m^3/d, and semi-annual if the gas rate is 1000 to 2000 m^3/d. In Saskatchewan, the frequency of GOR tests is annual if the gas rate is 0 to 1000 m^3/d, and semi-annual if the gas rate is 1000 to 2000 m^3/d. In contrast, new federal regulations suggest determining GOR annually if gas rate is 0 to 500 m^3/d, every 6 months if gas rate is 500 to 1000 m^3/d, and monthly if gas rate is 1000 to 2000 m^3/d (Government of Canada, 2020).

The GOR method is used for CHOPS and conventional oil wells, for reporting associated gas volumes, and has been in practice prior to concerns with GHG emissions. The GOR is a ratio of the volume of associated gas to the volume of produced oil. In conventional oil wells, GOR can be measured easily using test separators. At a CHOPS site, a GOR test value is found by temporarily metering the casing gas to measure the volume of gas during the test, adding the tank vent gas, and dividing the total by a pro-rated oil production volume for a time period that includes the gas measurement. The production volume of oil is estimated and not physically metered during a GOR test.

It is currently difficult to meter CHOPS oil flow during GOR tests because the stream is a mixture containing sand, water, gas, and foamy oil. In Alberta (Directive 017) oil production in the test is determined from change in tank inventory, in conjunction with total truck water and oil dispositions during a time period encompassing the duration of the gas measurement of the GOR test, pro-rated for the duration of the gas test. In addition, the producers use recent sand and water cut (BS&W) information to estimate the produced oil volume during the time period of the oil measurement. Saskatchewan Directive PNG017 (revision 5.0) was recently revised to allow inventory changes and disposition volumes to be used to determine the daily oil production rate (of the GOR test) for the same month as the metered gas volume of the test.

Some producers determine the oil production over a short time period of a few days encompassing the gas test volume measurement, while others use the oil production from the entire month, or multiple months where there is better information of BS&W. Longer time periods help to even out the variability in BS&W. There is a high amount of variability in BS&W of the produced fluid on a daily or monthly basis. The BS&W is accurately determined when loading oil and water to trucks, but BS&W is unknown for the volume of liquid that fills the tank during the time period of the oil measurement of the GOR test. On the other hand, the oil flow rate will sometimes change before and after the GOR test naturally or if the pump speed or downhole pressure is adjusted. If the oil flowrate changes during the time period of the oil production measurement, then the oil production volume cannot be pro-rated to the duration of the gas test, without introducing error to the GOR test value. The Government of Canada introduced new federal regulations to encourage greenhouse gas emission reduction from the oil and gas sector (Government of Canada, 2020). These regulations recommend using a 10-day time period, encompassing the gas test, for determining the oil production volume in the GOR test. The 10-day requirement was also a recommendation of a joint industry study (New Paradigm Engineering, 2004). However, these recommendations do not address the uncertainty in the BS&W value over a short 10-day time period.

As a result of the new federal regulations (Government of Canada, 2020), the Alberta and Saskatchewan directives were revised to specify more frequent GOR testing and longer gas measurement test periods for GOR tests. In the case of Alberta, the duration of the GOR and hourly rate tests is 72 hours (as of 2023). The Saskatchewan Directive PNG 017 no longer allows hourly rate tests for associated and vent gas reporting and stipulates operators must determine the gas values in the GOR by a 72-hour interval test unless the variation in the flowrate during the test period is low (Government of Saskatchewan, 2020).

Some producers complete GOR test gas measurements on the total casing gas stream while others complete measurements on the gas vented to atmosphere from a casing vent valve. The GOR test methodology assumes that either associated gas or vent gas is directly proportional to oil production in between GOR tests. An associated gas GOR test involves metering the total casing gas stream, and the vent gas GOR test involves metering only the casing gas from the vent valve to atmosphere:

$$GOR_{associated\ gas} = \frac{Total_{Casing\ Gas} + Tank\ Vent\ Gas}{Volume\ of\ oil\ production\ prorated\ to\ duration\ of\ casing\ gas\ test}$$

Equation 1

$$GOR_{vent\ gas} = \frac{Vented_{Casing\ Gas} + Tank\ Vent\ Gas}{Volume\ of\ oil\ production\ prorated\ to\ duration\ of\ casing\ gas\ test}$$

Equation 2

Typically, in both cases, an estimate of the tank vent gas is added to a direct measurement (metered) value of the casing gas. This can be confusing because now other sources of venting and fugitive emissions, in addition to the tank vent, must be metered/estimated and reported.

2.2.2.4 Hourly Rate Testing to Find Casing Gas Volumes

In the hourly rate test (Alberta) all casing gas streams are measured during the test. Saskatchewan's Directive PNG 017 only allows hourly rate testing for fuel volumes; when there is no manufacturer's information to estimate casing gas fuel consumption of a piece of equipment such as a heater or drive, an hourly rate test can be used to meter the fuel, and the test value can be used over the life of the equipment, as long as equipment operating conditions are unchanged.

2.2.2.5 Fuel and Flare Estimations

When there are no continuous meters on the fuel or flare gas or hourly rate testing, these volumes may be estimated by making assumptions of the rate of fuel consumption or flaring and the operating hours of the device.

2.2.2.6 Gas gathering and natural gas from other sites

Ideally gas entering or leaving the site is metered. When there are no continuous meters, these volumes are estimated. Volumes greater than 500 m^3/day must be metered.

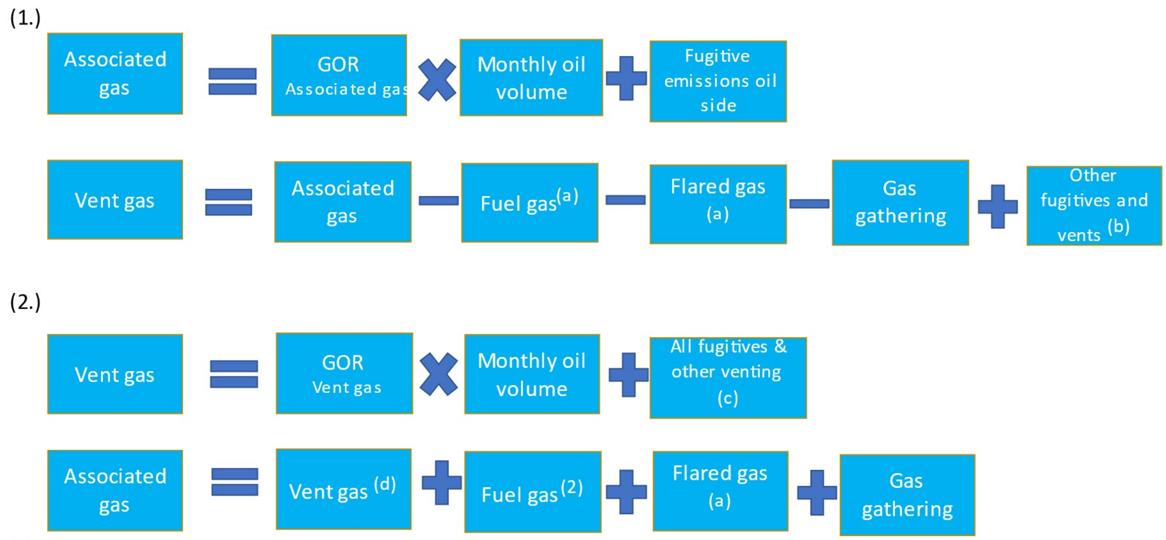
2.2.2.7 Other vent gas and fugitive emissions

PNG 035 (Saskatchewan, 2019) and Alberta Directives 17 and 060 (AER 2020a and AER 2021) describe how to estimate or measure all other venting sources and fugitive emissions which are not measured by the site's continuous meters or GOR/hourly rate testing. Sources include online gas analyzers, solid desiccant dehydrators, pig trap operations, pneumatic devices, compressor seals, engine crankcases, blowdowns for emergency or maintenance, well testing, completions and workovers, glycol dehydration equipment, engine and turbine starts, liquid loading of tank trucks, and fugitive emissions. In general, these can be determined by direct measurement. Alternatively, they can be estimated by inventorying a producers sites' activities (equipment, components, and operations such as truck loading) and using published or site-measured fugitive emission factors.

Alberta Manual 015 (AER, 2020b) and Saskatchewan Guideline PNG 035 (Government of Saskatchewan, 2019) suggest that fugitive emission volumes can be determined from direct measurement of the whole facility and then subtracting other tabulated venting/emission sources. Manual 015 also lists technologies for whole facility emission measurements such as sensor-mounted technologies or mobile tracer release methods.

2.2.2.8 Monthly associated and vent gas volumes

When using GOR testing, associated and vent gas volumes are partially found from the relationships shown in **Fig. 6**. These equations assume that tank venting has been incorporated into the GOR test value (**Equation** 1 and **Equation** 2) but other venting and fugitive sources need to be accounted for separately and added or subtracted as needed, using the relationships in **Fig. 5**. Monthly oil production is determined from total dispositions of oil out of the battery in the month. This is a reasonably accurate measurement of the monthly oil production. While changes to pump speed or downhole pressure introduce inaccuracies to the GOR test value, these changes are irrelevant to the determination of the monthly gas volumes and do not cause errors in these values. With the GOR test method, monthly volumes such as gas to and from gathering pipelines, fuel gas and flared gas are determined from continuous meters or from estimates.



(a) Can be estimated based on typical annual, operating hours business-wide.
(b) Includes other vents (pneumatics, seals, dryers, truck-loading, gas migration) but not oil side fugitives.
(c) Vent or fugitive sources not measured by vent gas GOR test (pneumatics, seals, dryers, truck-loading, gas migration).
(d) Exclude vent and fugitive sources which do not originate from associated gas (.e. fugitives from purchased natural gas).

Fig. 6 — Relationships for finding monthly vented and associated gas (1.) GOR test of total associated gas (2.) GOR test of vented gas values. In both cases, the tank vent gas is incorporated into the GOR test value.

In Alberta, if an hourly rate test is used, then the monthly vented gas and monthly associated gas volumes are partially based on the hourly rate test values, prorated from the duration of the test to the duration of the month. These will include the rate of the total casing gas, fuel gas, flared gas, gas to and from gathering lines, and casing gas vented from the vent valve. Then, similar to the GOR method, the producers need to incorporate other vent sources and fugitives as needed to determine associated and vent gas as per the relationships in **Fig. 5**.

In both provinces, where there are continuous meters on all casing gas streams, the records of monthly gas volumes are collected. Again, as with the GOR/hourly rate methods, the producers need to incorporate other vent sources and fugitives as needed to determine associated and vent gas (**Fig. 5**).

2.2.3 Regulatory Gas and Methane Reporting and GHG Mitigation

The reported volumes of associated and vent gas are used for regulated GHG emissions and mitigation. Directive PNG 036 (Government of Saskatchewan, 2020b) allows daily venting of up to 900 m^3/day of associated gas from oil wells. In addition, Saskatchewan has regulations that separately define emissions limits, in tonnes of carbon dioxide equivalent (CO_2e) per volume of total associated gas, for all facilities per production class, licensed by a producer (Government of Saskatchewan, 2019). These regulations allow a producer to strategically make emissions cuts throughout their sites. The producer's emissions limits are proportional to the intensity of venting, which is calculated from the ratio of vented to associated gas production of all sites in a production class. The producer must measure both vented gas and total associated gas. In Alberta, AER Directive 60 (AER, 2021) sets an overall vent gas limit of 15.0 10^3 m^3 of vent gas or 9.0 10^3 kg methane per month per site.

2.3 Challenges of CHOPS Gas and Methane Measurement and Reporting

The following section presents the challenges in measuring and reporting CHOPS gas and methane emissions. As well, the discussion illustrates how measurement challenges affect GHG mitigation regulations.

2.3.1 Scan of Studies on CHOPS Gas and Methane Measurement and Reporting

Several reports and studies from the past couple of decades investigate associated gas, vent gas and methane emissions from CHOPS wells and point out challenges with measurement and reporting.

A comprehensive, joint industry study of CHOPS associated gas and venting, which includes representatives of Nexen, CNRL and Husky, attempts to improve associated gas and venting quantification methods (New Paradigm Engineering, 2004). The study is re-visited in 2017 (New Paradigm Engineering, 2017).

Recent studies of CHOPS sites near Lloydminster measure methane emissions with airplane and truck-mounted technologies and indicate that actual methane emissions are greater than the venting volumes reported to Petrinex (Johnson et al, 2017 and Roscioli et al. 2018). Johnson et al. (2017) completed a top-down study of methane emissions from upstream oil and gas production in two areas of Alberta, one near Red Deer, and one near Lloydminster, Alberta in 2016. They used a plane to fly crisscross over a 60 by 60 km area above Lloydminster, with a large amount of CHOPS facilities. 89% of the oil and gas facilities in the Lloydminster study area were CHOPS production sites. They sampled the composition of the air and were able to quantify an overall volumetric rate of methane emissions from the area. They compared the measured methane volumes to the data reported to the Petrinex accounting system. In addition, they estimated the volumetric methane emissions from natural sources in the area. The results indicated that after subtracting the natural sources of emissions, the measured methane during the flights was close to four times larger than the regulatory reported vent gas and three time higher than Canada's reported national inventory of greenhouse gas sources and sinks of 1990-2014.

Roscioli et al. (2018) studied methane emissions from five CHOPS facilities in Alberta. They completed field measurements of methane and compared them to regulatory reported venting rates. They used a dual tracer ratio method to detect and quantify methane emissions. This method involves directly metering the flowrates of two tracer gases which were each released from separate gas canisters, from a site or piece of equipment where there was a known methane emission. Ambient samples were collected at the point of the emission and at a downwind point from the site, to measure concentrations of the tracer gases and methane. The ratio of the tracer to methane concentrations are proportional to the ratio of the emission flowrates of the tracer to the flowrate of the methane. The volumes of venting from the five sites, which were reported to Petrinex, for the month in which the study took place, were divided by the number of hours in the month to calculate the venting rate in kg/h of methane. The reported venting rates were compared to the measured site-wide emissions. For one site, the reported vent rate was 0, while the measured methane emission for the site was 4.24 kg/hr. For the other four sites the measured versus reported ratios ranged from 0.36 to 13.1.

Mackay et al. (2021) surveyed 6650 oil and gas sites in six upstream producing regions of Canada, including the region near Lloydminster, AB. The Lloydminster region had the highest absolute and intensity-based methane emissions. They surveyed the sites with truck-based technology in visits from 2015 and 2018. The methane emission intensity at Lloydminster is found to be 0 to 32 gCO_2e/MJ of energy produced, with an average of around 10 g CO_2e/MJ. The site level emission rate for Lloydminster sites ranges from 5 to over 1000 standard m^3/day of methane, with an overall mean of close to 100 m^3/day. The study approximates that the overall Alberta non-oilsands upstream oil and gas methane emissions may be 1.5 times higher than the values determined in the 2018 Environment and Climate Change Canada inventory.

In addition, a bottom-up methane inventory in Alberta, from upstream oil and gas, and the business case for a CHOPS Methane Challenge project point out there are problems with measurement and reporting of gas volumes from CHOPS sites (Clearstone Engineering, 2019 and Alberta Innovates 2018).

2.3.2 Challenges of CHOPS Gas and Methane Measurement and Reporting

The above-mentioned reports and studies suggest the following sources of error in the measurement and reporting of associated gas and venting from CHOPS sites. In addition, challenge 2.3.2.10 is identified by the author and technical advisory committee members but not mentioned in the literature scan. These problems could lead to measurement and reporting errors and problems with meeting GHG mitigation regulations:

2.3.2.1 Variable associated gas flowrates

Associated gas volumes in the casing and the production line can have large fluctuations daily, weekly and throughout the life of the well and thus it is difficult to get an accurate GOR test value (New Paradigm Engineering, 2004, 2017). The New Paradigm Engineering study (2004) suggested lengthening the time interval of total casing gas measurements from 24 to 72 hours in associated gas GOR tests for certain

CHOPS wells where the total casing gas flow is not steady state. This recommendation may have inspired recent federal regulations, and subsequent provincial regulations requiring longer (72-hour) GOR test intervals for CHOPS wells. Another recommendation of the New Paradigm Engineering study was to shut down all other casing gas destinations (heater, drives, pneumatics, and flaring) during total associated gas GOR tests. While longer total casing gas measurement intervals and sending all casing gas to atmosphere may improve measurement of total casing gas and associated gas, these actions may not improve measurements of vent gas and methane emissions from a CHOPS site. It is important to consider the objectives of the New Paradigm Engineering joint industry study. Although concerns with greenhouse gas emissions partly inspired the study, the primary objective of the study was to improve measurement of associated gas and GOR from CHOPS wells and not to improve methane emission measurement.

2.3.2.2 Variable GOR

The majority of vent gas reporting at CHOPS sites is based on the GOR testing method. Roscioli et al. (2018) suggest that there may be errors in applying the GOR test method for determining vent gas. They examine 2280 Lloydminster CHOPS wells in 2016 and find that the median and mean GOR values of this group are 101 and 1190 m^3 gas/m^3 oil, respectively. New Paradigm Engineering (2004) advises that a GOR of greater than 150 m^3/m^3 is likely due to a gas cap in the oil reservoir. Roscioli et al. (2018) also determine the median and mean site variability in the GOR values to be 36% and 109%, respectively. New Paradigm Engineering (2017) observes that oil production rates from wells on multi-well pads are often higher in the months of GOR testing, resulting in lower GOR test values; the authors speculate that oil production is not being assigned to the correct well in certain months. They also suggest that there is typically an increasing trend in GOR values over the life of the well, rather than a constant GOR in between tests. Johnson et al (2017) also raise concerns with the GOR testing methodology. The GOR testing method assumes that the GOR is constant in between tests and that the associated gas (or vent gas) is directly proportional to oil production. There are no public reports or studies demonstrating that either an associated or a vent valve GOR is in fact constant in between GOR tests at CHOPS sites.

2.3.2.3 Inaccurate fuel and flare volumes

One of the largest sources of error in regulatory reporting of associated gas and vented gas volumes are estimates of fuel use or flaring, when there is no continuous metering of the fuel or flared gas. Due to the large number of CHOPS sites, the average monthly operating hours of each type of gas-fired equipment is assumed for the equipment type and is not determined for each piece of equipment at each site per month. For instance, it may be assumed that all tank heaters will operate an average of 8 hours per day at every site, throughout the year. The average operating hours are then combined with the average manufacturer's rated fuel use to get an average monthly fuel use for all heaters. The number of pieces of equipment at a site are multiplied by the average fuel use rate of a heater or engine, to get monthly fuel consumption. In reality, operating hours and consumption rates will likely vary for gas-fired equipment within a site and from site to site depending on ambient temperatures, oil production flow rates, and other operating conditions, but it is not feasible to quantify these variables for each site. **Fig. 5** and **Fig. 6** show the relationships between fuel/flare volumes and associated/vent gas volumes. New Paradigm Engineering (2017) observes that estimated fuel and flare volumes will cause errors in the vented gas volumes.

2.3.2.4 Differences in methodology for the oil measurement in the GOR test

The oil volumes in the GOR test value may be determined for the duration of the gas flow measurement, or entire month of the test. Oil flowrate can change if the oil production pump rate or down- hole well pressures is changed. As a result, the oil flowrate during the gas measurement of the GOR test would be different than the average flowrate of the month. Different producers may determine GOR test values differently. New Paradigm Engineering (2017) emphasizes the need for an accurate measure of the oil during the GOR test. One of the reasons for using longer oil production durations, is that it is very difficult to determine the water and oil content in the produced liquid.

2.3.2.5 Variable tank venting and inaccurate tank vent estimations

When determining the associated gas or vented gas for all regulatory reporting, the vent gas from the production tanks is estimated and not measured and likely leads to inaccurate reported venting volumes (New Paradigm Engineering, 2017, and Clearstone Engineering, 2019). Tank vent volumes and variability in tank vent gas are significant when there is foamy oil or gas slugs entering the production tubing. In addition, venting is often greatest in the first year of life of a CHOPS well. In early production, most of the gas may be produced with the oil instead of flowing up the casing. As mentioned, test separators are generally not feasible at CHOPS sites. If using GIS, it is sometimes found only once during the life of a well, and CHOPS producers on the technical advisory committee of this project indicate that there is large variation in GIS measurements from samples taken the same day. Periodic testing with GIS measurements may not account for gas slugs in the oil or variability in the tank venting.

2.3.2.6 Reporting pneumatic venting as fuel gas

In the past, gas vented from pneumatic equipment was reported as fuel gas consumption (Roscioli et al., 2018). The reported vented and flared gas volumes did not include gas consumed by pneumatic equipment. Recent updates to Saskatchewan and Alberta regulations will help to alleviate this error.

2.3.2.7 Omission of other venting and fugitive emissions sources

In the past, most of the CHOPS casing gas was vented to atmosphere via a vent valve, and it was the dominant source of emissions from CHOPS production, followed by venting from oil production tanks. Vent gas from loading/unloading trucks and fugitive emissions on the casing or oil production side were neglected in reporting in past years. With the addition of casing gas recovery equipment such as on-site fuel use in heaters and drives, flares, combustors, gas gathering lines there are now many other sources of emissions (**Table 1**). These may not be accounted for with continuous gas meters or during GOR/hourly rate testing. For instance, fugitive emission leaks may occur upstream or downstream of continuous or test meters. Updated provincial regulations require reporting of all vent gas and fugitive emissions.

2.3.2.8 Errors in reporting

There are likely errors during regulatory reporting, such as reporting vented gas as flared or vice versa (Clearstone Engineering, 2019 and Roscioli et al., 2018).

2.3.2.9 Un-combusted methane

Roscioli et al. (2018) emphasize that the gas used in combustion equipment such as heaters and compressors is not completely combusted and will result in a small amount of methane emissions. These methane emissions are not included in the reported vented gas. The same is true for flaring equipment (open-flame flares, incinerators, or enclosed combustors) which is now used more frequently in the CHOPS sector. Flares and combustors can be unlit for a variety of reasons. Although un-combusted gas in fuel devices is usually low and constant, un-combusted gas from some flares and combustors increases at low flowrates. Tyner and Johnson (2021) completed airborne measurements methane above oil and gas sites in British Columbia. They found that the measured emissions in airborne survey were far larger than emissions estimated by site-level surveys with optical gas imaging cameras. They suggest that one of the causes of discrepancies is unlit flares. They speculate that combustion slip (un-combusted methane) is also a cause of the discrepancies. While in the past, flare stacks and enclosed combustors were uncommon at CHOPS sites, they may become more common as producers make further cuts to greenhouse gas emissions.

2.3.2.10 Inability to accurately measure oil production during GOR test

Estimates of oil production during GOR tests are likely inaccurate due to large variability in BS&W. BS&W can vary greatly in a short time. BS&W can be accurately determined from any truckloads taken from the tank during the GOR test but not for liquid produced to the tank during the test. Variability in BS&W is one of the reasons a producer may determine (measure) oil production in the GOR test over longer durations (1 to 3 months); however, the downside of longer durations is that oil flowrate may change due to pump speed or downhole pressure and cause error in the GOR value.

3. Assessment of CHOPS Gas Measurement Methodologies and Technologies

3.1 Introduction to Measurement Methodologies and Technologies

Associated and vented gas, and methane emissions are metered or estimated with a combination of methodologies and technologies. The scope of a measurement survey can range from a single piece of equipment to an entire region or country. Often for large, company-wide, or regional methane measurement surveys, it is advantageous to determine the emissions from each activity, whether the activity is a single component of an equipment (i.e., wellhead), or an operation (i.e., truck-loading event). Thus, the emissions per activity and emission category (fugitives, tank venting, pneumatic venting) can be agglomerated and compared in the survey. In other instances, it might be sufficient to use a technology that takes a single site-level measurement of emissions before and after the deployment of a methane mitigation project.

Fig. 7 illustrates a model of the relative accuracy of emission measurement. Measurement accuracy can range from rough estimates to direct, continuous measurements of every vent gas and emission source. Intermediate accuracy options include extrapolating regional measurements from a sample set of some of the emissions sources and using published emission factors to estimate sources that are difficult to measure. Accuracy is further improved by determining emissions from every source at every site and using site-specific emission factors. In theory, accuracy is improved with methodology and technology combinations further to the right on the scale of **Fig. 7**. Ultimately, field testing can compare and demonstrate the accuracy of different methodologies and technologies.

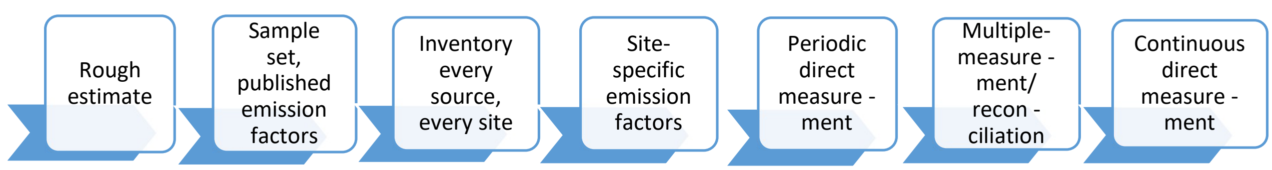


Fig. 7 — Model of the accuracy of emission measurement approaches.

Change has occurred rapidly in the domain of measurement of gas venting and methane emissions. Technology is advancing for both periodic and continuous direct measurement. New technologies have drastically changed the scale of gas and emission measurement. Technology mounted on satellites, airplanes, drones, and trucks has proven excellent for methane detection, in leak detection and repair programs. This technology is also applied to regional and site-level emission measurement. Some of these top-down and site-level options may soon provide accurate quantitative measurement at even the individual equipment and activity level. There are also new fixed methane flux sensors which can provide continuous, quantitative site and regional emission measurement. Advancing technologies may greatly decrease the costs involved with CHOPS gas measurement and reporting, as well as improve accuracy.

Some technologies are suitable when equipment is designed to have methane emissions while other technologies are very suitable for detecting and measuring fugitive emissions which are unplanned events. In general, methane emissions are the result of either ***operations*** (such as venting a natural gas pipeline to atmosphere prior to maintenance), ***design*** (CHOPS casing vent valves to atmosphere and fixed roof CHOPS tanks without vapour recovery), or ***unplanned events*** (fugitive emissions). As the oil and gas sector transitions away from design and operations-related methane emissions, top-down and site-level methane emission surveys will become a cost-effective method, which may meet many of the needs of both company stakeholders and government regulators.

3.2 Analysis of the Gaps in Measurement Methodologies and Technologies

Fig. 7 helps to conceptualize the gaps in measurement methodologies and technologies in the CHOPS sector and predict the relative accuracy of current and alternative measurement approaches. Several measurement challenges are identified in past studies (Section 2.3) and the top three gap areas are listed below. The gaps are also illustrated on **Fig. 8** along with other measurement methodologies. In theory, these gaps will be reduced with measurement methodology/technology combinations further to the right of **Fig. 7**.

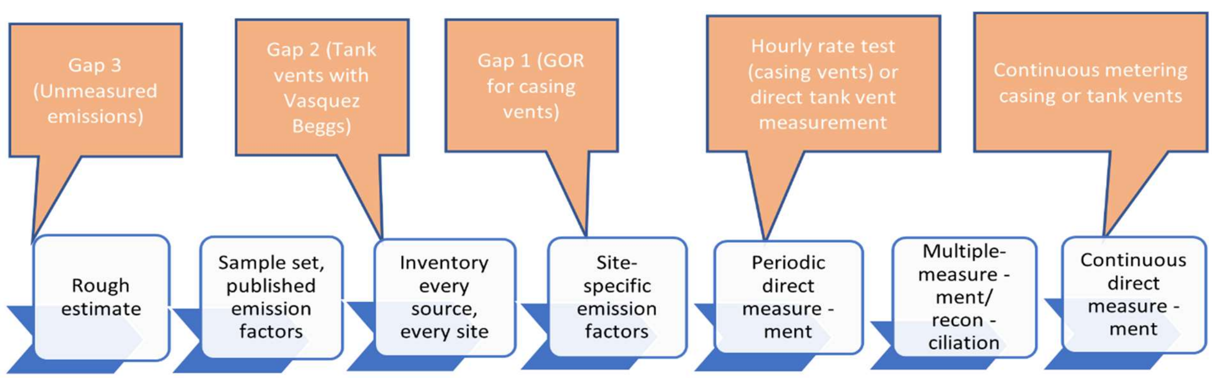


Fig. 8 — Current measurement methodologies and gaps

3.2.1 Gap 1 Inaccurate measurement of casing venting with GOR methodology

Current national and provincial regulations allow for various interpretations of GOR testing methodology which is used to infer methane emissions from casing valves. A small number of sites have continuous meters of casing gas and these likely have a high accuracy, far to the right on the scale of **Fig. 7**. The GOR methodology is similar to a site-specific emission. Several challenges with the GOR methodology listed in Section 2.3 may push the accuracy to the left on the scale of **Fig. 7**. The main challenges include estimating oil volumes in the GOR test and estimating fuel volumes. This gap can be evaluated by comparing various GOR test values to periodic and continuous direct measurements of vented casing gas. Hourly rate testing is a periodic direct measurement methodology.

3.2.2 Gap 2 Inaccurate measurement of tank emissions

CHOPS sector tank emissions are often found using the Vazquez Beggs correlation. This approach is similar to using a published emission factor, except this correlation was not designed for tank emissions from the CHOPS sector. It is possible that current tank emission measurement accuracy is on the left side of **Fig. 7**. This gap can be evaluated by comparing Vasquez Beggs to GIS testing and direct measurement of tank vents.

3.2.3 Gap 3 Absence of measurement of other methane sources

In the past, CHOPS producers primarily measured and reported only venting from atmospheric casing valves and tanks and did not measure other methane sources such as fugitive emissions. At CHOPS sites where these sources are not reported, the accuracy is very far to the left of **Fig. 7**. Accuracy will likely improve by measuring all sources at all sites.

There is little public data on other emission sources from the CHOPS sector to compare emission categories (casing vents, tank vents, fugitives, non-routine venting, etc.). This information would be beneficial to show the relative amount of casing and tank venting compared to other sources. As the CHOPS sector transitions to lower methane emissions by increasing conservation from of casing gas and tank vents, it would be helpful to understand the magnitude of these other emissions sources (fugitives, non-routine venting, etc.).

3.3 Measurement Methodologies and Technologies for CHOPS Sites

Table 2 summarizes conventional and emerging methodologies and technologies for CHOPS gas and methane emissions measurement. They are discussed in more detail in the following sections.

Table 2 —Associated Gas and Methane Methodologies and Technologies

Section	Methodology	Technology	Advantages	Disadvantages
3.3.1	Status quo: Current 72-hour GOR tests and tank vent estimates from Vasquez-Beggs correlation, along with determining other vent gas and emission sources with published or site-specific emission factors	*Casing gas streams:* • Orifice meter • Thermal anemometers • Positive displacement meters Other vent gas/fugitives: • For companies who use site-specific emission factors or direct measurement, the Hetek Hi Flow Sampler ® may be used.	• A GOR test is used to measure either associated gas or casing vent valve gas. • The method has lower labour because only one casing stream is measured instead of multiple streams. • Rather than using a single, annual, periodic measurement of casing gas for determining annual venting, the GOR methodology attempts to account for annual fluctuations, by adjusting vent volumes with oil production. • The Vasquez-Beggs correlation is simple.	• The GOR may not be constant in between GOR tests. • Total casing gas may have large fluctuations in between GOR tests. • Tank venting is not measured, and it may be variable over time. The Vasquez Beggs correlation does not account for slugs of gas or gas bubbles during foamy oil flow in the production line. • It is expensive to complete 72-hour versus 24-hour tests and there is no evidence that longer GOR tests improve estimates of methane emissions. • Fuel and flare flowrates are often unmetered. Inaccurate fuel and flare estimates can cause inaccuracies in venting/methane emission estimates. • The oil value in a GOR test may be inaccurate: the amount of sand/water in the produced fluid varies significantly daily or monthly and longer time intervals may result in changes to oil flowrate. • Regulations do not clearly define whether the GOR test is valid for both vent gas and associated gas. • Regulations now require all other vent sources to be determined. It is difficult to reconcile other vent sources and fugitive emissions with test to find associated gas and vent gas; very complicated especially with differences in vent gas definitions between provinces.
3.3.2	Continuous metering of casing gas streams	*Casing gas streams:* • Orifice meters • Rotary, positive displacement meters • Thermal anemometers • Vortex meters • Coriolis multi-phase meters (rare)	• Continuous metering is likely more accurate than GOR or hourly rate testing if GOR of CHOPS wells is not constant between tests. • Continuous metering increases the accuracy of associated gas measurement but will only increase the accuracy of vent gas and methane emission measurement when there are low levels of casing gas conservation. • IoT (internet of things) technology may make continuous flow meters on casing vent less expensive than periodic testing.	• Cannot meter emissions from fugitive releases, compressor/drive emissions, un-combusted methane, and venting during truck loading, maintenance, pressure relief valves lifting, or well completions. • As more of the CHOPS casing gas is conserved, and the industry reduces design-related emissions, continuous meters on casing gas streams will not improve vent gas/methane emissions measurement. • Orifice meters introduce back pressure to the casing gas side when they are under-sized, or the casing needs to be controlled at a low pressure. • A high level of expertise is required to size orifice meters properly. • The more accurate casing gas meters are more expensive and more difficult to maintain and operate (Coriolis), and some meters require water and liquids removal with a separator.

Section	Methodology	Technology	Advantages	Disadvantages
				• In some cases, continuous metering is costly and introduces more safety hazards.
3.3.3	Continuous metering of tank vent streams	• Volume meter • Thermal anemometer • On-line gas chromatogram analyzer	• Tank vent flowrates vary, and continuous metering would measure flow fluctuations, unlike periodic testing. • Less expensive and easier to operate if gas composition is estimated rather than using an on-line analyzer. • IoT technology may make continuous flow meters on tank vents less expensive than periodic direct measurement. • Less accurate, inexpensive meters can be used for detection to screen for corrective action or more accurate testing.	• Capital costs of flow meters may be high. • It would be unfeasible to install a GC analyzer on the tank vent. • Tanks require significant modification to be fully enclosed. • Moisture and cold weather would affect operation.
3.3.4	Periodic Tank Vent Testing		• Tank vent testing may improve upon the Vasquez Begs correlation which does not account for gas bubbles/slugs trapped in the viscous oil, which are not at equilibrium with the oil.	• It is difficult and costly to directly measure tanks: require good weather, aerial lift, two or three people. • Does not measure short-term high venting, perhaps when down-hole liquid level is lost.
3.3.4.11		• Take samples of tank vent for GC analysis and measure flowrate of tank vent using volume meter or pitot tube	• Volume meters are accurate at metering gas vents.	• Volume meters but not pitot tubes will put back pressure on the tank. • Vane anemometers and pitot tubes are affected by wind. • Sampling the vent stream for lab GC analysis, adds complexity to the testing.
3.3.5	Estimate of GOR	• Use an estimate of the maximum GOR based on oil production: $-0.5P_w+150$, where P_w is average m^3 oil produced in a day for the most recent month (Government of Canada, 2021).	• Simple • Inexpensive	• Accuracy may be poor. • Assumes the ratio between associated gas and produced oil is constant.
3.3.6	Computational Models of GOR	• Use a model to estimate total associated gas, then subtract total casing gas (direct measurement) to estimate tank vent emissions.	• A less costly and safer method of estimating tank venting emissions than periodic tank vent testing.	• Currently, there has been no success in creating useful models for predicting GOR at CHOPS sites.
3.3.7	Bottom-up emission surveys with handheld instruments		• In general, these include all emission sources (vent gas and fugitives), but they may not work well on large flowrates such as vented casing gas at a CHOPS site. • More accurate than published emission factors (fugitives, pneumatics). The higher accuracy may suit other purposes of methane emission measurement such as reporting the benefits of a methane mitigation project internally and to stakeholders. • Can also use for methane detection (leak detection and repair programs). • Less expensive than continuous metering and 72-hour GOR tests. • Can be used in combination with other methodologies/technologies of measuring CHOPS casing gas venting.	• Often more labor-intensive and costly compared to top-down methods. • These will not address measurement problems with total associated gas from CHOPS wells. • Periodic test rather than continuous measurement: the survey may miss large, infrequent emissions such as equipment failures; or may be skewed to include intermittent emissions which are more common in daytime working hours such as venting due to maintenance or oil/water truck loading.

Section	Methodology	Technology	Advantages	Disadvantages
3.3.7.1		• Hetek Hi Flow Sampler ®	• High accuracy for measuring low vent flows where there is little variation in composition of the vented gas.	• No access to tank vents for using the Hi Flow Sampler (arm extensions are difficult to seal). • Cannot measure vent flows above a maximum. It is likely that many atmospheric casing vents and tank vents at CHOPS sites exceed this maximum limit. • Tank vents at CHOPS sites have a varying composition, and it is difficult to calibrate the sampler for a changing composition. • Require a high amount of operator experience. • Require frequent calibrations.
3.3.7.2		• Quantitative optical gas imaging (QOGI) cameras	• Easier to deploy than a Hi Flow Sampler ®. • Do not require frequent calibrations. • Suitable for large surveys of multiple sites or regions.	• Limited access to tank vents. • Require a high amount of operator experience. • Many sources of interference with the quantitative volumes such as temperature of the equipment and surroundings, reflective surfaces, clouds, or movement in the background.
3.3.7.3		• Optical gas imaging camera and estimating magnitude of methane emissions from plume size	• Possibly equal accuracy to quantitative optical gas imaging. • Much easier to use than QOGI. • Faster surveys than other hand-held methods. • Extremely well-suited for leak detection and repair programs. • Can be used to screen casing vent valves and tank vents for more frequent direct measurement.	• Limited access to tank vents. • Require a high amount of operator experience. • Inaccurate estimates of tank vents and un-combusted (methane slip) sources.
3.3.8	Shorter Duration GOR tests (Decrease the gas measurement time interval from 72 to 24 or 1 hour	• Same as 72-hour GOR tests.	• Ease of use. • Possibly no improvement in accuracy versus 72-hour tests.	• Many of the same disadvantages as 72-hour testing.
3.3.9	Hourly rate testing, any duration of test. *Any methodology/technology for determining tank venting or other vent gas and emission sources*.	*Total associated and vented casing gas streams:* • Orifice meter • Thermal anemometers • Positive displacement meters	• Cost effective if 24 hours or less. • Eliminates challenges with measuring oil flowrate of GOR during the test (oil flowrate can change during test and it is difficult to determine the BS&W of the produced liquids during the test). • Far less confusing than applying the GOR methodology while determining all vent and methane emissions sources (fugitives, pneumatics, truck loading); less confusion may reduce reporting errors. • Equally applicable for sites whose venting is dominated by atmospheric casing vent valves and sites with nearly complete conservation of casing gas. • Total casing gas flow can also be measured.	• Periodic test rather than continuous measurement: the test may miss large, spikes in vented casing gas.
3.3.10	Site-Level surveys	• Various proprietary technologies	• High accuracy. • Quicker than methane emission surveys with hand-held instrumentation. • In general, these include all emission sources (vent gas and fugitives). • Detection of methane slip from combustion equipment and tank vents.	• These will not address measurement problems with total associated gas from CHOPS wells. • Periodic test rather than continuous measurement: the survey may miss large, infrequent emissions such as equipment failures; or may be skewed to include intermittent emissions which are more common in daytime working hours such as venting due to maintenance or oil/water truck loading.

Section	Methodology	Technology	Advantages	Disadvantages
			• More accurate than published emission factors (fugitives, pneumatics). The higher accuracy may suit other purposes of methane emission measurement such as reporting the benefits of a methane mitigation project internally and to stakeholders. • Less expensive than continuous metering and 72-hour GOR tests. • Suitable for large methane emission measurement surveys (regional, provincial, national). • Can be used in combination with other methodologies/technologies of measuring CHOPS casing gas venting.	• Longer survey time and possibly more expensive than aircraft-mounted technologies. • Current regulations do not accommodate technologies/methodologies for CHOPS vent gas and methane emissions measurement and reporting. • May not detect low level methane sources.
3.3.10.1		• Drone-mounted sensors	• Provides quantitative emission measurements at equipment and site level.	• Labour and time intensive.
3.3.10.2		• Truck-mounted sensors	• Provides quantitative emission measurements at site level. • Some technologies used in government and academic studies (i.e., Dual Tracer Method) provide quantitative emission measurements at equipment level. • An option for methane detection (leak detection and repair programs).	• Commercially available truck-mounted sensor surveys may not be able to differentiate methane emissions from individual sources.
3.3.11	Top-down emission surveys	• Various proprietary technologies	• Methane measurement can be completed at the same time as leak detection and repair survey. • Ideal for measurement of sites with low emissions related to design or operations, where the majority of emissions are from unplanned events. • In general, measures all emission sources (vent gas and fugitives) but may not pick up emissions from sites with low emissions. • Detection of methane slip from combustion equipment and tank vents. • More accurate than published emission factors (fugitives, pneumatics). The higher accuracy may suit other purposes of methane emission measurement such as reporting the benefits of a methane mitigation project internally and to stakeholders. • Suitable for large methane emission measurement surveys (regional, provincial, national). • Inexpensive. • Quick survey time. • Can be used in combination with other methodologies/ technologies of measuring CHOPS casing gas venting. • Can be used to screen casing vent valves and tank vents for mor frequent direct measurement.	• These will not address measurement problems with total associated gas from CHOPS wells. • Periodic test rather than continuous measurement: the survey may miss large, infrequent emissions such as equipment failures; or may be skewed to include intermittent emissions which are more common in daytime working hours such as venting due to maintenance or oil/water truck loading. • The lower limit of measurement varies between technologies and may not measure small emission sources. • Current regulations do not accommodate technologies/ methodologies for CHOPS vent gas and methane emissions measurement and reporting.
3.2.11.1		• Airplane-mounted sensors	• Some technologies provide accurate methane emission measurement at site and equipment level.	• Surveys require low wind conditions. • Surveys cannot be completed as frequently as for Satellite-mounted technology.

Section	Methodology	Technology	Advantages	Disadvantages
				• Surveys must be completed during the day thus it is difficult to quantify differences between day and night methane emissions (i.e., truck loading venting from CHOPS sites is a day activity).
3.3.11.2		• Satellite-mounted sensors	• Allows for extremely frequent surveys. • Some technologies provide accurate methane emission measurement at site and partial quantification at equipment level.	• Currently, lower detection limit is higher than airplane-mounted technologies but may change in near future. • Clouds and smoke interfere with survey results.
3.3.12	Continuous methane emission measurement or detection	• Various sensor technologies		
3.3.12.1		• Fixed Methane Flux Sensors	• Measures methane emissions that fluctuate over time. • Very suitable for sites where most methane emissions are an unplanned event (fugitives) and without equipment designed to vent methane (i.e., a fixed room oil tank without vapour recovery). • Provides site-level (not necessarily equipment-level) measurement data. • Can be used with IoT thus installation is cheap and does not require expensive programable logic controller or communication equipment. • An option for methane detection (leak detection and repair programs).	• Accuracy depends on the location of the sensors, as well as the magnitude of methane emissions. • Climate conditions, emission characteristics (flowrate, composition, temperature, pressure) affect the measurement. • It is difficult to differentiate between multiple emission sources.
3.3.12.2		• Fixed Methane Detectors	• Extremely inexpensive. • Can be used with IoT technology thus installation is cheap and does not require expensive programable logic controller or communication equipment. • Can be used to screen casing vent valves and tank vents for more frequent direct measurement. • An option for methane detection (leak detection and repair programs).	• Needs to be used as part of other comprehensive methane management plan along with other methodologies and technologies.
3.3.13	Stack Testing of combustion devices	• Gas chromatography or FTIR to measure gas composition in stack gas. • Vane anemometer or pitot tubes to measure stack velocity. • Various instruments to measure stack temperature, atmospheric pressure, and relative humidity.	• Accurate measurement of methane in combustion exhaust of engines, heaters, incinerators, or enclosed combustors.	• Not possible to use this method for methane emissions from flares. • Extremely labor-intensive, and often required aerial lift platforms.

3.3.1 Status quo

Status quo is the current provincial regulatory requirements for measuring and reporting associated gas, as well as venting from CHOPS casing vent valves. It involves using 72-hour GOR tests to estimate total casing gas and vented casing gas, the Vasquez-Beggs correlation for tank venting, and various measurement/estimates of other vent gas and methane emission sources. The GOR methodology is described in detail in Section 2.2.2, and the challenges are discussed in 2.3.2.

3.3.2 Continuous Metering of Casing Gas Streams

Direct, continuous metering of all the casing gas streams can increase the measurement accuracy of associated gas, vented gas, flared gas, on-site fuel use, and gas gathering streams (Section 2.2.2.2). At sites where the casing gas venting is high compared to other emission sources, continuous metering improves vent gas and methane emissions measurement. Continuous measurement of casing gas streams does not include the gas vented from the tanks. As well, continuous meters may not account for fugitive casing gas emissions depending on the location of the leaks compared to the location of the meters. Continuous casing gas meters will not account for leaks from piping containing gas from another site or gas leaks from the oil production piping. In addition, continuous meters on the casing side streams will not meter venting from drives or compressors, venting from pressure relief valves, venting during maintenance or well completions, venting from loading tanker trucks on site (oil or water), or un-combusted methane from gas-fired equipment. As the CHOPS sector reduces design-related emissions of casing gas, with conservation equipment, the other sources of emissions will begin to dominate; and continuous meters on the casing streams will not help with the accuracy of vent gas and methane emissions measurement.

Continuous metering of all casing gas streams is expensive. Technologies need to be sized accurately but flowrates can change over the life of a well. Orifice meters are often used but they can introduce undesirable back pressure to the casing side if the meter is sized too small. More accurate meters, with high flow ranges, are more expensive and require separation of liquids in the gas streams which may be challenging and expensive, introducing maintenance costs and safety concerns. New internet of things (IoT) technology may make continuous flow meters on casing streams cheaper than annual testing of the casing stream flows.

3.3.3 Continuous Metering of Tank Vent Streams

One option to increase the accuracy of vent gas reporting is to install continuous metering on the vents of all atmospheric CHOPS oil emulsion tanks. The capital and operating costs to install and maintain compositional analysis with an on-line gas chromatograph on the tank vent streams would be excessive. However, assumptions of the vent composition along with a continuous flow meter may provide more accurate measurement than comprehensive annual, periodic measurement of the vent flowrate and composition. IoT technology along with inexpensive thermal anemometer flow meters on the tank vent streams may also cheaper than annual, direct measurement of the tank flows; they could serve as high methane detection to trigger a corrective action or more frequent direct measurement.

3.3.4 Periodic Tank Vent Testing

Similar to periodic GOR testing, venting from the CHOPS oil emulsion tanks can be measured in annual tests. It may be possible to periodically test tank flow and composition during GOR or hourly rate testing of the casing gas streams. The main disadvantage of tank vent testing is that it is labour intensive and difficult for personnel to access the tank vents and to seal off multiple sources of venting on a tank such as holes. There may also be increased safety risks associated with periodic tank testing. In addition, periodic testing will miss occasional times when the vent flow is high.

3.3.4.1 Tank Vent Sampling and Flowrate Measurement

Flowrate can be measured from CHOPS tank vents using pitot tubes, vane anemometers, or volumetric and positive displacement meters. The composition of the vent gas also needs to be tested by taking a sample of the vent gas. A disadvantage of volumetric and positive displacement meters is that they introduce a small amount of back pressure to the oil tank and can force vent gas through joints connecting the vent to the meter. Wind affects the readings of pitot tubes and vane anemometers when the vent flow is very low.

3.3.5 Estimate of GOR

An easier and less expensive method of determining GOR is to use a rough estimate. New federal regulations offer an equation for estimating GOR of a CHOPS well if gas production is less than 2000 m^3/day (Government of Canada, 2021):

$$GOR = -0.5Pw + 150$$

Equation 3

where Pw is average volume oil produced in a day (m^3) for the most recent month.

A drawback of GOR estimate is that it may be less accurate than direct measurement of vented gas. This option of determining GOR has not been incorporated into either the Alberta of Saskatchewan Directives 017 or PNG 017, respectively.

3.3.6 Computational models of GOR

A possible solution to improve gas and methane reporting of CHOPS wells is to determine GOR from modelling. There are scant publicly available reports on modelling of CHOPS wells. A University of

Calgary Department of Chemical and Petroleum Engineering, Master's project attempts to model CHOPS wells (Sun, 2012). The thesis includes a literature review of other models applicable to CHOPS wells. The project includes numerical studies of pressure profiles, modelling sand production characteristics and wormhole propagation, and modelling GOR and oil recovery factors during foamy oil flow. The project uses the concept of a pseudo-bubble point pressure which is a pressure, below the actual equilibrium bubble point, where the bubbles in foamy oil will be liberated from the oil. When the reservoir pressure is between the actual equilibrium bubble point pressure and a pseudo bubble-point pressure, there is foamy oil. Solution gas, as bubbles, is entrained in the oil. Here the gas to oil ratio of the oil in the production line is low, and there is high oil recovery. The study notes that foamy oil serves as a mechanism that helps to increase production of oil. After pseudo bubble point is reached, the gas bubbles break through and form a continuous phase. Oil recovery decreases, and solution gas drive is now one of the main mechanisms of producing oil. The pseudo bubble point is found by monitoring reservoir pressure and oil production over time and looking for the pressure at which oil production slow down. Neither this thesis nor other models of CHOPS wells covered in the literature review of this thesis find a method to predict the GOR of the gas in oil in the reservoir or the associated gas GOR of the gas and oil produced at the wellhead. Instead, this thesis develops an empirical model, where known GOR and pressure data of several CHOPS wells is entered into the model and fitted to a computational model. The model cannot be used to predict GOR and pressure behaviour in other CHOPS wells.

There would be value in a future project that could predict GOR based on reservoir characteristics. Predictive GOR models would provide a cheaper alternative to periodic, direct measurement of tank vents for finding associated and vent gas, and methane emissions.

3.3.7 Bottom-up Emissions Surveys with Handheld Instruments

Handheld instrumentation for measuring methane emitted to the atmosphere can be used to measure emissions at their source and provide a bottom-up, periodic emission survey. Source level measurement allows comparison of emission categories (fugitives, pneumatic) and emissions by equipment type. In general, these surveys take time and require experienced operators. They are also a good method for leak detection and repair programs. These surveys may be less costly than hourly rate and GOR testing and be used for CHOPS casing vent valves that have low flowrates. Handheld instrumentation is also more accurate than published emission factors for certain emission sources and may even be quicker than conducting an equipment and component activity count survey and then estimating equipment/component emissions using published emissions factors. Handheld methane instrumentation does not address concerns with the accuracy of measuring total associated gas at CHOPS sites, but it can be used in combination with other methodologies and technologies.

3.3.7.1 Hetek Hi Flow Sampler®

Hetek Hi Flow Sampler® have been used for several decades for methane emissions surveys and are excellent for measuring fugitive methane emissions. Their main disadvantage is that they have a maximum flowrate limit. Often the flowrate of the vented casing gas valves at CHOPS sites exceeds the maximum limit of the sampler. In addition, it is difficult to use the Hetek Hi Flow Sampler® on tank vents as the vent needs to be ducted to ground-level to enter the hi-flow sampler. Also, the samplers work best for vent sources where the composition does not vary significantly. In general, the instrument must be calibrated regularly. A tank vent, with continually changing amounts of air would likely cause inaccurate measurement results.

3.3.7.2 Quantitative Optical Gas Imaging Camera

Quantitative optical gas imaging (QOGI) camera technology has emerged in the past several years. It offers an easy way of completing surveys compared to the Hi Flow Sampler®. Also, QOGI does not require frequent calibration. However, there are many sources of interference with QOGI caused by the temperature of the equipment and surroundings, reflective surfaces, clouds, or movement in the background. This is especially a concern for measuring methane slip from combustion devices or methane in tank vents. Accuracy has shown to be acceptable for large multiple site emissions surveys, where there are greater than fifty measurements (Ravikumar et al., 2020) The accuracy may not be acceptable for certain site or equipment measurement surveys such as a producer measuring the change in emissions after an emission mitigation project.

3.3.7.3 Optical Gas Imaging Camera with Plume Estimates

An alternative to using QOGI camera technology is to simply use an optical gas imaging camera with an experienced operator estimating methane emission flowrate from the plume size and appearance. This method is analogous to estimating the flowrate of water from different sources (kitchen faucet or open residential fire hydrant) based on appearance. This simpler optical gas imaging methodology/technology is much easier than QOGI and eliminates some of the interferences of QOGI. However, operators must be well-trained in this method. Nevertheless, this is an excellent survey technique for methane leak detection and repair programs which target fugitive emission sources. This type of survey can also be used for screening CHOPS casing vent valves or tank vents that require more frequent direct measurement.

3.3.8 Shorter Duration GOR Tests

Rather than 72-hour GOR tests to infer the vented casing gas volumes, one option is to return to less expensive and easier 24-hour GOR tests. Other than cost and ease of use, this option has the same advantages and disadvantages as the 72-hour test option. There are no available published reports or studies which demonstrate that longer 72-hour GOR testing improves the accuracy of vent gas and methane emissions measurement. A study attempting to improve total associated gas measurement at CHOPS sites, recommended longer duration GOR testing of 72-hours for certain CHOPS wells, but improvements in total associated gas measurement will not necessarily improve methane emissions measurement (Section 2.3.2)

3.3.9 Hourly Rate Testing

Hourly rate testing of the vented casing gas stream is a periodic testing methodology, involving direct measurement. Hourly rate testing can also be completed on the total casing gas stream and line supplying casing gas as fuel, to determine total associated gas and fuel flowrates.

Often at CHOPS wells, the flowrate of total casing gas and thus vented casing gas fluctuate hourly and daily (Section 2.3). Thus, longer hourly rate tests (24 hours) may improve the accuracy of measuring both the total casing gas and vented casing gas flowrates. In addition, more hourly rate tests may increase accuracy. A disadvantage of all periodic methodologies is that they may miss large intermittent spikes in emissions.

Now that other vent sources (fugitives, truck loading) are explicitly included in vent gas and methane emission reporting, hourly rate testing is less confusing and easier to apply than GOR testing at CHOPS sites. This is especially true when there is gas conservation equipment at the site such as associated gas used for emulsion tank heating or engine drives. Furthermore, hourly rate testing overcomes some of the challenges in CHOPS GOR testing when a test separator cannot be used for the GOR testing; it eliminates problems in accurately determining the oil flowrate of the GOR due to changes in oil flowrate throughout the oil measurement interval and difficulties in determining water cut (BS&W) during the oil measurement interval.

3.3.10 Site-Level Surveys

Hand-held technologies may not be able to measure all emissions sources. This makes site-level methane emission measurement surveys attractive. Periodic, site-level surveys accurately measure all methane emission sources (vented, fugitives, un-combusted) and are quicker than surveys with hand-held technologies. Similar to hand-held technologies, site-level surveys are more accurate than published emission factors for other emission sources such as fugitives and pneumatics. Site level surveys do not address concerns with the accuracy of measuring total associated gas at CHOPS sites, but they can be used in combination with other methodologies and technologies to reconcile quantities. Site-level surveys are possibly longer and more expensive than aircraft and satellite-mounted technologies. As with other top-down technologies, they may not detect low level emission sources.

3.3.10.1 Drone-mounted sensors

Drone-mounted sensors provide high measurement accuracy at both the site and the equipment level. These surveys involve considerable labour and time. Drone surveys are useful for developing site or sector - specific emission factors, validating other methane measurements, or investigating high emitting sources.

3.3.10.2 Truck-mounted sensors

Truck-mounted sensor surveys are a good option for methane detection for leak detection and repair programs, or for measurement at sites with negligible emissions related to emissions or design. Compared to drone-mounted surveys, commercially available truck-mounted surveys generally provide lower resolution at the equipment level.

On the other hand, various government and academic studies have used truck-mounted surveys with the dual tracer ratio method which can provide some resolution at the equipment level such as a study by Roscioli et al. (2018) of five CHOPS sites in Western Canada (Section 2.3.1). The dual tracer ratio method can be used for quantifying methane emissions for a short time period (typically under 4 hours) from an oil and gas site. This method involves directly metering the flowrates of two tracer gases which are each released from separate gas canisters, from a site or piece of equipment where there is a known methane emission. Ambient samples are collected at the point of the emission and at a downwind point from the site. This method requires measuring of the wind conditions to simultaneously model the dispersion of the plumes of the tracer gas and the methane gas that is being emitted from on-site equipment. The concentrations of the tracer gases and methane are determined in the samples. The ratio of the tracer to methane concentrations are proportional to the ratio of the emission flowrates of the tracer to the flowrate of the methane. Periodic dual tracer surveys of methane emissions have been completed simultaneously with other equipment level as airborne surveys, have shown that technology has very high accuracy (Yacovitch et al., 2017).

3.3.11 Top-down Emission Surveys

Top-down measurement surveys are inexpensive and quick compared to bottom-up surveys. They are excellent for methane detection and a single survey can provide information for a leak detection and repair program, at the same time as quantifying methane emissions for a measurement and reporting program. They are also excellent for site measurement where there are low emissions related to equipment design or operations, and the majority of emissions are from unplanned events. This type of survey can also be used for screening CHOPS casing vent valves or tank vents that require more frequent direct measurement.

Even for sites with emissions from operations and equipment design, top-down studies provide good accuracy for regional, provincial, and country wide measurement surveys. Bottom-up and drone-mounted sensor technologies provide better resolution at the equipment and site level. The lower limit of measurement varies between technologies, and they may not be able to provide sufficient measurement of sites with very low emissions. However, technologies are improving, and some may soon be able to provide excellent emission measurement at the equipment level. Top-down surveys do not address concerns with the accuracy of measuring total associated gas at CHOPS sites but can be used in combination with other methodologies and technologies. In addition, surveys cannot be completed at night to compare day and night methane emissions (i.e., truck loading venting from CHOPS sites is a daytime activity).

3.3.11.1 Aircraft-mounted sensors

Technologies are changing and some can provide valuable equipment-level measurement data. Aircraft-mounted sensor surveys require low wind conditions. Hundreds of sites can be flown per day. They are also suitable for screening, and leak detection and repair surveys because they reduce the risks involved in driving to multiple sites.

3.3.11.2 Satellite-mounted sensors

Satellite technologies allow for very frequent measurement surveys, and they can capture some of the variability in methane emissions. Smoke, precipitation, and wind conditions can interfere with results. Typically, satellite mounted sensors have lower resolution than aircraft-mounted sensors.

3.3.12 Continuous Methane Detection

These sensors can be used with IoT, powered by solar and batteries, for cheap, quick installation without expensive, programable logic controllers, electrical and communication equipment.

3.3.12.1 Fixed Methane Flux Sensors

Fixed methane flux sensors are a new technology which can provide continuous detection or measurement of methane at the site and regional level. Fixed methane flux sensors directly, continuously measure methane at the site and regional level. They can provide a small amount of resolution at the equipment level. However, they are more suitable for sites where most methane emissions result from unplanned events such as fugitive emissions. They may not be ideal for sites with many emission sources that are operational or design-related, where it would be desirable to know the amounts of emissions from each source category (pneumatics, tanks, fugitives). Methane flux sensors are also a good option for leak detection and repair programs

3.3.12.2 Fixed Methane Detection Sensors

Fixed methane detectors sensors provide continuous detection of methane and are often very inexpensive. They can be set to alarm at certain levels. They can be used as part of leak detection and repair programs. At CHOPS sites, where it is possible that there is intermittent, high venting from the casing or tanks, inexpensive sensors can alert producers to take corrective action or conduct more frequent direct measurement of the casing or tank vents.

3.3.13 Stack Testing

Methane in the exhaust from CHOPS enclosed combustors, incinerators, tank heaters and engines can be evaluated with stack testing. Stack extensions with measuring ports are placed on the exhaust lines. Instruments are used to measure gas flowrate, gas temperature, atmospheric pressure, and relative humidity. Samples of the exhaust gas are analyzed for air, hydrocarbon, and moisture content by either gas chromatography or FTIR (Fourier Transform infra-red) spectroscopy. Stack testing is very labour intensive and cannot be conducted on flare stacks.

3.4 Methodologies and Technologies for Field Testing:

Presently, there is not a single methodology and technology that suits all the gas and methane measurement needs of the CHOPS sector. The choice in methodologies and technologies depends on regulations, the flowrate of the gas/emission, and whether the gas/emission flow is continuous or intermittent. Furthermore, the preferred methodologies and technologies may change as the oil and gas sector reduces methane and moves away from design and operations-related methane emissions.

Currently, with many CHOPS sites containing design-related sources, bottom-up vent gas and methane measurement is practical because it provides information on the various emission categories and types of equipment. Bottom-up surveys are more expensive than top-down surveys. At CHOPS sites with negligible design and operations-related emissions, it might be possible to use site and top-down surveys for both methane detection and measurement, reconciled with another measurement method completed less frequently.

In addition, with both types of sites (with and without design and operations-related emissions), fixed methane detection sensors and top-down technologies could screen for equipment and sites with large emissions or emissions that deviate significantly from their previously reported values. Then producers could simply do more frequent bottom-up surveys at the screened sites or take corrective action. This sort of approach would require changes to regulations that currently prescribe the methodologies and frequencies for emission sources such as casing vent valves and tank vents.

In general, the gap analysis of Section 3.2 indicates that field testing should evaluate direct measurement options for casing and tank vents. These can be compared to existing approaches. There should be further evaluation of hourly rate and GOR testing of total and vented casing gas, at various test durations. As well, GOR based on total casing gas should be compared to GOR based on vented casing gas. The gas volumes predicted by these test values can be compared to continuous metered values. This assessment should also compare predicted values based on *estimated* fuel gas to values based on *metered* fuel gas.

Tank venting at CHOPS sites is another area that warrants testing. Field testing can evaluate various methodologies and technologies for determining tank venting: Vasquez-Beggs correlation, GIS sampling with PVT analysis, and composition samples along with pitot tubes, vane anemometers, or volumetric meters (diaphragm, positive displacement, or turbine). The above field testing involves bottom-up methodologies which are in sync with the current federal and provincial regulations.

In the future, it would be beneficial to survey other emission sources from CHOPS sites to assess gap 3. This survey would provide evidence on whether improvements to casing gas and tank venting measurements will help to narrow the gap between reported and actual methane emissions. This information would also indicate what the future may hold as the CHOPS sector transitions away from design-related emissions from casing and tanks. It would be worthwhile to survey low methane emission sources such as fugitives, pneumatic equipment vents, compressor seals, crankcases, truck-loading, and engines start-stops at a variety of CHOPS sites. This survey would demonstrate the typical magnitude of these types of emissions.

4. Field Testing of Measurement Methodologies and Technologies

4.1 Summary of Field-Testing and Data Collection

Field testing is divided into two phases:

- Phase 1 evaluates methodologies for determining associated and vent gas from the casing side of CHOPS sites.
- Phase 2 compares and validates methodologies and technologies for measuring tank venting.

4.2 Phase 1 Field Testing

4.2.1 Summary

This field test campaign evaluates methodologies for determining associated gas and vent gas based on the casing gas of CHOPS sites. SRC travelled to a total of 13 CHOPS sites in Alberta and Saskatchewan, owned and operated by two producers, the weeks of November 22nd and November 29th, 2021. These were all sites with existing, continuous meters on the casing gas lines. Here it is assumed that the continuous meters provide information on the actual casing gas flows. The actual rates are compared to values predicted from different methodologies (GOR estimate, GOR test and hourly rate test).

4.2.2 Objectives

Phase 1 testing accomplishes several objectives:

1. The primary objective is to compare various GOR test methodologies, hourly rate testing methodology, GOR estimate, and continuous metering for determining monthly total and vented casing gas, and thus associated gas, vent gas and methane emissions, for the month of the GOR/hourly test, and subsequent months. This objective is accomplished by comparing all methodologies to continuously metered casing stream values.

   - This includes an evaluation of vented casing volumes from *associated gas* GOR values with either estimates of fuel consumption or metered fuel consumption, and from *vent gas* GOR values.

2. A secondary objective is to compare GOR and hourly rate test values at different gas measurement intervals (1 hour, 24 hours and 72 hours).

3. Another objective is to compare GOR values determined by different oil measurement intervals (4-day, 10-day and 1 month).

4. Phase 1 field testing data will be used to investigate the variability in total casing gas and vented casing gas over time, and help to indicate the ideal frequency of GOR or hourly rate testing

5. A final objective is to investigate whether GOR testing can accurately predict associated gas, vented gas, and methane emissions volumes. In other words, this objective evaluates whether the total casing gas or vented casing gas is linearly proportional to oil production, in the time between GOR tests.

4.2.3 Deliverables

- Virtual hourly rate test of total casing gas and casing gas, which is not used as fuel, at various gas measurement intervals.

    - Use 1, 24 and 72-hour gas measurement intervals.

- Virtual GOR test of total casing gas and casing gas which is not used as fuel at various gas and oil measurement intervals.

    - Use 4-day, 10 day, and 1 month oil intervals.
    - Use 1-, 24- and 72-hour gas measurement intervals.

- Monthly, continuous measurement of all casing gas streams at each test site. Some casing streams do not have continuous meters and they are determined by the overall mass balance, by addition or subtraction of streams with continuous meters.

- Monthly oil production at each test site.

- Predicted total casing gas and casing gas, which is not used as fuel, based on virtual hourly rate and GOR testing.

4.2.4 Test Sites

There are 13 CHOPS test sites in Alberta and Saskatchewan, owned and operated by two producers, which were visited as part of this field test. These are all sites with existing, continuous meters on the casing gas lines. Some of the meters are orifice plates with differential pressure sensors with transmitters, sending time-stamped flowrate data to the site's supervisory control and data acquisition system (SCADA). Some of the meters are rotary positive displacement (PD) meters with totalizers that are manually read on a regular basis and the readings are entered into the SCADA. During the field test, SRC read these totalizer values at the start and end of each interval and took pressure and temperature measurements. Some of the sites have PD meters with totalizers with transmitters sending the total volumes to SCADA. Some sites are single well sites. The rest of the sites have 2 to 4 wells, where the total casing gas from each well combine before being used as fuel, gathered, flared, or vented to atmosphere.

Table 3 — Phase 1 Field Test Sites

Facility ID	Petrinex Reporting Subtype	Number of wells at site	Comment
I-3	331	1	
I-4	341	1	
I-5	341	1	
II-5	311	1	
II-6	321	3	
II-7	321	4	
II-8	321	1	
I-1	325	1	
I-2	311	1	
II-1	321	1	Test repeated in second week of testing; did not have a working fuel gas meter and only used for total casing gas values
II-1	321	1	
II-2	321	4	
II-3	321	3	
II-4	321	2	

4.2.5 Required Data Set and Methodology

- For all applicable casing gas meters that do not have on-line flowrates or totalizer readings, manually record totalizer volume readings, and measure and record stream pressure and temperature with calibrated instruments at time zero, 1 hour, 24 hours, and 72 hours during the field test (SRC).
- For all applicable casing gas meters that have on-line flowrates or totalizer readings, collect time-stamped data from time zero to 72 hours of the field test (producer).
- Take a sample of the casing gas (one sample per site) at each site in the first 6 hours of the field test and analyze by gas chromatograph in the SRC Regina site lab (SRC).
- For 4-day, 10-day, and one-month intervals encompassing the virtual test, determine total truck dispositions, both water and oil (SRC and producer).

- For 4-day, 10-day, and one-month intervals encompassing the virtual test, determine change in tank level (SRC and producer).
- For one-month interval encompassing the virtual test, determine BS&W of produced liquid (SRC and producer).
- For all applicable casing gas meters that have on-line flowrates or totalizer readings, collect time-stamped data from November 1st, 2021, to March 31st, 2022, from each site or monthly gas stream volumes (producer).
- Monthly gas, oil production volumes from each site for November 2021 to March 2022, inclusive; these are the values reported to Petrinex/regulators (producer). For all applicable casing gas meters that do not have on-line flowrates or totalizer readings, provide pressure and temperature correction factors for any meter reports (producer).
- Estimated fuel gas consumption rate of engines and tank heaters, used at the producer's other sites, for determining associated and vent gas volumes (producer).
- Estimate GOR from **Equation 3** for all months for each site using measured oil monthly oil production.
    - $GOR = -0.5Pw + 150$

Equation 4

4.2.6 Equipment and Instrumentation

J and K-type Thermocouples

All thermocouples will be verified in fluids of known temperature (e.g., programmable water bath, verified with calibrated thermometer) before transportation to the field site. Will be read with a Fluke 52 II Thermometer or Oakton thermometer or will be equipped with signal fire wireless transmitters to data log values.

Gas Chromatograph (GC)

The Shimadzu (model 8AIT) is a general-purpose system designed to analyze gases (nitrogen, oxygen, carbon monoxide, carbon dioxide, and hydrogen) and hydrocarbons (methane, ethane, propane, butanes, pentanes, hexanes, and heptanes). The software supplied is "Peak Simple." The Shimadzu GC will be calibrated, and the method confirmed prior to field deployment, then verified daily on testing days using a certified calibration gas.

Pressure Gauges

Calibrated pressure gauges of various ranges are used.

4.2.7 Analysis and Calculations

4.2.7.1 Evaluating *Vented Casing Gas* Measurement Methodology with *Non-Fuel* Gas

Most of the test sites have very little *vented casing gas*, because nearly all of the casing gas is used as fuel, flared, or gathered. Thus, the vented casing gas volumes are atypical of many CHOPS sites. Many CHOPS sites do not have gathered or flared casing gas; these sites use some casing gas as fuel and vent the remainder. In the following analysis, the value of *non-fuel* gas is introduced for comparing the GOR and hourly rate methodologies from the Phase 1 field testing program, where:

$$Non\ Fuel_{Casin\ \ Gas} = Total_{Casing\ Gas} - Fuel\ Use$$

Equation 5

and:

$$Non\ Fuel_{Casing\ Gas} = Vented_{Casing\ Gas} + Gathered_{Casing\ Gas} + Flared_{Casing\ Gas}$$

Equation 6

4.2.7.2 Evaluating GOR Measurement Methodology without Tank Venting Volumes

In this analysis, GOR is determined using casing gas measurement only, neglecting estimates of the tank venting. Normally for CHOPS sites, GOR is calculated by adding the vented tank gas to either total casing gas or vented casing gas. The ratio of vented tank gas to oil is often determined with the Vazquez Beggs correlation and is typically an extremely small number between 0 and 0.1 m^3 gas/m^3 oil. Thus, the tank vent value is neglected for simplicity in the Phase 1 field-testing evaluation of GOR methodologies:

$$GOR_{Associated\ Gas} = \frac{Total_{\ Casing\ gas} + Tank\ Venting}{Oil\ Production} \cong \frac{Total_{\ Casing\ gas}}{Oil\ Production}$$

Equation 7

$$GOR_{Vent\ Gas} = \frac{Vented_{\ Casing\ gas} + Tank\ Venting}{Oil\ Production} \cong \frac{Vented_{\ Casing\ gas}}{Oil\ Production}$$

Equation 8

As mentioned in Section 4.2.7.1, the vented casing gas is very low at the Phase 1 field testing sites, and the analysis will use *non-fuel* gas instead of *vented casing gas*. **Equation 8** becomes:

$$GOR_{Non-fuel} \cong \frac{Vented_{Casing\ Gas}}{Oil\ Production} \cong \frac{Non-fuel_{Casing\ gas}}{Oil\ Production}$$

Equation 9

4.2.7.3 Determination of *Non-Fuel* Gas

Non-fuel gas is calculated from four options:

1. The *non-fuel* hourly rate.
2. The *non-fuel* GOR (**Equation 9**).
3. From the *associated gas* GOR (Section 2.2.2.5) using estimated fuel gas:

$$Non-fuel_{Casing\ gas} = Oil\ Production\ x\ GOR_{Associated\ Gas} - estimated\ Fuel\ Gas_{Estimated}$$

Equation 10

4. From the *associated gas* GOR (Section 2.2.2.5) using measured (metered) fuel gas:

$$Non-fuel_{Casing\ gas} = Oil\ Production\ x\ GOR_{Associated\ Gas} - Fuel\ Gas_{Measured}$$

Equation 11

4.2.7.4 Gas Measurement in Virtual GOR and Hourly Rate Tests

For each of the test sites, virtual GOR and hourly rate test values are found. Total casing gas and *non-fuel* gas virtual test volumes are found for 1-, 24- and 72-hour gas measurement intervals, from the continuous meters. For several of the sites, the gas volumes are found from totalizer readings on the continuous meters at the start and end of each interval during the field test campaigns. However, several of the sites have transmitters on the continuous meters, sending gas flowrates to the site SCADA throughout the months of November and December. Gas volumes are found from time-averaging SCADA flowrate data. In order to provide more virtual GOR and hourly data points, additional 1, 24, and 72-hour virtual GOR and hourly rate test values are found at these sites at gas measurement intervals starting November 10th and December 10th, with flow readings every 5 to 15 minutes. One of the test sites only has metering of the total casing gas it is neglected in the analysis of vented casing (non-fuel) gas.

4.2.7.5 Oil Measurement in Virtual GOR Tests

Oil volumes in the virtual GOR values are determined for 4-day, 10-day and 1-month oil measurement intervals encompassing the gas measurement interval. Oil is not measured directly and inferred from liquid truck dispositions, sand, and water content of the produced liquid (BS&W), and tank levels (levels at the start and end of each oil measurement interval).

For one of the producers, tank levels are found indirectly from BS&W and oil production reports which use SCADA recorded tank levels to report the daily start and end oil inventories for the well or battery. For example, for a 4-day oil measurement interval:

$$Level_{End\ of\ 4th\ day} = \frac{Oil\ inventory_{End\ of\ 4th\ day}}{(100\% - BSW)}$$

Equation 12

For all sites, BS&W is found for the month of the test from the truck ticket and well production reports by finding the monthly production of oil and water and sand.

$$BSW = 100\% * \frac{Monthly\ volume\ of\ water\ and\ sand\ shipped}{Monthly\ volume\ of\ oil, and\ water\ and\ sand\ shipped}$$

Equation 13

The oil volume of each interval is calculated as follows:

$$Oil\ Volume_{4\ day} = (100\% - BSW)[(Level_{end\ of\ 4th\ day} - Level_{Start\ of\ day\ 0}) + Volume_{water,sand,oil\ tickets}]$$

Equation 14

4.2.7.6 Virtual Hourly Rate and GOR of Well or Battery

At the sites of one of the producers, total casing gas of each well is metered, but gathered, combustor, and fuel gas are metered for the entire multi-well battery. At these sites, the virtual *total casing gas* hourly rate and *associated gas* GOR values are found for each well at multi-well batteries. The virtual *non-fuel* hourly rate and *non-fuel* GOR values are found for the battery. The *non-fuel* hourly rate is divided by the number of producing wells at the battery.

At the sites of the other producer, the combined total casing gas of all wells is metered. Gathered, combustor, and fuel gas are also metered for the entire multi-well battery. At these sites, the virtual *total casing gas* hourly rate, *associated gas* GOR, *non-fuel* hourly rate, and *non-fuel* GOR values are all determined for the battery. The *total casing gas* and *non-fuel* hourly rate values are then divided by the number of producing wells at the battery.

4.2.7.7 Comparison of Actual Gas Volumes to Predicted Volumes

Actual monthly volumes of *total casing gas* and *non-fuel* gas are directly compared to values predicted by GOR estimate, virtual GOR test, and hourly rate test. Here, actual values are measured with continuous meters, for November 2021 to March 2022. Linear regression on Microsoft Excel is used to compare values. The actual *total casing gas* and *non-fuel* gas are compared to oil production over the five-month period, to analyze whether the relationship is linear, and to determine an appropriate testing frequency.

4.3 Phase 2 Field Testing

4.3.1 Summary

This field test campaign evaluates methodologies and technologies for measuring tank vent gas at CHOPS sites. Two SRC technicians tested 27 CHOPS tanks at sites in Alberta and Saskatchewan, owned and operated by three producers, the weeks of May 2nd, May 9th, May 24th, May 30th, June 27th, and July 11th, 2022.

4.3.2 Objectives

The objective of the Phase 2 field-testing program is as follows:
Compare methodologies and technologies for measuring tank venting (methane emissions) at CHOPS sites, including the following:

- Composition samples of tank vent stream, along with two or more conventional gas meters (rotary positive displacement, turbine, diaphragm, or orifice) to take flow measurements of each vent.

- GIS (gas-in-solution) analysis of produced liquid.
- Vasquez-Beggs correlation applied to produced oil.

4.3.3 Deliverables

The following are the main deliverables from field testing of each of the CHOPS tanks:

- Measurement of tank vent composition and flow rates with gas flow meters and validation of flow meter readings with pitot tube and vane anemometer.
- Measurement of tank pressure and temperature throughout conventional flowrate measurement.
- Estimation of tank venting by gas-in-solution analysis of samples of the produced liquid.
- Estimation of tank venting with the Vasquez-Beggs correlation from upstream and downstream pressures and temperatures.

4.3.4 Test Sites

Field testing of CHOPS tanks is completed at single and multi-well CHOPS sites, in both Alberta and Saskatchewan, owned and operated by two producers. Several sites have two or more wells, and some wells have two tanks in series on the same well. Some sites have only one well with 1 tank. Test sites are summarized in Table 4:

Table 4 — Phase 2 Field Test Sites

Site	Tank	Date	Comments
1	1	22-05-05	Vertical, new site, foamy oil
2	2	22-05-06	Directional, established, steady GOR
3	3	22-05-09	Old site, increasing GOR, multi tank site
3	4	22-05-09	Old site, increasing GOR, multi tank site
3	5	22-05-09	Old site, increasing GOR, multi tank site
4	6	22-05-11	New site, foamy oil, multi tank site
4	7		New site, foamy oil, multi tank site
5	8	22-05-13	Old site, increasing GOR
6	9	22-05-24	Directional, established, steady GOR
7	10	22-05-25	Directional, old site, decreasing GOR, multi tank site
7	11	22-05-25	Directional, old site decreasing GOR, multi tank site
8	12	22-05-26	Directional, established site, steady GOR, multi tank site
8	13	22-05-26	Directional, established site, steady GOR, multi tank site
9	14	22-05-29	Vertical, old site
10	15	22-05-30	Horizontal, established, decreasing GOR
11	16	22-05-31	Vertical, new site, foamy oil; testing stopped due to high winds
12	17	22-06-01	Old site, increasing GOR, multi tank site
13	18	22-06-02	Old site, increasing GOR, multi tank site
13	19	22-06-02	Old site, increasing GOR, multi tank site
14	20	22-06-03	New site, foamy oil
15	21	22-06-27	
16	22	22-06-28	
17	23	22-06-28	
18	24	22-06-29	
19	25	22-06-29	Wind may have blown testing hose off of tank during data collection.
20	26	22-06-30	
21	27	22-07-11	
22	28	22-07-12	
23	29	22-07-12	

4.3.5 Required Data Set and Methodology

For each tank:

- Measured tank vent flow by two or more gas flow meters at grade (positive displacement meter, turbine meter, diaphragm meter, orifice meter) for 45 to 60 minutes each. Rated hose connected the vent at the top of the tank to the flow meters at grade, while a fabricated cover sealed the thief hatch. Also, the level gauge opening was sealed off.

- Validated gas flow meters every 15-20 minutes with pitot tube, and vane anemometer mounted to a laboratory stand, in series with the conventional meter, to data-log flowrate over a 5-minute period (averaged).

- Sampled tank vent using Tedlar bags from grade, upstream of meters, for every gas flow meter test using lung sampler, and analyzed for dry gas (hydrocarbon and air) composition on GC.

- Measured moisture content in tank vent gas with an impinger, by sampling directly from top of tank with heated line to grade using isokinetic sampler train. The sampling line was connected to a fabricated thief hatch cover.

- Measured tank vent pressure and temperature at the gas flow meter, for correcting the measured volume of the flow meter to standard conditions. The positive displacement meter has built-in sensors for these values. When using other gas meters, pressure and temperature are measured with thermocouples and manometers separately. Temperature is monitored in the tank vapour space with a thermocouple installed in a fabricated thief hatch cover.

- Sampled produced liquid for GIS analysis into vacuum prepared sample cannisters, for a minimum of two samples per well source for later testing at SRC in Regina.

- Recorded parameters relevant to Vasquez Beggs Correlation: casing annuli pressure, production line pressure at wellhead (downhole pressure could not be measured), produced liquid temperature at wellhead (surface of production line), and tank vapour space temperature.

4.3.6 Equipment and Instrumentation

Volumetric flowmeter

AL425 diaphragm gas meter with pulse output and data logging software.

Rotary Positive displacement flowmeter

Roots 2M gas meter with Micro Corrector pulse cable and Micro Corrector software

Turbine meter and transmitter

1" Hoffer gas meter and transmitter

Pitot tube

Dwyer 160 series pitot tubes (various lengths) with Fluke 922 Airflow meter

Orifice meters

1 inch orifice meter with differential pressure sensor and transmitter in 3 sizes (Bore Size; 0.420, 0.525, 0.682 inch)

Vane anemometer

4-inch TSI 5725 Vane Thermo-Anemometer

J and K-type Thermocouples

All thermocouples are verified in fluids of known temperature (e.g., programmable water bath, verified with calibrated thermometer) before transportation to the field site. Will be read with a Fluke 52 II Thermometer or Oakton thermometer or will be equipped with signal fire wireless transmitters to data log values.

Gas Chromatograph (GC)

The Shimadzu (model 8AIT) is a general-purpose system designed to analyze gases (nitrogen, oxygen, carbon monoxide, carbon dioxide, and hydrogen) and hydrocarbons (methane, ethane, propane, butanes, pentanes, hexanes, and heptanes). The software supplied is "Peak Simple." The Shimadzu GC will be calibrated, and the method confirmed prior to field deployment, then verified daily on testing days using a certified calibration gas.

Differential Pressure Sensors, Digital Manometers and Transmitters

Multiple differential pressure gauges are used to measure the pressure of the gas, depending on the required range. The gauges are verified at SRC's labs prior to travelling to the field. They will either be physical reading gauges or be equipped with signal fire wireless telemetry units to data log values.

4.3.7 Analysis and Calculations

4.3.7.1 *Vasquez-Beggs correlation methodology for determining tank venting:*

The Vasquez-Beggs correlation is used to estimate the amount of gas from each CHOPS well that flashes from the produced oil in the atmospheric production tank and then vents from the tank. First the Vasquez-Beggs correlation is applied to find gas-in-solution ($R_{s,1}$) at equilibrium, at downhole conditions. Next, the correlation is applied to find the gas-in-solution at equilibrium, at tank conditions ($R_{s,2}$). The difference between these two gas-in-solution values is the volume of gas per volume of oil which flashes off in the tank and is released via the tank vent. The correlation of gas-in-solution (standard m^3 gas/m^3 oil) for each condition is as follows:

$$R_{s,at\ condition\ 1\ or\ 2} = C_1 \gamma_g p^{C_2} - \left(\frac{C_3}{\gamma_o T} - \frac{C_4}{T}\right)$$

Equation 15

Where:

T = Temperature at flash conditions (°K); at condition 1, T is the downhole temperature which is approximated by the temperature of the produced liquid at the wellhead; at condition 2, T is the tank temperature, measured by a thermocouple in the tank vapour space, inserted in a fabricated cover on the tank thief hatch.

p = Absolute pressure at flash conditions (kPa $_a$); at condition 1, p is downhole pressure; at condition 2, p is the tank vapour space pressure.

γ_o= specific gravity of the oil with respect to water (dimensionless); approximated as 0.985 throughout this analysis.

γ_g= specific gravity of the solution gas with respect to air (dimensionless); approximated as 0.71 for a solution gas containing 90 vol% methane, 10vol% ethane at standard conditions.

For oil with a specific gravity greater or equal than 0.876, the value of the constants in **Equation 15** are:

$C_1 = 7.803 \times 10^{-4}$
$C_2 = 1.0937$
$C_3 = 2022.19$
$C_4 = 1879.28$

Daily oil production is determined by dividing the monthly oil production by the number of days in a month. Then the daily gas vented from the tank (standard m^3/day) is found from the two gas-in-solution values, and the daily oil production (m^3/day):

$$Daily\ gas\ vented\ from\ tank = (R_{s,1} - R_{s,2}) x Daily\ oil\ production$$

Equation 16

4.3.7.2 *GIS Analysis methodology for determining tank venting:*

Another methodology to estimate the amount of venting from CHOPS tanks is GIS analysis. A sample of the produced liquid is taken and then the sample is heated to tank conditions. The volumes of liquid and gas are measured, and the volume of gas per volume of liquid is calculated. The liquid volume includes both water and oil, so the average water and sand content (BS&W) must be known. Then the daily gas vented from the tank is approximately:

$$Daily\ gas\ vented\ from\ tank = (Volume\ of\ gas\ per\ volume\ of\ liquid) x Daily\ oil\ production / BSW$$

Equation 17

5. Results and Discussion

This section presents the results of the field testing and data collection activities.

5.1 Phase 1 Investigation of Casing Gas Venting Measurement Methodologies

5.1.1 Introduction

Past studies suggest that casing vent valves are one of the main sources of methane emissions at CHOPS sites. A few sites have continuous meters to directly measure *total* and *vented* casing gas. At the majority of CHOPS sites, *total* and *vented* casing gas is found from the GOR test methodology. Phase 1 evaluates the accuracy of different casing gas measurement methodologies. In particular, the accuracy of GOR estimates, hourly rate testing, and GOR testing is compared to continuous meters. The test sites chosen for Phase 1 field testing have sufficient continuous meters on the streams of the casing side, to determine the casing gas, which is vented, used as fuel, treated in a combustor (flared), or gathered by pipeline, either directly or by adding and subtracting several meters. One of the test sites did not have a working fuel gas meter and data from this site was used only for *total casing gas* hourly rate and *associated gas* GOR evaluation.

5.1.2 Comparison of GOR and Hourly Rate Test at Various Gas and Oil Intervals

The *associated gas* GOR test value is found by measuring *total casing gas*, while the *vent gas* GOR test value is found by measuring the casing gas *vented* to atmosphere. **Fig. 9** compares *associated gas* GOR calculated based on *total casing gas*, at different gas measurement intervals (1, 24, and 72 hours). As mentioned in Section 4.2.7, tank venting is neglected in the Phase 1 field testing analysis. All of these GOR values are calculated at a 10-day oil measurement interval. There is good correlation (linear regression) between the 24-hour value and both the 1-hour and 72-hour values. The 24 and 72-hour values are highly correlated with a R^2 value of 0.99, and a slope close to 1.0. In general, the strength of the correlation between different gas measurement intervals decreases when GOR is greater than 300 m^3 gas/m^3 oil.

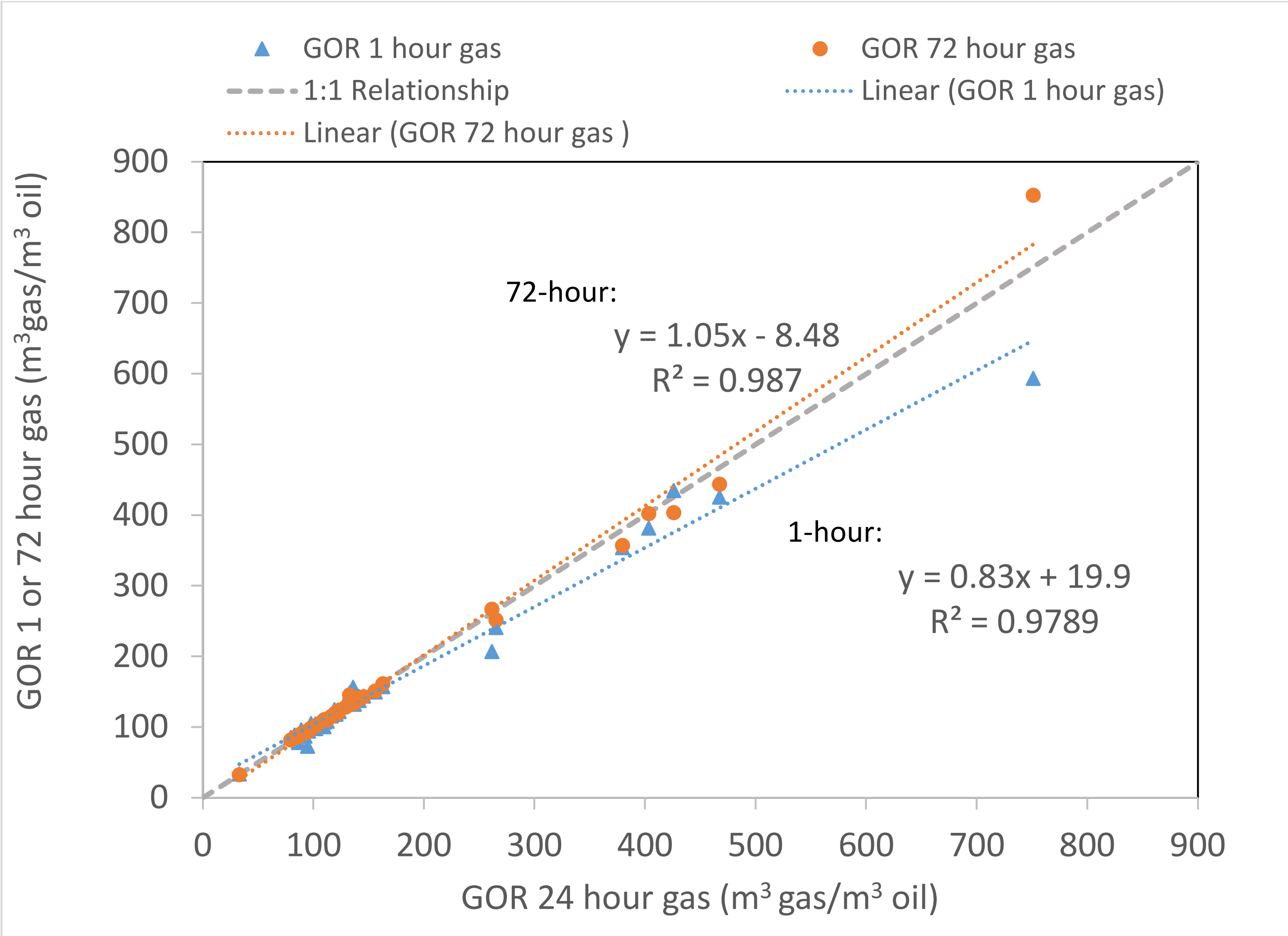


Fig. 9 — *Associated gas* GOR at different total casing gas measurement intervals All GOR at 10-day oil measurement interval.

Similarly, *total casing gas* hourly rate values are compared at different gas measurement intervals in **Fig. 10**. Both 1-hour and 72-hour values are very much correlated to the 24-hour values. The R^2 value and the slope is close to 1 for the relationship between the 24-hour and 72-hour values, and the trendline overlaps with the 1:1 relationship.

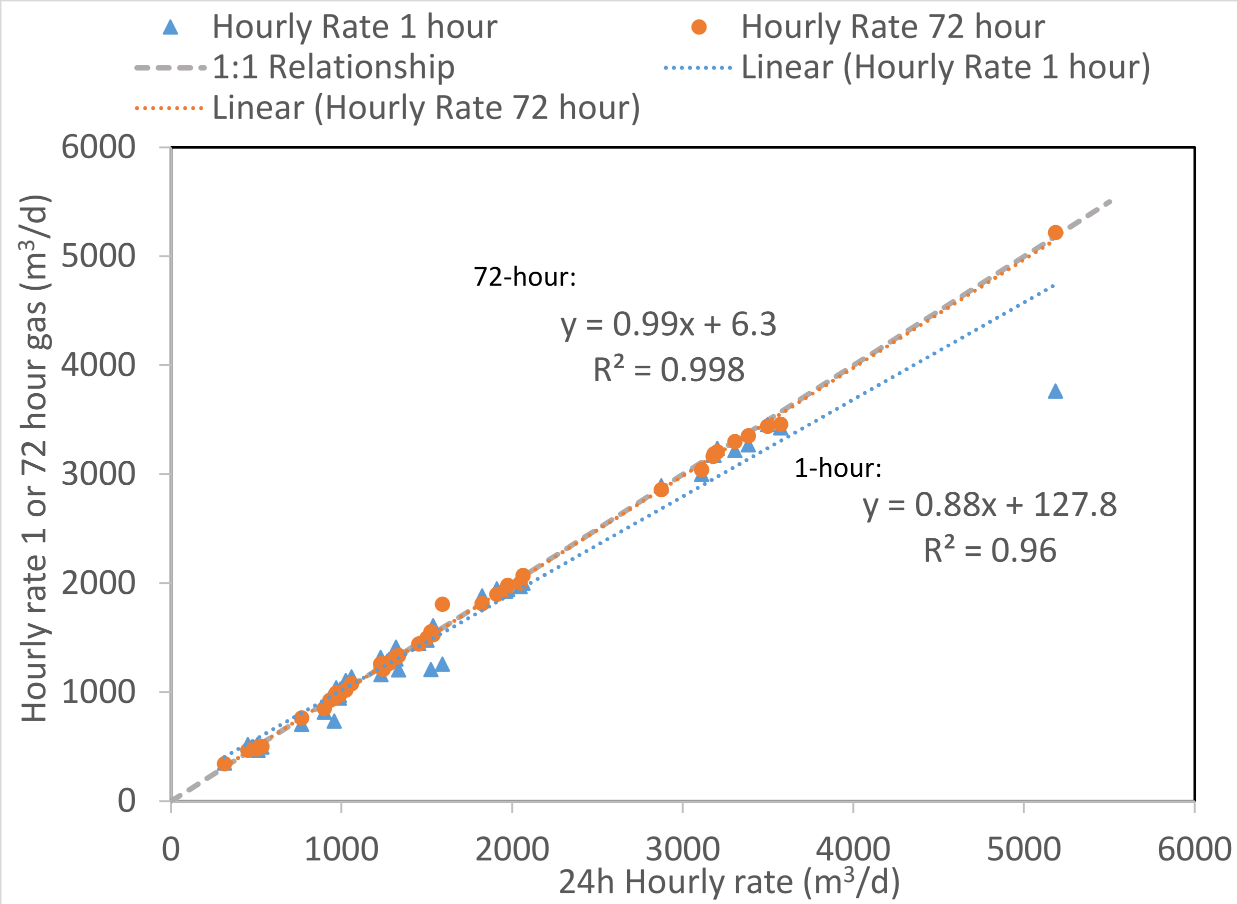


Fig. 10 — *Total casing gas* hourly rate at different gas measurement intervals.

Fig. 11 compares the *associated gas* GOR at 4 days and 1 month oil measurement intervals to values at a 10-day measurement interval. In this figure, all GOR's are calculated at 24-hour gas measurement intervals. There is a higher correlation for the 4-day versus 1 month interval but both plots deviate from the 1:1 relationship, especially at GOR's above 200 m^3 gas/m^3 oil. It is difficult to determine the ideal oil measurement interval based on **Fig. 11**. The graph suggests that the oil measurement interval can have a significant impact on the accuracy of the GOR test value. In addition, the graph suggests that there may be problems with the CHOPS GOR methodology because oil is estimated instead of directly metered in the GOR test. Factors which can increase errors in the estimate of oil volumes in GOR tests include:

- BS&W in the produced liquid can change quickly and it is difficult to determine the BS&W of the liquid during the oil measurement interval of the GOR test.
- Oil production rate can change during the GOR test oil measurement interval either intentionally (changing downhole pressure or pump speed) or naturally.

- Small errors in the oil volume in the GOR test value could cause large differences in the GOR test value, when either BS&W is very high, or the liquid production rate is very low.

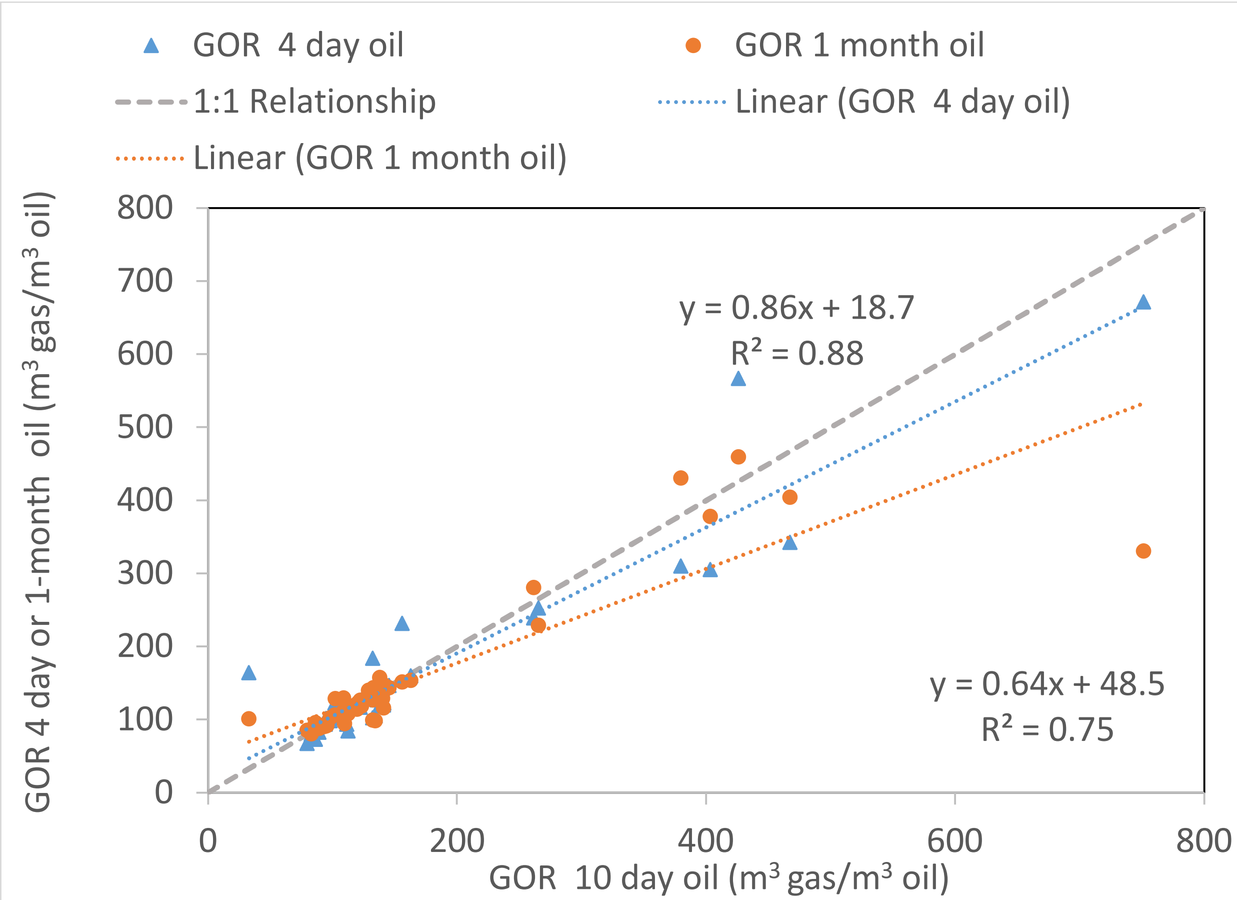


Fig. 11 — ***Associated gas* GOR at different oil measurement intervals, all at 24-hour gas measurement.**

Fig. 12 illustrates the *non-fuel* GOR values at different gas measurement intervals. In this graph, all GOR values are calculated at a 10-day oil measurement interval. This graph shows a high correlation between the 24 and 72-hour values of the *non-fuel* GOR. Similarly, **Fig. 13** compares hourly rate of *non-fuel* casing gas at different gas measurement intervals and there is a high correlation between the 24 and 72-hour values of the non-fuel use.

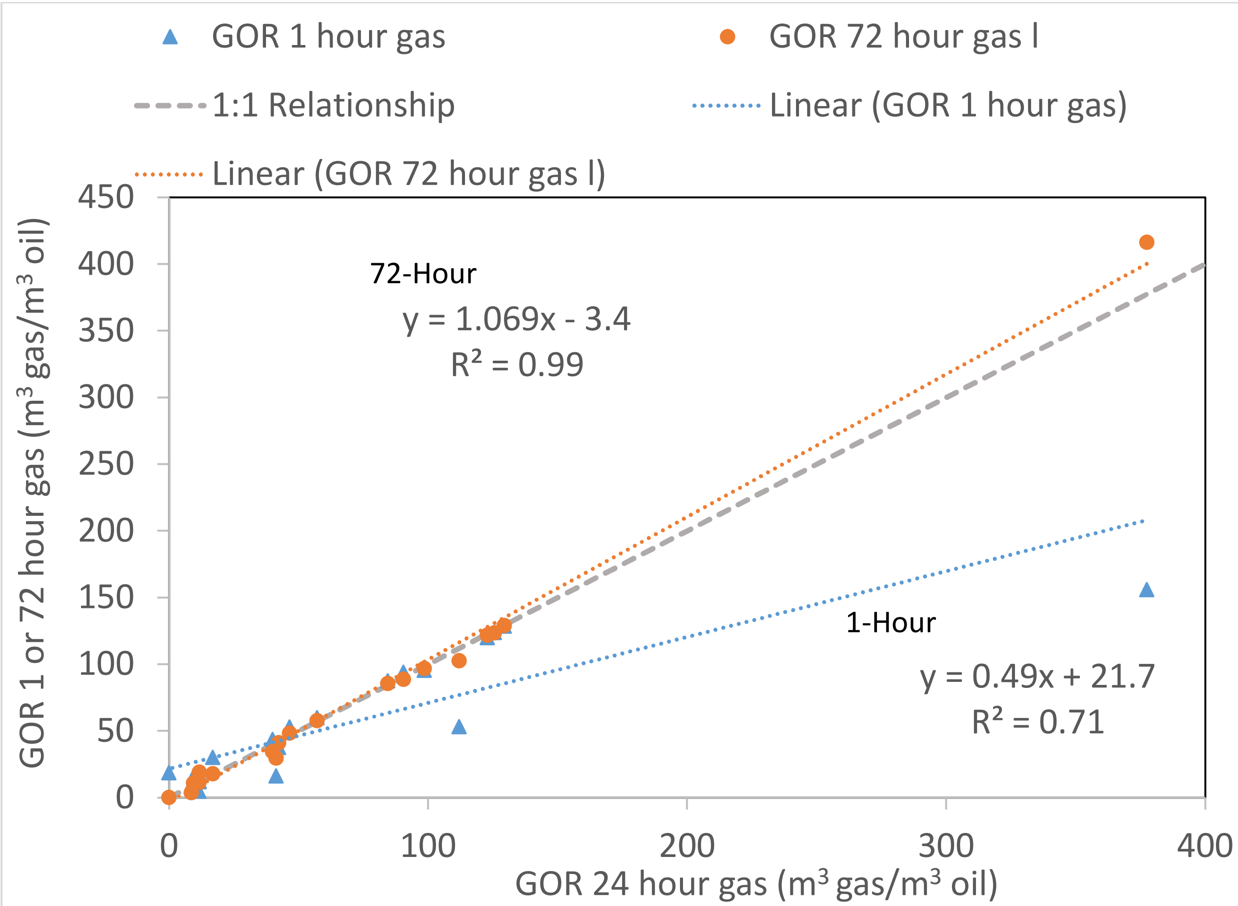


Fig. 12 — *Non-fuel* GOR at different gas measurement intervals, at 10-day oil measurement intervals.

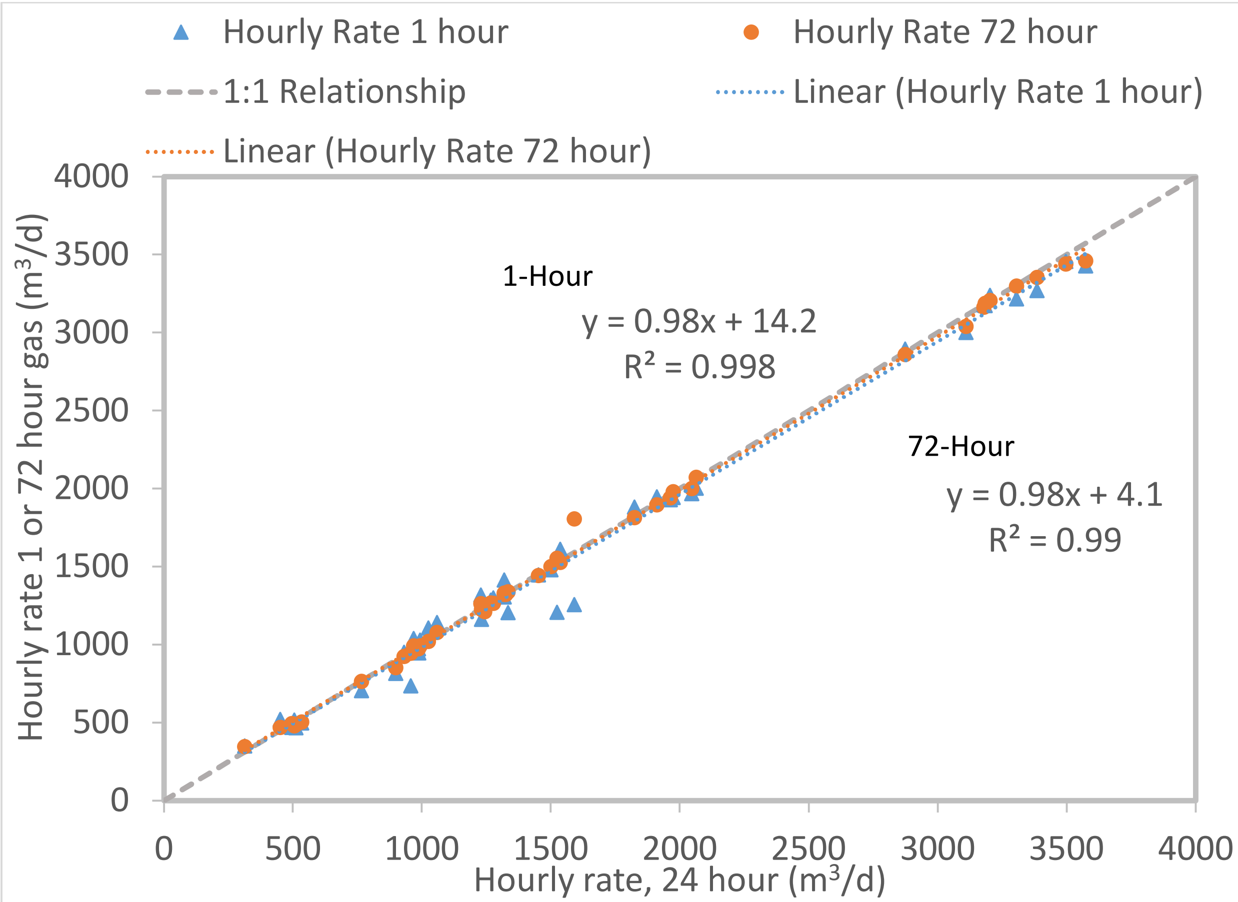


Fig. 13 — *Non-fuel* Hourly Rate at different gas measurement intervals.

These *associated* and *non-fuel* GOR and *total casing gas* and *non-fuel* hourly rate relationships indicate that there is little difference in accuracy when increasing from 24 to 72-hour gas measurement intervals, but there is a benefit in increasing the gas measurement interval from 1 to 24 hours. There is also an indication that estimating rather than metering oil volumes for the GOR test introduces inaccuracy to the GOR test methodology.

The above analysis does not address the recent regulatory changes requiring a higher frequency of GOR (or hourly rate) testing. It is certainly possible that more frequent testing will improve measurement accuracy of methane emissions. Past studies indicate that there is high variability in CHOPS *total casing gas* over time. Annual (or every several years) testing may not capture the average volumes of vented or total casing gas.

5.1.3 Comparison of GOR and Hourly Rate Testing with Continuous Meters

5.1.1.1 Total casing gas

Fig. 14 shows the monthly *total casing gas* predicted by *associated gas* GOR and *total casing gas* hourly rate at the month of the test, and subsequent months. GOR values are determined with 24-hour and 10-day gas and oil measurement intervals, respectively and hourly rate values are determined with 24-hour gas measurement intervals. Both test values predict the total casing gas, with the hourly rate test having a higher strength correlation (linear regression) and closer to the 1:1 relationship. Some values predicted by the *associated gas* GOR lie on the 1:1 relationship line; *associated gas* GOR may be accurate for some sites, but its suitability depends on characteristics of the site.

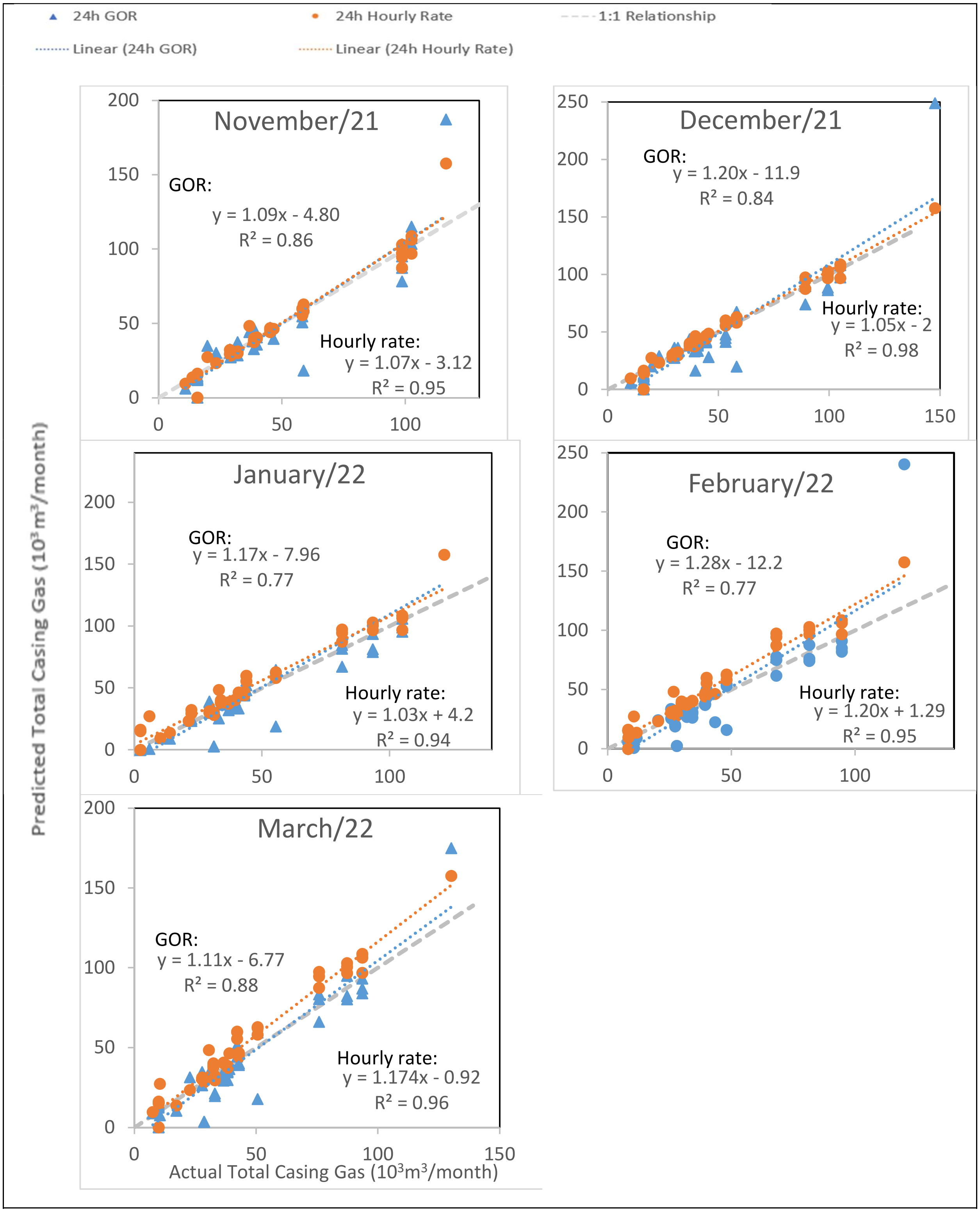


Fig. 14 — Predicted monthly *total casing gas* with *associated gas* GOR and *total casing gas* hourly rate Gas measurement interval of 24 hours, oil measurement interval of GOR is 10-days

The strength of the correlation of *total casing gas* predicted with hourly rate and GOR decreases with time after the test. It also appears that it is more difficult to predict *total casing gas* volumes with hourly rate and GOR test values at sites with volumes greater than 60,000 m^3 per month. This suggests that the timing of the test is important. However, sites with more than 60,000 m^3 per month would most likely require continuous metering as per existing provincial regulations.

There are a moderate number of CHOPS sites that vent all casing gas to atmosphere. For these sites, the *total casing gas* is equal to the *vented casing gas*. Thus, the *associated gas* GOR or *total casing* hourly rate values infer methane emissions from the atmospheric casing valves at these sites. **Fig. 14** indicates that for these sites, both the *associated gas* GOR and *total casing gas* hourly rate methodologies are reasonable at predicting the casing valve methane emissions, where hourly rate testing provides somewhat better results. For these sites, the following equations apply:

$$\boldsymbol{Vented_{Casing\ Gas}} = Total_{Casing\ Gas}$$

Equation 18

and:

$$GOR_{Vented\ Gas} = GOR_{Associated\ Gas}$$

Equation 19

and:

$$Hourly\ Rate_{Vented\ Casing\ Gas} = Hourly\ Rate_{Total\ Casing\ Gas}$$

Equation 20

5.1.1.2 Non-fuel gas

At sites that use some of the casing gas as fuel, producers often determine *vented casing gas* from an *associated gas* GOR (**Equation 1**) or a *vent gas* GOR (**Equation 2**):

$$GOR_{associated\ gas} = \frac{Total_{Casing\ Gas} + Tank\ Vent\ Gas}{Volume\ of\ oil\ production\ prorated\ to\ duration\ of\ casing\ gas\ test}$$

Equation 21

$$GOR_{vent\ gas} = \frac{Vented_{Casing\ Gas} + Tank\ Vent\ Gas}{Volume\ of\ oil\ production\ prorated\ to\ duration\ of\ casing\ gas\ test}$$

Equation 22

At sites without gas gathering or combustors, the *vent gas* GOR and *vented casing gas* hourly rates are similar to *non-fuel* (total casing gas – fuel use) values. When using an *associated gas* GOR to find *vented casing gas*, Directives 017 and PNG 017 allow *vented casing gas* to be found from either *measured* (metered) or *estimated* fuel use (Section 2.2.2). Thus, there are four options to predict *non-fuel* gas:

1. A *non-fuel* hourly rate
2. A *non-fuel* GOR.
3. An *associated gas* GOR and *measured (metered)* fuel (**Equation *10***).
4. An *associated gas* GOR and *estimated* fuel (**Equation *11***).

Fig. 15 compares actual (metered) monthly *non-fuel* gas to predicted values. **Table 5** summarizes the equations of the linear regression trendlines for each option compared to the actual values. Values predicted from *associated gas* GOR, and *estimated* fuel (option 4) are poorly correlated with the actual values. *Associated gas* GOR and *measured* (metered) fuel values (option 3) have slightly better correlation. Both *non-fuel* hourly rates and GOR (options 1 and 2) have high correlations at lower volumes of *non-fuel* gas, while the hourly rate appears to be the better method with a higher correlation over all volumes.

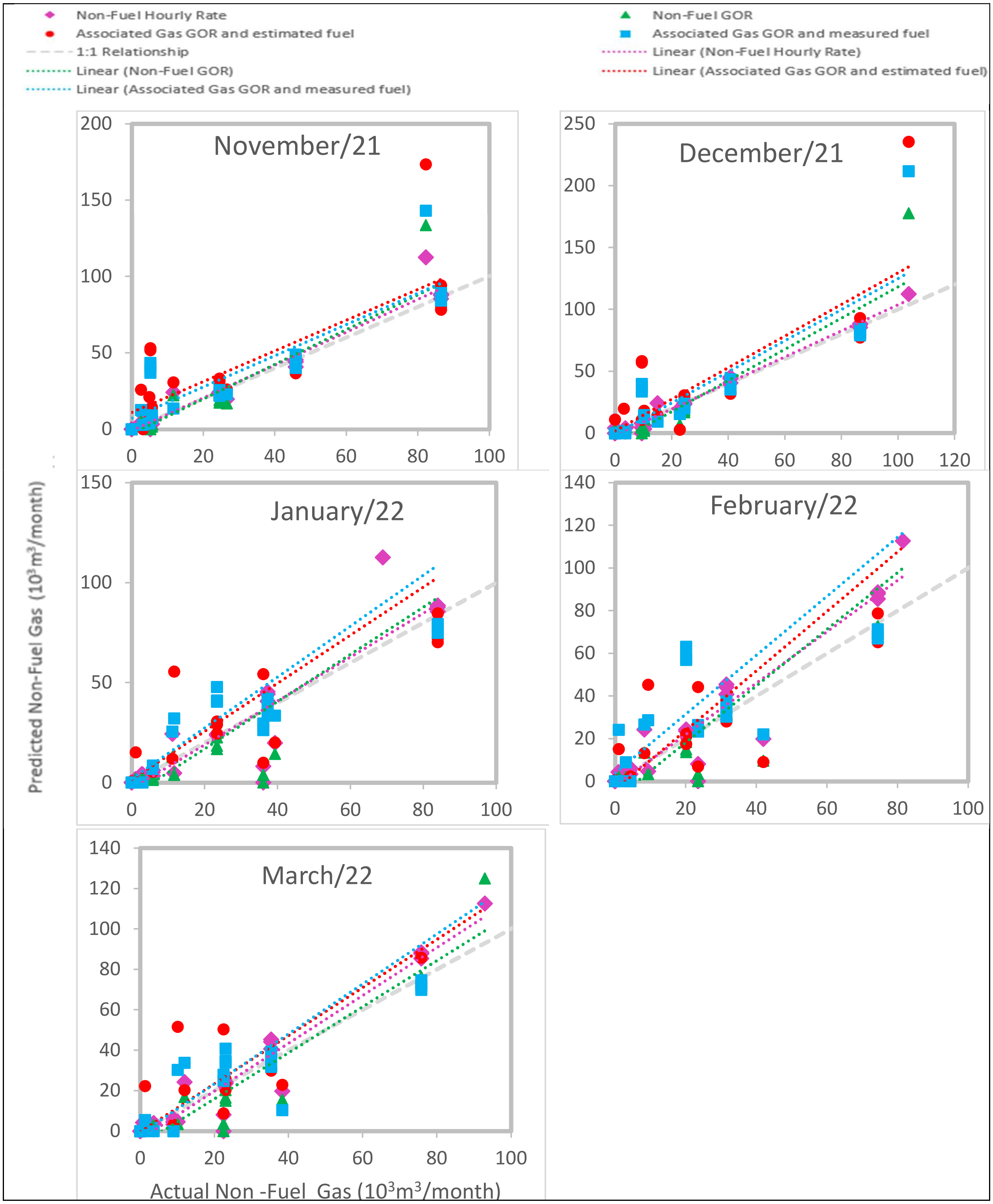


Fig. 15 — Predicted monthly *non-fuel* gas
(1) *Non-fuel* GOR (2) *Non-fuel* hourly rate (3) *Associated gas* GOR, metered fuel (4) *Associated gas* GOR, estimated fuel[1]

[1] Gas measurement interval of 24-hours for hourly rate and GOR, oil measurement interval of 10-days for GOR

Table 5 — Strength of Relationships Between Predicted and Actual *Non-Fuel* Gas[2]

Month	Option to predict monthly *Non-Fuel* Gas			
	(1) Non-Fuel Hourly Rate	*(2) Non-Fuel* GOR	*(3) Associated Gas* GOR and measured	*(4) Associated Gas* GOR and estimated
Nov/21	y=1.08x -1.06, R^2=0.96	y=1.14x -2.0, R^2=0.91	y=1.04x +7.12, R^2=0.75	y=1.01x +11, R^2=0.64
Dec/21	y=1.05x -1.57, R^2=0.99	y=1.21x -7.84, R^2=0.88	y=1.25x -1.83, R^2=0.75	y=1.28x +1.85, R^2=0.65
Jan/22	y=1.10x -3.0, R^2=0.81	y=1.18x -6.67, R^2=0.63	y=1.17x +1.49, R^2=0.61	y=1.20x -1.68, R^2=0.47
Feb/22	y=1.20x -2.03, R^2=0.89	y=1.33x -8.3 R^2=0.71	y=1.26x +4.41, R^2=0.59	y=1.39x -3.94, R^2=0.58
Mar/22	y=1.19x -3.9, R^2=0.93	y=1.14x -6.86, R^2=0.91	y=1.12x +0.44, R^2=0.88	y=1.19x -0.36, R^2=0.76

In **Fig. 15** the strength of the correlation with *non-fuel* hourly rates (option 1) decreases with an increasing number of months after the month of the test. This provides evidence that the timing of testing is important.

5.1.4 Comparison of GOR Estimates with Continuous Meters

As an alternative to GOR testing, the Government of Canada (2021) suggests using an estimate of GOR (**Equation 3**). **Fig. 16** shows the monthly *total casing gas* predicted by an estimate of *associated gas* GOR, with **Equation 3**, for the months of November and March. Although the strength of the correlation is poor compared to *total casing gas* hourly rate testing, many of the values predicted by the GOR estimate follow the 1:1 relationship line. **Equation 3** is useful for quick estimates of all *associated gas* produced by an entire region of the CHOPS sector.

[2] Linear regression trendline line equations and R^2 Values from **Fig. 15**

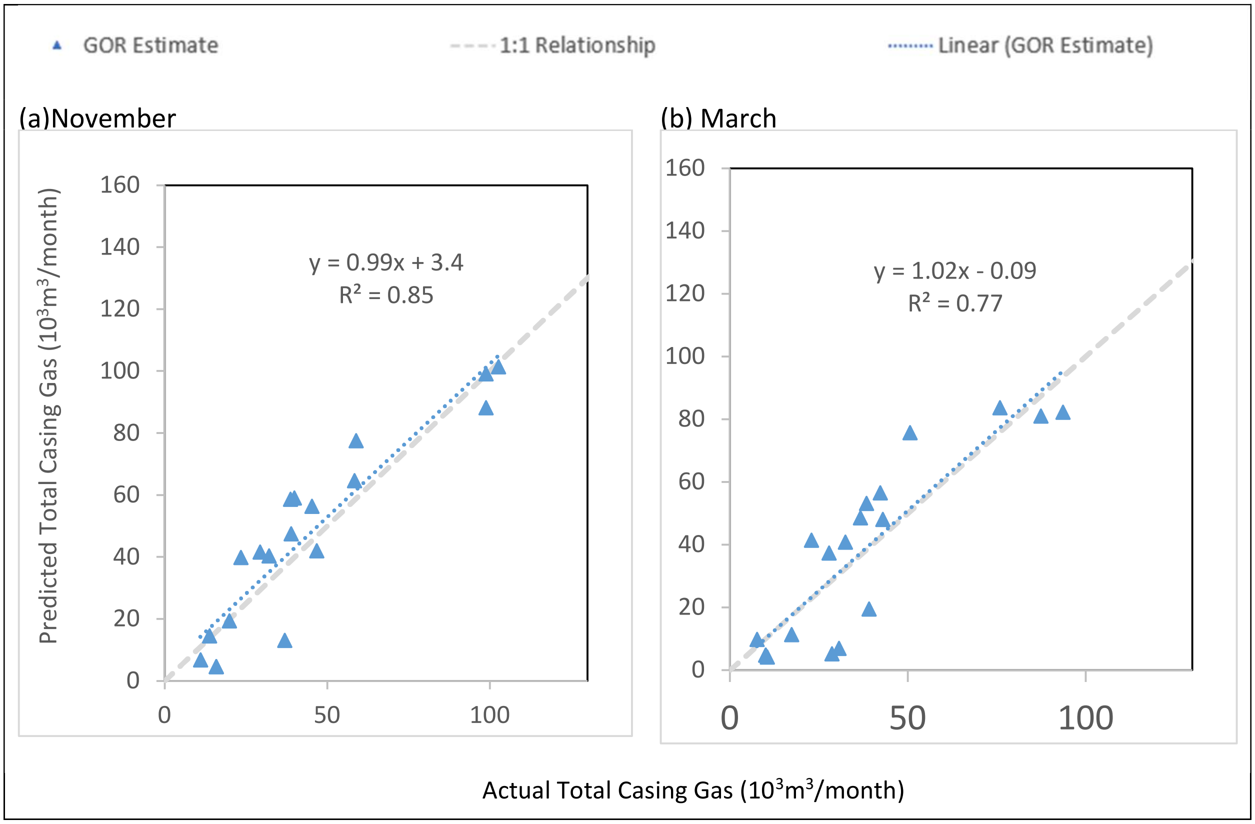


Fig. 16 — Predicted monthly *total casing gas* with estimate of *associated gas* GOR (a) November 2021 (b) March 2022.

The estimate of *associated gas* GOR can also be used to predict *non-fuel* gas via **Equation 10** and **Equation 11**. **Fig. 17** shows the monthly *non-fuel* gas predicted by an estimate of the *associated gas* GOR and *estimated* and *measured* fuel use for the months of November and March. The correlation is poor, and the *associated gas* GOR estimate is unlikely to be helpful for approximating vent gas and methane emissions at either the site or regional level.

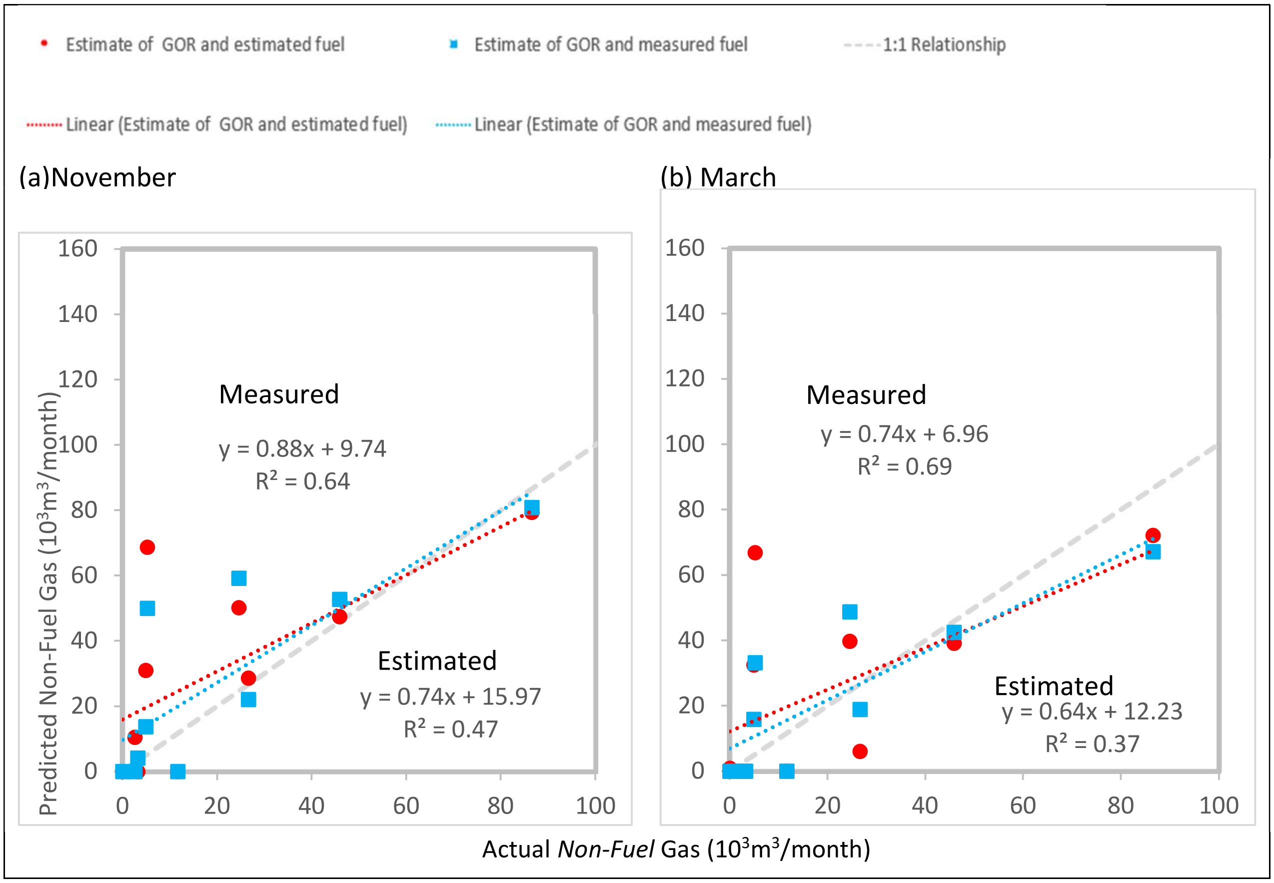


Fig. 17 — Predicted *non-fuel gas* with Equation 3 *associated gas* GOR and measured or estimated fuel (a) November 2021 (b) March 2022.

5.1.5 Evaluation of the GOR Methodology

This section looks at the concept of an *associated gas* GOR for predicting total associated gas from a CHOPS well (where any amount between 0 and 100% of the associated gas can be vented to atmosphere resulting in methane emissions) and a *vent gas* GOR for predicting gas vented to atmosphere (for sites where there is some use of the casing gas as fuel). In general, the GOR methodology assumes that GOR is constant in between tests. This means that the gas is linearly proportional to produced oil, and the slope of the relationship is the GOR value.

Fig. 18 compares monthly *total casing* gas to oil production for the test sites. Similarly,

Fig. 19 compares monthly *non-fuel* gas to oil production. The slope of each relationship is approximately the *associated gas* GOR and the *non-fuel* GOR, respectively, averaged for the months of November 2021 to March 2022.

Table 6 summarizes the virtual *associated gas* and *non-fuel* GOR values determined during field testing and the slope (average GOR of November to March) and R^2 values of the linear regression trendlines of each site, from

Fig. *18* and

Fig. *19*.

At many of the test sites, the virtual test value of the *associated gas* GOR, is very close to the slope of the linear trendline (5-month average GOR), at GOR values below 120 m^3 gas/m^3 oil. This analysis confirms that the concept of an *associated gas* GOR methodology is valid for many CHOPS sites. For some CHOPS sites that vent all casing gas to atmosphere, it confirms that the GOR methodology is helpful for estimating methane emissions. However, as noted previously, hourly rate testing of the *total casing gas* results in more accurate predictions of *total casing gas* than *associated gas* GOR, and at the majority of CHOPS sites associated gas volumes do not equal methane emissions.

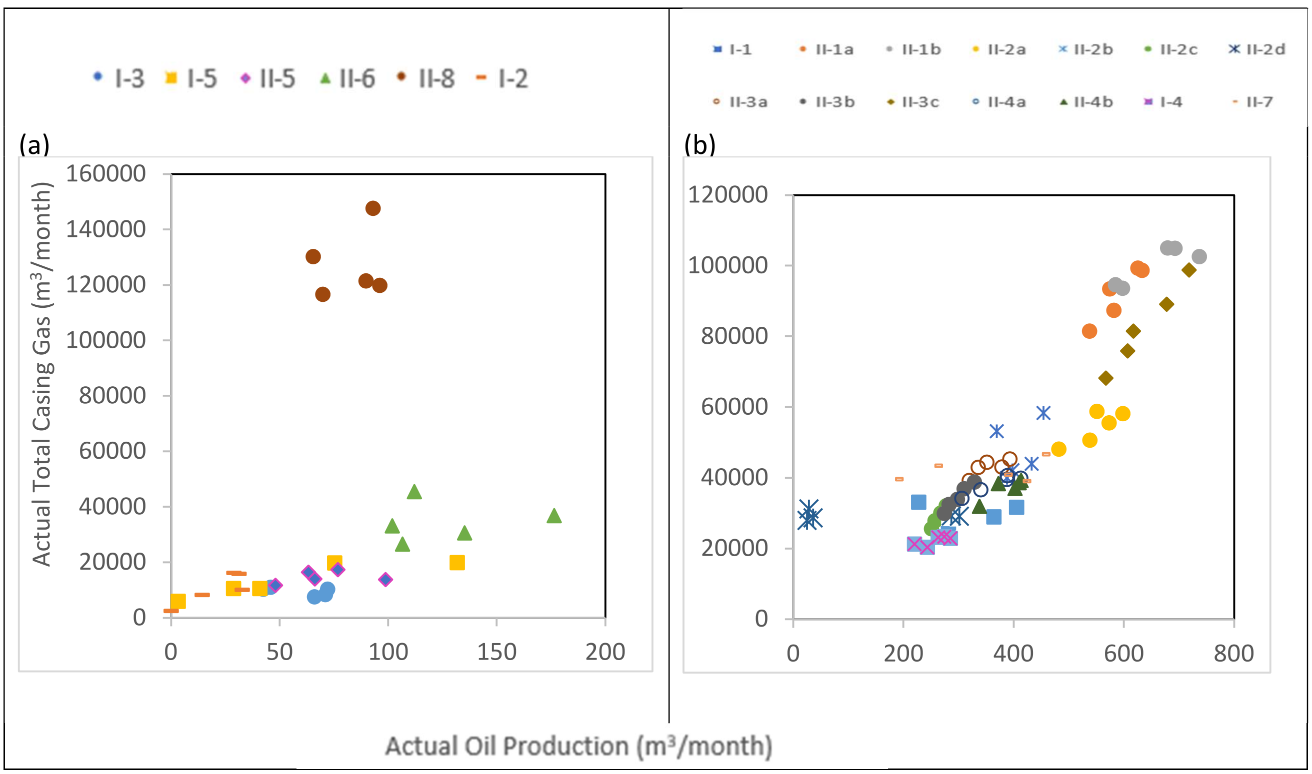


Fig. 18 — Monthly *Total Casing* gas versus oil production.
(a) Sites with oil production below 200 m^3/month (b) Sites with oil production more than 200 m^3/month.

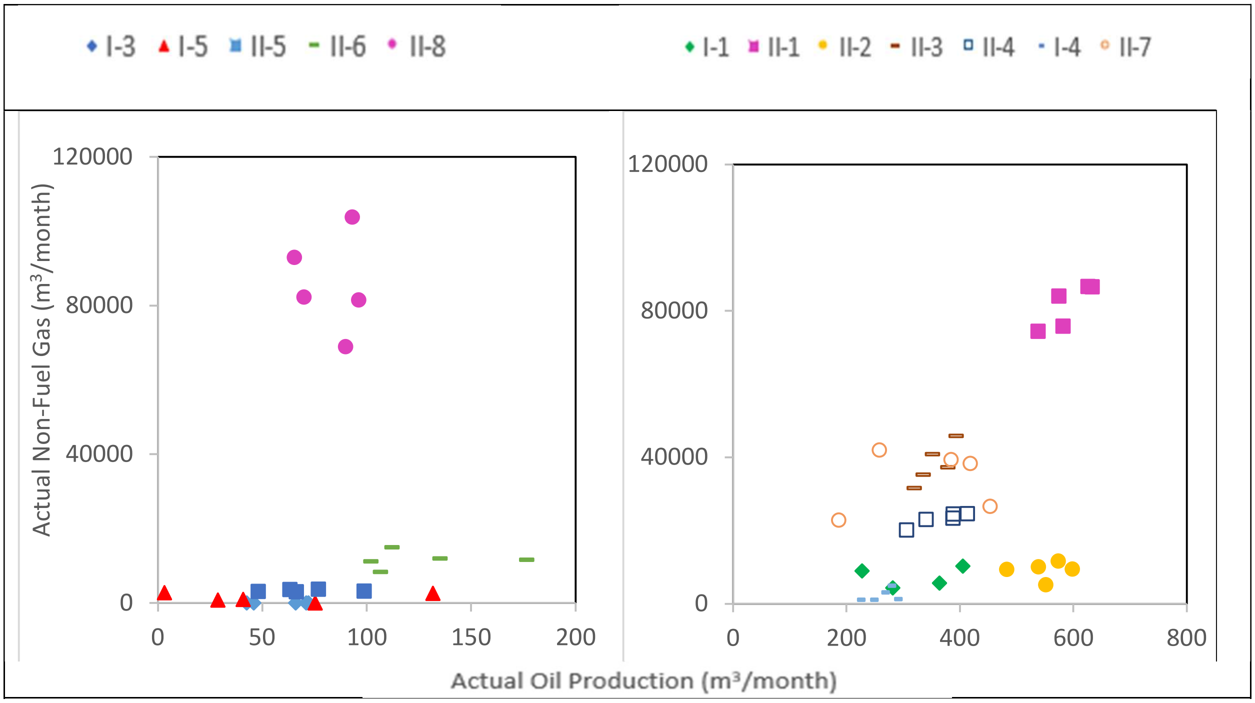


Fig. 19 — Monthly *Non-Fuel* gas versus oil production
(a) Sites with oil production below 200 m^3/month (b) Sites with oil production more than 200 m^3/month.

Table 6 — Virtual Field Test GOR and Average GOR from November 2021 to March 2022

	Associated gas		*Non-Fuel*	
Site	Virtual Field Test GOR	5-month average GOR (R^2 value)	Virtual Field Test GOR	5-month average GOR (R^2 value))
I-3	133	150 (0.91)	0	0
I-4	110	86 (0.99)	9	9 (0.73)
I-5	265	114 (0.84)	41	16 (0.41)
II-5	136	190 (0.89)	40	46 (0.94)
II-6	751	262 (0.93)	377	88 (0.99)
II-7	262	114 (0.93)	112	93 (0.90)
II-8	2680	1506 (0.98)	1915	1012 (0.96)
I-2	467	456 (0.93)	N/A	N/A
I-1	89	90 (0.95)	17	22 (0.89)
II-1a	141	156 (0.99)	123	140 (0.99)
II-1b	145	151 (0.99)		
II-2a	113	99 (0.99)	12	17 (0.95)
II-2b	112	116 (0.98)		
II-2c	134	108 (0.99)		
II-2d	95	113 (0.52)		
II-3a	120	120 (0.99)	99	108 (0.99)
II-3b	141	115 (0.99)		
II-3c	137	130 (0.99)		
II-4a	102	103 (0.99)	57	63 (0.99)
II-4b	94	95 (0.99)		

For some of the test sites, the observed 5-month average slope of *non-fuel* GOR is close to the virtual values, which mean that sometimes there is a linear relationship between *non-fuel* gas and oil. The *non-fuel* GOR may be appropriate for some sites but not others. To further explore this issue,

Fig. 20 shows the actual trend of *non-fuel* gas over time for several sites. For several sites there is less *non-fuel* gas in the colder months; this is to be expected because there is more fuel use in the cold months. Both

Fig. 19 and

Fig. *20* indicate that *non-fuel* gas, and thus *vented casing* gas, may not be linearly proportional to oil production. Fuel use is likely to change seasonally, with some sites using more fuel than others. Because there is not a strong linear relationship between *non-fuel* gas and oil production for all sites, hourly rate testing (direct measurement) is likely a better methodology for determining methane emissions from the casing vents of sites that use some of the casing gas as fuel.

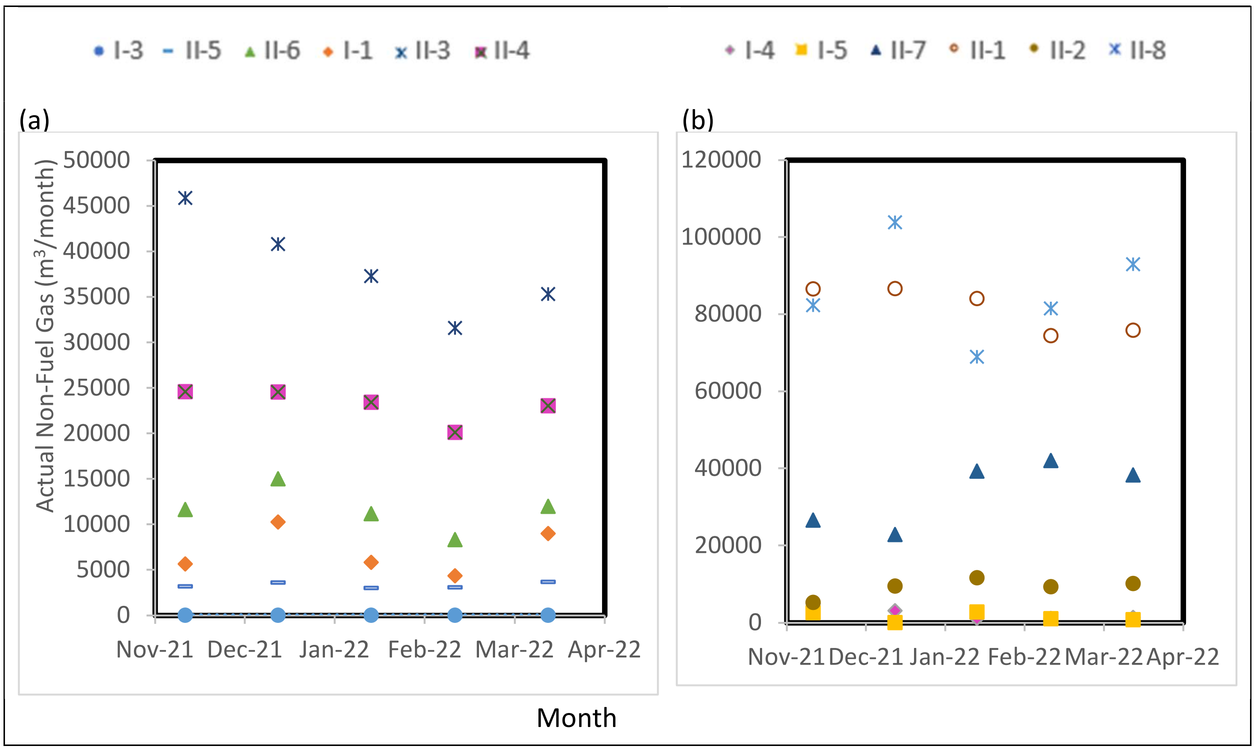


Fig. 20 — Trends of monthly *non-fuel* gas at different sites.
(a) 1st random set of test sites (b) 2nd random set of test sites.

The fact that *non-fuel* gas (and thus methane emissions) changes with the season suggests that an annual hourly rate test may not capture the annual variability in the methane emissions. One option is to take several measurements per year for sites that have high flowrates of vented casing gas. A practical approach may be to take one measurement at the peak season of vented casing gas and to validate measurements with other methane measurement surveys.

5.1.6 Composition of Casing gas at Phase 1 Field Test Sites

The composition of the casing gas is analyzed by gas chromatograph from samples at each Phase 1 test site and is shown below:

Table 7 — Casing Gas Composition in Volume Percent

Test site	Methane	Ethane	Propane/propene	C4+[3]	Air	Carbon Dioxide
I-1	90.7	1.12	0.09	0.02	4.05	4.03
I-2	94.6	1.05	0.03	0	2.5	1.80
I-3	95.2	3.6	0.17	0.03	0.79	0.20
I-4	98.9	0.27	0.01	0	0.50	0.28
I-5	99.1	0.26	0.03	0	0.48	0.15
II-1	95.3	0.44	0.09	0.57	2.87	0.76
II-2	94.4	0.43	0.03	0.08	4.2	0.87
II-3	94.2	0.44	0.07	0.43	3.37	0.75
II-4	93.8	0.57	0.11	0.83	3.58	0.99
II-5	94.4	0.42	0.02	0	4.16	0.95
II-6	94.7	0.61	0.01	0	3.20	1.53
II-7	94.2	0.76	0.03	0	3.03	1.94
II-8	93.8	0.59	0.01	0	3.9	1.66

5.1.7 General Discussion of Phase 1 Field Testing Results

At some CHOPS sites it may be difficult to complete an hourly rate test on the vented casing gas. At some of the Phase 1 field testing sites, the virtual *non-fuel* hourly rate values are found by adding and subtracting other metered casing gas streams. This indicates that at sites where it is not possible to directly meter a *vented casing gas* stream during an hourly rate test, producers can instead complete hourly rate tests of the other casing gas streams (fuel gas, gathered gas, flared gas, and total casing gas) and use calculations to find the *vented casing gas* (and thus methane emissions).

It is not possible to evaluate the accuracy of the existing continuous meters at the test sites of the Phase 1 Field testing campaign. General observations from field testing are that frequent, manual totalizer readings are helpful for flow totalizers that do not have transmitters. It is also important for the output of volumetric meters to be frequently corrected with temperature and pressure readings. In theory, (**Fig. 7**) continuous, direct measurement is the most accurate methodology to measure methane. Where continuous meters are

[3] C4+ includes any hydrocarbons larger than propane and propene.

available, they should be used for reporting casing gas venting rather than a periodic measurement methodology (hourly rate).

Phase 1 field testing analysis indicates that 24-h hourly rate testing of the *vented casing gas* is an improvement over GOR testing. Accuracy gains are especially large for hourly rate testing compared to *associated gas* GOR combined with *estimates* of fuel use. However, these problems alone do not seem to account for the three-fold difference in reported and measured methane emissions. The other gaps identified in Section 3 (tank venting measurement and absence of measurement of other emission sources such as fugitives) may account for the discrepancies. In addition, the reporting versus measured difference may be caused by confusion in applying the GOR methodology. It is possible that reporting accuracy will improve with hourly rate testing because it is a far simpler methodology compared to GOR. However, with only a few producers operating most of the CHOPS sites, where producers are well-versed in the GOR methodology, it is unlikely that confusion accounts for the large measurement gap.

It is possible that the frequency of testing has a large impact on measurement accuracy. Testing frequency can be further evaluated with collecting data from April to November 2022. Unfortunately, this field testing will not evaluate how testing frequency requirements change over the life of a CHOPS site; new sites may have extremely variable casing gas flowrates which require very frequent testing to capture the variability. Is also possible that a small number of sites, have very infrequent spikes in casing gas or tank venting which are contributing to a large portion of the CHOPS sector methane emissions. This could occur when gas from adjacent gas reservoirs is being produced for short periods of time or gas is produced in the production tubing. It would be difficult to design a study with sufficient sites to capture this behavior. In addition, one of the challenges of periodic testing for regular reporting is the difficulty in capturing rare, high-volume releases. Alternatively, there may be value to combine periodic tests with other measurement surveys. Other measurement surveys could involve a detection and screening approach using technology such as top-down surveys, or sensors/meters to detect spikes in emissions.

5.2 Phase 2 Tank Vent Measurement Methodologies and Technologies

5.2.1 Introduction

Phase 2 field-testing evaluates both technologies and methodologies for determining CHOPS tank venting. Technologies are included in this investigation because in the past, there has been little in the way of direct measurement of tank vents; however, in recent months, with the rapid transition of the energy sector to new methane emission targets, producers are trialing various flow meters on tank vents. Direct measurement technologies can be used to develop sector, business, or site-specific emission factors, and to complete periodic testing.

Phase 2 involves 29 tank tests, at CHOPS sites of three producers, in both Saskatchewan and Alberta. The following methodologies and technologies are evaluated:

- Direct measurement with tank vent composition samples and positive displacement, diaphragm, and turbine gas flow meters.
- Vasquez-Beggs correlation.
- GIS analysis.

5.2.2 Tank Vent Composition

Direct measurement of tank vent gas involves measuring vent gas composition and volumetric flowrate. Gas from each tank vent is sampled multiple times (3 to 6) and the composition of vent gas samples is analyzed via gas chromatograph (**Table 8**). *Site trip* refers to a field-testing visit to a single or multi-well battery. During some trips, a single tank at the battery is measured, while in other trips, multiple tanks at the battery are measured. *Tank test* refers to each separate field test measurement of a tank; in most cases separate tanks are measured for each test, except for site trip 12, tank test 17 which is a repeat measurement of the same tank measured in site trip 3, tank test 5. Some wells have two tanks in series on the same tank. Site characteristics are summarized in **Table 9**.

Table 8 — Dry Gas Composition in Tank Vents in Volume Percent

Site trip	Tank test	Methane	Ethane /ethene	Propane /Propene	C_4+	Oxygen	Nitrogen	Carbon dioxide
1	1	8.39	0.30	0.075	0.031	21.6	69.4	0.21
2	2	1.03	0.07	0.017	0.009	23.6	75.2	0.08
3	3	5.10	0.08	0.000	0.000	22.5	71.8	0.57
3	4	5.10	0.08	0.000	0.000	22.5	71.8	0.57
3	5	51.9	0.37	0.014	0.000	10.7	35.9	1.18
4	6	3.19	0.10	0.006	0.006	23.1	73.5	0.11
4	7	3.19	0.10	0.006	0.006	23.1	73.5	0.11
5	8	6.97	0.08	0.000	0.000	22.1	70.6	0.22
6	9	7.09	0.17	0.023	0.002	22.0	70.6	0.12
7	10	0.14	0.00	0.000	0.000	23.8	76.0	0.05
7	11	0.35	0.00	0.000	0.000	23.8	75.8	0.06
8	12	4.53	0.18	0.034	0.123	22.0	70.2	2.95
8	13	2.23	0.14	0.037	0.210	23.1	73.9	0.33
9	14	0.44	0.00	0.005	0.157	23.7	75.6	0.11
10	15	0.00	0.00	0.000	0.000	23.9	76.1	0.04
11	16	0.00	0.00	0.000	0.000	0.00	0.0	0.00
12	17	86.4	0.57	0.020	0.000	1.90	9.2	1.86
13	18	0.00	0.00	0.000	0.000	23.9	76.0	0.04
13	19	0.00	0.00	0.000	0.000	23.9	76.0	0.04
14	20	0.85	0.00	0.002	0.085	23.6	75.3	0.12
15	21	0.43	0.08	0.000	0.000	24.0	75.4	0.09
16	22	0.12	0.00	0.000	0.000	24.0	75.8	0.05
17	23	0.0	0.00	0.000	0.000	24.1	75.9	0.05
18	24	0.00	0.00	0.000	0.000	23.8	76.2	0.04
19	25	0.31	0.00	0.000	0.087	22.9	76.7	0.06
20	26	0.72	0.03	0.000	0.000	23.9	75.3	0.08
21	27	0.00	0.00	0.000	0.000	23.0	76.9	0.04
22	28	0.00	0.00	0.000	0.000	23.1	76.9	0.04
23	29	0.00	0.00	0.000	0.000	23.0	76.9	0.04

Table 9 — Site Characteristics

Site trip	Tank test	Site Characteristics	Comments
1	1	Vertical, new site, foamy oil	
2	2	Directional, established, steady GOR	
3	3	Old site, increasing GOR, multi-well site	1st of 2 tanks on well
3	4	Old site, increasing GOR, multi-well site	2nd of 2 tanks on well
3	5	Old site, increasing GOR, multi-well site	1st of 2 tanks on well (abnormal process)
4	6	New site, foamy oil	1st of 2 tanks on well
4	7	New site, foamy oil	2nd of 2 tanks on well
5	8	Old site, increasing GOR	
6	9	Directional, established, steady GOR	
7	10	Directional, old site, decreasing GOR	
7	11	Directional, old site decreasing GOR	
8	12	Directional, established site, steady GOR	
8	13	Directional, established site, steady GOR	
9	14	Vertical, old site	
10	15	Horizontal, established, decreasing GOR	
11	16	Vertical, new site, foamy oil	Testing stopped due to high winds
12	17	Old site, increasing GOR, multi-well site	1st of 2 tanks on well (abnormal process) same tank as tank test 5
13	18	Old site, increasing GOR, multi-well site	1st of 2 tanks on well
13	19	Old site, increasing GOR, multi-well site	2nd of 2 tanks on well
14	20	New site, foamy oil	
15	21	New site, foamy oil	
16	22	Established site	
17	23	Established site	
18	24	Established site	Wind blew off hose during testing
19	25	Established site	
20	26	New site, foamy oil	
21	27	Established site	
22	28	Established site	
23	29	Established site	

There is a high amount of air (**Table 10**) in the tank vents. Air is drawn into the tanks when the produced liquid (oil, water, and sand) in the tanks are unloaded, and when the vapour space cools due to ambient conditions. In general, moisture content of the vent gas is quite high, and it ranges from 2 to 30 volume %.

Water in the produced liquid turns to steam via tank heating. **Table 10** also includes vent temperature which is measured by a thermocouple at the thief hatch on top of the tanks.

Table 10 — Vent Gas Temperature, Air and Moisture Content

Site trip	Tank test	Vent temperature (°C)		Water in wet gas (Vol%)	Air in wet gas (Vol %)	
		average	STDDEV	average	average	STDDEV
1	1	61.2	0.15	21.6	71.3	1.8
2	2	55.9	2.00	16.6	82.4	1.5
3	3	39.0	2.10	8.2	86.5	4.8
3	4	57.6	0.56	17.0	78.2	4.3
3	5	56.1	2.10	12.8	40.6	23.8
4	6	39.9	1.36	6.3	90.5	3.5
4	7	56.6	1.29	15.1	82.0	3.2
5	8	37.4	0.12	6.10	87.1	2.6
6	9	62.7	3.84	18.7	75.3	1.4
7	10	55.0	1.03	15.1	84.7	0.1
7	11	61.5	1.10	19.3	80.4	0.1
8	12	51.3	2.43	12.5	80.6	2.6
8	13	55.8	0.98	14.0	83.5	0.3
9	14	52.4	1.33	12.4	87.0	0.2
10	15	19.0	2.44	2.1	97.9	0.001
11[4]	16	-	-	-	-	-
12	17	55.4	0.76	5.0	10.6	0.7
13	18	29.6	0.87	4.2	95.8	0.0
13	19	31.4	1.12	4.3	95.7	0.0
14	20	53.4	2.21	20.6	78.6	0.3
15	21	27.2	3.29	5.6	93.8	0.5
16	22	58.1	2.72	20.5	79.4	0.2
17	23	36.0	1.31	6.6	93.4	0.0
18	24	42.9	0.55	9.7	90.3	0.0
19	25	61.1	1.37	30.0	69.7	0.1
20	26	53.7	2.75	16.9	82.4	0.6
21	27	54.7	3.20	18.2	81.7	0.0
22	28	40.4	1.75	9.1	90.9	0.0
23	29	52.9	2.01	16.2	83.8	0.0

Methane content in the vent gas is very low, except for tank tests 5 and 17. These are repeat readings from the same tank. This tank is installed on a well with two production tanks in series. When testing the first

[4] Testing was halted due to poor weather conditions.

tank in series during the first site trip (designated as site trip 3, tank 5), an abnormal process was occurring, and vent flow was greater than 600 m^3/d. This high flowrate provided an opportunity to use the turbine meter which was ranged for flowrates of up to 1500 m^3/d. Casing gas conservation equipment at the site had failed. The site is designed such that un-conserved casing gas during an equipment failure will vent via the tank, along with gas from the production liquid. This is a fugitive emission and not routine venting. The problem with the gas conservation equipment was repaired quickly while SRC technicians were on site testing the tank, and the vent rate decreased to a very low value (less than 6 m^3/d). Upon return to the same well several weeks later to test the second tank at the well, a survey with the optical gas imaging camera indicated there was negligible gas venting from the second tank, while again there was very high amounts of venting from the first tank. Rather than testing the second tank, the first tank was re-tested (designated site trip 12, tank test 17). Re-testing this tank provided a second opportunity to use the turbine meter. Again, the producer repaired the gas conservation equipment at the site, to reduce venting from the tank to low rates.

5.2.3 Direct Measurement of Tank Vents

During Phase 2 field testing, volumetric tank vent flowrate was successfully measured with diaphragm, positive displacement (PD) rotary, and turbine flow meters. The field-testing meter models were selected for different flow ranges, where the diaphragm was ideal for low flowrates (0 to 100 m^3/d), the PD meter was ideal for low to moderate flowrates (15 to 800 m^3/d) and the turbine meter was ideal for high flowrates of 200 to 1500 m^3/d.

Table 11 summarizes the total vent flow, along with methane in the wet gas. The table uses the most ideal meter for the flow measurement. Appendix A contains further details on measurements from all three meters.

Table 11 — Summary of Tank Vent Flow and Composition

Site trip	Tank test	Flow meter	Liquid production (m^3/d)	Total tank vent gas flow Sm^3/d		Vol% Methane in wet gas	
				average	STDDEV	average	STDDEV
1	1	PD	8.4	17.3	10.1	6.6	1.7
2	2	Diaphragm	14.8	4.9	N/A	0.9	1.3
3	3	PD	23.6	67.0	78.3	4.7	4.3
3	4	No flow detected	23.6	0.0	0.0	4.2	3.9
3	5	Turbine	1.7	619.1	129.5	45.3	27.2
4	6	PD	9.8	28.8	3.3	3.0	3.3
4	7	No flow detected	9.8	0.0	0.0	2.7	3.0
5	8	PD	36.5	26.7	8.5	6.5	2.5
6	9	PD	6.0	40.9	9.2	5.8	1.3
7	10	PD	3.1	8.0	7.9	0.1	0.1
7	11	PD	10.1	27.2	5.5	0.3	0.1
8	12	PD	36.1	61.0	17.0	4.0	1.5
8	13	PD	7.1	27.2	5.5	1.9	0.2
9	14	PD	8.8	19.4	13.1	0.4	0.2
10	15	Diaphragm	40.3	1.9	N/A	0.0	0.0
11[5]	16		-	-	-	-	-
12	17	Turbine	1.7	646.5	6.0	82.1	0.7
13	18	Diaphragm	113.0	4.8	N/A	0.0	0.0
13	19	Diaphragm	113.0	6.13	N/A	0.00	0.00
14	20	PD	6.9	37.44	5.88	0.68	0.23
15	21	PD	17.0	16.20	8.35	0.40	0.38
16	22	Diaphragm	7.4	10.62	N/A	0.10	0.17
17	23	PD	41.2	17.57	5.73	0.00	0.00
18	24	No flow detected	8.8	0.00	N/A	0.00	0.00
19	25	Diaphragm	3.3	45.60	N/A	0.21	0.07
20	26	PD	4.2	14.49	7.49	0.60	0.59
21	27	PD	14.5	4.00	4.46	0.00	0.00
22	28	No flow detected	2.5	0.00	N/A	0.00	0.00
23	29	No flow detected	0.9	0.00	N/A	0.00	0.00

During each tank test, for validation purposes, periodic vane anemometer and pitot tube measurements were taken in series with the diaphragm, PD, or turbine meters. The vane anemometer and pitot tube could be used in series with the other flow meters because they would not introduce back pressure on the vent line. However, these instruments were unsuccessful. The readings of the anemometer and pitot tube were extremely small, and it is possible that wind interfered with the readings. The vane anemometer readings were only successful for three tank tests, but they did not provide good agreement with the PD and turbine

[5] Testing halted due to weather conditions.

meters. Furthermore, **Table 11** shows that the standard deviations of the diaphragm, PD or turbine meters vent flow measurements are high for some of the tank tests. The high standard deviations are partly due to the natural variation in vent flow and partly because the meters are over-sized for the low vent flows of the tanks. Due to the bulk of the diaphragm meter, it likely requires tubing to pipe the tank vent to grade level. This type of meter is readily available in smaller sizes that would be more suitable for some of the low flows observed during testing. PD and turbine meters can be directly connected to the tank vent or thief hatch and are also available for smaller flow ranges.

The vane anemometer and pitot tube measured an instantaneous flowrate because they did not have data-logging instrumentation. These instruments technologies could not capture the variability in CHOPS tank vent rates.

The testing did not evaluate whether venting increased due to ambient temperature changes during the day, where the vapour space of the tank heated up, causing more venting.

Although some tanks had vent flowrates of up to 70 m^3/d, the methane content was quite low. **Table 12** uses the methane content to calculate the flowrate of methane emissions from the tank vent.

Table 12 — Methane Emissions from Tank Vents

Site trip	Tank test	Total tank vent gas flow Sm^3/d average	Vol% Methane in wet gas average	Methane in tank vent Sm^3/d average
1	1	17.3	6.58	1.14
2	2	4.91	0.86	0.042
3	3	67.0	4.68	3.13
3	4	0.00	4.23	0.000
3	5	619.1	45.3	280.2[6]
4	6	28.8	2.98	0.86
4	7	0.00	2.70	0.000
5	8	26.74	6.54	1.75
6	9	40.9	5.76	2.36
7	10	8.03	0.12	0.010
7	11	27.2	0.28	0.077
8	12	61.0	3.96	2.42
8	13	27.2	1.92	0.52
9	14	19.39	0.39	0.08
10	15	1.89	0.00	0.0000
11	16	0.00	0.00	0.00
12	17	646.5	82.1	530.8
13	18	4.79	0.00	0.0000
13	19	6.13	0.00	0.0000
14	20	37.4	0.68	0.25
15	21	16.2	0.40	0.065
16	22	2.72	0.10	0.003
17	23	17.6	0.00	0.0000
18	24	0.00	0.00	0.00
19	25	45.6	0.21	0.10
20	26	14.5	0.60	0.09
21	27	4.00	0.00	0.0000
22	28	0.00	0.00	0.00
23	29	0.00	0.00	0.00

[6] Tank tests 5 and 17 measured an abnormal process (fugitive emission), not routine venting.

5.2.4 Vasquez Beggs Correlation

The Vasquez-Beggs correlation (refer to the equations in Section 4.3.7) is applied to an upstream and a downstream equilibrium condition. The correlation predicts the volume of gas in solution at each condition. Then in theory, the difference between the gas in solution values determined at each condition, is the tank vent gas, which flashes from the production tanks. **Table 13** shows the temperature and pressures used for the upstream and downstream conditions.

Table 13 — Upstream and Downstream Conditions for Input to Vasquez-Beggs

Site trip	Tank test	Upstream produced liquid temperature at wellhead	Option 1 upstream production line pressure at wellhead	Option 2 upstream estimated downhole pressure	Downstream tank vapour space temperature	Downstream tank vapour space pressure
		°C	kPa_g	kPa_g	°C	kPa_g
1	1	21.4	55	600	61.2	0
2	2	17.5	59	600	55.9	0
3	3	17.7	557	600	39.0	0
3	4	16.4	70	600	57.6	0
3	5	20.8	209	600	56.1	0
4	6	22.1	209	600	39.9	0
4	7	25.7	209	600	56.6	0
5	8	17.4	153	600	37.4	0
6	9	22.4	70	600	62.7	0
7	10	20.0	70	600	55.0	0
7	11	19.8	313	600	61.5	0
8	12	22.0	70	600	51.3	0
8	13	25.0	139	600	55.8	0
9	14	15.9	139	600	52.4	0
10	15	15.6	87	600	19.0	0
11	16					0
12	17	24.6	70	600	55.4	0
13	18	22.8	70	600	29.6	0
13	19	21.9	70	600	31.4	0
14	20	20.8	192	600	53.4	0
15	21	18.7	136	600	27.2	0
16	22	15.6	70	600	58.1	0
17	23	19.8	70	600	36.0	0
18	24	15.2	279	600	42.9	0
19	25	9.7	279	600	61.1	0
20	26	17.8	279	600	53.7	0
21	27	19.1	279	600	54.7	0

22	28	19.2	24	600	40.4	0
23	29	20.8	17	600	52.9	0

A concern with the Vasquez-Beggs correlation is that the upstream equilibrium condition cannot be properly defined. As mentioned in Section 2.1.5, the annulus between the well casing and the production tubing is vented at the wellhead, and the downhole area behaves as a separator. Thus, in theory, the liquid and gas mixture entering the production tubing is near equilibrium. This downhole area represents the upstream equilibrium condition and the gas in solution at this condition is calculated from the Vasquez-Beggs correlation. Unfortunately, the pressure at this upstream condition is unknown because it typically is not measured with instrumentation, although downhole temperature can be approximated from the produced liquid temperature at the wellhead. Instead, producers sometimes use the pressure of the produced liquid at the wellhead (option 1). This wellhead produced liquid pressure value is likely an inaccurate estimate of downhole pressure because it is only the backpressure as a result of pipe friction and liquid head between the wellhead and the tank. One producer estimates downhole pressure by measuring casing annulus pressure, and then calculating the pressure from estimates of the liquid depth (head) in the downhole area, above the entrance of the production line. For one instance, this downhole pressure was found to be 600 kPa_g. In the current study there is no information collected on the liquid depth during field-testing. In the absence of this information, a downhole pressure value of 600 kPa_g is used to re-calculate the downhole gas-in-solution values (option 2) simply to illustrate how the downhole pressure affects the calculation of tank vent gas. **Table 14** summarizes the calculated vent flows from the Vasquez-Beggs correlation at both option 1 and 2. The vent flow rates predicted by option 1 are extremely small. Option 2 results in larger estimates of tank vent gas. It was found that the vent flows predicted by the correlation (option 2) were actually greater than direct measurements of vent flow.

Table 14 — Vasquez-Beggs Correlation for Predicted Dry, Air-Free Vent Gas Flowrate

Site trip	Tank test	Average daily oil production m^3/d	Option 1, ratio of gas in produced oil based on production line pressure at wellhead Sm^3 gas/m^3 oil	Option 2 ratio of gas in produced oil based on estimate of downhole pressure Sm^3 gas/m^3 oil	Option 1, predicted dry, air-free tank vent gas based on production line pressure Sm^3/d	Option 2, predicted tank vent gas based on estimate of downhole pressure Sm^3/d
1	1	8.8	0.09	0.99	0.8	8.7
2	2	11.7	0.10	1.00	1.1	11.7
3	3	2.1	0.92	0.99	2.0	2.1
3	4	2.1	0.11	1.00	0.2	2.2
3	5	1.2	0.33	0.99	0.4	1.2
4	6	9.1	0.33	0.98	3.0	8.9
4	7	9.1	0.24	0.98	2.2	8.9
5	8	1.4	0.24	0.99	0.3	1.4
6	9	4.8	0.11	0.99	0.5	4.7
7	10	1.7	0.11	0.99	0.2	1.6
7	11	3.7	0.50	0.99	1.9	3.7
8	12	4.0	0.11	0.99	0.4	4.0
8	13	6.7	0.22	0.98	1.5	6.6
9	14	1.2	0.22	1.00	0.3	1.2
10	15	6.2	0.13	0.99	0.8	6.2
11	16					
12	17	1.2	0.11	0.98	0.1	1.2
13	18	2.5	0.11	0.98	0.3	2.4
13	19	2.5	0.11	0.98	0.3	2.4
14	20	5.4	0.30	0.99	1.6	5.3
15	21	4.2	0.21	0.99	0.9	4.2
16	22	1.0	0.11	1.00	0.1	1.0
17	23	1.8	0.11	0.99	0.2	1.8
18	24	2.4	0.45	1.00	1.1	2.4
19	25	1.0	0.46	1.01	0.4	1.0
20	26	3.4	0.45	0.99	1.5	3.4
21	27	1.0	0.45	0.99	0.4	1.0
22	28	1.0	0.04	0.99	0.04	1.0
23	29	0.5	0.03	0.99	0.02	0.5

Another concern with the Vasquez-Beggs correlation is that it may not be applicable to the viscous oil typical of CHOPS reservoirs. As discussed in Sections 2.1.5 and 3.3.6, foamy oil flow traps gas in the produced liquid as bubbles or slugs. Therefore, the amount of gas in solution at the upstream condition is likely greater than the equilibrium value during foamy oil flow.

The Vasquez-Beggs correlation is unsuitable for the CHOPS sector, even though the vent flow of most of the tanks in the phase 2 field testing campaign are very low.

5.2.5 GIS Analysis

GIS (gas in solution) analysis is an alternate methodology for finding vent gas from CHOPS tanks (Directives 017 and PNG 017). GIS analysis of samples of the produced liquid at the test tanks are summarized in **Table 15**. Complete GIS results and test procedure are included in Appendix B.

Table 15 — Gas in Solution Analysis[7]

Site trip	Tank test	Average BS&W (%)	GIS Sample 1 (S m³/m³)	GIS Sample 2 (S m³/m³)	GIS Sample 3 (S m³/m³)	Average GIS (S m³/m³)	STDDEV GIS (S m³/m³)	Methane in gas in GIS samples (Vol %)	Average daily oil prod. (m³/d)	Vent [8]flow from GIS (S m³/d)
1	1	36%	0.98	1.89	0.91	1.26	0.55	31.9	8.8	17.4
2	2	21%	1.26	2.02	0.91	1.40	0.57	53.4	11.7	20.7
3	3	91%	0.98	1.03	0.91	0.97	0.06	32.1	2.1	22.9
3	4	91%	0.92	1.05	-	0.98	0.10	32.1	2.1	23.2
3	5	31%	0.98	1.11	0.91	1.00	0.10	16.4	1.2	1.7
4	6	8%	1.51	1.84	0.91	1.42	0.47	86.1	9.1	14.0
4	7	8%	1.57	1.76	0.91	1.41	0.45	86.1	9.1	13.9
5	8	96%	1.46	2.10	0.91	1.49	0.60	50.3	1.4	54.4
6	9	21%	1.56	1.36	0.91	1.28	0.34	46.4	4.8	7.7
7	10	46%	1.26	1.15	0.91	1.11	0.18	68.6	1.7	3.4
7	11	63%	1.56	1.41	0.91	1.29	0.34	84.5	3.7	13.0
8	12	89%	1.95	2.10	0.91	1.65	0.65	70.0	4.0	59.6
8	13	5%	1.84	1.66	0.91	1.47	0.50	74.4	6.7	10.5
9	14	86%	1.32	1.03	0.91	1.08	0.21	60.4	1.2	9.6
10	15	85%	2.06	1.83	0.91	1.60	0.61	87.6	6.2	64.5
11[9]	16	-	-	-	-	-	-	0.0	-	-
12	17	31%	0.98	1.11	0.91	1.00	0.10	16.4	1.2	1.7
13	18	98%	1.05	0.98	0.91	0.98	0.07	36.7	2.5	110.7
13	19	98%	1.00	1.06	0.91	0.99	0.07	36.7	2.5	111.7
14	20	23%	1.56	1.61	0.91	1.36	0.39	74.5	5.4	9.4
15	21	75%	1.41	1.08	0.91	1.13	0.26	51.9	4.2	19.3
16	22	87%	2.34	1.90	0.91	1.72	0.73	86.2	1.0	12.8
17	23	96%	1.84	1.44	0.91	1.39	0.47	58.4	1.8	57.4
18[10]	24	73%	-	-	-	-	-	-	-	-
19	25	71%	1.55	2.30	0.91	1.59	0.70	59.5	1.0	5.3
20	26	19%	1.51	1.62	0.91	1.35	0.38	74.5	3.4	5.7
21	27	93%	1.95	2.04	0.91	1.63	0.63	48.7	1.0	23.6
22	28	58%	1.58	1.47	0.91	1.32	0.36	77.5	1.0	3.3
23	29	40%	1.03	1.75	0.91	1.23	0.45	58.8	0.5	1.1

There is a lot of variability between GIS results at the same site. Direct measurement with the flow meters also shows that the tank vent flow has a very high variability. It is difficult to take enough GIS samples to

[7] Testing is completed with a room pressure of 95.3 kPa_a and temperature of 25°C
[8] This is the predicted vent flow, excluding air and water.
[9] Testing of site 11 was halted due to weather.
[10] The GIS samples contained only water and no oil or gas.

represent these dynamics. On the other hand, the diaphragm, PD, and turbine gas flow meters are able to measure flow over an hour or several hours, resulting in more accurate measurement of tank vent flow. In addition, BS&W (water content) influences the success of GIS. Lower standard deviations of GIS measurements were achieved at sites with lower BS&W. All three samples from tank test 24 contained only water and no oil nor gas and could not be analyzed for GIS.

5.2.6 Comparison of Tank Vent Measurement

Table 16 summarizes tank vent gas determined from different methodologies. There is no agreement between directly measured vent gas and the Vasquez Beggs correlation or GIS analysis.

Table 16 — Comparison of Tank Vent Gas Measurement Technologies and Methodologies

		Total vent gas				*Vented hydrocarbon gas, dry and air-free*				
Site trip	Tank test	Diaphragm meter (S m^3/d)	PD meter (S m^3 /d)	Turbine meter (S m^3/ d)	HC[11] in vent gas (vol %)	Diaphragm meter (S m^3/d)	PD meter (S m^3 /d)	Turbine meter (S m^3/d)	Vasquez Beggs (S m^3/d)	GIS (S m^3/d)
1	1	16.4	17.3		7.1	1.16	1.22		8.7	17.4
2	2	4.9	10.3		1.0	0.0492	0.103		11.7	20.7
3	3	60.1	67.0		5.3	3.17	3.54		2.1	22.9
3	4	0.0	0.0		4.8	0.0000	0.0000		2.2	23.2
3	5	5.8	0.0	619.1	46.6	2.69	0.00000	288.7	1.2	1.7
4	6	10.7	28.8		3.2	0.340	0.918		8.9	14.0
4	7	0.0	0.0		2.9	0.0000	0.0000		8.9	13.9
5	8	11.5	26.7		6.8	0.788	1.83		1.4	54.4
6	9	35.5	40.9		6.0	2.14	2.47		4.7	7.7
7	10	0.0	8.0		0.161	0.0000	0.0129		1.6	3.4
7	11	8.7	27.2		0.334	0.0290	0.0908		3.7	13.0
8	12	47.5	61.0		6.9	3.28	4.20		4.0	59.6
8	13	25.6	27.2		2.5	0.648	0.691		6.6	10.5
9	14	10.2	19.4		0.631	0.0642	0.122		1.2	9.6
10	15	1.9	0.0		0.039	0.0007	0.0000		6.2	64.5
11	16	-	-	-	-	-		-	-	-
12	17	0.0	646.5	491.3	84.4	0.0000	545.8	414.8	1.2	1.7
13	18	4.8	0.0		0.039	0.0019	0.0000		2.4	110.7
13	19	6.1	0.0		0.039	0.0024	0.0000		2.4	111.7
14	20	25.5	37.4		0.842	0.214	0.315		5.3	9.4
15	21	0.0	16.2		0.562	0.0000	0.0911		4.2	19.3
16	22	2.7	10.6		0.137	0.0037	0.0146		1.0	12.8
17	23	0.0	17.6		0.046	0.0000	0.0080		1.8	57.4
18	24	0.0	0.0		0.035	0.0000	0.0000		2.4	0.0
19	25	14.9	45.6		0.318	0.0476	0.145		1.0	5.3
20	26	0.0	14.5		0.7	0.0000	0.0994		3.4	5.7
21	27	0.0	4.0		0.031	0.0000	0.0012		1.0	23.6
22	28	0.0	0.0		0.035	0.0000	0.0000		1.0	3.3
23	29	0.0	0.0		0.032	0.0000	0.0000		0.5	1.1

[11] HC is hydrocarbons (excludes air and water).

5.2.7 General Discussion of Tank Vent Measurement

The Vasquez Beggs correlation and GIS Analysis do not appear to be good methodologies of measuring CHOPS tank vent emissions. The Vasquez Beggs correlation actually over-estimates emissions for low-emitting tanks. Many CHOPS tanks have extremely low emissions. Periodic aerial or camera surveys can screen tanks that require periodic direct measurement or *site*-specific emission factors, from those with low vent flowrates. In the short-term future, low-emitting tanks could be measured with *published* emission factors determined with direct measurement of tank vent gas. As methane reductions occur, *company/field/site*-specific emission factors may become appropriate. In other words, more accurate measurement should be applied to sources/sites that contribute a larger share of emissions. Other measurement and detection measures should be considered for tanks which can vent excessive fugitive emissions of methane during an equipment failure (vapour recovery unit, separator level control valve, thief hatch, or gas conservation compressor).

Some of the tanks tested in the phase 2 field campaign were on new wells, which were identified by the producers to have the potential of foamy oil flow. However, these tanks did not exhibit higher methane venting than established and old wells. It is possible that high venting during foamy oil only occurs intermittently (i.e., a few days per month or a few months per year) and therefore the higher venting was missed during phase 2 field-testing. An aerial methane measurement survey of several hundred CHOPS sites could evaluate whether new wells exhibit higher than normal venting; any vents that are detected can be cross-referenced with producers to see if they are new wells with possible foamy oil flow. It is likely that only tanks venting methane flows of greater than 75 m^3/d, would be detected in an aerial survey. An aerial survey would also show how much tank venting contributes to methane emissions at CHOPS sites and help with designing measurement strategies.

Field testing included two tests of the same tank which had extremely high vent flowrates. The high venting was a fugitive emission, the result of an abnormal process, where equipment was not functioning as per its design. In these instances, casing gas that was designed to be conserved in gathering pipeline systems, was venting from the tanks. This indicates that tank venting consists of both design venting of associated gas as well as fugitive emissions. In addition, sites without any casing gas conservation could have casing gas vented via the production tanks. These sites should have periodic testing of the tank vent flows. There is likely diversity in the design of CHOPS sites (**Fig. 21**).

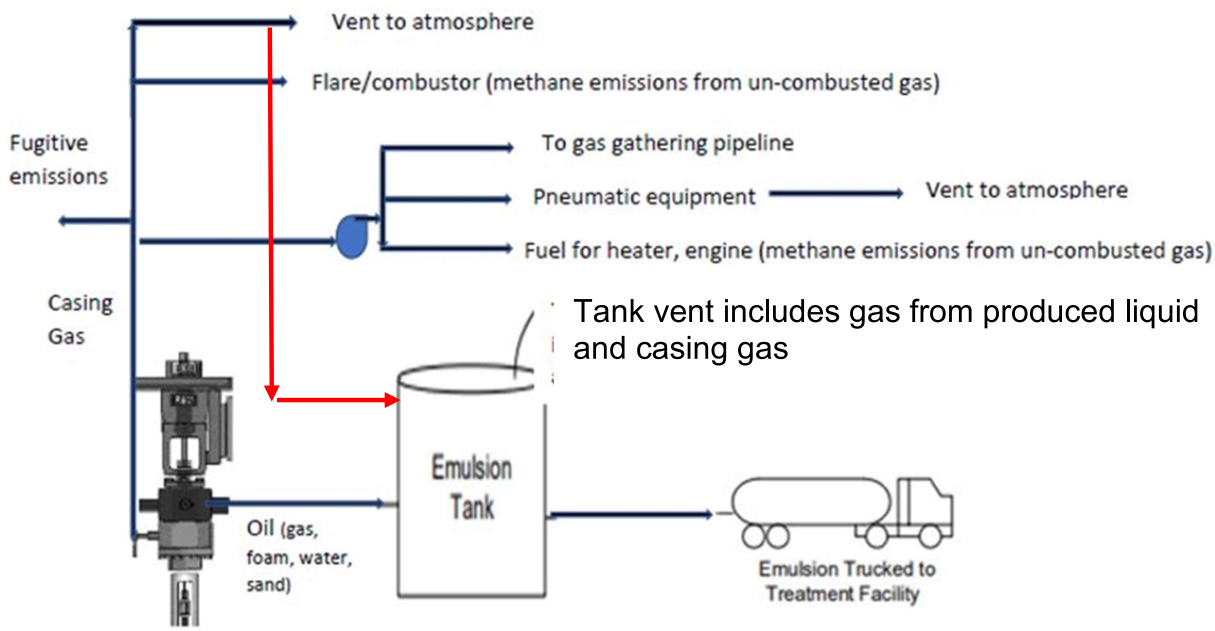


Fig. 21 — Revised flow diagram of a single-well CHOPS site.

Diversity in CHOPS site design is likely to increase as the sector transitions to new methane targets. Furthermore, the prevalence of intermittent, abnormal processes impacts the accuracy of *casing gas* measurement. It makes sense to implement a screening and detection program on sites with gas conversation equipment, which uses inexpensive technologies for detecting the occasional tank or casing line that is venting high amounts of methane. Instances of high venting can then trigger corrective action and additional bottom-up, direct measurement. Top-down airplane or satellite technologies should be evaluated to see if they can detect typical CHOPS vent flow anomalies. However, these technologies may require unreasonably high survey frequencies to detect anomalies. Alternatively, continuous detection technology may be a suitable option for both methane measurement and mitigation. Inexpensive thermal anemometer flow meters on the vent or methane sensors could trigger a corrective action. As well, the flowmeters could provide approximate values of the short-lived methane emissions during the flow anomaly. The need for continuous detection/measurement could be determined on a site-by-site basis, targeting sites with the possibility of high flowrates. These measures could also be used in trial form on new sites, to evaluate the possibility of high tank emissions during foamy oil flow.

6. Conclusions and Recommendations

This study leads to the following conclusions on gas and methane measurement in the CHOPS sector:

1. Currently there is a mixture of CHOPS sites with a variety of equipment. Some sites emit few methane emissions because associated gas is captured in gathering pipelines, and fugitive emissions are managed, while other sites vent all associated gas. Some CHOPS sites have a variety of sources of emissions including casing vent valves, tank vents, fugitives, truck-loading venting, un-combusted methane in engine, heater, or flare exhaust, pneumatic vents, and vents from compressor and engine seals, and crankcases or starters. Some methane sources are related to *design* or *operations*, while the rest are *unintended* (i.e., leaks and abnormal processes).

2. As the CHOPS sector reduces methane, there will be a reduction in many of the *design* and *operations* sources including casing and tank vents, as well as a reduction of *unintended* emissions. As designs change, some regulated methane measurement methodologies may become obsolete for certain sites. For instance, GOR methodology is used to report casing gas venting, but the sector may eliminate all casing venting in the coming years.

3. There is not a single methodology or technology to measure every type of gas or methane emission at every type of CHOPS site. The choice in methodology may have a large influence on measurement accuracy. In theory, accuracy is highest with continuous, direct measurements, followed in turn by periodic, direct measurement and then by site-specific emission factors. While continuous measurement is sometimes impractical, reconciliation of multiple, measurement methodologies/technologies may be more accurate than a single, periodic, direct measurement.

4. Studies have indicated a gap between reported CHOPS venting and methane measurement, prompting regulatory changes to testing frequency and gas measurement interval of the GOR methodology. A desktop review of past reports reveals three main gaps in methane measurement that should be considered first to address the discrepancy between reported and actual methane:

    - Inaccuracies with the GOR methodology for estimating casing venting.
    - Inaccuracies with tank measurement using the Vasquez-Beggs correlation.
    - Absence of measurement of other emission sources.

5. Phase 1 field testing, using continuous meters, evaluates the gap in GOR methodology. In the evaluation in Section 5, *vented* casing gas (methane emissions) is approximated by *non-fuel* gas, and in the following findings, the term *vented casing* gas will be used in place of *non-fuel* gas:

- 24- and 72-hour **hourly rate** test values of both *total casing gas* and *vented casing gas* are very similar, and highly correlated. There is little evidence that longer 72-hour tests are more accurate than 24-hour hourly rate tests.

- 24- and 72-hour **GOR** test values of both *associated gas* and *vented gas* are very similar, and highly correlated. There is little evidence that longer 72-hour tests are more accurate than 24-hour GOR tests.

- Both 24-hour hourly rate and GOR tests appear to be more accurate than 1-hour tests.

- There is a lot of variation in GOR test values (of both *associated gas* and *vented gas*) at different oil measurement intervals. This variation indicates that the CHOPS practice of estimating oil volumes versus directly metering the oil results in less accurate GOR values. Accuracy of GOR values may be especially a concern for sites with very high-water content or low oil production rates. There is not a practical way to meter oil production for CHOPS wells during GOR testing. Hourly rate testing, on the other hand, avoids this difficulty, because this methodology does not require measurement of the oil during the test.

- Both *associated gas* GOR and *total casing gas* hourly rate tests accurately predict monthly *total casing gas* for November to March. Hourly rate testing results in slightly better predictions. For the moderate number of CHOPS sites that vent *total casing gas* (all casing gas) to atmosphere, hourly rate testing followed by GOR testing will accurately predict methane emissions.

- There is poor correlation between actual *vented casing gas* (methane emissions) and volumes predicted from *associated gas* GOR and subtracting *estimated* fuel volumes. The predicted *vented casing gas* is somewhat improved using *measured* instead of *estimated* fuel volumes.

- 24-hour hourly rate testing of the *vented casing gas* is found to be the most successful method at predicting *vented casing gas* (methane emissions), followed by *vent gas* GOR testing.

- As time increases from the month of the *associated gas* or *vent gas* GOR and *total casing gas* or *vented casing gas* hourly rate tests (November 2021 to March 2022), there is decreasing accuracy in test values, especially at high gas flows. This indicates that higher frequency testing, especially for sites with high gas flows, will improve accuracy.

- Estimates of GOR with an equation, where GOR is a function of oil production, (Government of Canada, 2021) are much less accurate than hourly rate and GOR testing for determining both *total casing gas* and *vented casing gas*. However, the GOR estimate methodology may be an excellent method for quickly estimating the total *associated gas* (but not methane emissions) of a large CHOPS region from oil production.

- The principal behind the *associated gas* GOR methodology (a*ssociated gas* is linearly proportional to oil) is true for many, but not all CHOPS sites.

- For sites that use casing gas as fuel, there is a weak linear relationship between *vent gas* and oil production. This indicates that hourly rate tests of *vented casing gas* are a more universal methodology than *vent gas* GOR. Trends of *vented casing gas* versus time, show declines in colder winter months, when more casing gas would be expected to be used a fuel for heaters in oil production tanks. At sites that use casing gas as fuel, but do not have gathering or flaring, vent gas (and methane emissions) may change seasonally, and an annual test may not capture the seasonal variability in methane emissions.

- If vented casing gas is seasonally dependent, an annual test should be timed to accurately capture seasonal variability.

- Continuous meters appear to be a good method of determining *vented casing gas,* but the Phase 1 testing does not validate any of the meters. Where continuous meters are available, they should be used for reporting casing gas venting rather than a periodic measurement methodology.

6. Other than continuous metering on the casing gas streams, the most accurate, straightforward, bottom-up methodology to measure methane from casing vent valves is via 24-hour hourly rate tests of the *vented casing gas* rather than a GOR methodology. Hourly rate testing appears to be more accurate because it strictly involves direct measurement of vented casing gas, without estimates of oil volumes or estimates fuel use. Furthermore, GOR methodology is not applicable to the measurement of methane emissions at sites that capture all casing gas in gathering pipelines. Although the current technologies for measuring casing venting have disadvantages and limitations, a suite of measurement technologies are already used by some CHOPS producers. Appropriate technologies include orifice, turbine, positive displacement, and diaphragm meters. Orifice plates are often preferable because they do not require liquids knock-out. When it is not feasible to complete hourly rate testing on the vented casing gas, the vented casing gas can be calculated from hourly rate tests of total casing gas, fuel, gathered gas, and flared gas. The accuracy of hourly rate testing of casing gas to atmosphere may be further increased by reconciling the results with multiple measurements, including other methodologies and technologies. Outliers identified by other measurement surveys would be investigated with additional hourly rate tests.

7. Because the Phase 1 testing program only included 5 months of data, it was not possible to fully evaluate an appropriate frequency of hourly rate testing of casing gas venting to atmosphere. Additional data

spanning a complete calendar year or multiple years will help to evaluate testing frequency. Alternatively, a study assessing testing frequency over the life of a CHOPS well would be very informative but difficult to deploy. It would involve installing meters on all the casing gas streams of several new multi-well batteries and monitoring the casing gas, which is vented or used as fuel on-site, over several years. Such a study would answer questions about whether measurement frequency should change for the first year or final years in a well's life. However, in the current transition to new methane emission targets, routine casing venting to atmosphere may be mitigated in the short-term future. In addition, it makes more sense for producers to evaluate the success of an overall methane emission inventory (from all emission sources), by examining measurement frequency, in conjunction with reconciliation of multiple methodologies and technologies. For example, annual, hourly rate tests of casing venting along with several inexpensive aerial surveys and re-testing outliers may be equally accurate as bi-annual hourly rate tests of the casing gas.

8. Hourly rate testing can also measure a site's fuel volumes, which are used to calculate carbon dioxide emissions. At present, there is likely a lower requirement for testing frequency of fuel, because the equivalent carbon dioxide emissions are much higher for methane at CHOPS sites. However, CO_2 emissions may be of greater interest in the future.

9. Hourly rate testing can also measure a site's total casing gas, which is part of the site's total associated gas. The provinces use total associated gas information to manage gas resources from a strategic perspective. For this purpose, the test frequency prior to recent changes in regulations, should be adequate.

10. Phase 2 testing evaluates the gap in CHOPS tank venting measurement and compares methodologies and technologies:

    - The Vasquez-Beggs correlation is unsuitable for the CHOPS sector because downhole pressure cannot be measured directly, and it is possible that gas is trapped as bubbles or slugs in the produced liquid (foamy oil). It generally over-predicts methane emissions from dissolved gas in the production liquid.

    - GIS analysis is unsuitable for CHOPS sites because frequent fluctuations in tank vent gas flowrate are difficult to capture with GIS analysis. GIS sampling captures an instantaneous amount of the produced liquid, but the concentrations of water, oil and gas may change quickly. On the other hand, direct measurement of tank venting with certain types of gas flow meters can measure flow continuously over a given test period (1 to 2 hours) or provide a totalized flowrate. In addition, it is difficult and sometimes impossible to complete GIS analysis on produced liquid with high water content.

- Gas and methane emissions from CHOPS tank vents can be accurately and directly measured with diaphragm, positive displacement rotary, and turbine meters, along with analysis of dry gas composition and moisture content. The choice of meter depends on the magnitude of the flowrate.

11. CHOPS tank venting can be measured directly with diaphragm, positive displacement rotary, and turbine meters, along with analysis of dry gas composition and moisture content. Periodic testing can be performed or data from direct measurement can be used develop site, field, or company specific emission factors for tank venting. The accuracy of any of these methodologies may be further increased by using multiple methodologies and reconciling the results. More accurate methodologies should be used for tanks that are expected or known to contribute more methane to atmosphere:

    - It appears from this study, that most CHOPS tanks have extremely low methane emissions from routine venting, and it would likely suffice to use *published*, *company* or *field* specific emission factors reconciled with regular aerial surveys. At the same time, these surveys could screen for tanks with unexpectedly high emissions, which require periodic direct measurement.

    - For tanks with high amount of venting (such as sites with foamy oil flow) it makes sense to use site-specific emission factors or periodic tank vent measurement. Tanks with some or all casing gas vented from the tanks should be tested annually. Variability in CHOPS site design may increase as the sector transitions to new methane targets.

    - It is possible that a large portion of CHOPS tank methane emissions are the result of a small number of sites with short duration foamy oil flow or abnormal processes such as thief hatches stuck open or failure of vapour recovery units, or gas conservation equipment. These volumes may not be accurately measured by periodic measurement or emission factors. If so, screening and detection programs may be key to improving the accuracy of CHOPS sector methane measurement. Ideally screening and detection technologies on these sites would be continuous so that corrective action could be taken immediately, and emissions could be estimated. With the small number of tanks field-tested in the current study, it is not possible to quantify the benefits of methane screening and detection programs. An aerial methane survey of hundreds of CHOPS sites would provide data on the typical magnitude of tank emissions relative to other emissions sources and show how many of the CHOPS tanks have significant methane emissions.

12. It is difficult to conclude whether improvements to tank and casing gas vent measurement will improve the overall CHOPS sector methane emissions measurement, without having more data on other

CHOPS emissions sources, and total site emissions. It is important to understand how much of the CHOPS methane emissions are from routine venting of tanks and casing gas versus other sources, especially abnormal processes.

SRC recommends the following:

***Future investigations*:**

1. Determine total and relative contributions of all CHOPS sector emission sources. Combined with an aerial survey, use bottom-up, direct measurement of all methane emission sources from CHOPS sites including fugitives, pneumatic venting, combustion sources, and non-routine venting. Compare these emission sources to casing and tank venting, to understand the overall methane emissions of various types of CHOPS sites currently and into an energy transition. If the results confirm that casing and tank vents are the dominant sources of methane emissions, it will make sense to focus on accuracy improvements to casing and tank vent measurement; if not, it will make sense to focus on measurement solutions for other sources.

2. Alternatively, use existing producer direct measurement surveys (top-down or bottom up) to determine total and relative contributions of all CHOPS sector emission sources.

3. Conduct field testing to evaluate the reconciliation of multiple measurement methodologies/technologies, including drone or aerial surveys with periodic, direct measurement. Alternatively, it may be possible to draw conclusions from existing aerial surveys and producer methane emission surveys.

4. Conduct field testing to evaluate solutions for methane detection and screening CHOPS sites for more frequent direct measurement of casing or tank venting. Evaluate top-down surveys (satellites or airplanes) and continuous, inexpensive flow meters or methane sensors on the casing or tank vents. For example, extremely inexpensive methane sensors or thermal anemometers can capture infrequent, high venting anomalies which would rarely be captured by periodic, direct measurement tests. If in fact the suggested gap between reported and actual methane emissions is caused by a small number of sites that infrequently vent high amounts of methane, detection/screening also serves as a methane mitigation tool; the screening can trigger a corrective action such as temporarily installing a combustor or adjusting operation to prevent gas venting from the tanks.

5. Evaluate whether IoT devices can be used to reduce the labour costs of hourly rate testing of the casing vent flow. Test meters could be configured as IoT devices, with plug-and-play installation. These could be rotated regularly by field operations to each site when visiting for other purposes

and to collect several hourly rate tests of vented casing gas per year, per site. These could involve simple measurement technologies such as orifice meters, but with streamlined data capture to quickly provide flow readings to the operators. Thus, the operators could ensure that the device is working, and the orifice plate is suitably sized, before leaving the meter at the site.

The accuracy of site-level gas and methane measurement can improve with the following:

1. Measure all CHOPS site methane emission sources. Measurement accuracy should be based on emissions inventory. Thus, it would suffice to use published emission factors for sources that contribute a small percentage of emissions, and more accurate means for larger contributors.

2. At CHOPS sites, use direct measurement of casing gas venting with continuous meters or **24**-hour hourly rate testing rather than 72-hour hourly rate testing, 24/72-hour GOR testing, or GOR estimates. At sites where it is difficult to complete hourly rate testing of the vented casing gas, complete hourly rate testing of the other casing streams, and determine the vented casing gas from the difference. Consider hourly rate testing twice per year (to capture cold and hot operating months) or once per year in a hot operating month; however, it is ideal to select testing frequency based on an overall methane management program that measures methane of all sources by multiple means.

3. In instances where more accurate measurement of CHOPS total and fuel casing gas is required, use direct measurement of total and fuel casing gas with continuous meters or 24-hour hourly rate testing rather than GOR testing methodology.

4. For tanks with low venting, use *published* (current study) emission factors based on direct measurement techniques or use direct measurement techniques to develop, *company* or *field-wide* tank vent emission factors, and regularly reconcile these measurements with other direct measurement means such as truck, drone, or aerial surveys (rather than Vasquez Beggs or GIS analysis). At the same time, these surveys would screen for tanks with unexpectedly high emissions, which require periodic direct measurement with flow meters on the vents. If overall CHOPS methane monitoring and inventories indicate that low-emitting tanks are a very small percentage CHOPS sector methane, then published emission factors would suffice until other methane sources are mitigated.

5. For tanks with moderate to high venting (including those expected to have high foamy oil flow) use *site*-specific emission factors or periodic direct measurement. Periodic direct measurement is appropriate for sites where some or all of the casing gas routinely vents via the tank.

6. Install continuous detection (such as inexpensive thermal anemometer flow meters) on tank or casing vents that could have very high methane emissions during foamy oil flow or an abnormal process (failure of conservation equipment or stuck thief hatch).

7. Ideally, CHOPS tanks would be constructed such that they are both ready for vapour recovery units and they have features to facilitate flow meter testing on the vents, from secure access. For instance, the vents could be installed near stairs on the tanks. In addition, ports for level instruments and thief hatches could be designed so that they can be sealed off during tank vent testing.

8. Increase measurement accuracy of all methane emission sources (including casing gas venting) by using multiple measurement methodologies and technologies and reconciling the results.

9. Further increase methane measurement accuracy by increasing the frequency of measurement. Comparisons of emission inventories from low to high frequencies will provide indication of the relative benefit of increasing frequency.

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APPENDIX A

The following is the complete test data from different flow meters trialled sequentially in time. In most cases only the diaphragm and PD meters were trialled. The turbine meter was out of range for the vent flowrates of all tests except tank tests 5 and 17. The standard deviation was calculated for the PD and turbine meter flowrate measurements. Generally, standard deviation of the flowrate could not be calculated for the diaphragm meter because flowrates were low and there were too few data points of volume). The diaphragm meter only logged volume when the volume changed by 1 cubic foot.

Table 17 —Test Data of Total Tank Vent Gas with Flow Meters

		Diaphragm Meter						*Positive Displacement Meter*						*Turbine Meter*					
Site trip	Tank test	Actual flow (m^3/d)	Actual temp. (°C)	Actual pressure (kPa_a)	Duration of test (min)	Standard flow (S m^3/d)	Flow Std Dev (Sm^3/d)	Actual flow (m^3/d)	Actual temp. (°C)	Actual pressure (kPa_a)	Duration of test (min)	Standard flow (S m^3/d)	Flow Std Dev (S m^3/d)	Actual flow (m^3/d)	Actual temp. (°C)	Actual pressure (kPa_a)	Duration of test (min)	Standard flow (S m^3/d)	Flow Std Dev (Sm^3/d)
1	1	18.5	25.4	92.9	77	16.4	N/A	19.7	27.2	92.6	45	17.3	10						
2	2	5.5	20.3	91.6	59	4.9	N/A	11.6	19.0	91.4	62	10.3	9						
3	3	64.6	10.5	92.9	73	60.1	N/A	73.1	14.2	92.7	48	67.0	78						
3	4	0.0	4.0	93.6	120	0.0	N/A	0.0	5.8	93.4	38	0.0	0						
3	5	6.2	11.6	93.3	132	5.8	N/A	0.0	8.2	93.5	40	0.0	0	680.4	17.1	93.0	41	619.1	129.5
4	6	11.6	15.5	93.5	49	10.7	N/A	31.1	18.0	94.9	40	28.8	3						
4	7	0.0	14.0	95.2	120	0.0	N/A	0.0	21.7	94.8	46	0.0	0						
5	8	12.6	18.9	94.2	45	11.5	N/A	29.2	18.6	94.0	40	26.7	8						
6	9	40.8	34.0	93.9	50	35.5	N/A	47.0	32.8	93.7	48	40.9	9						
7	10	0.0	26.0	91.4	150	0.0	N/A	9.1	28.7	93.3	44	8.0	8						
7	11	9.7	21.0	92.8	59	8.7	N/A	30.3	25.0	94.2	44	27.2	5						
8	12	52.5	25.0	94.9	59	47.5	N/A	68.1	26.2	94.2	60	61.0	17						
8	13	28.6	24.9	93.7	50	25.6	N/A	30.3	25.0	94.2	44	27.2	5						
9	14	11.4	20.8	92.1	50	10.2	N/A	21.3	17.7	93.1	48	19.4	13						
10	15	2.0	13.8	95.6	41	1.9	N/A	0.0	16.9	94.0	0	0.0	0						
11[12]	16																		
12	17	0.0	22.1	92	110	0	N/A	710.1	22.2	95	48	646	6	554.1	23.7	93	41	491.3	6.0
13	18	5.4	22.5	92.4	23	4.8	N/A	0.0	18.2	94.5	48	0.0	0						
13	19	7.1	26.8	91.6	64	6.1	N/A	0.0	27.0	94.3	50	0.0	0						
14	20	28.7	31.5	94.9	45	25.5	N/A	42.4	31.7	94.6	48	37.4	6						
15	21	0.0	44.7	95.4	>45	0.0	N/A	17.9	25.4	95.1	54	16.2	8						
16	22	3.0	23.6	94.7	14	2.7	N/A	11.7	23.6	95.0	50	10.6	18						
17	23	0.0	28.2	94.7	>45	0.0	N/A	19.3	21.5	94.5	60	17.6	6						
18[13]	24	0.0	16.5	94.1	>45	0.0	N/A	0.0	17.0	93.8	50	0.0	4						
19	25	16.2	15.9	94.0	45	14.9	N/A	45.4	15.5	93.7	54	45.6	15						
20	26	0.0	24.6	0.0	>45	0.0	N/A	15.8	18.4	94.0	54	14.5	7						
21	27	0.0	29.4	94.8	>45	0.0	N/A	4.5	27.1	94.6	46	4.0	4						
22	28	0.0	29.5	94.5	>45	0.0	N/A	0.0	31.0	94.4	48	0.0	0						
23	29	0.0	29.5	94.2	>45	0.0	N/A	0.0	31.8	94.1	48	0.0	0						

[12] Testing halted due to poor weather conditions.
[13] Wind blew off hose during testing.

APPENDIX B

Table 18 — Complete Gas in Solution Data

			Sample 1						Sample 2						Sample 3							
Site trip	Tank test	Aver. BS&W (%)	Sample weight (g)	Liquid Volume (mL)	Density (g/mL)	Test Gas Vol. (mL)	Std. Gas Vol. (mL)	GIS (S m^3/m^3)	Sample weight (g)	Liquid Volume (mL)	Density (g/mL)	Test Gas Vol. (mL)	Std. Gas Vol. (mL)	GIS (S m^3/m^3)	Sample weight (g)	Liquid Volume (mL)	Density (g/mL)	Test Gas Vol.(mL)	Std. Gas Vol. (mL)	GIS (S m^3/m^3)	Average GIS (S m^3/m^3)	STD DEV GIS (S m^3/m^3)
1	1	36%	52.77	55.68	0.948	60	55	0.98	33.24	33.59	0.99	70	64	1.89	54.4	55.87	0.97	105	95	0.91	1.26	0.550
2	2	21%	65.32	64.82	1.008	90	82	1.26	48.58	49.39	0.984	110	100	2.02	66.29	65.18	1.02	115	105	0.91	1.40	0.570
3	3	91%	80.34	78.82	1.02	85	77	0.98	76.48	70.81	1.03	80	73	1.03	83.57	81.19	1.03	100	91	0.91	0.97	0.059
3	4	91%	70.3	69.41	1.013	70	64	0.92	77.66	77.73	0.999	90	82	1.05	-	-	-	-	-	-	0.98	0.096
3	5	31%	83.86	83.62	1.002	90	82	0.98	74.1	73.79	1.004	90	82	1.11	80.7	81.53	0.989	85	77	0.91	1.00	0.101
4	6	8%	59.8	60.2	0.993	100	91	1.51	44.15	46.83	0.943	95	86	1.84	60.24	61.04	0.986	130	118	0.91	1.42	0.474
4	7	8%	58.77	63.59	0.924	110	100	1.57	64.33	64.49	0.9975	125	114	1.76	53.53	54.27	0.985	120	109	0.91	1.41	0.448
5	8	96%	45.41	46.65	0.973	75	68	1.46	17.92	15.14	1.18	35	32	2.10	14.86	14.11	1.053	35	32	0.91	1.49	0.597
6	9	21%	63.31	63.96	0.99	110	100	1.56	67.38	66.72	1.01	100	91	1.36	71.78	72.74	0.987	100	91	0.91	1.28	0.335
7	10	46%	43.4	43.4	1	60	55	1.26	62.96	63.18	0.997	80	73	1.15	75.88	77.32	0.981	95	86	0.91	1.11	0.178
7	11	63%	62.75	64.1	0.98	110	100	1.56	75.06	77.42	0.97	120	109	1.41	22.58	22.53	1.002	40	36	0.91	1.29	0.341
8	12	89%	57.59	58.19	0.99	125	114	1.95	67.69	69.37	0.976	160	145	2.10	57.63	58.84	0.98	125	114	0.91	1.65	0.648
8	13	5%	81.42	83.76	0.972	170	155	1.84	65.89	68.28	0.965	125	114	1.66	60.56	62.8	0.964	110	100	0.91	1.47	0.496
9	14	86%	61.98	62.13	0.997	90	82	1.32	18.84	17.7	1.06	20	18	1.03	26.94	27.63	0.975	60	55	0.91	1.08	0.210
10	15	85%	13.74	13.24	1.038	30	27	2.06	15.79	14.87	1.062	30	27	1.83	20.01	19.51	1.026	50	45	0.91	1.60	0.610
11[14]	16																					
12	17	31%	83.86	83.63	1.003	90	82	0.98	74.1	73.79	1.004	90	82	1.11	80.7	81.53	0.99	85	77	0.91	1.00	0.101
13	18	98%	75.1	73.81	1.017	85	77	1.05	72.47	74.09	0.978	80	73	0.98	73.82	71.82	1.03	85	77	0.91	0.98	0.069
13	19	98%	86.36	81.86	1.055	90	82	1.00	74.78	73.08	1.023	85	77	1.06	76.2	72.7	1.05	85	77	0.91	0.99	0.075
14	20	23%	67.05	70.08	0.957	120	109	1.56	80.46	81.65	0.99	145	132	1.61	67.4	70.1	0.961	125	114	0.91	1.36	0.392
15	21	75%	72.76	77.13	0.942	120	109	1.41	75.56	75.68	0.998	90	82	1.08	73.73	77.96	0.946	115	105	0.91	1.13	0.257
16	22	87%	68.27	69.8	0.978	180	164	2.34	72.29	74.25	0.974	155	141	1.90	72.13	74.45	0.969	145	132	0.91	1.72	0.734
17	23	96%	39.72	39.6	1.003	80	73	1.84	60.53	60.15	1.006	95	86	1.44	64.67	65.68	0.985	110	100	0.91	1.39	0.465
18[15]	24	73%																				
19	25	71%	68.35	73.11	0.935	125	114	1.55	57.53	61.16	0.941	155	141	2.30	51.17	53.81	0.951	140	127	0.91	1.59	0.698
20	26	19%	78.78	81.11	0.971	135	123	1.51	72.37	75.81	0.954	135	123	1.62	68.23	70.68	0.965	135	123	0.91	1.35	0.383
21	27	93%	52.77	51.15	1.032	110	100	1.95	68.6	66.95	1.025	150	136	2.04	78.04	79.95	0.976	150	136	0.91	1.63	0.629
22	28	58%	75.06	77.88	0.964	135	123	1.58	77.55	80.32	0.966	130	118	1.47	71.19	74.02	0.962	110	100	0.91	1.32	0.359
23	29	40%	92.05	88.38	1.04	100	91	1.03	69.91	72.79	0.9605	140	127	1.75	80.27	84.73	0.947	145	132	0.91	1.23	0.454

[14] Testing halted due to weather an no GIS samples were taken.
[15] GIS samples contained only water and no gas nor oil.

The following is the procedure for GIS analysis of multiple samples from each site of the production liquid:

GIS Analysis Procedure

1) Using the syringe pump, set the pressure to 200 PSI and pressurize the sample cylinder with distilled water. Record the volume and the beginning and end of this step and note how much sample is in the cylinder
   (Sample container-(start volume-end volume) = Sample volume
2) Store in the oven at 50ºC (give the cylinder at least 4 hours to reach temperature)
3) Remove sample cannister from oven and wrap with silicone heater (heater should be set to approx. 70ºC), then attach the syringe pump injection line to the bottom port of the sample cannister and ensure pressure is still at 200 PSI (turn on the syringe pump and open the bottom valve of the sample cannister). Attach the sample outlet line to the top port of the sample cylinder (this will connect to our collection flask)
4) Allow the sample cannister to sit for at least 15 minutes with the heater on to help the oil and water separate so the oil is at the top to provide the sample.
5) Weigh out the collection flask. Take the collection flask and rubber stopper and connect to the gas meter, using Argon purge the flask and gas-meter (300 ml 3 times) to ensure as little air as possible is in the flask and gasmeter.
6) Before connecting the collection flask to the sample cannister purge the sample outlet line from the sample container to purge any gas or fluid (might hear a pop due to the gas cap inside the sample cannister) purge and let the sample flow for 3-5 seconds with constant sample coming out. Attach the collection flask now to the sample outlet line. Ensure the gasmeter has been fully vented and is reading zero.
7) Record the syringe pumps volume (initial volume) and the gasmeters volume (should be 0) and place the gasmeter valving into the sample collecting position
8) Ensure the collection flask is immersed in a hot water bath at around 85C to help the gas flash from the oil.
9) Open the top valve on the sample cannister to let the sample start flowing into the collection flask. Fill the flask to about 75 ml or with as much sample as possible depending on how much sample there was determined to be in step 1.
10) Allow the sample to sit in the flask for 15-45 min (or until bubbles stop forming) to ensure that all the gas in solution has been removed.
11) Record the final volume of the syringe pump, the final volume on the gas meter
12) Turn the gasmeter to the closed position and disconnect the gas meter from the flask and quickly cover the end of the tubing to prevent any air escaping or entering the tube. Hook that ends to the Micro GC and analyze the gas (switch the gas meter to sampling position when doing analysis)
13) Disconnect the collection flask from all the tubing and weigh the flask with the oil in it (be careful as it will be hot)

Fig. 22 — Total set up for GIS samples.
On the left is the syringe pump, middle is the heated bath and sample container, and gas meter on the right

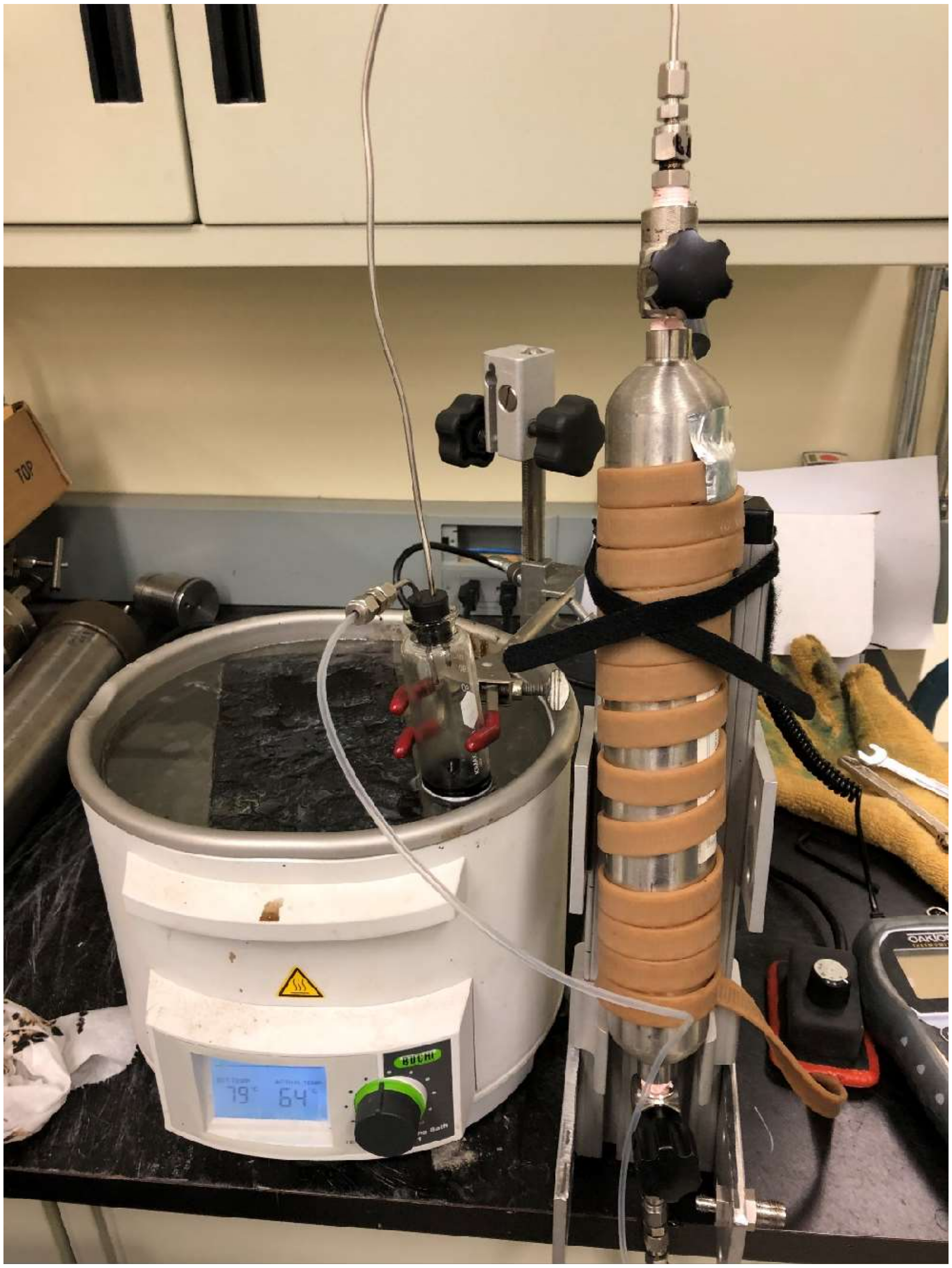

Fig. 23 — Sample cannister and heated bath

Fig. 24 — Gasometer