PETROLEUM TECHNOLOGY ALLIANCE CANADA

PTAC

Alberta Upstream Petroleum Research

QUANTIFICATION OF METHANE EMISSIONS IN STATIONARY ENGINE EXHAUST AND BEST MANAGEMENT PRACTICES FOR MITIGATION

Prepared for and with funding by PTAC, AUPRF, CanERIC and CRIN

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Accurata Inc thanks Petroleum Technology Alliance Canada (PTAC), the Alberta Upstream Petroleum Research Fund (AUPRF), Canadian Emissions Reductions Innovation Consortium (CanERIC) and Clean Resource Innovation Network (CRIN) for their funding to identify best management practices and advise abatement technology to reduce methane emissions in stationary, natural gas fuelled engine exhaust. That work resulted in a report revision (three) that was issued October 31 2023. This enhanced revision adds discussion on several topics. We offer thanks to the ARPC alone for the funding of the latest revision. Field measurements to quantify the effect of operating aspects on methane emissions support the conclusions for the best management practices. Accurata has joined forces with ASK Engine Consulting, Spartan Controls and Signet Monitoring to provide this comprehensive study.

This report presents the findings of an independent, unbiased study designed to evaluate the performance of engines as they relate to methane slip under specific real-world operational conditions. The primary objective of this study was to assess how stationary engines function within the unique parameters and constraints of the field environment, rather than to provide a comprehensive evaluation or endorsement of any technology itself.

The results and conclusions reflect observations and data collected during the study period and are specific to the conditions and context of the operations in which the technology was deployed. Variations in site conditions, operational practices, or technology configurations may yield different outcomes.

This report is not intended to be used as a definitive judgment of the overall effectiveness, reliability, or value of any technology, but rather as a resource to inform stakeholders about its performance in the observed context. The report contains best practices that may optimize engine performance. Stakeholders are encouraged to consider this information alongside other data and insights when making decisions regarding the technology's use.

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the [Parties], Clean Resource Innovation Network (CRIN) or its members.

EXECUTIVE SUMMARY

Methane slip is defined as natural gas in the engine exhaust. Methane slip volume is not well understood. A methane slip field test program collected exhaust emission samples from 100 engines and 116 tests. The objective is to gather as-found methane slip field test measurements. The sample contains the most common four cycle, natural gas fired engines in Alberta's natural gas production industry. An additional 22 Caterpillar G3600 series engine MSAPR tests from one producer offer test data from one operator and one engine type.

Four different engine combustion styles in the sample show characteristics that show they are mutually exclusive. The four combustion styles are rich burn without catalyst, rich burn with catalyst, open chamber lean burn and pre-chamber lean burn. Graphs of the data reveal possible correlation and identify relationships between the operating variables and methane slip. Methane emissions in the exhaust vary from near zero to more than 1,000 ppmvd @15%O_2 depending on the combustion style. Methane emissions increase with lower NO_x emissions in engines without a catalyst. The fuel savings associated with lean burn engines exceeds the methane emission reduction associated with a catalyst equipped rich burn engine. The following operating aspects reduce methane slip emissions.

- More adaptive control systems,
- higher exhaust temperature,
- higher fuel lower heating value (LHV),
- engine tuning as specified by the operating condition,
- lower excess oxygen (O2%) for combustion,
- add ingestive crankcase evacuation systems, and
- newer engine model age.

The following possible best management practices are discussed for the operator's consideration.

- Ensuring the engine is in good working condition and tuned for optimum operating characteristics at all times,
- Consider installing a fuel gas meter to ensure accurate fuel consumption measurements and to assist with determining engine health,
- Consider optimizing the load of the equipment driven by the engine,
- Consider installing an adaptive engine management system,
- Consider engine upgrades that offer increased efficiency due to geometry changes,
- Consider newer engines on greenfield projects with lower methane emissions in the exhaust,
- Consider adopting modern and best available technology to minimize methane slip,
- Consider installing more adaptive engine management systems components,
- Consider installing technology to increase the exhaust temperature,
- Consider conditioning the engine fuel to increase the fuel heating value (LHV),
- Consider adjusting the engine tuning to that specified by the operating condition,
- Consider optimizing the engine air-fuel ratio,
- Consider installing an ingestive crankcase vent system on in-service engines, and

- Consider driver electrification.
- Consider testing for CH_4 in emissions stack tests.

Of these, reducing fuel consumption via optimization and adding an ingestive crankcase evacuation system are the most affordable.

The study identifies the following areas for additional study.

- Air manifold pressure effect; especially on pre-chambered engines, to determine why the relationship between methane slip and air manifold pressure is normally inversely proportional.
- Hours since last overhaul effect; to determine why no directly proportional relationship with methane slip was observed.
- Crankcase emissions effect; to determine what relationship with methane slip is found with crankcase gas emissions alone.
- Oil ash content effect; to determine what relationship with methane slip is found with the ash content in engine oil.
- Oil ash content effect; to determine what relationship with methane slip is found with low ash content oils.
- Excess oxygen effect; especially on pre-chambered engines, to determine why this combustion style behaves contrary to theory.
- Engine coolant temperature effect; to determine why the relationship with methane slip is contrary to theory.
- Catalyst conversion efficiency effect; to determine how deterioration of the catalyst effects methane slip
- Low air manifold pressure effect; to determine how low manifold pressure causes ingestion of oil into combustion air and if it increases unburned hydrocarbons in the exhaust.

The relative magnitude of the various effects is undefined since many of them do not behave in a manner that theory would suggest. Thus, we do not fully understand the factors involved. Further study could provide that understanding.

Crankcase vent methane volumes are not well understood. Our study included review of a small sample of engines from our test results as well as those defined in the literature. The volume of methane in the crankcase vent gasses is most often defined as a percentage of the total methane slip. A wide range of percentages of the total methane slip volume is identified as between 20% and 60%. Correlation of the crankcase vent volume to the combustion style is implied by this estimate method which was questioned by the Accurata team. Howard Malm determined that a better correlation appeared to exist by using engine power as the dependant variable. Howard suggested that the mass flow of methane in the crankcase vent gasses in kg/h = (kW) * 0.0017. Please note that the low quantity of engines in our sample mandates that additional research is required to qualify this relationship.

Emission factors for methane slip are determined based on the engine samples in our test data. These factors are most accurate in units of ppmvd @ 15% O_2. The accuracy of the factors are eroded when converting to different units due to errors in measurement and assumptions. The concentration in ppm is also a direct measurement. Converting ppmvd @ 15% O_2 to g/kW-h will embed +/- 20% error. Converting ppmvd @ 15% O_2 to g/GJ will embed +/- 25% error. Converting ppmvd @ 15% O_2 to g/e3m3 will embed +/- 60% error. Selecting units for ease of calculation defeats scientific rigor.

Fleet estimates for total methane slip are determined based on the MSAPR engine data base courtesy of Environment and Climate Change Canada. Many assumptions are made in the qualification of the engine models to which quantities are applied. Our emission factors are applied to these engine quantities to obtain a rough estimate of the total methane slip from the most common stationary engines in the MSAPR fleet list. We estimated total methane slip emissions as approximately 182,500 T/y for Canada and approximately 127,800 T/y for Alberta. These estimates could contain at least 40% error due to the assumptions made on the engine models, rated power, combustion style and the assumption that all engines are operating at full power.

Additional estimates are derived from the MSAPR fleet list. Our analysis of crankcase vent volumes using a variety of emission factors are applied to the MSAPR list. We estimated total Crankcase vent methane emissions as approximately 73,700 T/y for Canada and approximately 53,100 T/y for Alberta. This estimate matched the order of magnitude of the totals using an emission factor of 40% of the total methane slip. The same error is embedded in the crankcase emission volume estimates as for the total methane slip emission volume estimate. The crankcase vent methane emissions are important because an ingestive crankcase vent system will eliminate that source of methane slip.

Ingestive crankcase vent systems are discussed in detail with examples of Waukesha, Caterpillar and White Superior engine models. White Superior engines have always been equipped with an ingestive crankcase vent system. New G3600 series Caterpillar and Waukesha VHP and VGF series engines are equipped with ingestive engine crankcase systems. Both Waukesha and Caterpillar offer retrofit kits for their larger engines. Third party ingestive crankcase system retrofit kits are available from Solberg and FleetGuard for virtually any model of stationary naturally gas fueled, reciprocating, four cycle engine. Tables are provided that identify which systems are available for which engines as well as the installation and maintenance costs for ingestive crankcase retrofit options. Installation costs vary between $20,000 and $80,000 depending on the engine model and the supplier of the retrofit system. The cost estimates are based on performing the installation at the same time as a major overhaul.

Methane slip attributed to engine design is discussed with regard to valve overlap and miller cycle. It is explained that the Miller cycle contributes to fuel saving and efficiency but has no contribution to methane slip. Similarly, the timing of valve overlap is designed to avoid methane slip. These aspects cannot be changed or managed by the engine operator.

One contribution to raw methane released in the exhaust is from an engine tuned extremely rich. This tuning set point allows NO_x reduction due to quenching from the excess fuel in the air fuel ratio. The uncombusted methane is then emitted with the exhaust. This operating method produces exhaust explosions which are dangerous to engine condition and create a safety risk for personal. Monitoring carbon monoxide (CO) emissions in the exhaust will allow detection of this operating mode. A recommendation of CO in excess of 5400 ppm is suggested to identify when an air fuel ratio is set extremely rich. The MSAPR regulation for NO_x emissions does not deal with this operating method. The engine manufacturers do not condone this practice.

Engine condition plays a large role in controlling methane slip. Our study identified that engines with spark plugs that are not firing emit a large volume of methane slip. Regular tuning and predictive maintenance are recommended to identify an engine with condition issues in order to control methane slip. Indeed, the wide variability of our data is due to engine condition issues. One way to identify problematic engine is to perform tunable diode laser absorption surveys to monitor the methane released in the exhaust. Another method is to monitor engine fuel consumption. A manual measurement method is provided to determine the brake specific fuel consumption (BSFC) for an engine. The intent is to routinely measure fuel consumption in order to identify when something has changed. Since changes can occur from operating conditions or changes to the driven load, then an investigation is required to assess if the change in fuel consumption is actually due to engine condition. The manual measurement method is detailed and tedious. Therefore, the installation of a fuel gas meter with remote monitoring is recommended. Monitoring fuel consumption with a meter will promote prompt action to resolve condition issues. That action will reduce fuel consumption by at least 10% and that fuel saving will pay for the meter installation in about 5 months.

Certified by Frank Zahner P.Eng. MBA for Accurata Inc

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1. Introduction

Methane slip is the term associated with unburned methane that passes through the combustion process in stationary engines. The methane is trapped in corners and crevices in the combustion chamber. It is released with the exhaust gasses exiting the chamber. It is referenced as methane slip as a common industry term. However, the emissions are really composed of natural gas, so other hydrocarbon elements will also be present. In this document, the terms methane slip and unburned methane and unburned natural gas may be considered as the same.

According to the AER, stationary engines are estimated to contribute 4.9 MT CO_2e (carbon dioxide equivalent) annually from unburned methane emissions in Alberta. The estimate is based on emission factors. The factors are derived from AP-42 based on a USA study of uncontrolled engines in 2000. These factors for methane slip in engine emissions have not been studied in appropriate depth to formulate a foundation for accurate quantification or regulatory framework in Canada.

This study identifies current best management practices and technology assessment for methane emission quantification, prediction and reduction in stationary, natural gas fuelled engines. Written components with discussions supporting comparison tables are provided. Theory and technical aspects are presented on combustion and how the emission components are affected by engine systems and their combustion processes. Contributions in kind are provided by the producers who allowed access to their engines for in-situ, in service testing.

Engine field tests are conducted for 22 engine models with a variety of electronic or mechanical control and monitoring systems. Five samples of each engine model are normally included in the field tests. Limited access to site and time constraints resulted in less than five tests performed on each engine and then some engines are tested more than once. Therefore, the final test program scope resulted in 116 tests performed on 100 engines with eight duplicate tests at the same site and eight repeat tests.

The testing program utilized as-found engines to capture variations in engine performance for each engine combustion style. The data was supplemented by 22 Caterpillar G3600 series engine MSAPR tests provided by a single producer. These tests are presented to compare the as-found engine data to a group of engines that have one operator.

The field test results are used to underpin the data in comparison tables of manufacturers' data and best management practices. Discussion and comparison of industry practices are presented and how the various systems perform. It should be noted that the engine manufacturers all publish data that is obtained in their test stands. The test stand data is legitimate but the test conditions normally cannot be reproduced in the field under real operating conditions. Therefore, it is imperative to obtain operating data under actual field conditions.

The field data is summarized to determine the contribution of the unburned natural gas in the exhaust associated with the various engine control and monitoring systems. The variance across engines for test results are identified with respect to engine condition and operating variables. The emissions factors are estimated based on the field test data along with differences in the operating conditions.

The differences in operating conditions produce a wide spread of results in the field data. The variation in field test data is mostly attributed to engine inputs such as fuel and air quality as well as control sophistication. However, the engine condition is the most significant contributor of the wide scatter of the data. Engine condition is widely variable depending on the diligence of the operator in monitoring engine performance and application of predictive maintenance programs that will maintain peak performance in an engine. In our experience, engine predictive maintenance is not a typical practice.

The sophistication of the control system may be able offset condition issues if the controls will adapt to divergence of a variable from the set points. Older engines with non-adaptive OEM controls systems are not equipped to manage adaptive changes in operating conditions. Thus, the engine will not operate at an optimal setting to reduce fuel consumption and methane slip. This is especially true of the White Superior 825 series engines. These engines were mostly installed in the 1960’s and 1970’s and they are extremely complex in their design. Several systems must be adjusted manually to coordinate effective operation. Maintaining the balance of all the systems is an ongoing challenge. A much larger variance in White Superior 825 series engine data results when compared with the measured data for Waukesha and Caterpillar data. This variance is evident in the graphs prepared to present the data.

The White Superior 825 series engine data may appear to be outliers compared with other engines. The data presented is for as-found engines. presenting data based on engine model when an insufficient engine sample size is measured will be misleading. The data is reliable and measured with the same accuracy in each test for all engines. Possible correlations in the data are identified with the summaries for the graphs. In most cases, the dispersion of the data points defies correlation of the trends. Accurata’s team members provided a best effort in suggesting trends or presenting data along with the accuracy expected.

A formal literature study often forms part of a comprehensive study. Methane slip has been studied by others but the test conditions and the accuracy of the test methods are not known. Determining reliable results suitable for comparison is difficult. A list of the most comparable articles is assembled for the readers’ consideration. It should be noted that the test results are not qualified to the efforts undertaken in this study and thus will not be compared to the analysis presented herein.

1.1. Reading List of Published Articles

A portion of the fuel delivered to a reciprocating engine is not combusted due either to improper ignition, boundary layer effects or trapping in crevices. Only a few articles report on measured methane emissions from units in the field. An example from a test engine that studied CO, NO_x and CH4 emissions by Li, Hailin et.al shows that both the CO and CH_4 exhaust emissions increase as the air-fuel ratio becomes leaner.

AP-42 deals with unburned hydrocarbon and methane emission factors. The guideline was based on field measurements published in July 2000 (US EPA). The AP-42 factors are provided in Table 1 for uncontrolled engines, namely, 4 stroke rich-burn engines (exhaust O2 <4%), 2 stroke lean-burn engines and 4 stroke lean-burn engines. No data was included for crankcase emissions. Methane emissions were calculated as the difference between total organic carbon (TOC) and the sum of non-methane, non-ethane organic carbon (VOC) and ethane emissions (Methane ≈ TOC – VOC – Ethane). The data from AP-42 is used for stationary natural gas reciprocating engine emission factors for methane emissions in the Alberta publication for GHG quantification methodologies (Alberta Greenhouse gas quantification methodologies 2020). A single methane emissions factor for all stationary facilities using natural gas fuel is included in Table 2 of the BC methodologies (BC Best practices methodology for quantifying greenhouse gas emissions 2020).

Table 1: Combustion component emission factors sorted by combustion style in AP-42

Engine Type	TOC g/m3 (lb/MMBTU)	VOC g/m3 (lb/MMBTU)	Ethane g/m3 (lb/MMBTU)	Methane g/m3 (lb/MMBTU)	# of Units tested
4-stroke rich-burn (uncontrolled)	5.85 (0.358)	0.48 (.0296)	1.15 (.0704)	3.76 (0.230)	6
4-stroke lean-burn (uncontrolled)	24.0 (1.47)	1.93 (0.118)	1.71 (0.105)	20.4 (1.25)	22
2-stroke lean-burn (uncontrolled)	28.8 (1.64)	1.96 (0.12)	1.15 (0.0709)	24.2 (1.48)	43

Note: lb/MMBTU based fuel heating value of 1020 BTU/scf.
Note: ppmv = g/m3 / methane density (methane density = 671 g/m3 at 15C, 101.3 kPa)
A more recent publication by Vaughan et.al covers methane emissions from 133 natural gas 4-stroke engines in the USA. The results shown in Table 2 are the mean emission rates calculated from directly measured exhaust concentrations of methane and flows using a tracer method. Crankcase emissions are not included. As noted by Vaughan et. al. there is a considerable difference according to the engine design technology.

Table 2 Mean methane emissions without crankcase emissions by Vaughan, et al

Engine Type	Methane Content g/m3 (lb/MMBTU)	# of Units tested
4-stroke rich-burn (controlled)	1.6 (0.10)	39
4-stroke lean-burn (controlled)	18.7 (1.15)	63

The study results by Vaughan et. al are sorted according to engine make and model. Emissions rates are converted to methane in g/kW-h based on methane fuel. The results are shown in the following graphs for three of the major engine designs used in natural gas stationary engines. All the reported engines have control technology such that NO_x emissions did not exceed regulatory limits.

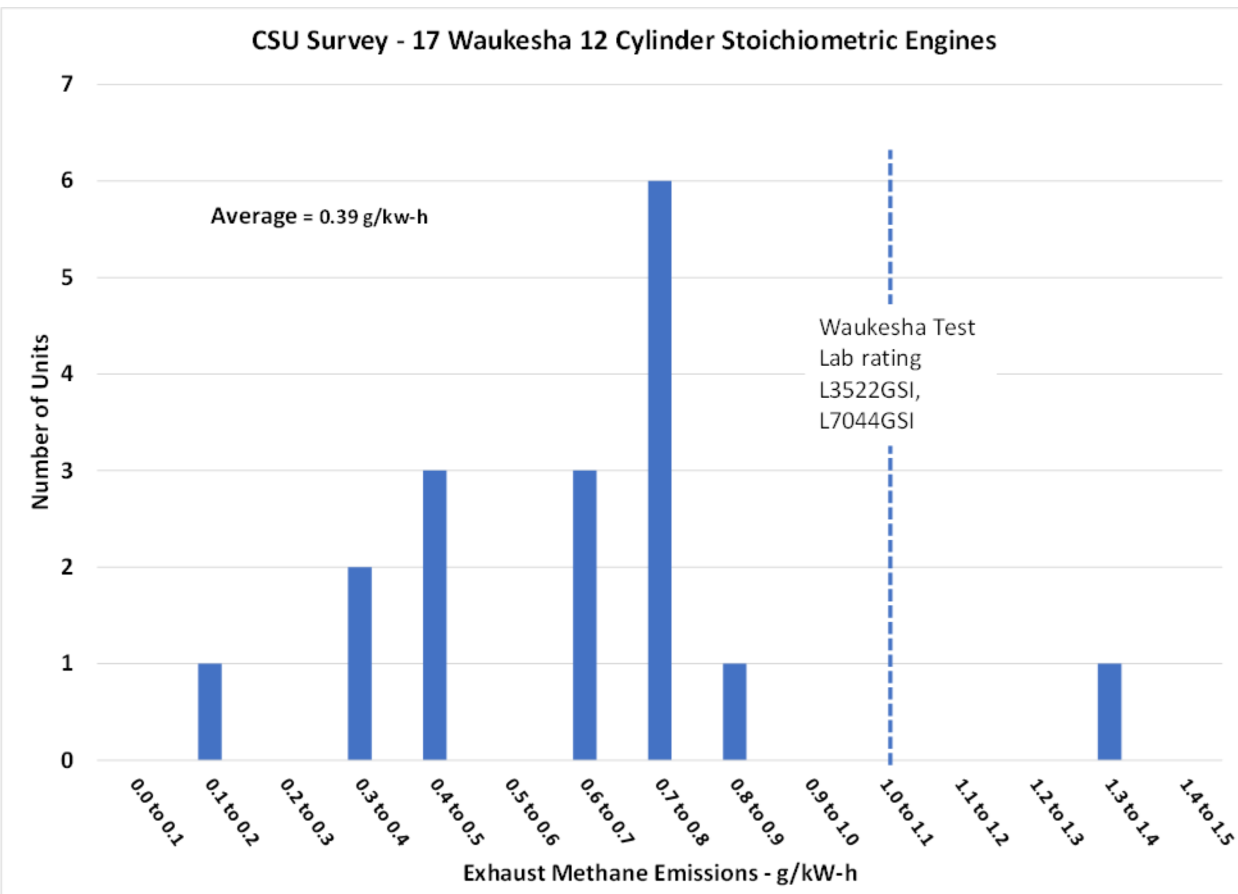

Figure 1 Methane emissions rate for 12 Waukesha stoichiometric engines

Figure 1 shows methane emissions downstream of the NSCR catalytic convertors for 17 controlled Waukesha stoichiometric engines. Only one engine produced more than Waukesha

Series 4 laboratory test result at about 1 g/kW-h. The methane emissions range from about 0.1 to 1.4 g/kW-h. Most engines in the sample fall within the range of about 0.7 to 0.8 g/kW-h.

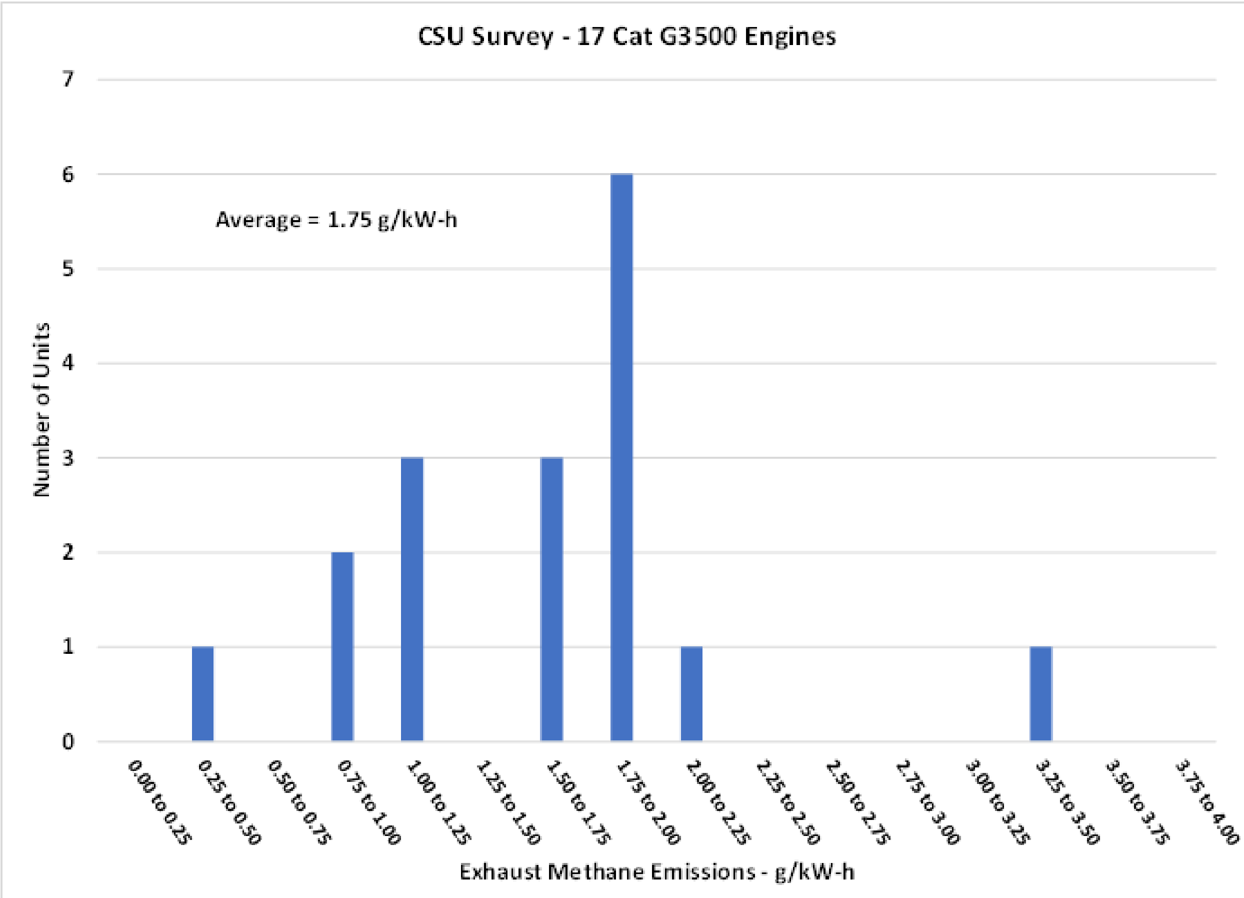

Figure 2 Methane emissions for the Cat G3500 engine model

Figure 2 shows the methane measurements for the lean open-chamber design of the Caterpillar G3500 engine series. The average is 1.75 g/kW-h. The methane emissions range from about 0.25 to 3.5 g/kW-h. Most engines in the sample fall within the range of about 1.075 to 2.0 g/kW-h.

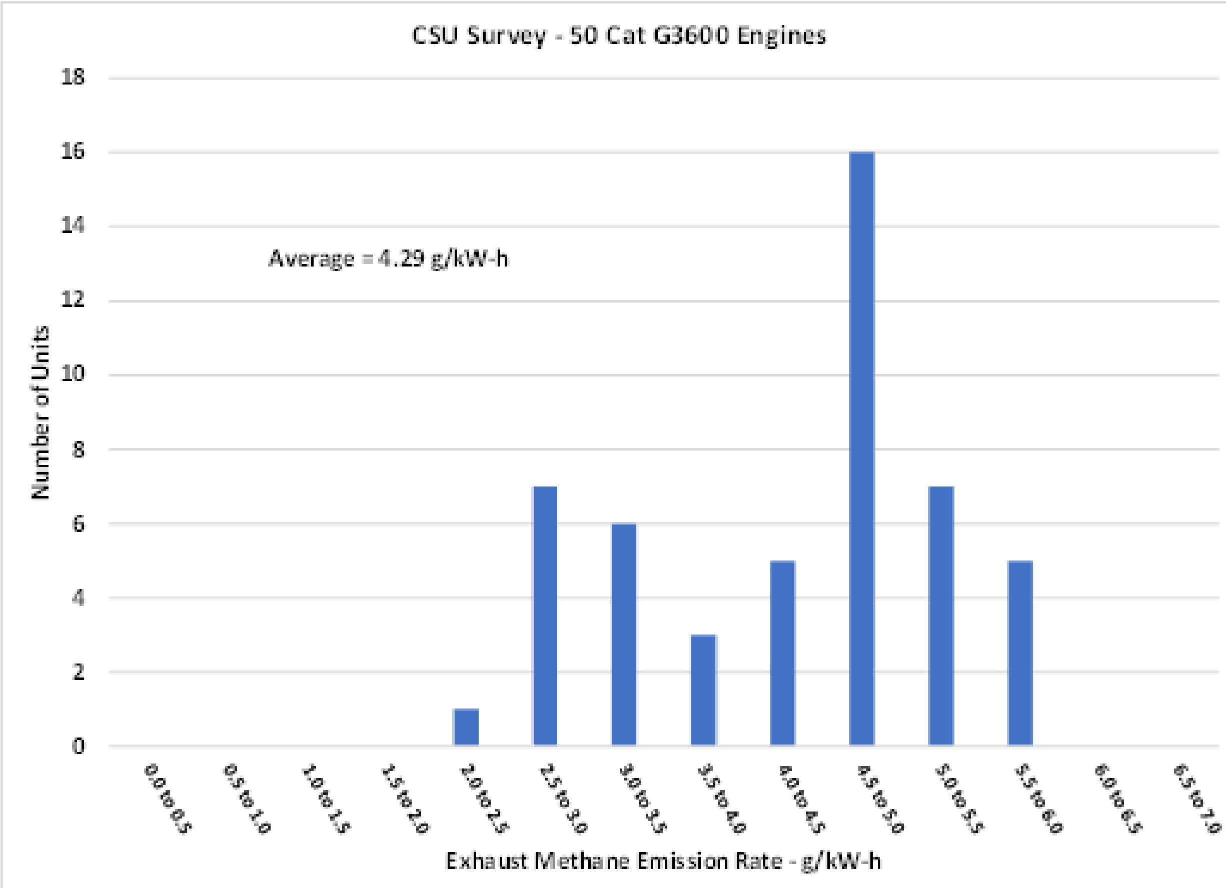

Figure 3 Methane emissions for Cat G3600 engines

Figure 3 shows the methane measurements for the G3600 design which uses pre-combustion chambers for combustion management. The average is 4.29 g/kW-h. The methane emissions range from about 2.0 to 6.0 g/kW-h. Most engines in the sample falls within the range of about 4.5 to 5.0 g/kW-h.

A considerable spread in the distribution and amplitude of the reported methane emissions for each engine design is evident. The data also illustrates that methane emissions increase as the excess oxygen content of the exhaust stream increases. The range associated with all engine combustion styles is 0.1 to 6.0 g/kW-h (Vaughan, et al). Crankcase emissions are reported by Johnson et.al (Johnson 2015 49). Their measurements show that methane emissions from the crankcase range from 0.2 to 11.1 kg/h for their sample of 4-stroke lean-burn engines. Their values comprised 4% to 20% of the total methane emissions for those engines (turbines excluded).

Table 3 presents a list of published articles that captures the extent of the literature available on methane slip. Table 4 presents a summary of the REMEDY (Reducing Emissions Every Day of the Year) program undertaken in the USA. These articles and the project work do not add any more value to the previous discussion.

Table 3 List of published articles containing information on methane slip

List of Published Articles				
	Title	Published	Authors	Abstract
Methane Slip	Exhaust Emissions for a Gas-Fuelled S.I Engine	2005	Hailin Li (National Research Council Canada) Ghazi A. Karim (U of C)	The emission characteristics of an engine operated in turn on CH4, H2, CO and some of their mixtures are examined experimentally. The role of changes in some key factors affecting the production of the pollutants CO, NOx and unburned hydrocarbons were investigated. Guidelines for reducing the undesirable emissions are outlined.
Methane Slip	An Experimental Investigation of S.I. Engine Operation on Gaseous Fuels Lean Mixtures	2005	Hailin Li (National Research Council Canada) Ghazi A. Karim (U of C)	The paper presents experimental data obtained in a single cylinder, variable compression ratio, S.I., CFR engine when operated on a number of gaseous fuels and some of their mixtures. A gradual leaning of the operating mixture can affect adversely in turn, emissions of CO and unburned fuel and cyclic variation The extent of deterioration in these operating parameters is shown to correlate well with the corresponding values of the combustion period, a key combustion indicator.
Methane Slip	LEAN BURN ENGINE TECHNOLOGIES MEET GAS COMPRESSION EMISSIONS CHALLENGE	2009	Victor L. Sheldon, Jr. Caterpillar Inc Houston, Texas	This paper examines a variety of lean burn combustion options considered for compliance to lower NOx emissions requirements. A non-technical overview of the evolution of lean burn engine technologies is provided. The general technologies available to incorporate into a lean burn gas compression engine are discussed with the benefits and challenges of each.
Methane Slip	Gas Engine Emissions and Exhaust Aftertreatment Application and Installation Guide LEBW4984-08	2020	Caterpillar Inc.	This section of the Application and Installation Guide generally describes Gas Engine combustion, Emissions and Exhaust Aftertreatment for Cat® engines
Methane Slip	Gas engine emissions technology IWK-019017-EN (contact Waukesha Rep or Distributor)	2019	Waukesha INNIO	This document discusses in a basic way how air pollutants are formed in natural gas engines along with the health risks and atmospheric deterioration which result from these pollutants. Some of the current emissions regulations are presented and how they apply to gas engines is addressed. Technology for reducing emissions is also discussed.
Methane Slip	EMISSION FACTOR DOCUMENTATION FOR AP-42 SECTION 3.2, NATURAL GAS-FIRED RECIPROCATING ENGINES	2000	Alpha-Gamma Technologies, Inc	The revised AP-42 section described in this report replaces the section published in September 1996 as Supplement B to the Fifth Edition. This background report replaces the Emission Factor (EF) Documentation for AP-42 section 3.2, Heavy-Duty Natural Gas-Fired Pipeline Compressor Engines, issued February 1993 and amended in 1996 to support Supplement B of the Fifth Edition. The purpose of this background report is to provide technical documentation supporting the revisions to AP 42 section 3.2
Methane Slip	Alberta Greenhouse Gas Quantification Methodologies	2021	Alberta Environment and Parks	This document details quantification methodologies for both the benchmark application and annual compliance reports for aggregate facilities under TIER. Annual compliance reports are mandatory for regulated facilities and must be submitted by the deadline established in the TIER regulation. Benchmark applications for aggregate facilities are elective
Methane Slip	Specified Gas Reporting Standard (Specified Gas Reporting Regulations)	2022	Alberta Environment and Parks	The Specified Gas Reporting Standard details who is required to report specified gas emissions and how the information is collected. Facilities that are subject to reporting requirements under the SGRR must follow the requirements set out in the Specified Gas Reporting Standard.
Methane Slip	2020 B.C. BEST PRACTICES METHODOLOGY FOR QUANTIFYING GREENHOUSE GAS EMISSIONS	2020	Ministry of Environment and Climate Change Strategy **BC**	This document sets out the current best practices for quantifying and reporting greenhouse gas (GHG) emissions from B.C.'s provincial public sector organizations, local governments and communities
Methane Slip	Methane Exhaust Measurements at Gathering Compressor Stations in the United States	2021	Timothy L. Vaughn,* Benjamin Luck, Laurie Williams, Anthony J. Marchese, and Daniel Zimmerle	Unburned methane entrained in exhaust from natural gas-fired compressor engines ("combustion slip") can account for a substantial portion of station-level methane emissions. A novel in-stack, tracer gas method was coupled with Fourier transform infrared (FTIR) species measurements to quantify combustion slip from natural gas compressor engines at 67 gathering and boosting stations owned or managed by nine "study partner" operators in 11 U.S. states.
Methane Slip	Methane Emissions from Leak and Loss Audits of Natural Gas Compressor Stations and Storage Facilities	2015	Derek R Johnson, April N Covington, Nigel N Clark	Researchers completed leak and loss audits for methane emissions at three natural gas compressor stations and two natural gas storage facilities. Researchers employed microdilution high-volume sampling systems in conjunction with in situ methane analyzers, bag samples, and Fourier transform infrared analyzers for emissions rate quantification.
Crankcase Emissions	Keep it Clean. No Methane Left Behind	2023	Peter Strezo (Berkshire Hathaway Energy Compression Services) Joel LeBlanc, P.E. (TCB Energy Services, LLC)	The emission characteristics of an engine operated in turn on CH4, H2, CO and some of their mixtures are examined. Major engine emission sources defined as Combustion, Starter Exhaust, Pre/Post-lube pump and Crankcase vent. Examined closed loop system with Crancase vent emissions recycled back into air inlet.
Crankcase Emissions	Interim Report on Methane Emissions from Waukesha and White Natural Gas Engines	2020	Howard Malm Internal report REM Technology division of Spartan Controls Ltd	The report discusses natural gas engine crankcase emissions and provides measurements made on 5 SI natural gas engines.
Crankcase Emissions	Managing Engine Blow-by with Crankcase Ventilation System	2023	Jason Cox, Solberg (Solberg website)	This article discusses engine blow-by, the issues blow-by causes, and the use of Crankcase Ventilation Systems to manage blowby.The different types of Crankcase Ventilation Systems were explained.
Crankcase Emissions	Characterization of Crankcase Ventilation Gas on Stationary Natural Gas Engines	2023	Arturo E Quintero Castillo, Andrew Zdanowicz, Bret Windom, and Daniel B Olsen. Colorado State University	Colorado State University (CSU) is collaborating with Caterpillar on a project funded by the Department of Energy (DOE) to achieve a CH4 conversion efficiency of ≥99.5% in lean-burn natural gas stationary engines to limit methane-slip emissions. The main focus of this project is the development of a closed crankcase recirculation/filtration (CCRF) system that would significantly reduce methane emissions contributed by crankcase ventilation gas.
Crankcase Emissions	Methane Emissions from Natural Gas Compression Operations in Gaslift and Gathering and Boosting Service	2024	Colorado State University METEC, funding by The Environmental Partnership (TEP).	Methane emission rates from gas compression operations in upstream (gaslift) and midstream (gathering and boosting) services were measured directly at 24 facilities in both the Permian and Bakken/Williston basins. Measurements were limited to compressor packages (gas compressors driven by natural gas-fired engines). Stack testing was performed to quantify the methane portion of "combustion slip", the fraction of fuel gas that escapes the engines unburned. Engine crankcase vents were also measured.
Crankcase Emissions	Crankcase Ventilation Systems	2021	Caterpillar Inc., Application and Installation Guide, LEBW4958-07.	This section of the Application and Installation Guides describes the requirements and options available for ventilation of the engine's crankcase
Crankcase Emissions	Gas engine emissions technology IWK-019017-EN (contact Waukesha Rep or Distributor)	2019	Waukesha INNIO	This document discusses in a basic way how air pollutants are formed in natural gas engines along with the health risks and atmospheric deterioration which result from these pollutants. Some of the current emissions regulations are presented and how they apply to gas engines is addressed. Technology for reducing emissions is also discussed.
Crankcase Emissions	Methane Leak and Loss Audits of Natural Gas Fueled Compressor	2014	Derek Johnson and April Covington Proceedings of the ASME 2014 Internal Combustion Engine Division Fall Technical Conference ICEF2014-5626	Reports on methane emissions from 5 sites with natural gas powered engines with measurements of methane, ethane, propane, carbon dioxide and nitrogen oxides for engine exhaust, compressor packing, crankcase emissions, and engine leaks.
Crankcase Emissions	POTENTIAL REDUCTION OF FUGITIVE METHANE EMISSIONS AT COMPRESSOR STATIONS AND STORAGE FACILITIES POWERED BY NATURAL GAS ENGINES	2014	Derek Johnson and April Covington International Mechanical Engineering Congress and Exposition IMECE-2014 – 38532	Estimates that if retrofit CCV technologies were implemented, the methane losses at the five sites that were studied could be reduced by 7.0%
Crankcase Emissions	Methane Emissions from Leak and Loss Audits of Natural Gas Compressor Stations and Storage Facilities	2015	Derek Johnson, April Covington, and Nigel N. Clark Environ. Sci. Technol. 2015, 49, 8132−8138	Compares measured methane emissions with AP-42

Table 4 USA REMEDY program project descriptions

REMEDY (Reducing Emissions of Methane Every Day of the Year)					
Title	**Location**	**Term**	**Award**	**Participants**	**Project Innovation**
Ultra Low Methane Slip Reciprocating Engine	Waukesha Wisconsin	03/15/2022 - 03/14/2025	$2,230,693	INNIO Waukesha Gas Engines	INNIO's Waukesha Gas Engines will develop a new piston, liner, and head gasket design that dramatically reduces crevice volumes, the largest source of unburned fuel, in engine combustion chambers. The team will optimize a large-bore steel piston to achieve the same reciprocating mass as current aluminum pistons. The new technology will broadly apply to all natural-gas-fueled lean-burn engines and can be used to retrofit a fleet of existing engines with little-to-no increase in budgeted costs. The technology will reduce emissions of regulated pollutants such as carbon monoxide, volatile organic compounds, and formaldehyde, while nitrogen oxides will stay the same, meaning no emissions re-permitting will be necessary after installation. The new technology will reduce operating costs and is similar to existing components, meaning support technicians will not need to retrain.
Lean-burn Natural Gas Engine System to Achieve Near-zero Crankcase Methane Emissions from Existing and Future Engine Fleet	Fort Collins, Colorado	07/01/2022 - 06/30/2025	$1,500,000	Colorado State University (CSU) and Caterpillar Inc.	Colorado State University (CSU) and Caterpillar will develop technology to reduce methane emissions from lean-burn natural gas engines by reducing methane ventilation through the crankcase. Methane that leaks past the ring and valve seals during compression and combustion enters the crankcase and is usually vented to the atmosphere. The team proposes a system that would capture the crankcase methane, treat it, and reroute it back to the engine intake where it would be re-ingested and combusted. This would simultaneously reduce methane emissions and improve engine efficiency. The team will first perform baseline laboratory tests to determine the amount of methane that leaks through the crankcase. The goal is to reduce the emissions from crankcase gas by at least 75%.
Methane Oxidation Catalysts for Lean-burn Natural Gas Engines	Farmington Hills, Michigan	07/25/2022 - 07/24/2025	$3,253,088	MAHLE Powertrain	MAHLE Powertrain proposes an aftertreatment package to minimize methane emissions from natural gas-fired lean and ultra-lean burn engines. The package features a methane oxidation catalyst with a novel hydrothermally stable catalyst formulation that significantly increases methane conversion efficiencies under low temperature exhaust conditions. The methane source addressed is methane that "slips" through the engine, unconverted to other species during combustion. The burden falls on the emissions control system to oxidize methane slip; however, in lean and ultra-lean burn engines, the aftertreatment system must perform this operation at low exhaust temperatures. Methane oxidation catalysts (MOCs) have historically required relatively high temperatures to ensure acceptable methane conversion efficiencies. The proposed concept will incorporate a novel MOC formulation that demonstrates good hydrothermal stability and high conversion efficiencies under low temperature conditions consistent with ultra-lean burn engine exhaust. The MOC is coupled with a selective catalytic reduction approach to significantly reduce NOx emissions as well.
Methane Oxidation Catalysts for Lean-burn Natural Gas Engines	Milwaukee, Wisconsin	06/01/2022 - 05/31/2025	$3,975,058	Marquette University	Marquette University will enable an innovative combustion technology for lean-burn (high air-fuel ratio) natural gas engines to potentially reduce the amount of methane slip—or methane in the inlet fuel stream that escapes to the atmosphere—to 0.25% of the inlet fuel stream. The 0.25% target would represent a 90% reduction from current levels. The proposed system aims to achieve a non-premixed, mixing-controlled combustion process with natural gas in a lean-burn engine through an actively fueled prechamber. Simulations have shown that this non-premixed combustion system yields a 10-fold reduction in methane slip compared with a conventional lean-burn natural gas engine. This system could be retrofitted to existing lean-burn engines or as a new engine technology.
Reducing Emission of Methane through Advanced Radical Kinetics and Adaptive Burning in Large Engines (REMARKABLE)	College Station, Texas	08/15/2022 - 08/14/2025	$2,824,815	Texas Engineering Experiment Station (TEES)	Texas Engineering Experiment Station (TEES) seeks to reduce methane emissions from compressor station natural gas (NG) engines by improving lean-burn operation, thereby reducing exhaust methane and carbon dioxide (CO2) emissions and maintaining low-criteria pollutant emissions. The project team will develop a nanosecond non-thermal plasma-based ignition system capable of generating radicals, ions, and highly reactive intermediate species that result in rapid self-sustaining combustion, and a cyclic combustion control strategy that predicts and mitigates partial-fire and misfire cycles. The proposed work will demonstrate a field-tested, prototype plasma ignition system and model-based, feed-forward combustion control system that would be transformative for large NG engines with potential for large-scale market adoption.

2. Combustion Theory, Methane Slip and Current Technology Development

2.1. Emission Components

Natural gas is composed mainly of gaseous hydrocarbons with methane being the main component. Methane released from combustion into the atmosphere is important because it provides a relatively high global warming potential in the quantification of CO_2e. Methane is also the component requiring the highest temperature to fully combust. The following discussion will focus on methane combustion in reciprocating natural gas fuelled engines. This study and the following discussion is limited to four stroke natural gas fueled engines.

Combustion is the chemical reaction between fuel and oxygen that releases energy. The ideal combustion of methane and air is revealed in the following equation:

$$CH_4 + 2O_2 + 7.55(N_2\text{+Ar}) = 2H_2O + CO_2 + 7.55(N_2\text{+Ar})$$

Ideal combustion of methane as shown by this equation results in only water vapor, carbon dioxide, and nitrogen with argon in the exhaust. Combustion in a real-world natural gas engine is far from ideal. It is a complex process involving many variables and multiple intermediate chemical processes. Non-ideal or incomplete combustion in natural gas engines arise from:

- incomplete air-fuel mixing,
- excess air,
- insufficient air,

- non-ideal ignition,
- crevice traps, and
- cool surfaces.

At high temperatures some of the nitrogen component of the air also combine with oxygen. These non-ideal conditions lead to the engine exhaust emissions of NO_x (oxides of nitrogen; normally NO and NO_2), CO (carbon monoxide), CH_4 (methane) and NMHC (non-methane hydrocarbons). The real, non-ideal methane combustion is reveled in the following equation:

$$CH_4 + 2O_2 + 7.55(N_2+Ar) \rightarrow C0_2 + 2H_2O + 7.55(N_2+Ar) + \{O_2 + CO + NO_x + CH_4 + NMHC\}$$

The NO_x and CO, normally < 1% of the exhaust composition, are undesired emissions. NO_x emissions are subject to Canada-wide Multi-segment Air Pollution Regulations (MSAPR). Oxygen (O_2) may be present due to incomplete combustion. If excess air is available then the fraction of O_2, N_2 and Ar in the exhaust increase.

Unburned hydrocarbons (CH_4 and NMHC) are emitted from natural gas engines due to the following sources.

1) *Crevices*
During compression and combustion, some of the unburned mixture is pushed into the small crevices due to the pressure rise through compression by the piston motion and flame propagation. Part of this trapped unburned fuel-air mixture flows out of the crevices during the expansion stroke as the cylinder pressure decreases and contributes to the emissions of unburned hydrocarbons. This mechanism contributes significantly to the emissions of unburned hydrocarbons.
2) *Flame quenching adjacent to the wall surfaces of the combustion chamber*
Flame quenching occurs when the energy released through combustion does not compensate for the heat loss from the propagating flame during the combustion cycle. The result is incomplete combustion of the air-fuel mixture.
3) *Bulk quenching within the main body of the mixture*
If excess air is available, either for the full combustion volume or in portions due to incomplete air-fuel mixing before ignition, the flame may become increasingly quenched or totally extinguished within the bulk mixture as well as adjacent to the combustion chamber surfaces. As the mixture becomes leaner, the emissions of CO and unburned fuel increase, while NO_x emissions decrease.
4) *Misfire or spark failure*
Increased cyclic variation can lead to the occurrence of a misfire where most or all the fuel flows to the exhaust. At extremely lean mixture operation, part of the fuel may not be ignited at all resulting in increasing emissions of unburned fuels.
5) *Insufficient air*
Insufficient air for complete combustion of the natural gas causes unburned or partially burned hydrocarbons to appear in the exhaust emissions. This result may be due to

insufficient air for the full combustion volume, or in portions, due to incomplete air-fuel mixing before ignition.

6) *Leakage to the crankcase (crankcase blowby)*
Some of the air-fuel mixture escapes past the piston rings during the engine compression and power strokes. The gasses leak into the crankcase where it is released to atmosphere via the crankcase vent. Crankcase vents are either directed to atmosphere, into the exhaust plenum or to the inlet air plenum (ingestive system).

2.2. Valve Overlap and Miller Cycle

Valve overlap is a design aspect of a reciprocating engine where the intake valve opens before the exhaust valve is closed. The degrees of crankshaft rotation while both valves are open normally defines the valve overlap. The timing of the valve actuation will dictate the possibility of the fuel being introduced into the exhaust manifold via the open exhaust valve. The fuel delivery method will also determine if fuel can enter the exhaust manifold. Carbureted engines will always be able to deliver fuel when the exhaust valve is open because fuel is part of the air fuel mixture. Fuel injected engines may introduce the fuel separately into each cylinder and the timing of the fuel delivery can be initiated when the exhaust valve is closed. The combustion air alone would then be introduced via the intake valve. Inducing methane slip on fuel injected engines may then be avoided. Pre-chambered engines are normally equipped with a separate fuel supply for the pre-chamber. Fuel delivery for the combustion chamber may be supplied with injected fuel, via an admission valve or an air fuel mixture from a carburetor.

Most stationary engines incorporate valve overlap to scavenge the exhaust gasses from the combustion chamber. It is expected that the intake manifold pressure is higher than the exhaust manifold pressure in order to expel the gasses into the exhaust manifold. If the overlap period is too long then the air fuel mixture will be diluted with exhaust gasses and the fuel mixture may be expelled from the combustion chamber.

Lower speed engine operation may not provide a higher intake manifold pressure than the exhaust manifold pressure. At lower speed operation it is possible to expel exhaust gasses into the intake manifold (known as internal exhaust gas recirculation). The timing of the intake valve opening is designed to prevent the fuel mixture from exiting through the open exhaust valve. Therefore, the possibility of inducing methane slip is negligible. Valve overlap is also less for cylinder heads with four valves versus two valves due to the increased flow area of the valves.

Table 5 and Figure 4 show valve overlap by engine model and combustion style along with our measured methane slip. Valve overlap data for the White Superior 825 Series engines was not available. The previously identified trends of higher methane slip for lean burn engines is demonstrated. However, the volume of methane slip does not show a correlation to the degrees of valve overlap. Another feature of the graph is that the addition of a catalyst does not reduce the methane slip (in the context of the accuracy of the data). This is likely because the catalyst is activated by the heat of combustion, which is increased by a richer fuel mixture, rather than fuel combustion in the catalyst.

Caterpillar and Waukesha were asked to comment on methane slip and specifically valve overlap. Their comments did not offer any enlightening information that would contribute to a better understanding of the phenomenon or the behavior of their engine designs. Their responses did reinforce that the phenomenon is complicated and that the engine manufacturers cannot offer much in the way of methane slip quantification. Too many variables are at play to offer definitive direction. Recall that our measured data was not all obtained at the same conditions. It is unwise to assume that the trends presented offer any more than a relative comparison. Table 5 illustrates the degrees of crankshaft angle where valve overlap is present.

Table 5 Valve overlap and methane slip data from our field tests and OEM published values by engine model

Model	Number of Engines	Valve Overlap Value	Catalyst?	CH4				CO		
				OEM		Test		OEM	Test	
				g/kW-hr	ppmvd 15%O2	g/kW-hr	ppmvd 15%O2	g/kW-hr	g/kW-hr	ppmvd 15%O2
CAT G3600 Pre-Chamber LB	58	104	N	5.93	1065	4.96	843	3.22	2.15	212
CAT G3500 Open Chamber LB	12	35	N	3.63	589	2.49	360	2.58	2.82	233
Waukesha VGF GL Open Chamber LB	11	43	N	3.72	580	3.68	457	2.25	3.65	259
Waukesha VHP GL Pre-Chamber LB	5	37	N	6.12	954	7.16	1012	3.67	3.67	297
Waukesha VHP LT Open Chamber LB	15	37	N	4.63	721	3.33	418	2.72	2.58	190
Waukesha VHP GSI Open Chamber RB	13	37	Y	2.34	228	1.66	220	9.97	19.29	1454
Waukesha VHP GSI Open Chamber RB	17	37	N	2.07	234	1.84	246	7.64	22.70	1714

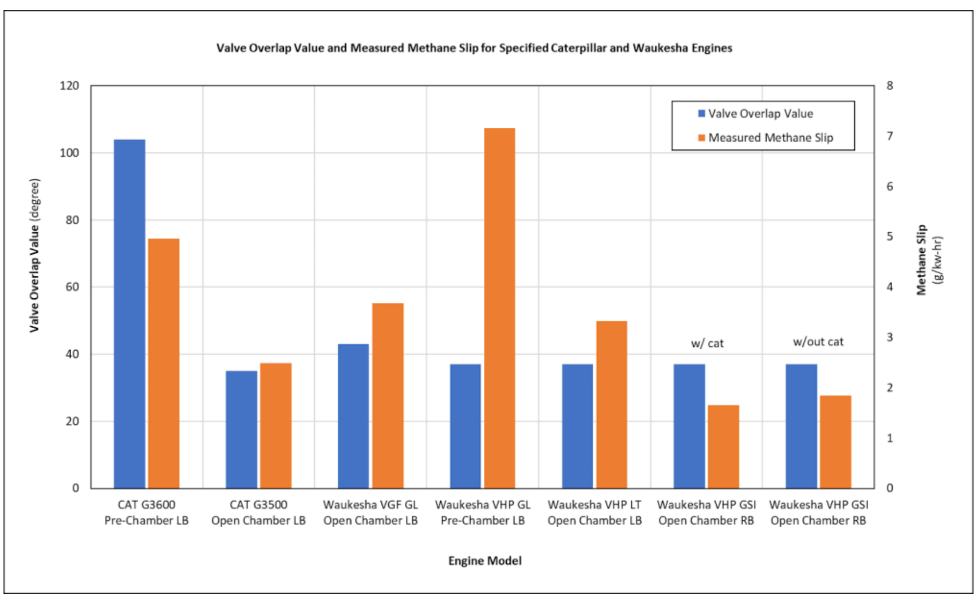

Figure 4 Graphical presentation of valve overlap and measured methane slip by engine model

Conventional four stroke engine design is known as an Otto Cycle. The Otto Cycle opens the valves at or near top dead center on the intake and exhaust stroke. The Miller cycle is a modification of the valve timing that allows for improved fuel efficiency on the order of 20%. It requires the engine to be equipped with a turbocharger or supercharger. The basic principle is to keep the intake valve open during the beginning of the compression stroke. Rather than do the work of compression during first part of the compression stroke, the piston will expel the air fuel mixture through the valve and back into the intake manifold. The pressure from the turbocharger or super charger is used to pressurize the air fuel mixture. It is assumed that the air fuel mixture will expand into the combustion chamber on the intake stroke to some pressure lower than the manifold pressure. The Miller Cycle engine takes advantage of the air manifold pressure to reduce the length of the compression stroke doing work until after the intake valve is closed. Less heating of the air-fuel mixture also occurs within the engine cylinder. The result is a reduction in combustion temperature compared with an Otto Cycle engine. The Miller cycle both increases the engine efficiency and reduces NO_x generation.

illustrates the degrees of crankshaft angle where the intake valve opening for a turbocharged or supercharged engine on a Miller Cycle engine is present.

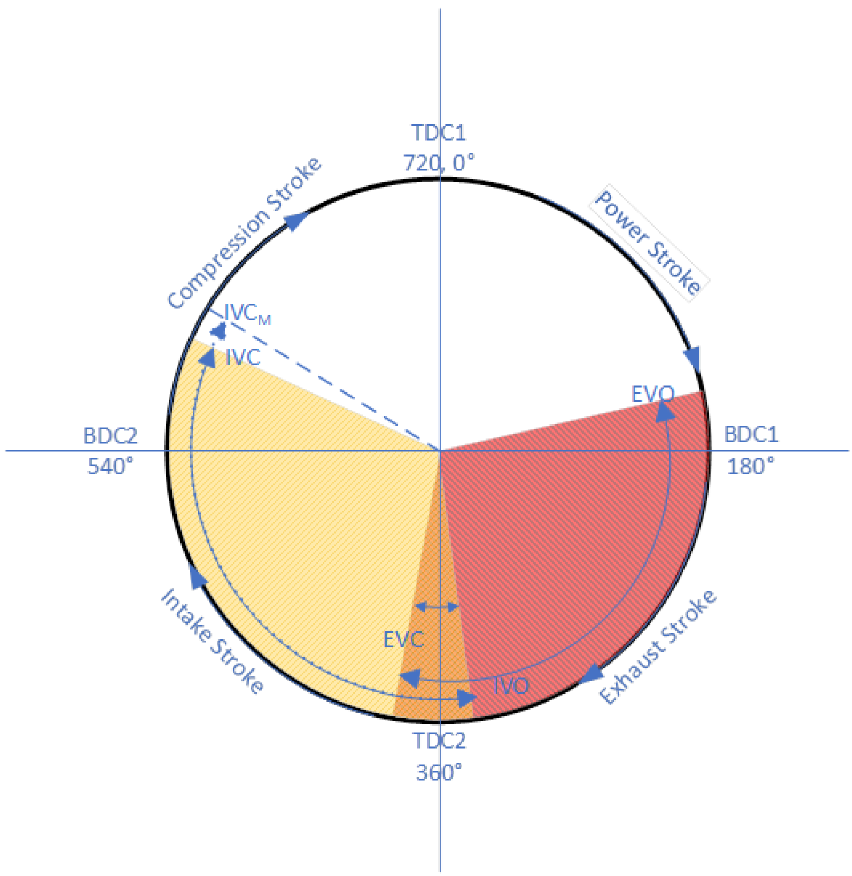

Figure 5 Relationship of the valve actuation in degrees of crankshaft rotation for valve overlap and the Miller Cycle (courtesy of Howard Malm).

The diagram in Figure 5**Error! Reference source not found.** shows the exhaust and intake valve opening angles (EVO and IVO) and closing angles(EVC and IVC) of a Waukesha VHP naturally aspirated engine. The exhaust valve open period is displayed in red, while the intake valve open period is yellow. The overlap period appears in orange. The standard intake valve closure is indicated by IVC, while the later intake valve closure is shown by IVCM.

Methane slip is associated with unburned methane issued into the exhaust. Since the Miller cycle does not affect the timing of the exhaust valve to be open, then theoretically the methane slip should not be affected. The efficiency gain is thought to be the result of power reduction required for the work of compression in the combustion chamber. However, if the combustion of the air fuel mixture is more complete then it is possible to reduce the methane slip. Crevice volumes are assumed to be constant in this discussion. It should also be noted that a naturally aspirated engine can perform in a similar fashion. This engine design is known as the Atkinson Cycle. It achieves the same result as the Miller Cycle by adding linkage to the connecting rod which is then acting similar to a supercharger or turbocharger in the Miller cycle. Atkinson Cycle engines are much larger and are not found in oil and gas operations.

2.3. Relationships Between Air Fuel Ratio and Exhaust Components for Unburned Methane Contribution

The emissions of CO_2 (carbon dioxide), CO (carbon monoxide), NO_x (oxides of nitrogen) and CH_4 (methane) are all effected by the engine air fuel-ratio. The CO_2 and CO are the direct products of the natural gas combustion, while the NO_x results from the combination of the nitrogen and oxygen from the air at high combustion temperatures. The CH_4 emissions are from the unburned fraction of the natural gas fuel. The exhaust concentrations of these items depend strongly on the initial air-fuel ratio and the uniformity of the air-fuel mixture.

Figure 6 shows schematic relationship between the various exhaust components and the air-fuel ratio under conditions of perfect air and fuel mixing. Exactly enough air is available for complete combustion with stoichiometric combustion. Insufficient air is available for complete combustion in rich mixtures. Excess air is available for complete combustion in lean mixtures. (Graph prepared by Accurata Inc)

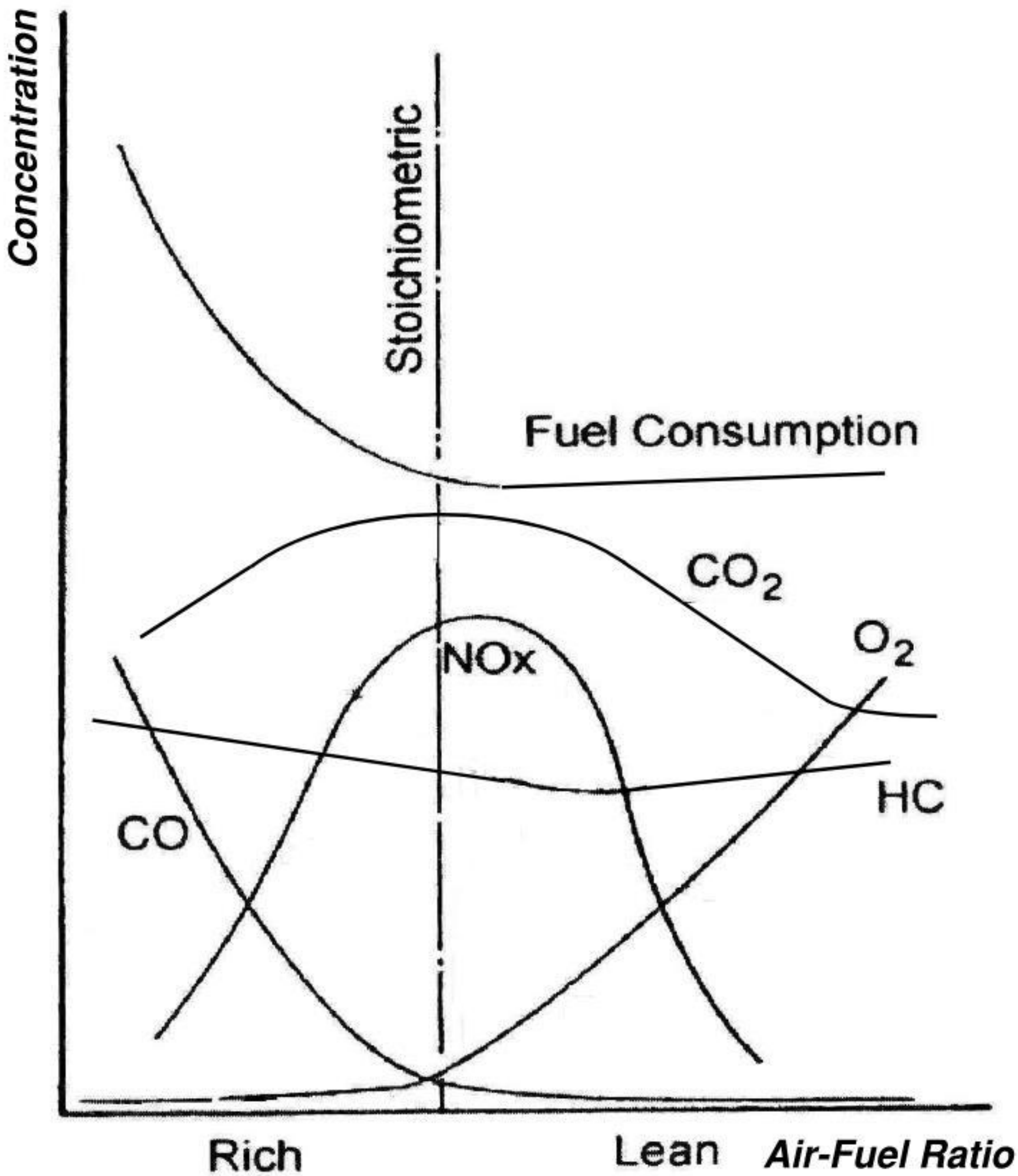

Figure 6 Relative behaviour of combustion elements with respect to air fuel ratio

CO_2 is produced by the combustion of the fuel. Excess air increases the exhaust flow while diluting the concentration of CO_2 in the exhaust. Less air reduces the exhaust flow but only slightly reduces the CO_2 concentration. CO concentrations dramatically increase if insufficient air is provided. The CO concentration is reduced with lean mixtures.

NO_x emissions are low when insufficient air is available and increase to a maximum when the mixture has some excess air. A further increase in the amount of air reduces the maximum combustion temperature and reduce the NO_x concentration. NO_x concentration may increase by a small degree under very lean conditions.

CH_4 (denoted HC, or hydrocarbon, on Figure 4) concentrations are highest when insufficient air is available. CH_4 concentrations drop to a low level at near stoichiometric mixtures. CH_4 concentrations increase when excess air cools the combustion zone. The cool quenching zone adjacent to the combustion chamber walls also increase in thickness with excess air. Poor combustion events as the mixture becomes very lean cause CH_4 emissions to increase dramatically.

The combustion process dictates how the engine will perform. The control system on the engine will manage the combustion process. Construction details on the engine are needed to support the combustion process. How these interact to determine the engine operation and their emissions will determine the behaviour of the combustion process and the methane emissions in the exhaust.

2.4. Relationships Between Carbon Monoxide Exhaust Components for Unburned Methane Contribution

Engine manufacturers specify tuning set points for air-fuel ratio on all engines. Rich burn engines are equipped with a catalyst to achieve MSAPR compliant NO_x concentrations in the exhaust. Observation of Figures 7 Figure 7, 8 and 9 show the behavior of CO, NO_x and HC combustion elements in the exhaust (Figures 2 and 3 shown on the graphics are as presented in Caterpillar literature). Tuning the engines very rich (lambda much less than1) can reduce the NO_x concentration due to the cooling effect of the excess fuel. That tuning will also dramatically increase CO concentration and unburned fuel (methane slip). Note that the CO concentration increases asymptotically to the Y axis for a very rich air fuel ratio. Catastrophic failures due to exhaust explosions can result when operating the engine at very rich air fuel ratios. The engine manufacturers do not support very rich operation because the excess fuel introduced into the exhaust line produces and unsafe operating environment.

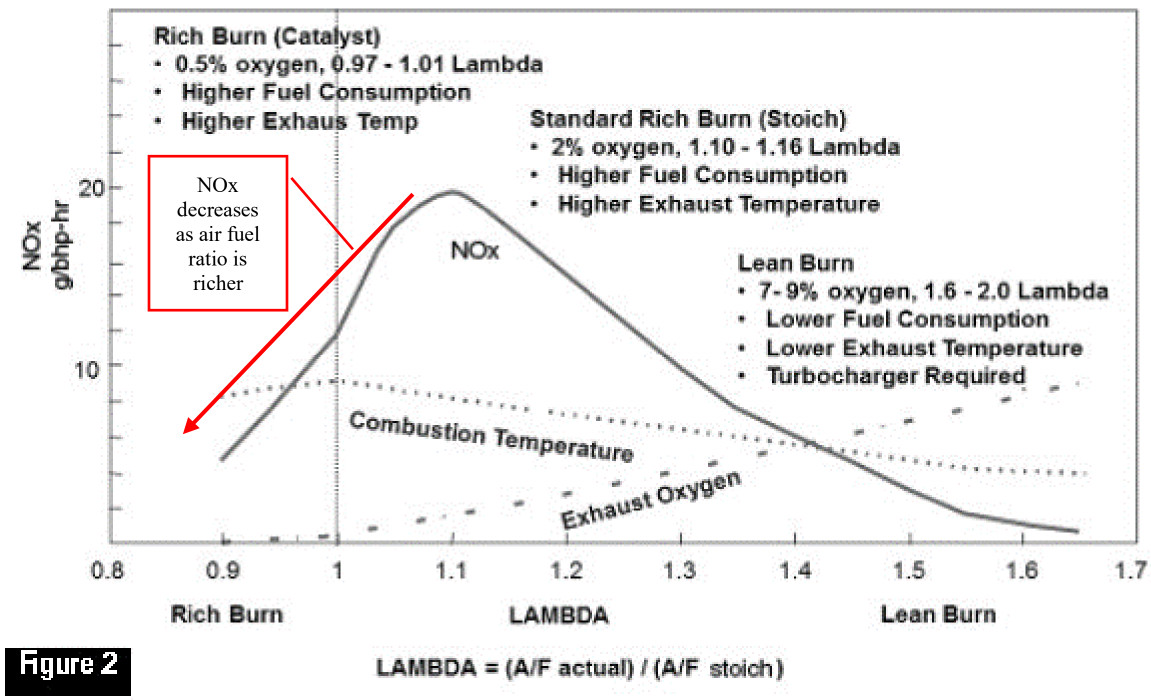

Figure 7 NO_x vs air fuel ratio (Cat gas engine emissions LEBW4984; Figure 2, Page 7, Caterpillar copywrite 2015)

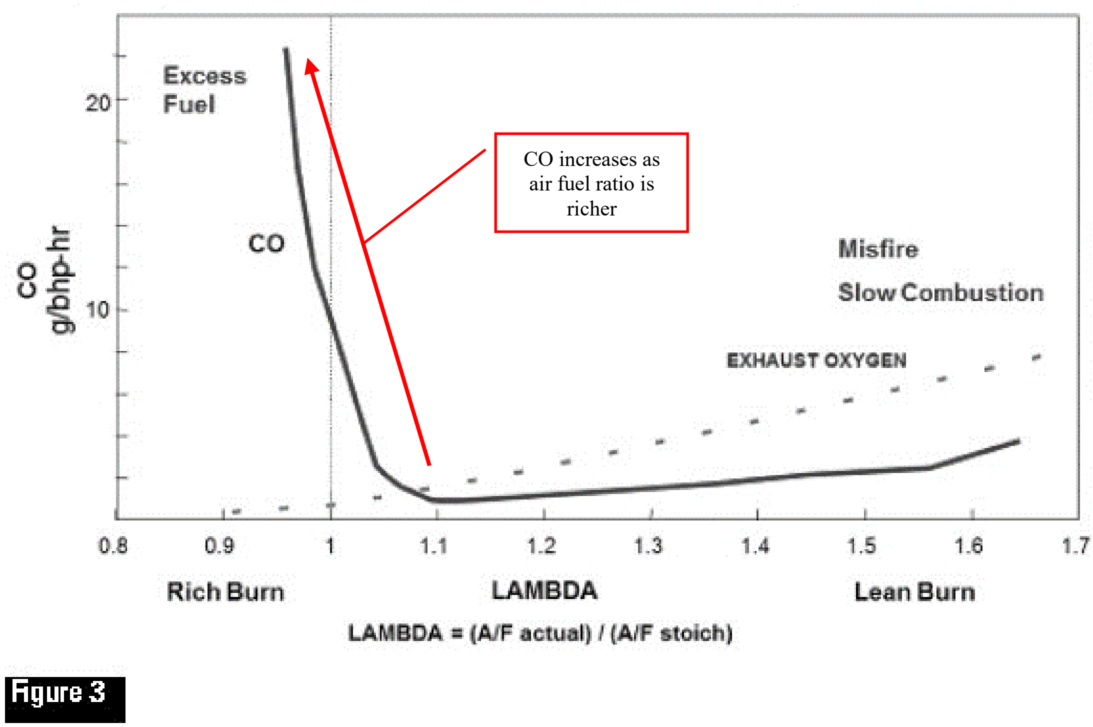

Figure 8 CO vs air fuel ratio (Cat gas engine emissions LEBW4984; Figure 3, Page 8, Caterpillar copywrite 2015)

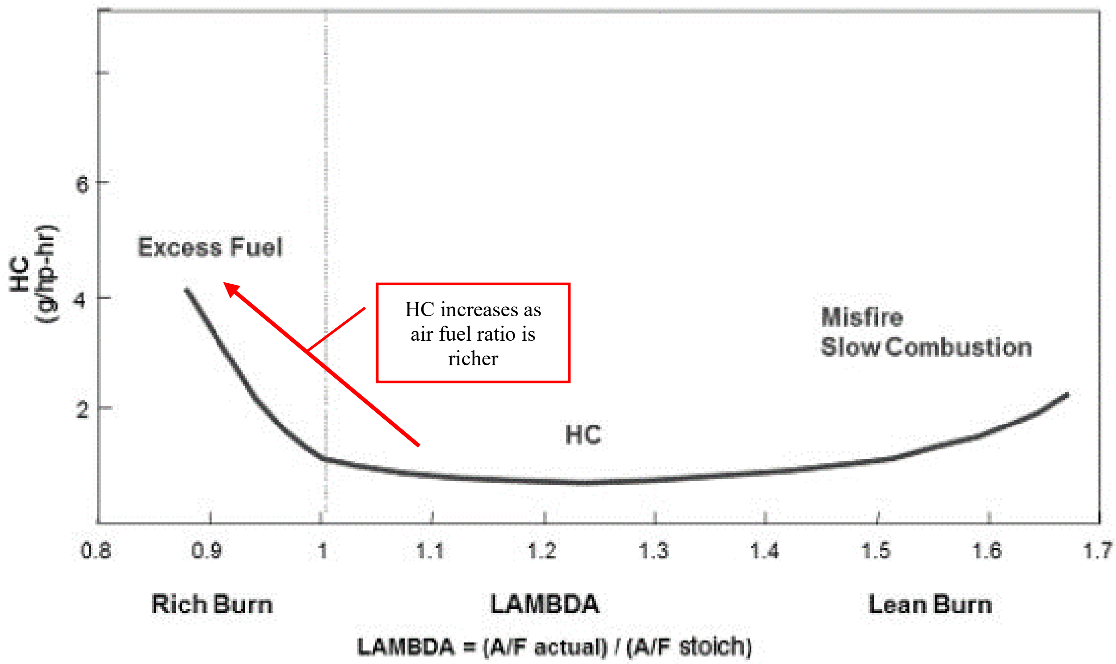

Figure 9 Unburned fuel vs air fuel ratio (Cat gas engine emissions LEBW4984; Unnamed Figure, Page 10, Caterpillar copywrite 2015)

Table 6 presents the OEM specified emission component concentrations for rich burn engines at different air-fuel ratio set points. The CO and NO_x values vary considerably depending on where the engine is tuned. Waukesha provides data at different tuning set points while Caterpillar does not. Consequently, the operator will be confused if they attempt to compare OEM emission element concentration data to determine a maximum CO value for safe operation. Cooper does not publish as comprehensive list of emission components values for the 825 series engines.

Engine manufacturers specify the maximum CO limit at less than 3800 ppm for optimum tuning of open chamber rich burn engines at stoichiometric conditions (i.e. best power air fuel ratio setting). Any CO concentrations that are higher is running the engine rich. We suggest a CO concentration exceeding 5,400 ppm will indicate the engine is certainly running too rich.

Table 6 OEM emission component values for rich burn engines

Engine Model	Engine Configuration and Air Fuel Ratio Set Point	CO vs NOx vs MS Exhaust Concentration (PPMvd @ 15% O2)					CO vs NOx vs MS Exhaust Concentration (g/kW-h)					CO vs NOx vs MS Exhaust Concentration (g/BHP-h)					Exhaust Oxygen (%)	Reference
		CO	NOx	THC	NMHC	CH4	CO	NOx	THC	NMHC	CH4	CO	NOx	THC	NMHC	CH4		
Caterpillar G3516NA	Standard	220	1,190	412	20	392	1.3	28.2	1.7	0.5	1.2	1.0	21.0	1.3	0.4	0.9	2	DM5142-00
	Catalyst	1,013	907	745	33	712	15.5	17.2	4.9	0.7	4.2	11.6	12.8	3.7	0.6	3.1	0.5	DM0540-01
Caterpillar G3516TA	Standard	122	1,475	323	16	307	1.5	20.4	4.6	0.3	4.3	1.1	15.2	3.4	0.2	3.2	2	DM5208-00
	Catalyst	1,623	657	413	18	395	17.4	14.9	2.5	0.4	2.1	13.0	11.1	1.9	0.3	1.6	0.3	DM5172-00
Caterpillar G3512NA	Standard	283	1,533	531	25	506	2.9	26.3	3.1	0.5	2.6	2.2	19.6	2.3	0.4	2.0	2	TM9512-03
	Catalyst	1,316	923	769	34	735	14.9	17.3	5.0	0.8	4.3	11.1	12.9	3.7	0.6	3.2	0.5	DM0557-01
Caterpillar G3512TA	Standard	111	1,521	314	15	299	2.0	27.7	2.0	0.3	1.7	1.5	20.7	1.5	0.2	1.3	2	TM9502-02
	Catalyst	1,476	756	443	20	423	16.8	14.1	2.9	0.4	2.5	12.5	10.5	2.2	0.3	1.8	0.3	DM0553-01
Caterpillar G3412NA	Standard	616	1,582	332	50	282	2.0	29.4	2.1	0.3	1.8	1.5	21.9	1.6	0.2	1.4	2	TM9220-01
	Catalyst	589	756	317	48	269	18.1	14.7	2.1	0.3	1.8	13.5	11.0	1.6	0.2	1.3	0.5	DM5101-00
Caterpillar G3412TA	Standard, 9.7:1 CR	337	1,584	392	59	333	3.8	29.1	2.5	0.4	2.2	2.8	21.7	1.9	0.3	1.6	2	DM5197-00
	Standard, 8.5:1 CR	198	1,631	365	55	310	2.2	29.1	1.5	0.2	1.3	1.6	21.7	1.1	0.2	1.0	2	DM5206-00
	Catalyst	1,530	891	536	80	456	16.2	15.5	3.2	0.5	2.7	12.1	11.6	2.4	0.4	2.0	0.4	DM5104-00
Caterpillar G3408NA	Standard, 9.7:1 CR	907	1,512	274	41	233	2.0	27.3	1.7	0.3	1.5	1.5	20.4	1.3	0.2	1.1	2	TM9151-01
	Catalyst	847	761	256	38	218	17.7	14.7	1.7	0.3	1.4	13.2	11.0	1.3	0.2	1.1	0.5	DM5090-00
Caterpillar G3408TA	Standard, 8.5:1, CR	206	1,866	365	55	310	2.1	29.5	2.1	0.3	1.8	1.6	22.0	1.6	0.2	1.4	2	TM9213-01
	Standard, 9.7:1 CR	193	1,567	541	81	460	2.1	28.1	3.5	0.5	3.0	1.6	20.9	2.6	0.4	2.2	2	TM9181-01
	Standard, 9.7:1CR, LFF	190	1,545	454	68	386	2.1	28.5	3.0	0.4	2.6	1.6	21.3	2.2	0.3	1.9	2	DM5095-00
	Catalyst, 9.7:1CR, 90F	1,493	872	616	92	524	16.6	15.9	3.9	0.6	3.3	12.4	11.9	2.9	0.4	2.5	0.4	DM5096-00
Caterpillar G3406NA	Standard	1,132	1,671	317	48	269	1.9	28.7	1.9	0.3	1.6	1.4	21.4	1.4	0.2	1.2	2	TM8513-01
	Catalyst	1,063	819	298	45	253	16.5	15.0	1.9	0.3	1.6	12.3	11.2	1.4	0.2	1.2	0.5	DM5076-00
Caterpillar G3406TA	Standard	199	1,561	428	64	364	2.1	27.4	2.6	0.4	2.2	1.6	20.4	1.9	0.3	1.6	2	TM9164-01
	Catalyst	1,594	871	509	76	433	16.7	15.0	3.0	0.5	2.5	12.5	11.2	2.2	0.4	1.9	0.5	DM5081-00
Waukesha VHP G, GSI	Equal NOx and CO	1,320	804	446	68	378	16.0	16.0	3.1	0.3	2.8	12.0	12.0	2.3	0.4	2.0	0.3	S8483-04
	Best Power	3,520	570	446	68	378	42.7	11.3	3.1	0.5	2.6	32.0	8.5	2.3	0.4	2.0	0.3	S8483-04
	Catalyst	990	871	388	58	330	12.0	17.3	2.7	0.4	2.3	9.0	13.0	2.0	0.3	1.7	0.3	S8483-04
	Best Economy	165	1,474	291	49	243	2.0	29.3	2.0	0.4	1.6	1.5	22.0	1.5	0.3	1.3	1.35	S8483-04
Waukesha F3524GSI, L7044GSI	Equal NOx and CO	1,540	938	49	39	10	18.7	18.7	0.3	0.3	0.0	14.0	14.0	0.3	0.2	0.1	0.3	S8483-04
	Catalyst	1,430	1,005	213	58	155	17.3	20.0	1.5	0.4	1.1	13.0	15.0	1.1	0.3	0.8	0.3	S8483-04
	Best Economy	220	1,541	155	39	116	2.7	30.7	1.1	0.3	0.8	2.0	23.0	0.8	0.2	0.6	1.35	S8483-04
Waukesha L7044GSI, G, L7042GSI S4	Catalyst	1,210	938	485	78	407	14.7	18.7	3.3	0.5	2.8	11.0	14.0	2.5	0.4	2.1	0.3	S8483-6
Waukesha L7044GSI S5, L7042GSI S5	Catalyst	1,100	871	175	58	116	13.3	17.3	1.2	0.5	0.7	10.0	13.0	0.9	0.3	0.6	0.3	S8483-6
Waukesha F3524GSI, G; F3514GSI S5	Catalyst	1,430	1,072	194	39	155	17.3	21.3	1.3	0.3	1.1	13.0	16.0	1.0	0.2	0.8	0.3	S8483-6
Waukesha L5794GSI	Equal NOx and CO	1,485	905	582	87	495	18.0	18.0	4.0	0.6	3.4	13.5	13.5	3.0	0.5	2.6	0.3	S8483-04
	Catalyst	1,595	737	563	68	495	19.3	14.7	3.9	0.5	3.4	14.5	11.0	2.9	0.4	2.6	0.3	S8483-04
	Best Economy	330	1,474	466	78	388	4.0	29.3	3.2	0.5	2.7	3.0	22.0	2.4	0.4	2.0	1.35	S8483-04
Waukesha P9394GSI	Catalyst	1,188	777	136	39	97	14.4	15.5	0.9	0.3	0.6	10.8	11.6	0.7	0.2	0.5	0.3	S8483-6
Waukesha VGF G (catalyst)	Equal NOx and CO	1,100	1,005	388	58	330	13.3	20.0	2.7	0.4	15.0	10.0	15.0	2.0	0.3	1.7	0.3	S8483-04
	Catalyst	1,100	1,072	388	58	330	13.3	21.3	2.7	0.4	2.3	10.0	16.0	2.0	0.3	1.7	0.3	S8483-04
	Best Economy	88	1,876	252	58	194	1.1	37.3	1.7	0.4	1.3	0.8	28.0	1.3	0.3	1.0	2.4	S8483-04
	Best Power	3,080	804	388	58	330	37.3	16.0	2.7	0.4	2.3	28.0	12.0	2.0	0.3	1.7	0.3	S8483-04

We surveyed our data for rich burn engines obtained during our field tests. Figure 12 shows NO_x versus methane slip. It does not present any correlation between the two variables for rich burn engines. Figure 10and Figure 11 suggest that higher concentrations of CO do not produce higher levels of methane slip. That is because the engines in our test data are not tuned rich enough to reduce NO_x concentrations.

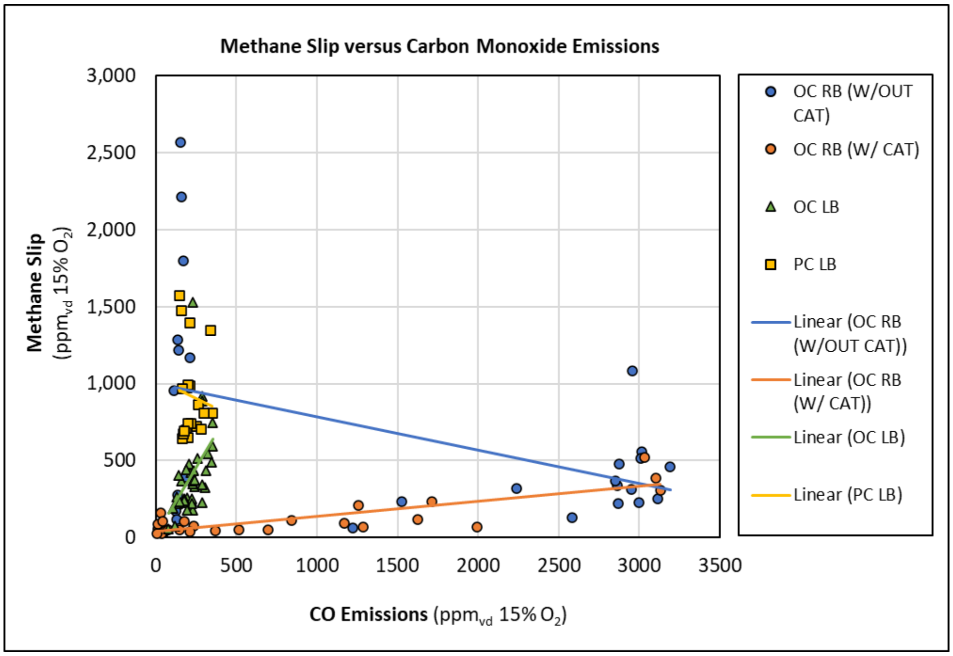

Figure 10 Methane slip vs CO from the study test data, all engine combustion styles

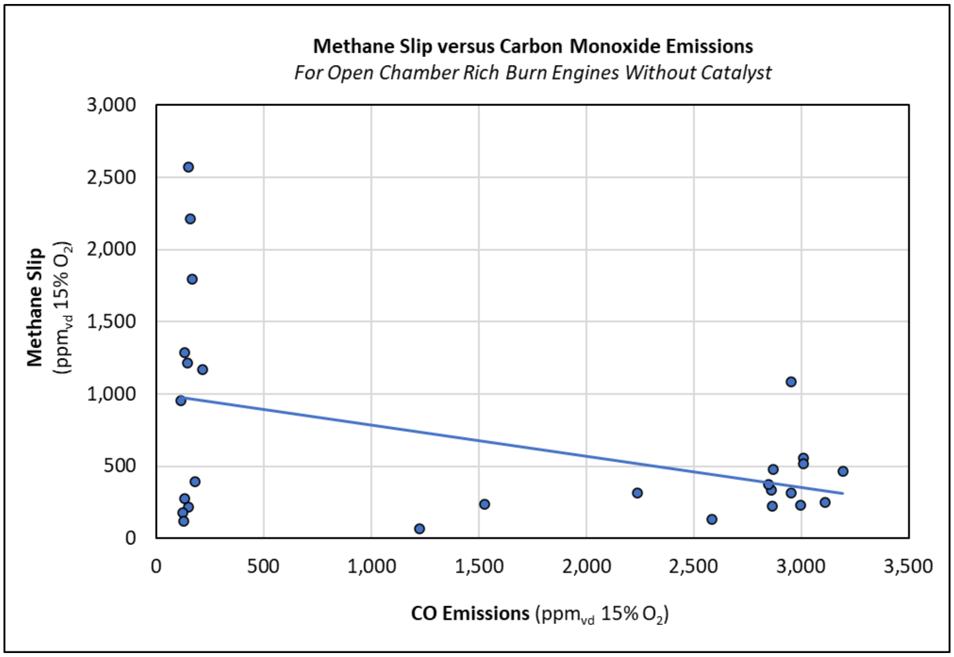

Figure 11 Methane slip vs CO from the study test data, open chamber rich burn combustion style without catalyst

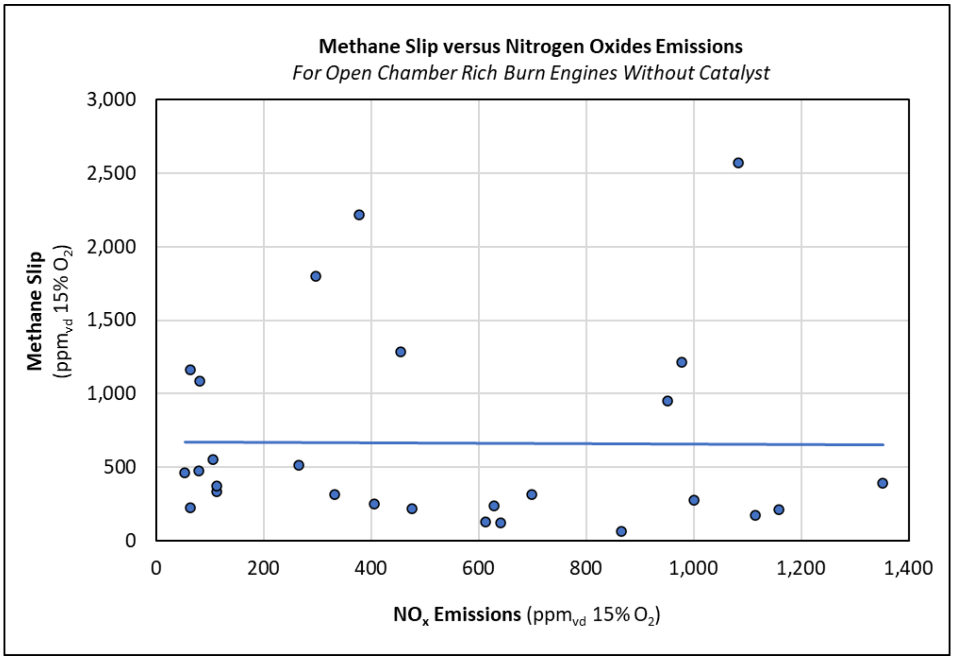

Figure 12 Methane slip vs CO from the study test data, open chamber rich burn combustion style without catalyst

Monitoring CO concentration can identify when the engine is running very rich. Some service providers are marketing rich tuning to meet MSAPR NO_x compliance without the need for a catalyst. CO emission concentrations of about10,000 to 12,000 ppm will produce NO_x concentrations of about 3 g/kW-h. The service providers do not specify a particular CO concentration to meet the MSAPR NO_x limit. Rather, the engine is tuned progressively richer until the desired NO_x concentration is achieved.

An appropriate CO sensor must be provided to measure the high CO concentrations in the exhaust. The capability of CO sensors to detect emissions levels varies. Most CO Sensors will not measure CO concentrations much beyond 10,000 or 20,000 ppm.

2.5. Engine Management System and Design Aspects that Determine the Behaviour of the Combustion Process

Natural gas reciprocating engines are normally classified as rich-burn or lean-burn. These engines can be either electronically controlled for their air-fuel ratio or mechanically controlled. The largest contributions to engine methane emissions are poor or no-combustion events. The presence of engine monitoring systems to provide warnings or cause engine shutdowns is essential. All natural gas reciprocating engines have leakage, which includes methane, to the crankcase. By recirculating these crankcase gases into the air intake the methane emission exhaust component from the crankcase can be virtually eliminated. Further, since excessive wear causes leakage to the crankcase to increase, regular engine overhaul is thought to be essential.

The specifics of the engine's design play a direct role in determining the makeup of the exhaust stream from that engine. These aspects are repeated here for the convenience of the reader. The following aspects all play a role in the volume of unburned methane emissions in the exhaust:

- air-fuel ratio,
- air-fuel mixing,
- charge turbulence,
- piston crevice volume,
- spark plug location,
- spark plug type,
- jacket water temperature, and
- control system capability (ignition timing, inlet charge, mixture control and flame front propagation).

The mechanical design aspects of a specific engine cannot be easily changed. The correct choice of operating parameters and ignition devices can have a large effect on exhaust methane. The mixing time for the air and fuel before the combustion event is limited, so the mixture is invariably non-homogeneous leading to small volumes that may not combust well. Increased charge turbulence is beneficial. Likewise, for carbureted engines an increase in the intake manifold volume is beneficial. Intake mixers have also demonstrated some benefit in improved charge homogeneity. The detection and correction of partial or complete misfire events is paramount. Exhaust temperature, exhaust oxygen or crank-speed monitoring are effective methods to detect abnormal combustion occurrence.

Rich-burn engines are operated at stoichiometric or near stoichiometric air-fuel ratios. This combustion style produces relatively high combustion temperatures. The boundary thickness where flame quenching occurs contributes a relatively small fraction of the unburned methane. Most of the unburned methane originates from crevice volumes. Crevice volumes depend on the piston and ring design, on the presence of accumulated residues on the walls of combustion chamber and the condition of gaskets. Regular borescope examination may be able to determine if head refurbishment or gasket replacement is warranted.

Nonselective catalytic reduction (NSCR) catalysts can reduce exhaust methane emissions to some degree depending strongly on the catalyst condition and composition. Electronically controlled rich-burn engines are equipped with NSCR catalysts and are subject to regular compliance monitoring. The application of NO_x emission regulations dictated by MSAPR suggests that the fraction of engines without electronic control will be reduced in Canada.

Electronically controlled lean-burn engines are either open-chambered or equipped with pre-combustion chambers. The pre-combustion chambers (PCC) enable the air-fuel mixture in the combustion chamber to be leaner than normal which reduces NO_x emissions. The reduced combustion temperatures characteristic of lean-burn engines leads to an increase in the boundary layer thickness where quenching occurs. Leaner air-fuel mixtures increase surface quenching to become the dominant source of methane emissions in engines with pre-combustion chambers.

Open-chamber lean-burn engines have less surface quenching. Air-fuel homogeneity and ignition energy become more important to the presence of unburned methane. Efforts to enhance air-fuel mixing tend to reduce methane emissions. A “draw-thru” arrangement where the fuel is added to the air before the turbocharger also enhances the air-fuel mixing. Chambered spark plugs provide initial ignition within a small internal chamber. These devices have also shown some benefit in reducing methane emissions for open-chambered engines.

The crevice volumes are also important for open chambered engines. These volumes depend on the piston and ring design, on the presence of accumulated residues on the walls of combustion chamber and the condition of gaskets. Regular borescope examination may be able to determine if head refurbishment or gasket replacement is warranted. The detection and correction of partial or complete misfire events is paramount. Exhaust temperature, exhaust oxygen or crank-speed monitoring are effective methods to detect abnormal combustion occurrence.

2.6. Crankcase Blowby

A source of unburned methane is derived from the crankcase. The engine’s crankcase is enclosed by the cylinder block, the oil pan and the underside of the pistons. Methane that leaks from the combustion chamber into the crankcase is known as blowby. This occurs when gasses leak past the piston rings or are released from suspension in engine oil. Blowby is present in every engine. The gasses vented from the crankcase are normally collected and injected into the exhaust stack downstream of the engine, injected into the engine combustion air or vented directly to atmosphere.

The crankcase commonly operates at slight positive pressure relative to atmospheric pressure. Crankcase ventilation systems control the pressure in the engine crankcase and vent crankcase fumes. Crankcase pressures that are much higher than atmospheric pressure can affect component life, lubrication, engine emissions and oil leaks. Deterioration of engine seals can lead to contamination of the oil or the engine enclosure. Some engines have devices to create a slightly negative crankcase pressure in order to reduce oil leakage. Modern Caterpillar and Waukesha large gas engines are equipped with Crankcase pressure sensors connected to the Engine Control system. The engine control system will initiate a shut down event if the crankcase pressure becomes too high. Most medium and large engines will also employ crankcase explosion relief valves integrated into the crankcase access doors.

Blowby volume varies with cylinder firing pressure, piston ring integrity, piston ring contact pressure and component wear. The flow volume of crankcase emissions is thus difficult to specify. Caterpillar estimates the Crankcase hydrocarbon emissions are typically about 3% of the total exhaust hydrocarbon emissions but are thought to increase to as much as 20% as the engine wears (Caterpillar Application and Installation Guide; Crankcase Ventilation Systems, LEBW 4958-07, 2021: 0.04 m3/kW-hr blowby rate for a worn engine). Waukesha does not offer estimates for hydrocarbons content in Crankcase blowby.

Research conducted by Spartan Controls shows that crankcase hydrocarbon emissions may vary between 20% to 60% of the total methane slip volume. The field tests conducted by Accurata suggests a median value of the crankcase emissions as fraction of the total methane slip emissions should be about 40% of the total methane slip volume. The Accurata study data is not a large enough sample to provide a reliable estimate of methane emissions in Blowby. Additional study on this topic should be considered to validate the OEM predicted crankcase vent volumes.

The crankcase emissions are normally stated as fraction of the total methane slip in most literature sources. It was not clear that the combustion style should have an impact on the crankcase vent emissions. The total methane slip emissions increase on lean burn engines. Using a fraction of the total methane slip emissions would indicate a correlation exists between crankcase methane emissions and the combustion style. Howard Malm reviewed that aspect and discovered a reasonable correlation between the methane slip crankcase vent fraction and engine power (Figure 13Figure 13).

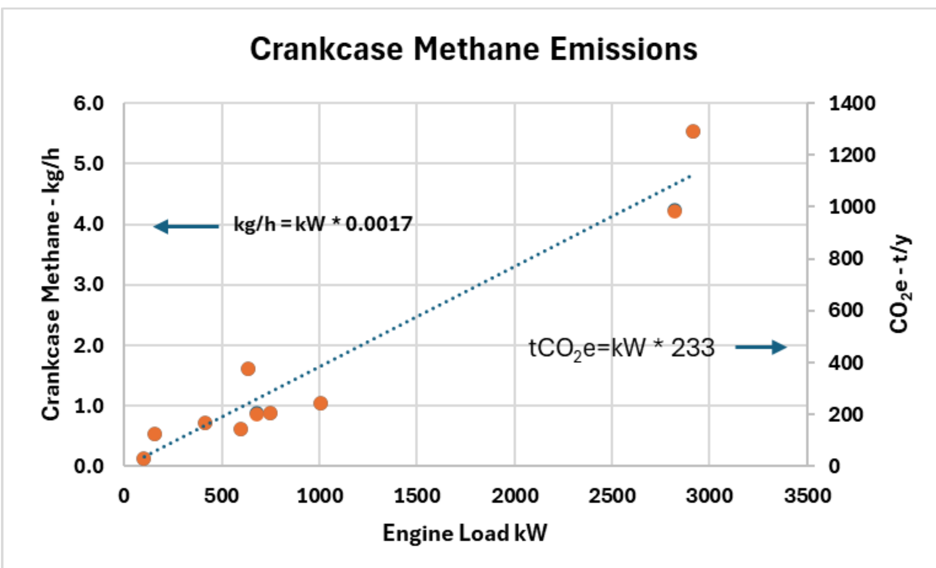

Figure 13 Howard Malm analysis of crankcase emission vents volume based on Accurata and Spartan field data

A table is presented in Appendix K in an effort to estimate the total crankcase emissions in the Alberta and Canadian fleets of stationary natural gas fueled engines. Columns for OEM estimate and Accurata estimates are presented in this table. Four methods of estimating the crankcase vents are shown, namely;

- 3% of the blowby volume (Colorado State University (CSU) study),

- 20% of the total methane slip (OEM prediction),
- 40% of the total methane slip as suggested by our field data, and
- Howard Malm's suggestion (kg/h = 0.0017*kW).

The fleet estimates vary significantly. This variance suggests that the OEM estimates may be understated. A summary of the fleet estimates stated in Table 7 are as follows.

Table 7 Summary of fleet emissions estimated in Appendix K

	Individual Methane Emissions in Engine Blowby (worn engine)				Total Methane Emissions in Engine Blowby (m3/h) (worn engine)							
	CSU Data (3 % of OEM Blowby Rate)	OEM Emission Factor (20 % of Total OEM Predicted Methane Slip)	Accurata Estimate (40% of Total Methane Slip Based on Emission Factors applied to MSAPR list)	Howard Malm Estimate (kW*0.0017/0.9)	CSU Data (3 % of OEM Blowby Rate)		OEM Emission Factor (20 % of Total OEM Predicted Methane Slip)		Accurata Estimate (40% of Total Methane Slip Based on Emission Factors applied to MSAPR list)		Howard Malm Estimate (kW*0.0017/0.9)	
	m3/h				Canada	Alberta	Canada	Alberta	Canada	Alberta	Canada	Alberta
Total estimated Methane Emissions in blowby (m^3/h)					11,307	8,472	4,586	3,106	9,261	6,483	9,345	6,739
Total estimated Methane Emissions in blowby (m^3/y)					99,048,758	74,212,581	40,172,708	27,206,670	81,122,821	56,790,267	81,860,215	59,030,366
Total estimated Methane Emissions in blowby (Tonnes/h) based on 0.9 kg/m^3					10	8	4	3	8	6	8	6
Total estimated Methane Emissions in blowby (Tonnes/y) based on 0.9 kg/m^3					89,144	66,791	36,155	24,486	73,011	51,111	73,674	53,127
								Total Fleet Methane Slip (Tonnes/y)			182,500	127,800

Both Howard Malm's method and the 40% estimate produce almost the same total crankcase emissions. Our fleet sample is not representative of every engine. Howard Malm's method should be more universally applicable since using power is more representative of compression ratio and engine size than the total methane slip emission estimates using our suggested emission factors.

Other products of combustion such as NO_x, are also present in the crankcase gases. These combustion products will vary with engine combustion type. Thus lean-burn gas engines will have lower concentrations of NO_x in the crankcase than rich-burn gas engine models. The presence of sulfur compounds or aldehydes will be similarly dependent upon the type of engine, fuel quality, and the condition of the engine.

Crankcase emissions carry entrained oil droplets that will be expelled through the ventilation system piping at its outlet. Oil mist exiting the ventilation system is normally collected by a coalescing filter. Oil mist that does not coalesce can be entrained in the combustion air and clog air filters. Crankcase fumes that are emitted into an engine room deposits oil on the surfaces of the equipment and inside the enclosure. A fire hazard, housekeeping issues and a risk to personnel health may result. Ventilation piping must convey crankcase fumes outside the engine enclosure. Crankcase emissions may be required to be included in the total engine emissions. The state of California and parts of Europe already require including crankcase emissions in the total engine emissions.

2.7. Ingestive and Non-Ingestive Systems for Crankcase Emissions

Crankcase ventilation systems can be categorized as either closed or open. Closed systems are known as ingestive and the crankcase fumes are separated from oil droplets and routed back to the engine's air inlet. This entrains the fumes into the combustion air to consume unburned hydrocarbons in the combustion process. Filtered oil is usually returned to the engine crankcase. Open systems are considered non-ingestive where the crankcase fumes are either vented directly to the atmosphere or into the exhaust line and then to atmosphere.

The effectiveness of an ingestive system depends on the quality of oil filtration and the interaction with engine control system. The air fuel ratio will be affected by the introduction of the additional fuel into engine air intake. Engine OEMs employ high quality oil separation in order to mitigate fouling of the turbo charger, valves and intercooler.

A recent study conducted by Colorado State University in collaboration with Caterpillar on a lean burn G3516J engine and a rich burn CG137-8 engine suggests that the crankcase methane contribution to the total exhaust emissions is higher for a lean burn engine. However, the engine combustion style is not related to the effectiveness of the crankcase ventilation system.

2.7.1. Ingestive Crankcase Ventilation Systems

Ingestive systems normally employ a positive crankcase ventilation system to convey gasses into the air inlet. Entrained oil droplets can impinge on turbocharger compressors and clog intercoolers. Naturally aspirated engines do not employ turbochargers and thus do not present this hazard. The pressure available from a turbocharger offers a different strategy for operating an ingestive system than is available on a naturally aspirated system.

A naturally aspirated engine must rely on the suction from the engine piston movement to draw in crankcase fumes into the air inlet. Similarly, a turbocharged engine offers a low pressure region upstream of the turbocharger compressors which can convey the crankcase fumes into the engine air inlet. These systems are known as low pressure ingestive systems.

High pressure ingestive systems employ a blower to introduce crankcase fumes into a high pressure region (i.e. downstream of the turbochargers). This configuration will avoid the possibility of oil contamination or impingement on turbocharger compressors and perhaps intercoolers. Oil filtration is recommended in either system to prevent damage to components downstream of the injection point.

2.7.2. Non-Ingestive Crankcase Ventilation System

Open crankcase ventilation systems on older and smaller engines are normally a simple vent located at an opening on the valve cover. The vent is tubed to a location outside the engine enclosure and away from the engine air inlet. Routing the vent through a venturi and then directing the fumes into the exhaust line downstream of the turbocharger is also common. Downstream components like catalytic converters will be damaged by oil mist so these vents are always tubed to downstream of such devices on the exhaust line. Filtration canisters are normally provided as part the design. Engine manufacturers have been including the crankcase evacuation systems on their new engines on more recent models while the packager designed those systems on older engine models.

2.8. OEM Systems that Reduce Crankcase Emissions

Caterpillar is working on solutions for ingestive crankcase systems. Caterpillar currently offers few ingestive options. Caterpillar is concerned about the deleterious affect of the oil entrained in the crankcase fumes. Pressure from customers in response to environmental and regulatory considerations has resulted in application of Caterpillar's blower for crankcase emissions to create an ingestive system (Caterpillar. n.d.).

This blower was originally designed as an aftermarket addition for engines in electric power generation service on their G3500 series gas engines. The system is reputed to be expensive, complicated and require significant maintenance effort. It is not a popular upgrade in the industry. Caterpillar has recently developed a closed loop (ingestive) crankcase ventilation system for G3600A4 and G3600A3 models. The system features their "Advanced Fumes Disposal Filter and Breather Groups". The system separates oil droplets from gasses and returns the oil to the crankcase. The gasses go to combustion process via the turbocharger inlet. CAT advertises 8,000 hours as a service interval for this system. All new G3600A4 engines have the CCV (crank case ventilation) system installed. Engines without a CCV system are discontinued.

Caterpillar has also introduced the ADEM 4 second generation system in 2023 that replaces the ADEM4 engine management system on new engines. The upgraded G3600 series engine with an ADEM 4 second generation system claims to reduce methane emissions in the exhaust by half compared with the previous models. The new engine model features geometry changes to the engine design as well as control modifications.

Waukesha once supplied three different crankcase breather systems on VHP engines. The current VHP breather system is limited to one model. These systems use vacuum to evacuate the crankcase vapors. The breathers utilize an oil separator to remove oil mist from the vapors before entering the intake or exhaust stream. The difference in the systems is the source of vacuum.

Naturally aspirated (G) engines use vacuum behind the air cleaner and draw the crankcase vapors into the air cleaner housing downstream of the filter element. The vapors are then burned in the combustion process. Note that Waukesha has discontinued all naturally aspirated models from production lines.

Old turbocharged rich burn (GSI) engines use a venturi in the exhaust system to create a vacuum which draws the crankcase vapor into the exhaust stream. This design is sensitive to exhaust system back-pressure. Waukesha now employs factory installed, self regulated ingestive breather systems on their VHP GSI Engines. Waukesha advertises increased efficiency of oil to crankcase vapor separation, Improved control of negative crankcase pressure, an increased replacement interval of element to 8,000 hours and Automatic adjustment of negative crankcase pressure.

Old turbocharged lean burn (GL) engines employ an eductor which uses compressed intake air as the motive gas (pre-intercooler) from the turbocharger to create a vacuum. The eductor introduces the vapours into the exhaust stream. Newer GL engines (VHP and VGF) use a self regulated ingestive system similar to GSI models. Note that Waukesha has discontinued all VHP GL engines from product lines. All VHP LT models will also be discontinued on January 1 2025.

The largest Waukesha 12V and 16V – 275GL+ models are available with a forced ventilation system. This non ingestive system employs a crankcase blower to maintain a slight crankcase pressure to extract crankcase emissions. Fumes are not separated from oil drops and are not returned to the engine air inlet. Operators should determine if air pollution regulations allow a separate atmospheric vent.

White-Superior offers an ingestive breather ventilation option on all engines as a standard factory attachment. The usual system arrangement is employed. Crankcase fumes are separated by oil drops and blowby emissions. Oil returns to the engine crankcase and gasses are returned to the engine combustion at the air intake.

2.9. Regulatory Aspects for Methane Emissions in Engine Exhaust

Canada does not have any regulated limits regarding methane and unburned hydrocarbon emissions from stationary natural gas engine exhaust. Environment Canada is considering the introduction of legislation for regulatory limits. Some limits were proposed for comment in late 2022 that proposed limiting these emissions to 1 g/kW-hr. The USA is also considering limits.

The EPA does not regulate methane emissions from stationary internal combustion engines. Mandatory reporting is required in accordance with the "Greenhouse Gas Reporting Rule" of the Environmental Protection Agency (Environmental Protection Agency n.d.). This document refers to a default methane emission factor for stationary natural gas fuel as 0.001 (kg/mmBtu) in Table C-2.

The EPA recently opened a discussion process published as "Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule" (EPA n.d.). This document proposes implementation of revised methane emission factors based on the statement that "combustion slip is dependent on the type of engine and not the application." Their proposed emission factors are 0.522 (kgCH4/mmBtu) for 4 stroke lean burn engines and 0.045 (kgCH4/mmBtu) for 4 stroke rich burn engines (Paragraph 75). The proposal is still under review at the time of this writing. Colorado State University (Colorado State University 2021, 55) conducted a study published as "Methane Exhaust Measurements at Gathering Compressor Stations in the United States." The study suggests that proposed EPA factors do not accurately represent methane emissions from any type of engine.

2.10. Manufacturer Published Methane Emissions in Engine Exhaust

Most engine manufacturers publish unburned methane emissions as well as unburned hydrocarbon emissions. The unburned hydrocarbon emissions are sourced from combustion of lubricants. Total hydrocarbon emissions are also sometimes reported by Caterpillar and Waukesha. A trend in the Caterpillar data suggests the unburned hydrocarbon emissions appear to be expressed as a constant ratio of the unburned methane emissions. This apparent correlation was not repeated in the Waukesha data. In general, the total hydrocarbon (THC) emissions should be the sum of the non-methane hydrocarbons (NMHC) and the methane hydrocarbons (C_1 or C_xH_y).

Manufacturer's data is collected for comparison with field measured data. Many variables affect the production of unburned methane and hydrocarbon emissions. It is not known if the test procedure for the measured values by the engine manufacturers will be the same as the MSAPR test procedures. Furthermore, Cooper Machinery Services, the manufacturer of the White Superior engine, provided unburned methane emissions for a limited number of engine models. Cooper's published data is limited to unburned hydrocarbons and total hydrocarbons. The measured data does not include engine crankcase (blowby) emissions.

A turbocharged White Superior engine combustion operates differently than the engines made by Caterpillar or Waukesha. White engines utilize valve overlap to introduce a large volume of air into the combustion chamber to sweep out the exhaust fumes to increase engine efficiency. However, it does not affect the mass flow of the combustion components. The combustion event in the cylinder is open chamber, rich burn. The air is added after the combustion event so that the oxygen content in the exhaust emissions is higher than would be expected for stoichiometric ideal air-fuel ratios. The result is exhaust emissions with both high volumes of NO_x and O_2 components.

The MSAPR regulations define a lean burn engine as "other than rich burn." A rich burn engine is defined by having less than 4% excess oxygen in the exhaust. By this definition the White turbocharged engines without pre-combustion chambers are classified as lean burn. However, the combustion process is rich burn and they should be considered as such. Some turbocharged, open chamber White engine models may be tuned to a lean air-fuel ratio with sufficient modifications to the control system but these controls are typically sourced from third party technology suppliers. The excess oxygen introduced into the exhaust stream by valve overlap disqualifies these engines from the use of an NSCR catalyst.

The engine manufacturers' unburned methane and hydrocarbon data is presented according to the type of combustion process. Table 8 shows the rich burn engines equipped with a catalyst. Table 9 shows the rich burn engines without a catalyst. Table 10 shows data for open chambered lean burn systems. Table 11 shows data for pre-chambered lean burn systems.

Rich burn systems seem to produce lower emission levels of unburned hydrocarbons. Even so, significant variance is presented for methane and total hydrocarbon emissions between engine models with the same combustion style. These differences can be attributed to engine geometry and test conditions at the various factories. Also, the NO_x and, to a lesser extent, CH_4 emissions downstream of a catalyst should be less since that device requires unburned methane to react in the catalysts. Poor maintenance of the catalyst or improper tuning will increase those emissions. It should also be noted that the practice of tuning a rich burn engine to very rich to reduce NO_x (see Figure 6) will dramatically increase the unburned hydrocarbon emissions. The impact of that operating scenario is not presented in these tables.

Tables 8, 9, 10 and 11 are organized according to combustion style. Tables 12, 13, 14 and 15 are organized by methane slip emissions in the exhaust of more than and less than 1 g/kW-h. The tables illustrate how only a small group of engines emit less than 1 g/kW-h.

Table 8 Unburned methane and hydrocarbon emissions for rich burn engines with a catalyst (measured upstream of the catalyst)

Engine Exhaust Emission Factors (OEM vs. Field)

Rich Burn Engines with Catalyst Ratings (OEM data - engine out emissions)	Engine Models		Emission factors (OEM factors corrected to rated load and speed)													Number of Engines
			Hydrocarbons										O2		OEM Reference	
			OEM						Field				OEM	Field		
			THC		NMHC		Methane		Methane							
	Models	Settings	g/kw-hr	ppmvd 15%O2	g/kw-hr	ppmvd 15%O2	g/kw-hr	ppmvd 15%O2	Average g/kw-hr	Range g/kw-hr	Average ppmvd 15%O2	Range ppmvd 15%O3	% DRY			
CAT G3400 TA series, 1800 RPM	G3408TA	9.7:1	3.90	616	0.58	92	3.32	524	Not Tested				0.4	Not Tested	DM5096	0
		8.5:1	2.2	365	0.33	55	1.87	310	1.79	1.79	207	207	2.0	0.0	TM9213	1
Waukesha VHP GU, GSI	S5	Catalyst	1.22	175	0.41	58	0.82	117	0.41	0.31 - 0.53	61	36 - 76	0.3	0.0	Ref. S8483-6	3
	S4	Catalyst	3.40	194	0.54	39	2.86	155	0.34	0.18- 0.69	45	27 - 86	0.3	0.1	(February 2022)	10
	S2	Catalyst	2.72	388	0.41	58	2.31	330	2.76	1.13 - 4.10	356	158 - 523	0.3	0.7	Ref. S8483-4	3
	F3521	Catalyst	2.72	388	0.41	58	2.31	330	2.63	2.63	308	308	0.3	1.2	(April 2001)	1
White G825	6G	Standard	Not Available		0.27	Not Available			Not Tested				Not Available	Not Tested	Superior Engine	0
	8G	Standard			0.27				0.74	0.54 - 0.88	94	70 - 107		0.1	Exhaust	4
	12G	Standard			0.27				Not Tested					Not Tested	Emissions	0
	16G	Standard			0.27										10/25/2019 by	0

Table 9 Unburned methane and hydrocarbon emissions on rich burn engines without a catalyst

Engine Exhaust Emission Factors (OEM vs. Field)

Rich Burn Engines without Catalyst. Standard Ratings (OEM data - engine out emissions)	Engine models		Emission factors (OEM factors corrected to rated load and speed)													Number of Engines
			Hydrocarbons										O2		OEM Reference (Standard spec)	
			OEM						Field				OEM	Field		
			THC		NMHC		Methane		Methane							
	Models	Settings	g/kw-hr	ppmvd 15%O2	g/kw-hr	ppmvd 15%O2	g/kw-hr	ppmvd 15%O2	Average g/kw-hr	Range g/kw-hr	Average ppmvd 15%O2	Range ppmvd 15%O3	% DRY			
CAT G3400 TA series, 1800 RPM	G3408TA	CR 9.7:1	3.5	541	0.52	81	2.98	460	1.46	1,26 - 1.66	194	174 - 214	2.0	2.8	TM9181-01	2
CAT G3400 TA series, 1800 RPM		CR 8.5:1	2.2	365	0.33	55	1.87	310	Tested as catalyst				2.0	Tested as cat	TM9213-01	0
Waukesha VHP G, GU, GSI	F3521GSI	Best Economy	3.13	446	0.48	68	2.65	378	1.90	1.57 - 2.43	276	250 - 317	0.3	0.7	Waukesha	4
	F3521GU		2.04	291	0.34	49	1.70	243	2.35	2.35	335	335	1.4	0.3	Ref. S8483-4	1
	F2895GU								3.52	3,52	392	392	1.4	1.0	(April 2001)	1
Waukesha VHP GU, GSI S2	L7042GSI	Best Economy	2.04	291	0.34	49	1.70	243	2.52	1.66 - 3.40	335	226 - 477	1.4	0.8	Waukesha	4
	L7042GU		2.04	291	0.34	49	1.70	243	3.72	3.70 - 3.75	535	514 - 556	1.4	0.3	Ref. S8483-4	2
	L5794GSI		3.27	466	0.48	68	2.79	398	Not Tested				1.4	Not Tested	(April 2001)	0
Waukesha VHP GSI S4	L7044GSI	Customer catalyst	3.40	485	0.54	78	2.86	407	0.46	0.46	64	64	N/A	0.0	Ref. S8483-6	1
Waukesha VHP GSI S5	L7044GSI		0.68	97	0.07	10	0.61	87	Not Tested				N/A	Not Tested	EngCalc 4.3	0
	L7042GSI		0.95	136	0.10	14	0.86	122					N/A			0
White G825	6G	Standard	Not Available		0.27	Not Available			Not Tested				N/A	Not Tested	Superior Engine Exhaust Emissions 10/25/2019 Provided by Rick Lucas Cooper Machinery Services	0
	8G	Standard			0.27				3.2	0.90 - 10.00	363	120 - 1083	N/A	1.4		5
	12G	Standard			0.27				Not Tested				N/A	Not Tested		0
	16G	Standard			0.27				Not Tested				N/A	Not Tested		0
White GT825	6GT	Standard			1.36				Not Tested				N/A	Not Tested		0
	8GT	Standard			1.36				18.42	18.42	2627	2627	N/A	8.5		1-misfire
White GTL825	6GTL	Standard			0.67				Not Tested				N/A	Not Tested	Superior Turbocharged Gas Engines TC-613/1-89	0
	8GTL	Standard			0.67				15.52	7.94 - 33.85	2287	1166 - 5039	N/A	9.6		5
	12GTL	Standard			0.67				Not Tested				N/A	Not Tested		0
	16GTL	Standard			0.67				Not Tested				N/A	Not Tested		0
White SGT825	8SGT	Standard			1.00				Not Tested				N/A	Not Tested	Superior Turbocharged Gas Engines	0
	12SGT	Standard			0.67				7.82	7.82	952	952	N/A	7.7		1
	16SGT	Standard			0.67				8.18	8.18	1287	1287	N/A	8.3		1

Table 10 Open chamber lean burn engine unburned methane and hydrocarbon emissions

Engine Exhaust Emission Factors (OEM vs. Field)

Open Chamber Lean Burn Engines	Engine models		Emission factors (OEM factors corrected to rated load and speed)												OEM Reference (Standard spec)	Number of Engines
			Hydrocarbons										O2			
			OEM						Field				OEM	Field		
	Models	Settings (Nox; CR)	THC		NMHC		Methane		Methane				% DRY			
			g/kw-hr	ppmvd 15%O2	g/kw-hr	ppmvd 15%O2	g/kw-hr	ppmvd 15%O2	Average g/kw-hr	Range g/kw-hr	Average ppmvd 15%O2	Range ppmvd 15%O3				
CAT G3500 TALE series (EIS)	G3516, 1200rpm	1.5 g/hp-hr	4.43	705	0.66	106	3.77	599	2.89	2.44 - 3.33	422	368 - 476	8.2	7.9	DM5154-00	3
	G3512, 1200rpm	2 g/hp-hr	4.16	676	0.62	101	3.54	574	Not Tested				8.2	Not Tested	DM0150-03	0
	G3516, 1200rpm		4.31	685	0.65	103	3.66	582	2.10	1.55 - 2.39	309	228 - 352	8.0	7.4	DM0107-03	2
	G3512, 1400rpm	1.5 g/hp-hr	4.56	429	0.68	64	3.88	365	Not Tested				8.3	Not Tested	DM5120-00	0
	G3516, 1400rpm		4.10	643	0.62	46	3.48	597					8.3		DM5155-00	0
	G3512, 1400rpm	2 g/hp-hr	4.10	639	0.62	45	3.48	594					8.2		DM5118-00	0
	G3516, 1400rpm		3.90	620	0.58	44	3.32	576					8.3		DM5168-00	0
CAT G3500 ADEM3 series (corrected ppm to 0% O2)	G3512, 1200rpm	1.5 g/hp-hr	4.43	675	0.66	101	3.77	574	1.72	1.61 - 1.82	246	233 - 259	8.5	7.8	DM8564-04	2
	G3516, 1200rpm		4.43	699	0.66	105	3.77	594	Not Tested				8.2	Not Tested	DM8536-06	0
	G3512, 1200rpm	2 g/hp-hr	4.16	676	0.62	101	3.54	574					8.2		DM8561-04	0
	G3516, 1200rpm		4.30	680	0.65	102	3.65	578					8.0		DM8539-06	0
	G3512, 1400rpm	1.5 g/hp-hr	4.56	712	0.68	107	3.88	605					8.3		DM8567-04	0
	G3516, 1400rpm		4.20	644	0.62	97	3.58	547					8.3		DM8542-08	0
	G3512, 1400rpm	2 g/hp-hr	3.97	639	0.60	96	3.37	543	3.14	2.65 - 3.63	440	370 - 516	8.2	8.1	DM8617-04	3
Waukesha VHP LT series	L5774LT	Standard	5.45	848	0.82	127	4.63	721	3.69	1.86 - 13.61	482	250 - 1526	8.0	7.4	Waukesha Ref. S8483-6 (Feb 2022)	5
	L5794LT	2.6 g/hp-hr	5.45	848	0.82	127	4.63	721	Not Tested				7.8	Not Tested		0
Waukesha VGF GL series	F18GL, H24GL	8.7:1 CR	4.08	636	0.61	95	3.47	541	3.83	1.38 - 7.00	470	179 - 886	7.4	7.3		7
		11:1 CR	5.30	827	0.48	74	4.82	753	2.76	2.66 - 2.86	372	341 - 403	8.0	7.0		2
Waukesha VHP GSI with REMVue Rich to Lean	L7042GSI	RB to LB	Not Applicable (field retrofit)						2.18	0.55 - 6.83	286	75 - 916	Not Appl.	7.3	Not Applicable	7
White VGT825	12VGT	REM Techn.	Not Available						40.87	40.87	5310	5310	Not Av.	12.5	Not Available	1/misfire

Table 11 Pre-chamber lean burn engine unburned methane and hydrocarbon emissions

Engine Exhaust Emission Factors (OEM vs. Field)

Prechamber Lean Burn Engines	Engine models		Emission factors (OEM factors corrected to rated load and speed)												OEM Reference (Standard spec)	Number of Engines
			Hydrocarbons										O2			
			OEM						Field				OEM	Field		
	Models	Settings (NOx; AFR)	THC		NMHC		Methane		Methane				% DRY			
			g/kw-hr	ppmvd 15% O2	g/kw-hr	ppmvd 15% O2	g/kw-hr	ppmvd 15% O2	Average g/kw-hr	Range g/kw-hr	Average ppmvd 15% O2	Range ppmvd 15% O3				
CAT G3600 ADEM3 series	G3606	0.5 g/hp-hr	8.46	1636	1.27	245	7.19	1390	Not Tested				12.8	Not Tested	DM8605-07	0
	G3608		8.46	1506	1.27	226	7.19	1280					12.0		DM8606-07	0
	G3612		8.66	1688	1.3	253	7.36	1435					12.8		DM8607-06	0
	G3616		8.46	1522	1.27	228	7.19	1294					12.0		DM8608-06	0
	G3606	0.7 g/hp-hr	8.06	1558	1.21	234	6.85	1324					12.5		EM1990-00	0
	G3608/1767kW		8.06	1442	1.21	216	6.85	1226	5.68	4.53 - 6.38	855	719 - 987	11.7	11.5	DM5561-07	3
	G3608/1823kW		7.86	1396	1.18	209	6.68	1187	4.42	4.38 - 4.45	719	698 - 739	11.6	11.3	DM5136-07	2
	G3612		8.25	1597	1.24	239	7.01	1357	Not Tested				12.5	Not Tested	EM1998-00	0
	G3616		8.06	1447	1.21	217	6.85	1230					11.7		DM5563-07	0
CAT G3600 ADEM4 series	G3606	0.3 g/hp-hr	7.01	1187	0.65	110	6.36	1077					11.0		EM1402-04	0
	G3608		5.93	1037	0.55	96	5.38	941					11.3		EM1410-04	0
	G3612		6.03	1092	0.56	101	5.47	991					11.5		EM1418-05	0
	G3616		5.74	1023	0.53	95	5.21	928					11.2		EM1426-04	0
	G3606	0.5 g/hp-hr	6.18	1054	0.57	97	5.61	956					10.9		EM0555-07	0
	G3608		5.51	983	0.51	91	5.00	892					11.3		EM0655-06	0
	G3612		5.31	968	0.49	90	4.82	879	4.01	3.73 - 5.81	680	642 - 994	11.4	11.2	EM0755-09	5
	G3616		5.33	969	0.49	90	4.84	879	Not Tested				11.2	Not Tested	EM0455-08	0
Waukesha VHP GL	L7042GL	1.5 g/hp-hr	7.48	1166	1.36	212	6.12	954	7.50	4.92 - 9.76	1063	703 - 1395	9.8	9.4	Waukesha Ref. S8483-6 (February 2022)	4
	L5790GL								5.79	5.79	805	805		8.6		1
Waukesha AT GL	AT25GL	28:1 AFR	10.87	1696	1.34	212	9.53	1484	Not Tested					Not Tested		0
	AT27GL	28:1 AFR	6.8	1060	0.67	106	6.13	954								0
	275GL	32:1 AFR	5.17	742	0.54	85	4.63	657					11.2			0
	275GL+	34:1 AFR	8.16	1272	0.82	127	7.34	1145					11.6			0
White GTLB825	6GTLB	2g/hp-hr	Not Available		1.01	Not Available			Not Tested				Not Avail.	Not Tested	Superior Engine Exhaust Emissions 10/25/2019 Provided by Rick Lucas Cooper Machinery Services	0
	8GTLB	2g/hp-hr			1.01				54.64	54.64	7354	7354		13.1		1/misfire
	12GTLB	1.5 g/hp-hr			0.82				Not Tested					Not Tested		0
	16GTLB	1.5 g/hp-hr			0.82				Not Tested					Not Tested		0
White GTLE825	6GTLE	2g/hp-hr	Not Available		Not Avail.	Not Available			Not Tested				Not Avail.	Not Tested		0
	8GTLE	2g/hp-hr			1.70				9.95	9.58 - 10.31	1522	1475 - 1569		10.0		2
	12GTLE	1.5 g/hp-hr			Not Avail.				Not Tested					Not Tested		0
	16GTLE	1.5 g/hp-hr			Not Avail.				Not Tested					Not Tested		0

Table 12 Rich burn methane slip up to 1 g/kW-h

Methane Exhaust Emission Factors (OEM vs. Field) for Open chamber RB Engines Tested 1 g/kw-hr or less

Emission factors (OEM factors corrected to rated load and speed)

Rich Burn Engines with Catalyst Ratings (OEM data - engine out emissions)	Engine Models: Models	Engine Models: Settings	OEM THC g/kw-hr	OEM THC ppmvd 15%O2	OEM NMHC g/kw-hr	OEM NMHC ppmvd 15%O2	OEM Methane g/kw-hr	OEM Methane ppmvd 15%O2	Field Methane Average g/kw-hr	Field Methane Range g/kw-hr	Field Methane Average ppmvd 15%O2	Field Methane Range ppmvd 15%O2	O2 OEM (% DRY)	O2 Field (% DRY)	OEM Reference	Number of Engines
Waukesha VHP GU, GSI	S5	Catalyst	1.22	175	0.41	58	0.82	117	0.41	0.34 - 0.53	62	52 - 76	0.3	0.0	Ref. S8483-6	4
	S4	Catalyst	3.40	194	0.54	39	2.86	155	0.34	0.22 - 0.69	45	28 - 86	0.3	0.1	(February 2022)	11
	S4	RB to LB	Not Available (field retrofit)						0.47	0.40 - 0.55	64	54 - 75	N/A	6.4	N/A	2
White G825	6G	Standard	Not Available		0.27	Not Available			Not Tested				Not Available	Not Tested	Superior Engine Exhaust Emissions 10/25/2019 by	0
	8G	Standard			0.27				0.82	0.54 - 0.97	105	70 - 130		0.7		7
	12G	Standard			0.27				Not Tested					Not Tested		0
	16G	Standard			0.27											0

Table 13 Rich burn methane slip more than 1 g/kW-h

Methane Exhaust Emission Factors (OEM vs. Field) for Open chamber RB Engines Tested over 1 g/kw-hr

Emission factors (OEM factors corrected to rated load and speed)

Rich Burn Engines. Standard and Catalyst Ratings (OEM data - engine out emissions)	Engine models: Models	Engine models: Settings	OEM THC g/kw-hr	OEM THC ppmvd 15%O2	OEM NMHC g/kw-hr	OEM NMHC ppmvd 15%O2	OEM Methane g/kw-hr	OEM Methane ppmvd 15%O2	Field Methane Average g/kw-hr	Field Methane Range g/kw hr	Field Methane Average ppmvd 15%O2	Field Methane Range ppmvd 15%O2	O2 OEM (% DRY)	O2 Field (% DRY)	OEM Reference (Standard spec)	Number of Engines
CAT G3400 TA series, 1800 RPM	G3408TA	CR 9.7:1	3.5	541	0.52	81	2.98	460	1.46	1.26 - 1.66	194	174 - 214	2.0	2.8	TM9181-01	2
CAT G3400 TA series, 1800 RPM		CR 8.5:1	2.2	365	0.33	55	1.87	310	1.79	1.79	207	207	2.0	0	TM9213-01	1
Waukesha VHP G, GU, GSI	F3521	Catalyst	2.72	388	0.00	58	2.72	330	2.63	2.63	308	308	0.3	1.2	Waukesha Ref. S8483-4 (April 2001)	1
	F3521GSI	Best Economy	3.13	446	0.48	68	2.65	378	1.90	1.57 - 2.43	276	250 - 317	0.3	0.7		4
	F3521GU		2.04	291	0.34	49	1.70	243	2.35	2.35	335	335	1.4	0.3		1
	F2895GU								3.52	3.52	392	392	1.4	1.0		1
Waukesha VHP GU, GSI S2	L7042GSI	Best Economy	2.04	291	0.34	49	1.70	243	2.52	1.66 - 3.40	335	226 - 477	1.4	0.8	Waukesha Ref. S8483-4 (April 2001)	4
	L7042GU		2.04	291	0.34	49	1.70	243	3.72	3.70 - 3.75	535	514 - 556	1.4	0.3		2
	L5794GSI		3.27	466	0.48	68	2.79	398	Not Tested				1.4	Not Tested		0
	L7042GU	Catalyst	2.72	388	0.41	58	2.31	330	4.1	523	410	523	0.3	0.5		1
	L7042GSI		2.72	388	0.41	58	2.31	330	2.25	1.01 - 3.04	283	119 - 387	0.3	0.7		4
Waukesha VHP GSI S5	L7044GSI	Customer catalyst	0.68	97	0.07	10	0.61	87	Not Tested				N/A	Not Tested	EngCalc4.3	0
	L7042GSI		0.95	136	0.10	14	0.86	122					N/A			0
White G825	6G	Standard	Not Available		0.27	Not Available			Not Tested				N/A	Not Tested	Superior Engine Exhaust Emissions 10/25/2019 Provided by Rick Lucas Cooper Machinery Services	0
	8G	Standard			0.27				6.6	3.19 - 10.00	726	370 - 1083	N/A	0.6		2
	12G	Standard			0.27				Not Tested				N/A	Not Tested		0
	16G	Standard			0.27				Not Tested				N/A	Not Tested		0
White GT825	6GT	Standard			1.36				Not Tested				N/A	Not Tested		0
	8GT	Standard			1.36				18.42	18.42	2627	2627	N/A	8.5		1-misfire
White GTL825	6GTL	Standard			0.67				Not Tested				N/A	Not Tested	Superior Turbocharged Gas Engines TC-613/1-89	0
	8GTL	Standard			0.67				15.52	7.94 - 33.85	2287	1166 - 5039	N/A	9.6		5
	12GTL	Standard			0.67				Not Tested				N/A	Not Tested		0
	16GTL	Standard			0.67				Not Tested				N/A	Not Tested		0
White SGT825	8SGT	Standard			1.00				Not Tested				N/A	Not Tested	Superior Turbocharged Gas Engines	0
	12SGT	Standard			0.67				7.82	7.82	952	952	N/A	7.7		1
	16SGT	Standard			0.67				8.18	8.18	1287	1287	N/A	8.3		1

Table 14 Open chamber lean burn methane slip more than 1 g/kW-h

Methane Exhaust Emission Factors (OEM vs. Field) for Open chamber LB Engines tested over 1 g/kw-hr

Emission factors (OEM factors corrected to rated load and speed)

Open Chamber Lean Burn Engines	Engine models: Models	Engine models: Settings (Nox; CR)	OEM THC g/kw-hr	OEM THC ppmvd 15%O2	OEM NMHC g/kw-hr	OEM NMHC ppmvd 15%O2	OEM Methane g/kw-hr	OEM Methane ppmvd 15%O2	Field Methane Average g/kw-hr	Field Methane Range g/kw-hr	Field Methane Average ppmvd 15%O2	Field Methane Range ppmvd 15%O2	O2 OEM (% DRY)	O2 Field (% DRY)	OEM Reference (Standard spec)	Number of Engines
CAT G3500 TALE series (EIS)	G3516, 1200rpm	1.5 g/hp-hr	4.43	705	0.66	106	3.77	599	2.89	2.44 - 3.33	422	368 - 476	8.2	7.9	DM5154-00	3
	G3512, 1200rpm	2 g/hp-hr	4.16	676	0.62	101	3.54	574	Not Tested				8.2	Not Tested	DM0150-03	0
	G3516, 1200rpm		4.31	685	0.65	103	3.66	582	2.10	1.55 - 2.39	309	228 - 352	8.0	7.4	DM0107-03	2
	G3512, 1400rpm	1.5 g/hp-hr	4.56	429	0.68	64	3.88	365	Not Tested				8.3	Not Tested	DM5120-00	0
	G3516, 1400rpm		4.10	643	0.62	46	3.48	597					8.3		DM5155-00	0
	G3512, 1400rpm	2 g/hp-hr	4.10	639	0.62	45	3.48	594					8.2		DM5118-00	0
	G3516, 1400rpm		3.90	620	0.58	44	3.32	576					8.3		DM5168-00	0
CAT G3500 ADEM3 series (corrected ppm to 0% O2)	G3512, 1200rpm	1.5 g/hp-hr	4.43	675	0.66	101	3.77	574	1.72	1.61 - 1.82	246	233 - 259	8.5	7.8	DM8564-04	2
	G3516, 1200rpm		4.43	699	0.66	105	3.77	594	Not Tested				8.2	Not Tested	DM8536-06	0
	G3512, 1200rpm	2 g/hp-hr	4.16	676	0.62	101	3.54	574					8.2		DM8561-04	0
	G3516, 1200rpm		4.30	680	0.65	102	3.65	578					8.0		DM8539-06	0
	G3512, 1400rpm	1.5 g/hp-hr	4.56	712	0.68	107	3.88	605					8.3		DM8567-04	0
	G3516, 1400rpm		4.20	644	0.62	97	3.58	547					8.3		DM8542-08	0
	G3512, 1400rpm	2 g/hp-hr	3.97	639	0.60	96	3.37	543	3.14	2.65 - 3.63	440	370 - 516	8.2	8.1	DM8617-04	3
Waukesha VHP LT series	L5774LT	Standard	5.45	848	0.82	127	4.63	721	3.69	1.86 - 13.61	482	250 - 1526	8.0	7.4	Waukesha Ref. S8483-6 (Feb 2022)	5
	L5794LT	2.6 g/hp-hr	5.45	848	0.82	127	4.63	721	Not Tested				7.8	Not Tested		0
Waukesha VGF GL series	F18GL, H24GL	8.7:1 CR	4.08	636	0.61	95	3.47	541	3.83	1.38 - 7.00	470	179 - 886	7.4	7.3		7
		11:1 CR	5.30	827	0.48	74	4.82	753	2.76	2.66 - 2.86	372	341 - 403	8.0	7.0		2
Waukesha VHP GSI with REMVue Rich to Lean	L7042GSI	RB to LB	Not Applicable (field retrofit)						2.41	1.41 - 6.83	316	179 - 916	Not Appl.	7.3	Not Applicable	7
White VGT825	12VGT	REM Techn.	Not Available						40.87	40.87	5310	5310	Not Av.	12.5	Not Available	1/misfire

Table 15 Pre-chamber lean burn methane slip more than 1 g/kW-h

Methane Exhaust Emission Factors (OEM vs. Field) for Pre-chamber Engines Tested over 1 g/kw-hr

Emission factors (OEM factors corrected to rated load and speed)

Prechamber Lean Burn Engines	Engine models: Models	Engine models: Settings (NOx; AFR)	Hydrocarbons OEM THC g/kw-hr	OEM THC ppmvd 15% O2	OEM NMHC g/kw-hr	OEM NMHC ppmvd 15% O2	OEM Methane g/kw-hr	OEM Methane ppmvd 15% O2	Field Methane Average g/kw-hr	Field Methane Range g/kw-hr	Field Methane Average ppmvd 15% O2	Field Methane Range ppmvd 15% O2	O2 OEM % DRY	O2 Field % DRY	OEM Reference (Standard spec)	Number of Engines
CAT G3600 ADEM3 series	G3606	0.5 g/hp-hr	8.46	1636	1.27	245	7.19	1390	Not Tested				12.8	Not Tested	DM8605-07	0
	G3608		8.46	1506	1.27	226	7.19	1280					12.0		DM8606-07	0
	G3612		8.66	1688	1.3	253	7.36	1435					12.8		DM8607-06	0
	G3616		8.46	1522	1.27	228	7.19	1294					12.0		DM8608-06	0
	G3606	0.7 g/hp-hr	8.06	1558	1.21	234	6.85	1324					12.5		EM1990-00	0
	G3608/1767kW		8.06	1442	1.21	216	6.85	1226	5.68	4.53 - 6.38	855	719 - 987	11.7	11.5	DM5561-07	3
	G3608/1823kW		7.86	1396	1.18	209	6.68	1187	4.42	4.38 - 4.45	719	698 - 739	11.6	11.3	DM5136-07	2
	G3612		8.25	1597	1.24	239	7.01	1357	Not Tested				12.5	Not Tested	EM1998-00	0
	G3616		8.06	1447	1.21	217	6.85	1230					11.7		DM5563-07	0
CAT G3600 ADEM4 series	G3606	0.3 g/hp-hr	7.01	1187	0.65	110	6.36	1077					11.0		EM1402-04	0
	G3608		5.93	1037	0.55	96	5.38	941					11.3		EM1410-04	0
	G3612		6.03	1092	0.56	101	5.47	991					11.5		EM1418-05	0
	G3616		5.74	1023	0.53	95	5.21	928					11.2		EM1426-04	0
	G3606	0.5 g/hp-hr	6.18	1054	0.57	97	5.61	956					10.9		EM0555-07	0
	G3608		5.51	983	0.51	91	5.00	892					11.3		EM0655-06	0
	G3612		5.31	968	0.49	90	4.82	879	4.01	3.73 - 5.81	680	642 - 994	11.4	11.2	EM0755-09	5
	G3616		5.33	969	0.49	90	4.84	879	Not Tested				11.2	Not Tested	EM0455-08	0
Waukesha VHP GL	L7042GL	1.5 g/hp-hr	7.48	1166	1.36	212	6.12	954	7.50	4.92 - 9.76	1063	703 - 1395	9.8	9.4	Waukesha Ref. S8483-6 (February 2022)	4
	L5790GL								5.79	5.79	805	805		8.6		1
Waukesha AT GL	AT25GL	28:1 AFR	10.87	1696	1.34	212	9.53	1484	Not Tested					Not Tested		0
	AT27GL	28:1 AFR	6.8	1060	0.67	106	6.13	954								0
	275GL	32:1 AFR	5.17	742	0.54	85	4.63	657					11.2			0
	275GL+	34:1 AFR	8.16	1272	0.82	127	7.34	1145					11.6			0
White GTLB825	6GTLB	2g/hp-hr	Not Available		1.01	Not Available			Not Tested				Not Avail.	Not Tested	Superior Engine Exhaust Emissions 10/25/2019 Provided by Rick Lucas Cooper Machinery Services	0
	8GTLB	2g/hp-hr			1.01				54.64	54.64	7354	7354		13.1		1/misfire
	12GTLB	1.5 g/hp-hr			0.82				Not Tested					Not Tested		0
	16GTLB	1.5 g/hp-hr			0.82				Not Tested					Not Tested		0
White GTLE825	6GTLE	2g/hp-hr	Not Available		Not Avail	Not Available			Not Tested				Not Avail.	Not Tested		0
	8GTLE	2g/hp-hr			1.70				9.95	9.58 - 10.31	1522	1475 - 1569		10.0		2
	12GTLE	1.5 g/hp-hr			Not Avail				Not Tested					Not Tested		0
	16GTLE	1.5 g/hp-hr			Not Avail				Not Tested					Not Tested		0

Emission factors to estimate the methane slip in the exhaust of stationary natural gas engines are provided for each of the four combustion styles. These are more generic and can be applied to a series of popular engine models. Power and fuel consumption vary between models and their legacy predecessors that add to assumptions required to specify one factor. The field data is employed to identify a range of values to specify an upper and lower bound to present a most representative factor for each engine model series.

Several additional units of measure are also specified. However, these additional units add layers of assumptions which erode the accuracy of the estimate. The units for ppvmd@15% O_2 is a direct measurement and thus the most accurate. Using any of the other units will introduce at least 20% error. Tables 16 and 17Table 17 summarize the choice of recommended emission factors based on our field data.

The following conversion factors may be applied to approximate the additional units.

- Multiply ppmvd@15%O_2 by 0.007 to obtain g/kW-h.
- Multiply g/kW-h by 277.8 to obtain g/GJ.
- Multiply g/kW-h by 2.78 to obtain g/kW-e^3m^3.

Note that estimates of fuel flow rate and power are required for all units except ppmvd @15% O_2. The exhaust mass flow rate is needed to determine the total methane emission mass flow rate when using ppmvd@15% O_2.

Table 16 Engine methane slip emission factors for Caterpillar and Waukesha engines

Combustion Type	Make	Model	Catalyst	# of Engines	g/kW-hr		ppmvd at 15% O2		g/GJ	g/kW-e3m3	g/kW-hr	g/kW-hr	g/kW-hr	g/GJ	g/GJ	g/GJ	g/kW-e3m3	g/kW-e3m3	g/kW-e3m3	ppmvd @ 15% O2	ppmvd @ 15% O2	ppmvd @ 15% O2
					OEM	Test Average	OEM	Test Average	Test Average	Test Average	Suggested Emission Factor	Upper bound Emission Factor	Lower bound Emission Factor	Suggested Emission Factor	Upper bound Emission Factor	Lower bound Emission Factor	Suggested Emission Factor	Upper bound Emission Factor	Lower bound Emission Factor	Suggested Emission Factor	Upper bound Emission Factor	Lower bound Emission Factor
Open RB	Waukesha	S5	Y	3	0.82	0.41	117	61	114	1.14	0.40	0.45	0.30	111	111	83	1.11	1.25	0.83	125	155	115
			N	1		0.43		65	119	1.19												
		S4	Y	10	2.86	0.34	155	45	94	0.94												
			N	1		0.46		64	128	1.28												
		S2	Y	3	2.31	2.76	330	356	767	7.67	2.70	2.76	2.25	750	767	625	7.5	7.67	6.25	345	356	305
			N	9	1.70	2.56	243	344	711	7.11												
		F3521	Y	1	2.31	2.63	330	308	731	7.31												
			N	6	1.70	2.25	243	305	625	6.25												
	Caterpillar	G3408	Y	2	1.87	1.79	310	207	497	4.97												
			N	1	2.98	1.46	460	194	406	4.06												
	Average	All	Y	19	2.07	1.57	274	195	436	4.36												
			N	18		1.43		194	397	3.97												
Open LB	Waukesha	L5774LT	N/A	5	4.63	3.69	721	482	1,025	10.25	3.70	3.80	2.00	1,028	1,056	556	10.28	10.56	5.56	485	485	260
		L7042GSI RB to LB	N/A	9	N/A	1.96	N/A	260	544	5.44												
		VGF GL LCR	N/A	9	3.47	3.83	541	470	1,064	10.64												
	Caterpillar	G3512/16	N/A	12	3.63	2.49	589	360	692	6.92												
	Average	All	N/A	35	3.91	2.99	617	393	831	8.31												
Pre-Chamber	Waukesha	VHP GL S2	N/A	4	6.12	7.16	954	1,012	1,989	19.89	5.50	7.20	4.00	1,528	2,000	1,111	15.28	20.00	11.11	890	1015	5.5
	Caterpillar	G3600A3	N/A	5	6.78	5.18	1,210	801	1,439	14.39												
		G3600A4	N/A	7	4.82	4.5	879	766	1,250	12.50												
	Caterpillar MSAPR	G3600A3	N/A	30	6.89	5.71	1,227	1,004	1,586	15.86												
		G3600A4	N/A	16	4.98	4.1	899	723	1,139	11.39												
	Average	All	N/A	62	5.92	5.33	1,034	861	1,481	14.81												

Table 17 Engine methane slip emission factors for White Superior engines

Combustion Type	Make	Model	Catalyst	# of Engines	g/kW-hr		ppmvd at 15% O2		g/GJ	g/kW-e3m3	g/kW-hr	g/kW-hr	g/kW-hr	g/GJ	g/GJ	g/GJ	g/kW-e3m3	g/kW-e3m3	g/kW-e3m3	ppmvd @ 15% O2	ppmvd @ 15% O2	ppmvd @ 15% O2
					OEM	Test Average	OEM	Test Average	Test Average	Test Average	Suggested Emission Factor	Upper bound Emission Factor	Lower bound Emission Factor	Suggested Emission Factor	Upper bound Emission Factor	Lower bound Emission Factor	Suggested Emission Factor	Upper bound Emission Factor	Lower bound Emission Factor	Suggested Emission Factor	Upper bound Emission Factor	Lower bound Emission Factor
Open RB	White Superior	8G825	Y	4	N/A	0.74	N/A	94	206	2.056	1	1	0.75	278	278	208	2.778	2.778	2.083	94	94	94
			N	5		3.2		363	889	8.889	3	3	3	833	833	833	8.333	8.333	8.333	363	363	363
		12SGT825	N	1	N/A	7.82	N/A	952	2,172	21.722	8	11	7.8	2,222	3,056	2,167	22.222	30.556	21.667	1,600	1,600	950
		16SGT825	N	1	N/A	8.18	N/A	1,287	2,272	22.722												
		8GTL825	N	4	N/A	10.94	N/A	1,599	3,039	30.389												
	Average	All	Y	4	N/A	0.74	N/A	94	206	2.056												
			N	12	N/A	7.54	N/A	1,050	2,094	20.944												
	White Superior	8GTL825 Anomaly	N	1	N/A	33.89	N/A	5,039	Cylinder 8 not firing		35	X	X	9,722	X	X	97.222	X	X	5,039	X	X
	White Superior	8GT825 Anomaly	N	1	N/A	20.05	N/A	2,684	Cylinder 2 not firing		20	X	X	5,556	X	X	55.556	X	X	2,684	X	X
Open LB	White Superior	12VGT825 Anomaly	N/A	1	N/A	>55.65	N/A	>7,269	Cylinder 1 not firing		>56	X	X	>1,5555	X	X	>155.556	X	X	>7,269	X	X
Pre-chamber Lean Burn	White Superior	8GTLE825	N/A	1	N/A	9.58	N/A	1,475	2,661	26.611	10	10.5	9.5	2,778	2,917	2,639	27.778	29.167	26.389	1,500	1,570	1,475
			N/A	1	N/A	10.31	N/A	1,569	2,864	28.639												
	Average	All	N/A	2	N/A	9.95	N/A	1,522	2,763	27.625												
	White Superior	8GTLB825 Anomaly	N/A	1	N/A	58.63	N/A	7,932	Cylinder 8 not firing		60	X	X	16,667	X	X	166.667	X	X	7,932	X	X

Table 18 Canadian and Alberta fleet methane emissions for the most common stationary engine models based on an inventory list from ECCC's MSAPR engine database

Make	Model Designation as per MSAPR list	Total number of engines		Assumed Engine Models	Nameplate power (kW) (estimated)	Suggested Emission Factor (g/kW-h)	Total Emissions Based on Suggested Emission Factors (Kg/h)	
		Canada	Alberta				Canada	Alberta
Waukesha	8LAT27GL	8	5	Pre-chamber LB	1570	5.5	69.1	43.2
	12V AT25GL	9	1		1940	5.5	96.0	10.7
	12V AT27GL	6	4		2335	5.5	77.1	51.4
	16V AT27GL	1	1		3375	5.5	18.6	18.6
	16V275GL	5	0		3356	5.5	92.3	0.0
	L7042GL/GLS3/GL ESM	415	325	Pre-chamber LB	1103	5.5	2,517.6	1,971.6
	L7042GSI/GU/GSIU/S4/GSI ESM/GSIL	507	405	Rich burn	1103	2.7	1,509.9	1,206.1
	L7042GSI S4	38	33	Rich burn	1103	0.4	16.8	14.6
	L7042GSI S5	37	29	Rich burn, modern	1119	0.4	16.6	13.0
	L7044GSI/GSI ESM/G	303	233	Rich burn	1253	2.7	1,025.1	788.3
	L7044GSI S4	3	3	Rich burn	1253	0.4	1.5	1.5
	L7044GSI S5	24	24	Rich burn, modern	1417	0.4	13.6	13.6
	P9390GSI/GSIU	24	24	Rich burn	1476	2.7	95.6	95.6
	P9394GSI	12	10	Rich burn	1476	2.7	47.8	39.9
	P9390GL/REM	17	17	Pre-chamber LB	1476	5.5	138.0	138.0
	P9394GSI S5	1	1	Rich burn modern	1864	0.4	0.7	0.7
	F3521GSI/GU/GSIU/GSL/G/NA; F3524GSI	255	196	Rich burn	551	2.7	379.4	291.6
	F3521GL	53	40	Pre-chamber LB	551	3.7	108.1	81.5
	F3514GSI/GSI ESM/GU	25	19	Rich burn	552	2.7	37.3	28.3
	F2895GU/GSIU/GSI	58	44	Rich burn	455	2.7	71.3	54.1
	F2895G	11	11	Rich burn	314	2.7	9.3	9.3
	F2895GL/GL ESM	6	6	Lean burn	455	3.7	10.1	10.1
	L5790GU/GSIU	38	28	Rich burn	949	2.7	97.4	71.7
	L5790G	11	8	Rich burn	630	2.7	18.7	13.6
	L5790GL	46	39	Pre-chamber LB	906	5.5	229.2	194.3
	L5774/LT/LTE/LT ESM; L5794LT/ESM/LTE	108	76	Lean burn	954	3.7	381.2	268.3
	L5794LT/ESM/LTE	136	96	Lean burn	1081	3.7	544.0	384.0
	H24GL/GLD/GL LCR/GL HRC	330	265	Lean burn	400	3.7	488.4	392.2
	H24GSI/H2475G	9	9	Rich burn	400	2.7	9.7	9.7
	F18GLGL LCR/GL HCR/	234	202	Lean burn	300	3.7	259.7	224.2
	F18GSI/SE/GSID	4	3	Rich burn	300	2.7	3.2	2.4
	L36GL/GL HCR/GL LCR; P48GL	57	37	Lean burn	600	3.7	126.5	82.1
	P48GL	58	46	Lean burn	800	3.7	171.7	136.2
	L36GSI/GSID; P48GSI	4	4	Rich burn	600	2.7	6.5	6.5
	P48GSI	1	1	Rich burn	800	2.7	2.2	2.2
Caterpillar	G3606/TAW/TALE/TA/LE/GCTA	82	56	Pre-chamber LB	1324	5.5	597.1	407.8
	G3606 A4	6	6		1417	5.5	46.8	46.8
	G3608/TAWLE/TAW/LE/SITA	302	178		1767	5.5	2,935.0	1,729.9
	G3608 A4	19	19		1864	5.5	194.8	194.8
	G3612/TAW/TA/SITA/LE/A3	152	80		2647	5.5	2,212.9	1,164.7
	G3612 A4	2	2		2796	5.5	30.8	30.8
	G3616/TALE/AFRC/TA/LE/GC	79	41		3531	5.5	1,534.2	796.2
	G3616A DEM4	2	2		3729	5.5	41.0	41.0
	G3516TALE/AFRC/LE/B/C	418	303	Lean burn	858	3.7	1,327.0	961.9
	G3516TA	34	34	Rich burn	809	2.7	74.3	74.3
	G3516NA	9	7	Rich burn	492	2.7	12.0	9.3
	G3520/LE/B LE/TALE/H/C/H EP TALE/B 1.34	40	33	Lean burn	1104	3.7	163.4	134.8
	G3512/TA/TAW/SITA	37	28	Rich burn	589	2.7	58.8	44.5
	G3512TALE/AFRC/LE/B	310	240	Lean burn	642	3.7	736.4	570.1
	G3512NA	10	5	Rich burn	391	2.7	10.6	5.3
	G3508TALE/TAWLE/LE	25	18	Lean burn	500	3.7	46.3	33.3
	G3508/TA,SITA	4	4	Rich burn	391	2.7	4.2	4.2
	G379TA	4	3	Rich burn	259	2.7	2.8	2.1
	G398TA/TAW/SITA	13	11	Rich burn	348	2.7	12.2	10.3
	G398NA	9	9	Rich burn	272	2.7	6.6	6.6
	G399TA/TAW/SITA	4	4	Rich burn	518	2.7	5.6	5.6
	12-CG137	4	4	Rich burn	447	2.7	4.8	4.8
	8-CG137	1	1	Rich burn	298	2.7	0.8	0.8
	G3408TA/TAW	96	74	Rich burn	298	2.7	77.2	59.5
	G3408 LE/CLE/C	30	11	Lean burn	298	3.7	33.1	12.1
	G3412TA/TAW/SITA/NA	96	76	Rich burn	448	2.7	116.1	91.9
	G3412NA	2	2	Rich burn	272	2.7	1.5	1.5
	G3412LE/C/CLE/TALE/AFRC	56	27	Lean burn	448	3.7	92.8	44.8
	G3406NA	4	4	Rich burn	160	2.7	1.7	1.7
	G3406TA	18	10	Rich burn	242	2.7	11.8	6.5
	G3306/B/BTA/TA/ATAAC/NA	19	16	Rich burn	108	2.7	5.5	4.7
	G3306TA	2	2	Rich burn	149	2.7	0.8	0.8
White Superior	6G825	26	21	Rich burn	447	3	34.9	28.2
	8G825	78	71	Rich burn	597	3	139.7	127.2
	12G825	15	15	Rich burn	895	3	40.3	40.3
	16G825	18	18	Rich burn	1193	3	64.4	64.4
	8GT/GTL	81	63	Rich burn	820	8	531.4	413.3
	12SGT	4	4	Rich burn	1491	8	47.7	47.7
	16GT/GTL	6	6	Rich burn	1641	8	78.8	78.8
	16SGT	18	10	Rich burn	1976	8	284.5	158.1
	8GTLE/B/X	9	9	Pre-chamber LB	820	10	73.8	73.8
	12SGTLE/SGTB/	5	3	Pre-chamber LB	1491	10	74.6	44.7
	16SGTB/SGTD	19	17	Pre-chamber LB	1976	10	375.4	335.9
			Total estimated methane emissions in stationary engine exhaust (Kg/h)				20,834	14,585
			Total estimated methane emissions in stationary engine exhaust (Tonnes/y)				182,508	127,763

Most of the engine models presented in MSAPR inventory are not described with enough definition to agree with the OEM nomenclature. For example, "G3512GL" contains both Caterpillar (G3512) and Waukesha (GL) nomenclature. The engine model stated in the MSAPR list is normally incomplete which required guessing for the engine models. Waukesha and Caterpillar engine models are assumed as listed in Table 18. The Caterpillar models did not specify the combustion style. Accurata estimated the Caterpillar engine combustion styles as

- G3500 as 75% Lean Burn,
- G3500 as 25% Rich Burn,
- G3400 as 60% Rich Burn, and
- G3400 40% Lean Burn.

Power varies with the actual load, engine speed and the age of the engine model. The name plate power is assumed to be the most common OEM specified full load speed and power pertaining to each engine model. Significant error is embedded in the estimate due to the variety of assumptions required in order to assemble the estimate. The following aspects affect the accuracy of the estimate.

- Full speed and load nameplate power is assumed for each model.
- The engine operation period of 8760 hours per year.
- The units of g/kW-h contain inherent errors of +/- 20%.
- Our experience suggests that only 20% of the fleet is operating at OEM full speed and load.
- Errors in the engine model assumption will also introduce at least +/- 30% error.
- The accumulated errors will be offset by the overstated engine power and speed assumption.

Accurata is not able to speculate on the actual error embedded in the exhaust methane emission estimates. The quality of the database will not support compiling a reasonable error estimate. The fleet estimate is based on larger engines where MSAPR regulations apply. The approximate methane emissions in the exhaust of stationary natural gas engines is 128 kT/y in Alberta and 183 kT/y in Canada.

Crankcase emission estimates (blowby) are examined from literature and our test data. Additional research was undertaken for published literature and I OEM manuals to determine blowby estimates. The reading list references have been updated to include the articles on blowby.

An examination of crankcase blowby recirculation (exhaust gas recirculation) systems is presented. These systems extract the blowby gasses, filter the oil from the stream and direct the gasses back into the engine air inlet. The methane may then be blended with the primary fuel supply and combusted in the engine. The oil is returned to the engine crankcase. Several systems are available from both OEM and third-party suppliers. These systems are described with their applicability to engine models and the costs to install and maintain them.

The crankcase emissions consist of methane and unburned hydrocarbons from lubricants. The data presented is focused on methane, excluding unburned hydrocarbons. Crankcase methane emissions were found to be a contribution to methane slip volumes in the exhaust of stationary natural gas engines. Accurata and Spartan field data estimates suggested between 20% to 60% of the exhaust volume is methane slip (CH4) attributed to engine blowby. We used 40% as a representative estimate. That volume estimate was applied to the MSAPR fleet engine list to estimate the volumes of methane emissions attributed to the Alberta and Canadian engine fleets. Table 19Table 19 below summarizes that effort.

Table 19 Crankcase blowby estimates of the Alberta and Canadian fleets

Make	Model Designation as described in ECCC MSAPR list	Total number of engines		Assumed Engine Models	Total Methane Emissions in Engine Blowby (m3/h) (worn engine)							
					CSU Data (3 % of OEM Blowby Rate)		OEM Emission Factor (20 % of Total OEM Predicted Methane Slip)		Accurata Estimate (40% of Total Methane Slip Based on Emission Factors applied to MSAPR list)		Howard Malm Estimate (kW*0.0017/0.9)	
		Canada	Alberta		Canada	Alberta	Canada	Alberta	Canada	Alberta	Canada	Alberta
Waukesha	8LAT27GL	8	5	Pre-chamber LB	24	15	26	16	31	19	24	15
	12V AT25GL	9	1		41	5	23	3	43	5	33	4
	12V AT27GL	6	4		28	18	29	19	34	23	26	18
	16V AT27GL	1	1		6	6	7	7	8	8	6	6
	16V275GL	5	0		31	0	15	0	41	0	32	0
	L7042GL/GLS3/GL ESM	415	325	Pre-chamber LB	1,691	1,324	623	488	1,119	876	865	677
	L7042GSI/GU/GSIU/S4/GSI ESM/GSIL	507	405	Rich burn	2,066	1,650	250	200	671	536	1,056	844
	L7042GSI S4	38	33	Rich burn	155	134	27	23	7	6	79	69
	L7042GSI S5	37	29	Rich burn, modern	151	118	8	6	7	6	78	61
	L7044GSI/GSI ESM/G	303	233	Rich burn	1,235	950	170	130	456	350	717	551
	L7044GSI S4	3	3	Rich burn	12	12	2	2	1	1	7	7
	L7044GSI S5	24	24	Rich burn, modern	98	98	6	6	6	6	64	64
	P9390GSI/GSIU	24	24	Rich burn	122	122	16	16	43	43	67	67
	P9394GSI	12	10	Rich burn	61	51	11	9	21	18	33	28
	P9390GL/REM	17	17	Pre-chamber LB	87	87	34	34	61	61	47	47
	P9394GSI S5	1	1	Rich burn modern	5	5	0	0	0	0	4	4
	F3521GSI/GU/GSIU/GSL/G/NA; F3524GSI	255	196	Rich burn	520	399	53	41	169	130	265	204
	F3521GL	53	40	Pre-chamber LB	108	82	40	30	48	36	55	42
	F3514GSI/GSI ESM/GU	25	19	Rich burn	51	39	5	4	17	13	26	20
	F2895GU/GSIU/GSI	58	44	Rich burn	118	90	8	6	32	24	50	38
	F2895G	11	11	Rich burn	22	22	1	1	4	4	7	7
	F2895GL/GL ESM	6	6	Lean burn	12	12	4	4	4	4	5	5
	L5790GU/GSIU	38	28	Rich burn	155	114	11	8	43	32	68	50
	L5790G	11	8	Rich burn	45	33	3	2	8	6	13	10
	L5790GL	46	39	Pre-chamber LB	187	159	57	48	102	86	79	67
	L5774/LT/LTE/LT ESM; L5794LT/ESM/LTE	108	76	Lean burn	440	310	106	75	169	119	195	137
	L5794LT/ESM/LTE	136	96	Lean burn	554	391	151	107	242	171	278	196
	H24GL/GLD/GL LCR/GL HRC	330	265	Lean burn	158	127	102	82	217	174	249	200
	H24GSI/H2475G	9	9	Rich burn	4	4	1	1	4	4	7	7
	F18GLGL LCR/GL HCR/	234	202	Lean burn	84	73	54	47	115	100	133	114
	F18GSI/SE/GSID	4	3	Rich burn	1	1	0	0	1	1	2	2
	L36GL/GL HCR/GL LCR; P48GL	57	37	Lean burn	41	27	26	17	56	37	65	42
	P48GL	58	46	Lean burn	56	44	36	28	76	61	88	70
	L36GSI/GSID; P48GSI	4	4	Rich burn	3	3	1	1	3	3	5	5
	P48GSI	1	1	Rich burn	1	1	0	0	1	1	2	2
Caterpillar	G3606/TAW/TALE/TA/LE/GCTA	82	56	Pre-chamber LB	130	89	166	114	265	181	205	140
	G3606 A4	6	6		10	10	9	9	21	21	16	16
	G3608/TAWLE/TAW/LE/SITA	302	178		640	377	817	482	1,304	769	1,008	594
	G3608 A4	19	19		42	42	39	39	87	87	67	67
	G3612/TAW/TA/SITA/LE/A3	152	80		483	254	616	324	984	518	760	400
	G3612 A4	2	2		7	7	6	6	14	14	11	11
	G3616/TALE/AFRC/TA/LE/GC	79	41		335	174	427	222	682	354	527	273
	G3616A DEM4	2	2		9	9	8	8	18	18	14	14
	G3516TALE/AFRC/LE/B/C	418	303	Lean burn	430	312	289	210	590	428	677	491
	G3516TA	34	34	Rich burn	33	33	9	9	33	33	52	52
	G3516NA	9	7	Rich burn	5	4	3	2	5	4	8	7
	G3520/LE/B LE/TALE/H/C/H EP TALE/B 1.34	40	33	Lean burn	53	44	36	29	73	60	83	69
	G3512/TA/TAW/SITA	37	28	Rich burn	26	20	7	6	26	20	41	31
	G3512TALE/AFRC/LE/B	310	240	Lean burn	239	185	161	124	327	253	376	291
	G3512NA	10	5	Rich burn	5	2	2	1	5	2	7	4
	G3508TALE/TAWLE/LE	25	18	Lean burn	15	11	10	7	21	15	24	17
	G3508/TA,SITA	4	4	Rich burn	2	2	1	1	2	2	3	3
	G379TA	4	3	Rich burn	1	1	0	0	1	1	2	1
	G398TA/TAW/SITA	13	11	Rich burn	5	5	1	1	5	5	9	7
	G398NA	9	9	Rich burn	3	3	1	1	3	3	5	5
	G399TA/TAW/SITA	4	4	Rich burn	2	2	1	1	2	2	4	4
	12-CG137	4	4	Rich burn	2	2	1	1	2	2	3	3
	8-CG137	1	1	Rich burn	0	0	0	0	0	0	1	1
	G3408TA/TAW	96	74	Rich burn	34	26	18	14	34	26	54	42
	G3408 LE/CLE/C	30	11	Lean burn	11	4	6	2	15	5	17	6
	G3412TA/TAW/SITA	96	76	Rich burn	52	41	29	23	52	41	81	64
	G3412NA	2	2	Rich burn	1	1	0	0	1	1	1	1
	G3412LE/C/CLE/TALE/AFRC	56	27	Lean burn	30	15	14	7	41	20	47	23
	G3406NA	4	4	Rich burn	1	1	0	0	1	1	1	1
	G3406TA	18	10	Rich burn	5	3	2	1	5	3	8	5
	G3306/B/BTA/TA/ATAAC	19	16	Rich burn	3	3	0	0	3	3	5	5
	G3306NA	2	2	Rich burn	0	0	0	0	0	0	0	0
White Superior	6G825	26	21	Rich burn	14	11	N/A	N/A	15	13	22	18
	8G825	78	71	Rich burn	56	51	N/A	N/A	62	57	88	80
	12G825	15	15	Rich burn	16	16	N/A	N/A	18	18	25	25
	16G825	18	18	Rich burn	26	26	N/A	N/A	29	29	41	41
	8GT/GTL	81	63	Rich burn	80	62	N/A	N/A	236	184	125	98
	12SGT	4	4	Rich burn	7	7	N/A	N/A	21	21	11	11
	16GT/GTL	6	6	Rich burn	12	12	N/A	N/A	35	35	19	19
	16SGT	18	10	Rich burn	43	24	N/A	N/A	126	70	67	37
	8GTLE/B/X	9	9	Pre-chamber LB	9	9	N/A	N/A	33	33	14	14
	12SGTLE/SGTB/	5	3	Pre-chamber LB	9	5	N/A	N/A	33	20	14	8
	16SGTB/SGTD	19	17	Pre-chamber LB	45	40	N/A	N/A	167	149	71	63
Total estimated Methane Emissions in blowby (m3/h)					**11,307**	**8,472**	**4,586**	**3,106**	**9,261**	**6,483**	**9,345**	**6,739**
Total estimated Methane Emissions in blowby (m3/y)					**99,048,758**	**74,212,581**	**40,172,708**	**27,206,670**	**81,122,096**	**56,789,541**	**81,860,215**	**59,030,366**
Total estimated Methane Emissions in blowby (Tonnes/h) based on 0.9 kg/m3					**10**	**8**	**4**	**3**	**8**	**6**	**8**	**6**
Total estimated Methane Emissions in blowby (Tonnes/y) based on 0.9 kg/m3					**89,144**	**66,791**	**36,155**	**24,486**	**73,010**	**51,111**	**73,674**	**53,127**

2.11. Technology Options to Reduce or Capture Methane Emissions in Engine Exhaust

The regulatory aspects of NO_x compliance in Canada have offered two paths of combustion style for engine owners. Open chamber and pre-chamber lean burn combustion styles offer the operator an option to meet NO_x compliance with the benefits of lower fuel consumption and longer service intervals. Unfortunately, these combustion styles should produce higher methane slip emissions.

Rich burn combustion styles with an NSCR catalyst will theoretically produce much lower methane slip emissions than the lean burn models. However, the following characteristics impose higher operating costs for the engine owner compared with the lean burn engines:

- higher carbon tax from higher fuel consumption,
- more frequent NO_x compliance testing,
- catalyst maintenance costs, and
- shorter service intervals due to higher engine cylinder operating temperatures.

An NSCR catalyst utilizes natural gas in the exhaust stream to react with the catalyst and reduce the NO_x concentration. Theoretically the methane slip in the exhaust can replace some of the methane introduced by the rich air-fuel ratio provided to manage the catalyst reaction. But the NSCR catalyst is not designed to destruct unburned methane in the exhaust. The combustion temperature will significantly exceed the exhaust temperature to do so specifically for destruction of methane gas. A change in engine geometry might offer a compromise to obtain the best of both worlds in reduction of NO_x and methane slip.

Waukesha advertises reduced crevice volumes in their latest VHP GSI Series 5 engine upgrades. They offer a kit to upgrade existing VHP GSI, GL and LT engines to their latest Series 5 technology. The conversion includes upgraded cylinder heads, turbochargers, pistons and engine management systems. The design requires an NSCR catalyst to condition the exhaust gasses. The engine may be tuned rich to burn more fuel in the catalyst and produce less raw methane in the exhaust stream. The NOx emissions will be compliant but the operating costs will be much higher than lean burn combustion engines producing the same rated power. CO2 emissions will also increase.

Cooper, Caterpillar and Waukesha have all advertised testing of hydrogen fuels to reduce carbon emissions. The use of hydrogen fuels offers potential to eliminate methane slip but industry wide hydrogen distribution for use as fuel is not available at present. Cooper has not announced any measures to reduce methane slip at the time of this writing.

Few options are currently available for mitigation of methane in the engine exhaust released to the atmosphere. Waukesha has installed a crankcase recirculation system on their VHP GSI and GF engines (Waukesha INNIO n.d.). This system directs the crankcase fumes through a filter and into the air inlet to reprocess the gasses in the combustion chamber. Similar crankcase ventilation systems are available from Solberg and FleetGuard. No other available technology upgrades are currently commercially available to address methane slip. As previously discussed, development projects by engine manufacturers are underway to address methane slip. Some retrofit options are available from the OEM's and third party suppliers.

2.11.1. Retrofit Options for Crankcase Vent Capture

No standard CCV retrofit option is available for White Superior 825 series engines from third-party suppliers and the OEM model is equipped with an ingestive system as standard. Caterpillar has developed retrofit kits for the G3600A4 and G3600A3. We are not aware of any retrofit crankcase vent kits installed on G3600 engines in Alberta. The typical CCV retrofit kit from Caterpillar includes:

- fumes disposal filter group,
- cylinder block cover group (breather),
- heat shield group,
- filter support group (mounting),
- turbo lines group,
- air lines group,
- coolant lines group, and
- engine reprogramming with registration is after kit installation.

On GSI or GL engines where catalyst or heat recovery equipment are utilized, Waukesha offered an option to replace the venturi style crankcase breather on GSI engines with the eductor system. This option also allows the breather vapors from the eductor system to be routed downstream of any catalyst or heat recovery equipment. Catalytic converters can be contaminated by any oil additives suspended in the crankcase vapors. Also, any oxygen that is pulled into the breather system may prevent the reduction reaction from taking place in the catalytic converter.

Waukesha offers upgrade kits for Standard and Series Four 6, 12 and 16-cylinder VHP models and claims that this system reduces blowby emissions by 90%. The Waukesha VHP Advanced Crankcase Breather system maintains a slight negative pressure in the crankcase. The eductor will remove harmful water vapors and combustion gases, which help to prevent sludge buildup, oil contamination, and oil leaks.

The advanced breather system creates a suction from the turbos that pull the gases from the crankcase. The gases go through a pre-separator and main filter separator to remove oil vapor before the gases are drawn into the engine. The separated oil is returned to the crankcase through a return tube that contains a check valve to prevent backflow of oil vapor into the separator. The specified negative crankcase pressure is maintained by the pressure regulating valve, even when speed and load changes. The typical CCV retrofit kit from Waukesha includes:

- breather pre-separator,

- crankcase pressure regulator valve,
- breather separator assembly,
- breather check valve,
- breather insulation blanket,
- breather system tubing, and
- mounting brackets

Two popular third party suppliers offer CCV ingestive systems for retrofit. These are FleetGuard and Solberg. Other ingestive systems are available but these are used primarily on engines for rolling equipment.

Cummins Filtration developed crankcase ventilation filters. These are formerly known as Crankcase Emission Absorbers (CEAs). They supplied them for diesel and gasoline engines for over 40 years. The brand name has now changed to "FleetGuard EcoVent Recirculator", but the product is the same. The system is used on industrial diesel and natural gas engines in North America and Europe. FleetGuard claims that the EcoVent Recirculator removes 99% of oil mist and airborne particles. The crankcase vapors are introduced into the air cleaner for an ingestive crankcase ventilation system. Separated oil drops are returned to the engine crankcase.

Separation of mist and oil is accomplished through a static absorbent filter. The only maintenance is to change the filter. No maintenance of moving parts or periodic cleaning is necessary. FleetGuard does not provide service intervals. The filter element is replaced when the differential pressure is too high.

FleetGuard systems are available to marine, industrial, diesel, gasoline or natural gas engines in a variety of engine sizes. Several filters can be arranged in parallel to balance the flow or provide capacity for in 25 cfm flow increments. For example, one model 93192A unit can be used for CAT G3412, G3508 or G3512 engines but four units are required for CAT G3612 or G3616 engines. We have limited knowledge of this product installed in Alberta and Canada.

FleetGuard are not offering custom solutions for specific engines. At the time of this writing, most of their products are out of stock with no information from FleetGuard for when the products will be available. Also, the user provides and installs all the connection lines (CCV inlet, oil drain and emissions). The typical retrofit kit from FleetGuard includes:

- EcoVent recirculator,
- mounting brackets, and
- u-tube manometer.

Solberg Filtration Systems manufactures number of crankcase ventilation systems models to capture crankcase emissions. They service both marine and stationary reciprocating engines. The Solberg systems include a high efficiency filtration which protects the turbocharger, intercooler and exhaust catalyst from contamination. The system employs automatic controls to regulate the crankcase pressure.

Solberg's Advanced Crankcase Ventilation System (ACV Series) is an ingestive design. It is sized based on the worn crankcase gas emissions of the engine. This style uses suction from the engine intake and turbocharger to draw the oil mist emissions through the high efficiency oil coalescing filter. An integrated diaphragm-style valve controls the vacuum level on the crankcase side of the filter to meet the engine manufacturer's requirements.

Solberg claims that oil coalescing filters are up to 99.97% efficient at 0.3 micron droplet size. We have limited knowledge of installations of these systems in Alberta or Canada. Solberg advised that a number of ACV systems were successfully installed and operated on NG engines in the USA. Solberg offers large variety of customized systems for practically all models of stationary engines.

A typical retrofit from Solberg generally includes:

- ACV unit,
- multi-position and field reversible mounting bracket (x1),
- standard NPT to hosebarb blowby connections (x2),
- petroleum grade blow-by hose (10 feet),
- hose clamps for blow-by hose (x4),
- clear, vacuum rated, drain line hose (3 feet),
- brass hosebarbs for drain line connections (x2), and
- brass check valve for drain line installation (x1).

A summary table indicating which third-party ingestive systems are available for each engine model is provided in Table 21. Table 20 illustrates which systems may be available from engine manufacturers.

Table 20 OEM ingestive CCV retrofit kits for the most common stationary engine models

Make	Model Designation as per MSAPR list*	Ingestive Retrofit Kit Availability		
		OEM		
		CAT	Waukesha	White
Waukesha	8LAT27GL			
	12V AT25GL			
	12V AT27GL			
	16V AT27GL			
	16V275GL			
	L7042GL/GLS3/GL ESM		X	
	L7042GSI/GSIU/S4/GSI ESM/GSIL		X	
	L7042GU			
	L7042GSI S4		X	
	L7042GSI S5		X	
	L7044GSI/GSI ESM/G		X	
	L7044GSI S4		X	
	L7044GSI S5		X	
	P9390GSI/GSIU			
	P9394GSI		X	
	P9390GL/REM			
	P9394GSI S5		X	
	F3521GSI/GSIU/GSL; F3524GSI		X	
	F3521GU/G/NA			
	F3521GL			
	F3514GSI/GSI ESM		X	
	F2895GSIU/GSI		X	
	F2895G/GU			
	F2895GL/GL ESM			
	L5790GU/GSIU			
	L5790G			
	L5790GL		X	
	L5774/LT/LTE/LT ESM; L5794LT/ESM/LTE		X	
	L5794LT/ESM/LTE		X	
	H24GL/GLD/GL LCR/GL HRC		X	
	H24GSI/H2475G		X	
	F18GLGL LCR/GL HCR/		X	
	F18GSI/SE/GSID		X	
	L36GL/GL HCR/GL LCR; P48GL		X	
	P48GL		X	
	L36GSI/GSID; P48GSI		X	
	P48GSI		X	
Caterpillar	G3606/TAW/TALE/TA/LE/GCTA	X		
	G3606 A4	X		
	G3608/TAWLE/TAW/LE/SITA	X		
	G3608 A4	X		
	G3612/TAW/TA/SITA/LE/A3	X		
	G3612 A4	X		
	G3616/TALE/AFRC/TA/LE/GC	X		
	G3616A DEM4	X		
	G3516TALE/AFRC/LE/B/C			
	G3516TA			
	G3516NA			
	G3520/LE/B LE/TALE/H/C/H EP TALE/B 1.34			
	G3512/TA/TAW/SITA			
	G3512TALE/AFRC/LE/B			
	G3512NA			
	G3508TALE/TAWLE/LE			
	G3508/TA,SITA			
	G379TA			
	G398TA/TAW/SITA			
	G398NA			
	G399TA/TAW/SITA			
	12-CG137			
	8-CG137			
	G3408TA/TAW			
	G3408 LE/CLE/C			
	G3412TA/TAW/SITA/NA			
	G3412NA			
	G3412LE/C/CLE/TALE/AFRC			
	G3406NA			
	G3406TA			
	G3306/B/BTA/TA/ATAAC/NA			
	G3306TA			
White Superior	6G825			X
	8G825			X
	12G825			X
	16G825			X
	8GT/GTL			X
	12SGT			X
	16GT/GTL			X
	16SGT			X
	8GTLE/B/X			X
	12SGTLE/SGTB/			X
	16SGTB/SGTD			X

Table 21 Retrofit crankcase vent ingestive systems for various engine models

Make	Model Designation as per MSAPR list*	Ingestive Retrofit Kit Availability	
		Aftermarket	
		Solberg	FleetGuard
Waukesha	8LAT27GL	Custom	
	12V AT25GL		
	12V AT27GL		
	16V AT27GL		
	16V275GL	X	
	L7042GL/GLS3/GL ESM	X	
	L7042GSI/GSIU/S4/GSI ESM/GSIL	X	
	L7042GU	X	
	L7042GSI S4	X	
	L7042GSI S5	X	
	L7044GSI/GSI ESM/G	X	
	L7044GSI S4	X	
	L7044GSI S5	X	
	P9390GSI/GSIU	X	
	P9394GSI	X	
	P9390GL/REM	X	
	P9394GSI S5	X	
	F3521GSI/GSIU/GSL; F3524GSI	X	
	F3521GU/G/NA	X	
	F3521GL	X	
	F3514GSI/GSI ESM	X	
	F2895GSIU/GSI	X	
	F2895G/GU	X	
	F2895GL/GL ESM	X	
	L5790GU/GSIU	X	
	L5790G	X	
	L5790GL	X	
	L5774/LT/LTE/LT ESM; L5794LT/ESM/LTE	X	
	L5794LT/ESM/LTE	X	
	H24GL/GLD/GL LCR/GL HRC	X	
	H24GSI/H2475G	X	
	F18GLGL LCR/GL HCR/	X	
	F18GSI/SE/GSID	X	
	L36GL/GL HCR/GL LCR; P48GL	X	
	P48GL	X	
	L36GSI/GSID; P48GSI	X	
	P48GSI	X	
Caterpillar	G3606/TAW/TALE/TA/LE/GCTA	X	X
	G3606 A4	X	X
	G3608/TAWLE/TAW/LE/SITA	X	X
	G3608 A4	X	X
	G3612/TAW/TA/SITA/LE/A3	X	X
	G3612 A4	X	X
	G3616/TALE/AFRC/TA/LE/GC	X	X
	G3616A DEM4	X	X
	G3516TALE/AFRC/LE/B/C	X	X
	G3516TA	X	X
	G3516NA	X	X
	G3520/LE/B LE/TALE/H/C/H EP TALE/B 1.34	X	X
	G3512/TA/TAW/SITA	X	X
	G3512TALE/AFRC/LE/B	X	X
	G3512NA	X	X
	G3508TALE/TAWLE/LE	X	X
	G3508/TA,SITA	X	X
	G379TA	X	X
	G398TA/TAW/SITA	X	X
	G398NA	X	X
	G399TA/TAW/SITA	X	X
	12-CG137	X	
	8-CG137	X	
	G3408TA/TAW	X	X
	G3408 LE/CLE/C	X	X
	G3412TA/TAW/SITA/NA	X	X
	G3412NA	X	X
	G3412LE/C/CLE/TALE/AFRC	X	X
	G3406NA	X	
	G3406TA	X	
	G3306/B/BTA/TA/ATAAC/NA	X	X
	G3306TA	X	X
White Superior	6G825	Custom	
	8G825		
	12G825		
	16G825		
	8GT/GTL		
	12SGT		
	16GT/GTL		
	16SGT		
	8GTLE/B/X		
	12SGTLE/SGTB/		
	16SGTB/SGTD		

2.11.2. Ingestive Crankcase Vent Retrofit Costs

Crankcase recirculation systems are standard equipment on new engines from Waukesha and Caterpillar. Waukesha installs these systems on their new VHP and VGF engines. Caterpillar installs crankcase gas recirculation system on their new G3600A4 series engines. Retrofit options with approximate costs are available in kits and from third party suppliers as described in Table 22.

FleetGuard retrofit kits are the least expensive because they provide only a filter housing. This option may be a good option on smaller engines which might be more cost sensitive for retrofits. Solberg offers solutions for most engine models. Waukesha offers kits for their VHP models. The pricing for Waukesha kits is similar to Solberg's offerings. Caterpillar options for 3600 series engines are the most expensive.

Field installation cost may vary from $5,000 for smaller engines to $90,000 for large Caterpillar models if done at the time of engine overhaul. Installation of this system at a time dedicated to only the ingestive system will add up to $50,000 for site preparation and travel expenses. The labor cost for installation is dramatically reduced if done at the time of overhaul because the items that are removed for the ingestive system installation are part of the overhaul labor.

Maintenance considerations include cleaning of the filter canister and replacement of the filter element. The manufacturer provides instructions on the replacement requirements and the when the service life of the filter has been accomplished. Both the OEM and aftermarket vendors recommend filter replacement rather than cleaning them. The cost of the filter elements varies widely from $100 for the FleetGuard system up to $2,500 for an advanced filter for a Caterpillar G3600 engine. Service intervals depend on oil and fuel quality, engine condition and engine load. Our observations suggest that the efficiency of the filter is key to system performance. Caterpillar's filter system appears to be more sophisticated than some of the others. Only Solberg provided filter efficiency information.

Table 22 Ingestive crankcase vent system costs and maintenance aspects

Vendor	Engine models	Factory Installed	Kit ID	Price	Unit includes	Labor estimate	Site Preparation	Total	Filter Element Replacement	Price per element	Service Interval (hr)
Caterpillar	G3606/G3608	Y	N/A	$43,000	Ready to install	installation is included in price	$3,000.00	46,000	Caterpillar	$2,500.00	8,000
	G3612/G3616	Y	N/A	$86,000				89,000	Caterpillar	$2,500.00	8,000
Waukesha	VHP 6 cylinder	Y	G-962-1193	$13,345	Ready to install	$3,000	$1,500.00	17,845	Waukesha	$3,003.75*	8,000
	VHP 12 cylinder	Y	G-952-540/1	$14,430		$4,000		19,930		$1,103.00	8,000
	VHP 16 cylinder	Y	G-962-1255C	$16,143		$5,000		22,643		$1,103.00	8,000
White	All 825	Y	N/A	N/A	N/A	N/A	N/A	N/A	Information not available		
FleetGuard	CAT G3300	N	93195A	$2,246	Included: recirculator (canister), clamps and U-tube manometer. All connections by user	$2,000.00	$5,000 (including purchasing of all missing components required for installation)	$9,246.00	88467A	$106.41	Pressure differential level has to be monitored
	CAT G3412, G3508, G3512	N	93192A	$1,431.14		$4,000.00		$10,431.14	88465A	$208.42	
	CAT G3516, G3606, G3608	N	93192Ax2	$2,628.28		$7,000.00		$14,268.28	88465A	$208.42	
	CAT G3612, G3616	N	93192Ax4	$5,724.56		$12,000.00		$22,724.56	88465A	$208.42	
Solberg	CAT G3606/08	Y	ACV4068x2	$15,000.00	Ready to install with minimal adjustments	$5,000.00	$1,500.00	$21,500.00	EWP40Q	$1,125.00	4,000
	Cat G3612/16	N	ACV4068x3	$21,980.00		$7,000.00		$30,480.00	EWP40Q	$1,125.00	4,000
	CAT G3300	N	ACV2000	$1,165.00		$2,000.00		$4,665.00	ACV7020	$227.00	4,000
	CAT G3400	N	ACV2000	$1,165.00		$2,000.00		$4,665.00	ACV7020	$227.00	4,000
	CAT G3512, G3516 Waukesha VHP 12 cyl	N/Y	ACV4068	$8,040.00		$4,000.00		$13,540.00	EWP40Q	$1,125.00	4,000
	Waukesha VGF	Y	ACV2000	$1,165.00		$2,000.00		$4,665.00	ACV7020	$227.00	4,000
	Waukesha 275GL	N	ACV4068x3	$21,980.00		$7,000.00		$30,480.00	EWP40Q	1,125.00	4,000

2.12. Technology Options to Reduce or Capture Methane Emissions in Engine Exhaust

Few options are currently available for mitigation of methane in the engine exhaust released to the atmosphere. Waukesha has installed a crankcase recirculation system on their VHP GSI and VGF engines (Waukesha INNIO n.d.). This system directs the crankcase fumes through a filter and into the air inlet to reprocess the gasses in the combustion chamber. Similar crankcase ventilation systems are available from Solberg, FleetGaurd and Alfdex. Alfdex is not popular for stationary natural gas engines in the oil and gas sector. No other available technology upgrades are currently commercially available to address methane slip. New development projects by engine manufacturers are underway to address methane slip.

The regulatory aspects of NO_x compliance in Canada have offered two paths of combustion style for engine owners. Open chamber and pre-chamber lean burn combustion styles offer the operator an option to meet NO_x compliance with the benefits of lower fuel consumption and longer service intervals. Unfortunately, these combustion styles should produce higher methane slip emissions.

Rich burn combustion styles with an NSCR catalyst will theoretically produce much lower methane slip emissions than the lean burn models. However, the following characteristics impose higher operating costs for the engine owner compared with the lean burn engines:

- higher carbon tax from higher fuel consumption,
- more frequent NO_x compliance testing,
- catalyst maintenance costs, and
- shorter service intervals due to higher engine cylinder operating temperatures.

An NSCR catalyst utilizes natural gas in the exhaust stream to react with the catalyst and reduce the NO_x concentration. Theoretically the methane slip in the exhaust can replace some of the methane introduced by the rich air-fuel ratio provided to manage the catalyst reaction. But the NSCR catalyst is not designed to destruct unburned methane in the exhaust. The combustion temperature will significantly exceed the exhaust temperature to do so specifically for destruction of methane gas. A change in engine geometry might offer a compromise to obtain the best of both worlds in reduction of NO_x and methane slip.

Caterpillar is experimenting with the geometry of the combustion chamber to reduce crevice volumes on their lean burn engines. They intend to reduce the methane slip in the exhaust stream from unburned hydrocarbons. Additional measures are also under development. Caterpillar is considering an exhaust gas recirculation system as well.

Waukesha advertises reduced crevice volumes in their latest VHP GSI Series 5 engine upgrades. They offer a kit to upgrade existing VHP GSI, GL and LT engines to their latest Series 5 technology. The conversion includes upgraded cylinder heads, turbochargers, pistons and engine management systems. The design requires an NSCR catalyst to condition the exhaust gasses. The engine may be tuned rich to burn more fuel in the catalyst and produce less raw methane in the exhaust stream. The NO_x emissions will be compliant but the operating costs will be much higher than lean burn combustion engines producing the same rated power. CO_2 emissions will also increase.

Cooper, Caterpillar and Waukesha have all advertised testing of hydrogen fuels to reduce carbon emissions. The use of hydrogen fuels offers potential to eliminate methane slip but industry wide hydrogen distribution for use as fuel is not available at present. Cooper has not announced any measures to reduce methane slip at the time of this writing.

3. Field Testing Program and Test Results

Success of the field data collection program is dependant on the engine management system and the engine condition. The following characteristics are stipulated for the test sample in order to allow the best chance for success.

- The engines are driving reciprocating compressors or generators so that engine load can be readily estimated. Engine load can be measured if the driven equipment is a reciprocating compressor and a performance test is performed.
- The engine condition can be verified to be adequate.
- The test engines are equipped with the specified engine management system.
- The engines are equipped with sensing points on the exhaust lines at the appropriate locations.
- The engine crankcase vents may be readily disconnected and routed through a temporary sampling apparatus for the duration of the test.

Each system is different and selection of each unit with the different technologies ensured the sample of that specific technology is representative. The various engine models have evolved over the years with improvements and upgrades. Each engine model tested is duplicated by others in their group.

Spartan Controls and Signet provided the data acquisition and analysis for the field test data. Their CEMS (Continuous Engine Monitoring System) field test apparatus is fitted with an oxygen sensor to perform each field test. Signet performed the tests. A few exhaust samples are also analyzed in the lab to compare with the field data collection. Some exhaust gas elements in the field measurement devices are calculated rather than measured.

The field data is input in a spreadsheet for analysis. The data is arranged in groups for each engine and one of four combustion styles. Five data points for each engine model is expected to support any trends. Scatter graphs are employed to identify trends. Observations on the test data and trends are presented.

3.1. Engines Included in the Tests

Common engines available in the field are selected for our testing program. The goal is to capture emissions of a representative sample of common engines as they are operating in the field. The objective is to test five of each of 22 engine models for a total of 110 field tests. The engines choices are limited to four stroke, natural gas fueled stationary engines. The engines are selected to be located at different sites and by different operators. These criteria allowed as-is engine condition testing to capture test data by

- a variety of engine operators,
- used in a variety of applications,
- a variety of fuel quality, and
- at a variety of elevations.

In some cases, difficulty was encountered identifying five sites that with one engine model. In that case, testing of different engines at the same site was implemented. This applies primarily to White Superior 825 engine models which are popular but becoming fewer in service. Many are installed as spare capacity but are not currently in service. Unavailable engine models are replaced with smaller engines. A few owners requested these smaller engines be field tested instead as they are plentiful. Furthermore, limits on site access and time constraints reduce the number of engines tested. Some engines are noted to be operating with condition faults and are retested to offer a comparison between an engine with and without condition issues. Eight engines are retested in this category. In all, 116 field tests are completed on 100 engines. The engine models included in the field testing and their quantities are included in Appendix A."

3.2. Field Testing

Spartan Controls and Signet Monitoring and Analysis assembled a list of engines with their owners from their client files. Engine owners responded to requests for their participation in the study. The response was overwhelming. More test candidates were made available than required. Signet filtered the lists of available engines to seek the models within 600 km of Red Deer (a requirement of our proposal). Signet then sorted the engine candidates to seek five models of each of the selected engine models in accordance with the criteria specified in Section 3.1.

3.2.1. Test Procedure

Signet Monitoring and Analysis Inc performed the field tests using a CEMS measurement system. The field measurements are used to carry out calculations of the emissions components in the office. The calculations are complex and detailed. In general, they are based on exhaust emission gas flow rates calculated in accordance with Method 19. The accuracy limits on the reported measured values are difficult to ascertain. Many methods are employed to collect samples and perform calculations. Ned Shappley (Shappley 2023) of the US EPA to was requested to advise the test method accuracy. His response is as follows.

> "*I can speak to this generally, Method 2 accuracy is typically +/- 10% and the uncertainty comes from the pressure drop reading, moisture, and temperature measurements.*
>
> *Accuracy of Method 19 is typically greater than 10% and the uncertainty comes from the fuel content, fuel meter readings, and oxygen measurements. Typically the accuracy of the fuel meter drives the accuracy of the measurement, unless it is a pay meter, these meters are often not very accurate.*
>
> *Generally Method 2 is more accurate.*"

Instrumentation accuracy is managed by calibration procedures and field accuracy checks with reference gasses. Measurements of pressure difference, moisture and temperature are captured at each site. Calibrated fuel gas meters are expected to provided accuracy within +/- 2%. These checks are described in each test report. Their accuracy should be contained within the limits specified above. Appendix B contains the test procedures with details of test methods provided.

The data collection methods itemized in Appendix B assume that all instruments for fuel flow and engine power determination are present. Unfortunately, this is not the case on the vast majority of natural gas fueled engines serving natural gas processing facilities. Calculated values are then employed. These do not have the same accuracy as measured values. The errors affect values derived from calculations using the estimates.

The engine power is estimated from the measured electrical output of engine powered generators. For compressors, engine power could not be measured using a compressor load performance test because the machine would require a shut down to connect measurement equipment. The operators did not expect an outage and would not appreciate this activity. Thus, this parameter is estimated using compressor performance software or engine OEM engine power estimates.

Compressor performance software will yield an accuracy within +/-3% if all the configuration and gas analysis properties are correct in the simulation. Compressor cylinder configuration can not be assessed by viewing the outside of the cylinders. Reliance on the operator is required for these details. The engine power shown on the control panel (if present) or by calculation in OEM software will yield accuracy of +/-15% since it is normally based on engine manifold pressure.

Fuel meters are normally not present except where a REMVue© air-fuel ratio control is installed. The engine fuel consumption is estimated using OEM published values. Previous field tests by the author determined that the OEM published fuel consumption values are understated between 10% and 15%. Calculations using the estimated fuel consumption embed this error.

The Environment Canada MSAPR conversion for NO_x is based on an engine efficiency of 30% based on the ratio of brake-load to the LHV of the fuel (Greg Brown in 2013). This is equivalent to a BSFC of 12000 kJ/kW-h (8493 BTU/HP-h). This logic applied to CH4 provides a conversion method using the atomic weights of NO2 (46.01 amu) and CH4 (16.04 amu) which yields 1 g/kW-h = 150.8 ppm@15% O_2 and 1 g/GJ = 0.5429 ppm@15% O_2.

The ratio of ppmvd@15% O_2 to g/kW-h and g/GJ will be greater than 150.8 and 0.5429, respectively, if an engine is more efficient than 30%. Therefore, the ppmvd @ 15%O_2 will not match the g/kW-h or g/GJ based on measured or calculated compressor load, OEM BSFC and fuel composition. As such, the units of measured ppmvd @ 15%O_2 are employed to present the data analysis. Figure 14 shows the deviation of the MSAPR calculation method for g/kW-h versus ppmvd @ 15% O_2 may introduce as much as 25% error. Figure 15 shows the same comparison of MSAPR calculation to measured ppmvd @ 15% O_2 for engines emitting less than 5 g/kW-h. Similarly, Figure 16 shows the deviation of the MSAPR calculation method for g/GJ versus ppmvd @ 15% O_2 may introduce as much as 25% error.

The ratio of ppmvd@15% O2 to g/e3m3 includes Environment Canada MSAPR conversion assumptions, assumptions about fuel composition, temperature, and pressure, and measurement error, as outlined above. The errors embedded in the estimates of fuel consumption and power create errors in the normalized calculations for emissions factors; namely g/kW-h and g/GJ. Assumptions about fuel composition, temperature, and pressure are used to determine methane slip in units of g/e3m3. As each assumption is introduced, the error associated with this unit increases. Figure 17 shows the deviation of the calculated g/e3m3 methane slip versus ppmvd@15% O_2 may introduce as much as 60% error.

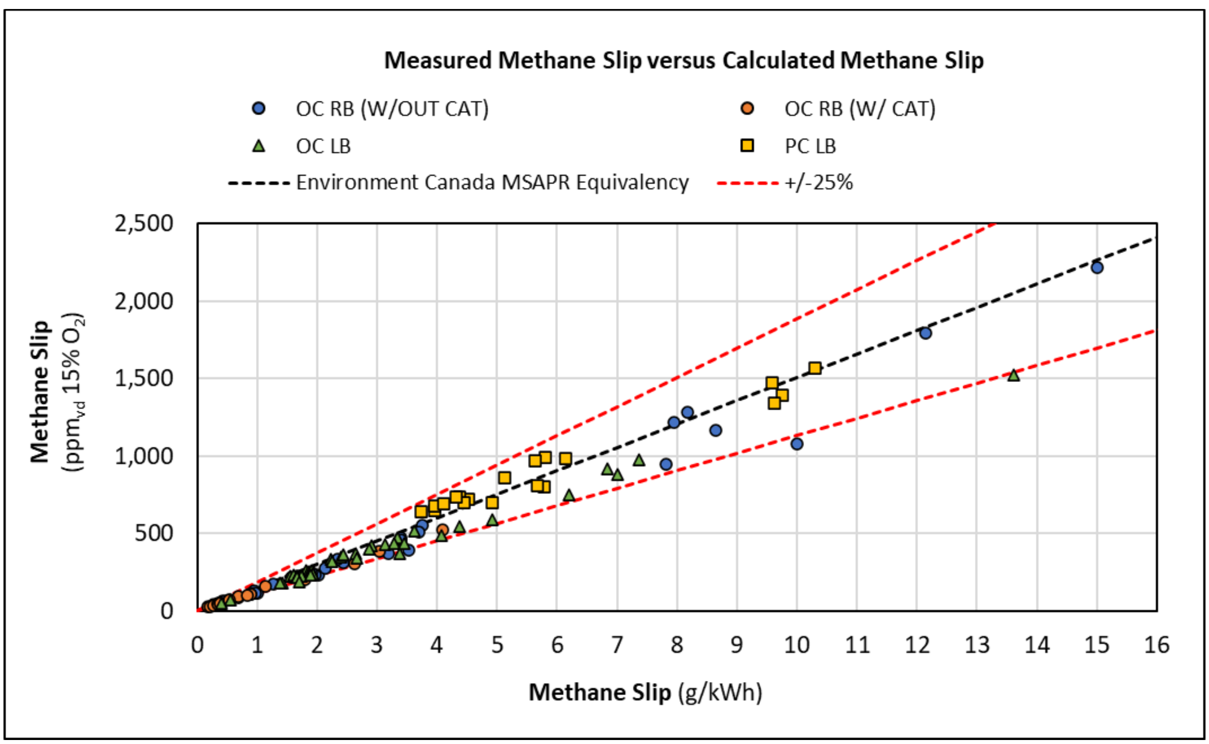

Figure 14 Exhaust methane concentration at 15% O_2 versus g/kW-h showing the measured data is captured within +/- 20% of the MSAPR ratio.

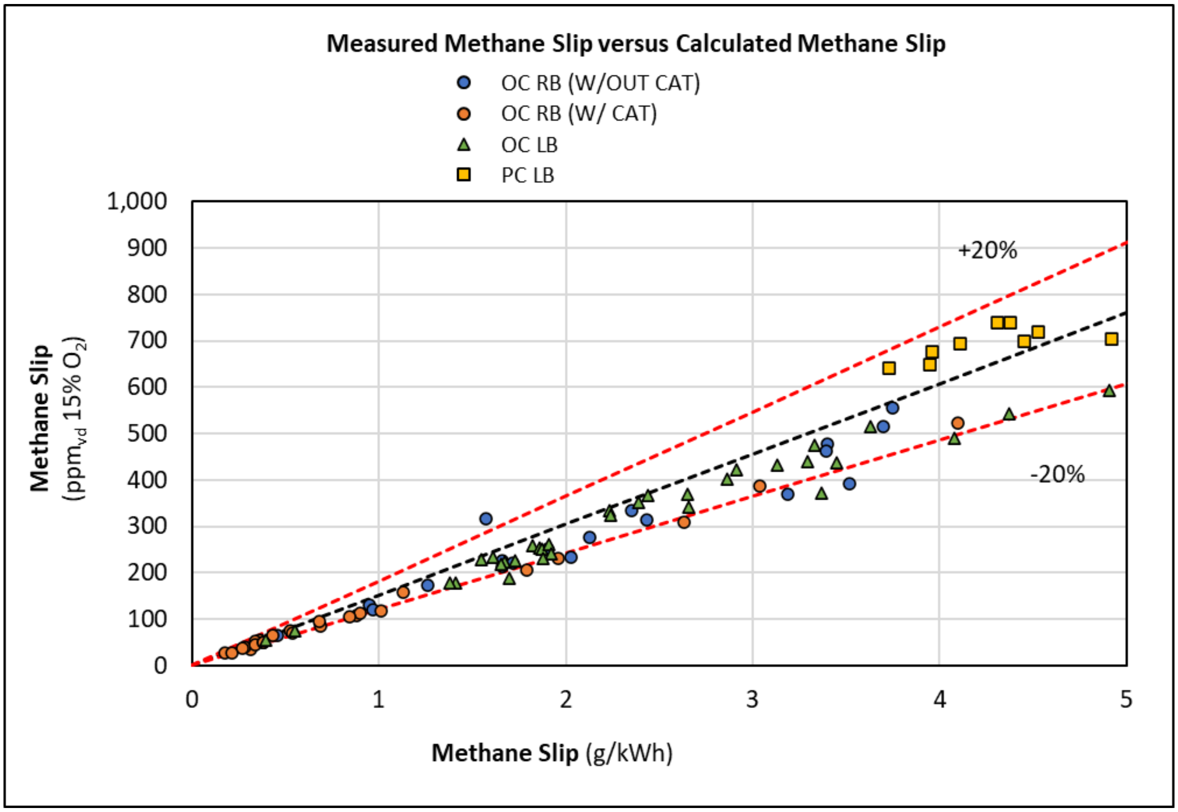

Figure 15 Methane slip for engines emitting less than 5 g/kW-h

Figure 14 presents a wider range of engine data. It is possible that the presentation may be different for a narrower range of methane slip emissions. Figure 15 illustrates that the graph provides the same relationship for a more limited range of emissions. It should be noted that only 11 engines are equipped with fuel gas meters supplied on REMVue rich to lean conversions. Installing a fuel gas meter will reduce the error embedded in the estimates of fuel gas consumption based on calculations. The low quantity of engines equipped with fuel gas meters is not sufficient to skew the data.

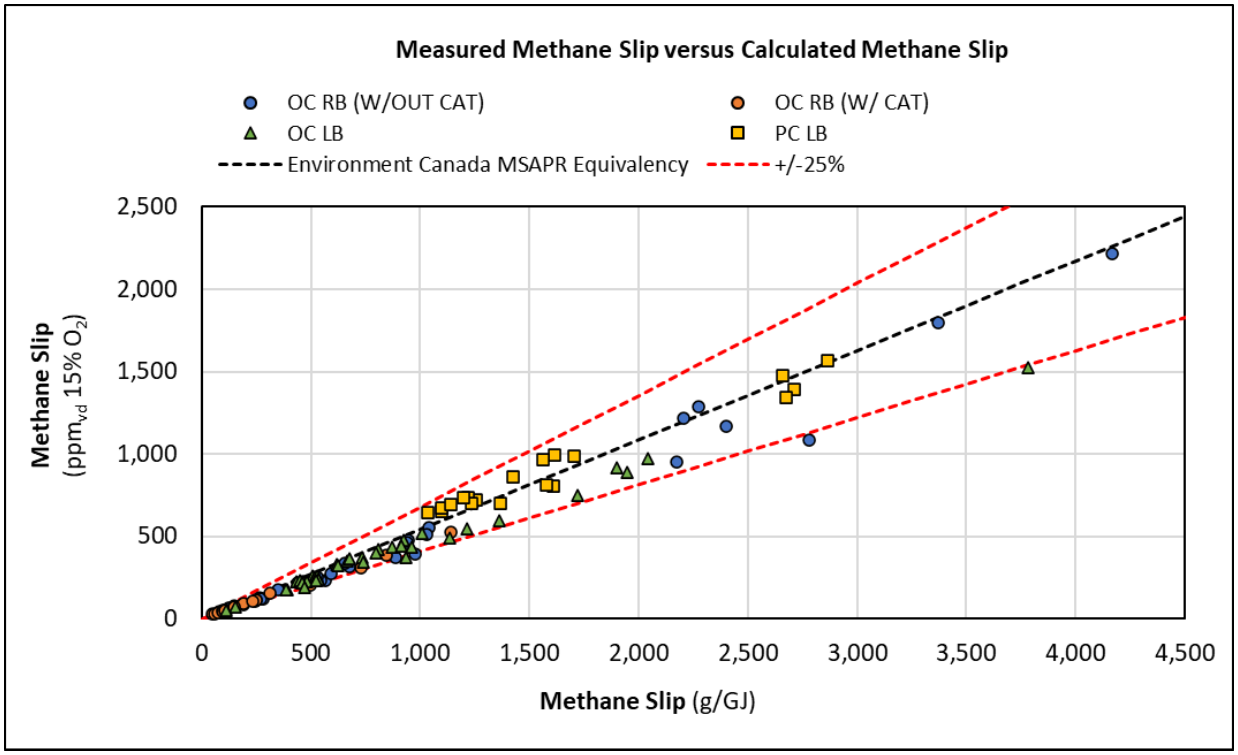

Figure 16 Methane slip in ppmvd@15%O_2 vs methane slip calculated as g/GJ

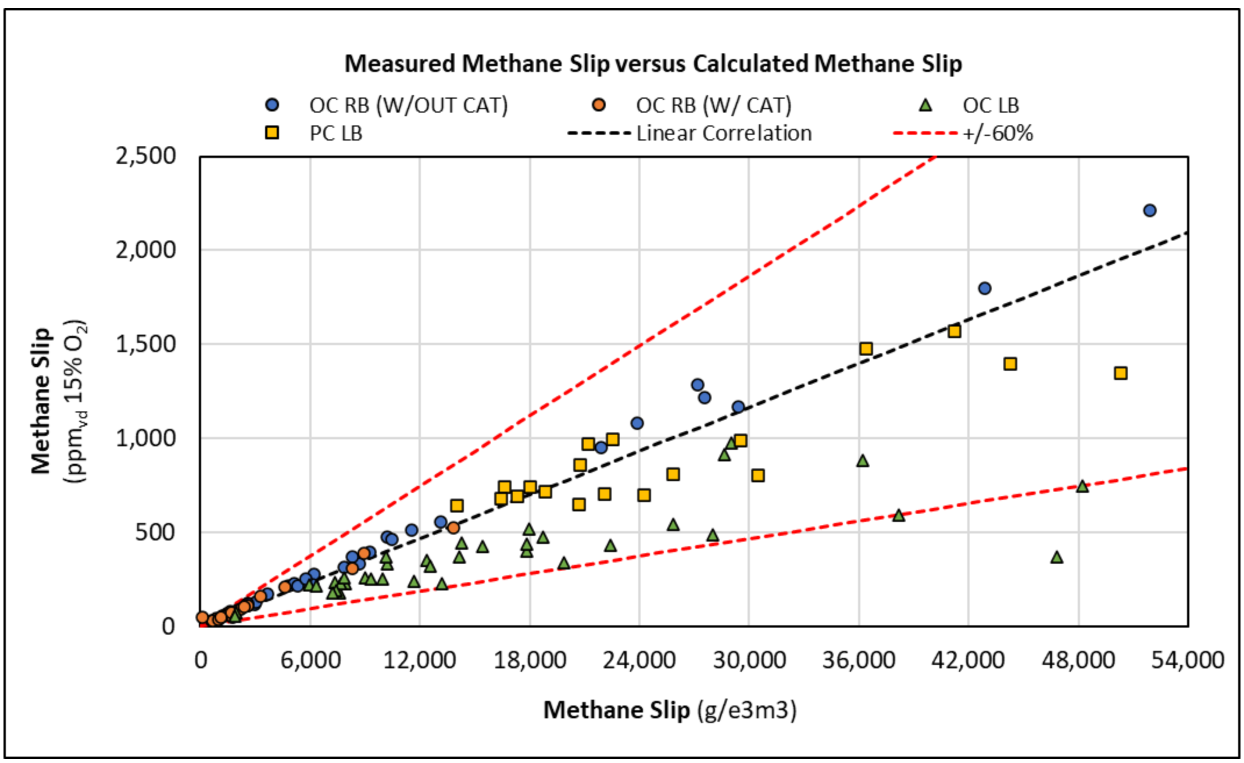

Figure 17 Methane slip in ppmvd@15%O_2 vs methane slip calculated as g/e3m3

The engine manufacturers provide guidance for conversion of measured concentration to normalized factors most wish to use for convenience of estimating emission volumes. Waukesha offers a table of conversion factors (Waukesha INNIO. Gas Engine Exhaust Emission Levels. EN: E2011043, Date: 2/22, Ref. S-8483-6). The factors change with engine combustion style and model. Caterpillar also offers formulae to convert values (Caterpillar, Gas Engine Emissions and Exhaust Aftertreatment, Application and Installation Guide, LEBW4984-08, August 2020).

Clearly, direct measurements of concentration as ppm and then normalized ppmvd@15%O_2 will produce the most reliable concentrations of methane slip. Other units will offer an easier task of producing mass flows and volume estimates. However, this convenience embeds excessive errors which will defeat a claim of scientific rigor.

3.2.2. Test Results

A summary of each field test result without all the calibration data for brevity is presented in Appendix C. Appendix D contains an example of a full test report with calibration data to illustrate the instrumentation accuracy and ambient condition checks undertaken on each test. Engine owners and site locations are withheld for privacy reasons.

Appendix E provides a spreadsheet that summarizes all of the test data and comments collected during the testing. As discussed earlier, the combustion style will dictate the behaviour of the engine. Four tables are thus presented in the spreadsheet as follows.

- Rich burn with catalyst (RB w Cat)
- Rich burn without catalyst (RB wo Cat)
- Open chamber lean burn (OCLB)
- Prechamber lean burn (PCC).

The following parameters are presented in the tables. Some of the parameters are derived using calculations based on estimated values. These are indicated with an asterisk.

A. Engine Data
    a. Make
    b. Model
    c. Power rated
    d. Power available
    e. Power tested (*)
    f. Build date
    g. Ignition brand/model
    h. Air-fuel ratio control brand/model
B. Emission level
    a. CH_4 OEM g/kW-h
    b. CH_4 test g/kW-h (*)

  a. CH_4 OEM ppmvd @ 15%
  b. CH_4 test ppmvd @ 15%
  c. NO_x OEM g/kW-h
  d. NO_x test g/kW-h (*)
  e. NO_x test ppmvd @ 15%
  f. CO OEM g/kW-h
  g. CO test g/kW-h (*)
  h. CO test ppmvd @ 15%
  i. CO_2 OEM g/kW-h
  j. CO_2 test g/kW-h (*)
  k. CO_2 test ppmvd @ 15%

C. Operating conditions
  a. Engine hours: total
  b. Engine hours since last service
  c. Engine hours since last head swing
  d. Engine hours since last overhaul
  e. Load % of rated at specified RPM (*)
  f. RPM OEM
  g. RPM test
  h. Ignition timing (degrees)
  i. O_2% OEM
  j. O_2% test
  k. JW Coolant temperature
  l. SC coolant temperature
  m. Engine oil brand
  n. Engine oil model
  o. Engine oil ash
  p. Engine oil TAN
  q. Engine oil TBN
  r. Fuel gas pressure
  s. Fuel gas temperature
  t. Fuel gas flow rate (*)
  u. Cylinder head or exhaust temperature (left and right bank)
  v. Air manifold temperature (left and right bank)
  w. Air manifold pressure (left and right bank)

D. Ambient conditions
  a. Temperature
  b. Pressure
  c. Humidity
  d. Elevation

E. Fuel quality
    a. BSFC OEM
    b. BSFC test (*)
    c. LHV OEM
    d. LHV test
    e. Specific gravity
    f. density
F. Reference
    a. Signet report number
G. Comments and engine condition

The following observations are noted on the field test values versus OEM predicted CH_4 exhaust concentration in Tables 8, 9, 10 and 11. Overall, the predicted values specified by the OEM's are higher than the measured values. Some of the differences may be attributed to the engine operating settings in the OEM laboratory and the test conditions in the field. However, it strongly suggests that the OEM values may be considered to be conservative.

- Caterpillar PCC OEM predictions are higher than tested,
- Waukesha PCC OEM predictions are not defined,
- White PCC OEM predictions are not specified but measured values are very high,
- OCLB Caterpillar OEM predictions are overstated compared with test values,
- OCLB Waukesha OEM predictions are overstated compared with test values,
- OCLB Waukesha REMVue retrofit OEM predictions do not apply but the measured values are lower than Waukesha LT models,
- OCLB White Superior OEM predictions are not specified but the measured values are very high.
- OCRB without catalyst OEM Caterpillar predictions are overstated compared with measured values,
- OCRB without catalyst OEM Waukesha predictions are generally understated compared with measured values,
- OCRB without catalyst OEM White Superior predictions are not specified but measured values are generally very high.
- OCRB with catalyst OEM Caterpillar predictions are overstated compared with measured values,
- OCRB with catalyst OEM Waukesha predictions are overstated compared with measure values
- OCRB with catalyst OEM White Superior not specified but measured values are generally very high.

Table 23 identifies the variables that are plotted. The following data comparisons seek to identify the possible emergence of relationships. Plots use ppm_{vd} @ 15% O_2 as a directly measured parameter to avoid the error inherent in power and fuel consumption estimates.

Graphs of the test data for this study are found in Appendix F to demonstrate the results. Best fit trend lines are provided along with an equation for the line and the correlation coefficient.

In addition, one Producer shared their MSAPR test results on Caterpillar G3600 series engines. The data for 22 MSAPR tests are provided on these engines. That data offers a comparison for a fleet of engines with the same owner and operator rather than the intentionally randomized as-found data in the remainder of the study. The data for the Caterpillar G3600 series engines is found in Appendix G and the graphs are presented in Appendix H.

Table 23 Variables plotted to determine if relationships exist with correlation

Methane Slip Possible Relationships	Combustion Styles					
Methane Slip versus variable	Open chamber rich burn with catalyst	Open chamber rich burn without catalyst	Open chamber lean burn	Pre-chamber lean burn	All combustion styles together	Cat 3600 Series MSAPR tests
% Units tested	x	x	x	x	x	x
Ingestive crankcase vent	x	x	x	x		
Engine hours since last overhaul	x	x	x	x	x	
Exhaust temperature	x	x	x	x	x	
Load percent	x	x	x	x	x	x
Engine defect: condition anomalies	x	x	x	x	x	
Engine oil ash content	x	x	x	x	x	
Engine oil toal base number	x	x	x	x	x	
RPM	x	x	x	x	x	x
Air manifold temperature	x	x	x	x	x	x
Air manifold pressure	x	x	x	x		x
Ambient temperature	x	x	x	x	x	x
Ambient humidity	x	x	x	x	x	x
Adaptive engine management system	x	x	x	x	x	x
Coolant temperature	x	x	x	x	x	x
Engine vintage (year built)	x	x	x	x	x	x
O_2%	x	x	x	x	x	x
Fuel gas LHV	x	x	x	x	x	x
Fuel gas SG	x	x	x	x	x	x
NO_x	x	x	x	x	x	x

3.2.3 TEST OBSERVATIONS TO DETERMINE POSSIBLE RELATIONSHIPS BETWEEN METHANE SLIP AND OTHER VARIABLES

Selected graphs are presented in the body of the report to illustrate the spread of the data and any trends that might emerge. These graphs provide a strong correlation or demonstrate results that may appear to be counterintuitive with respect to the theory. A strong correlation is found in only a few of the comparisons. The first graphs show the characteristics of the test sample.

3.2.3.1 GRAPHS DESCRIBING TEST SAMPLE CHARACTERISTICS

The following graphs show the characteristics of the test sample with the year of manufacture and the combustion style. The percentage of the total sample is indicated. The Caterpillar MSAPR test engines are not included in these graphs.

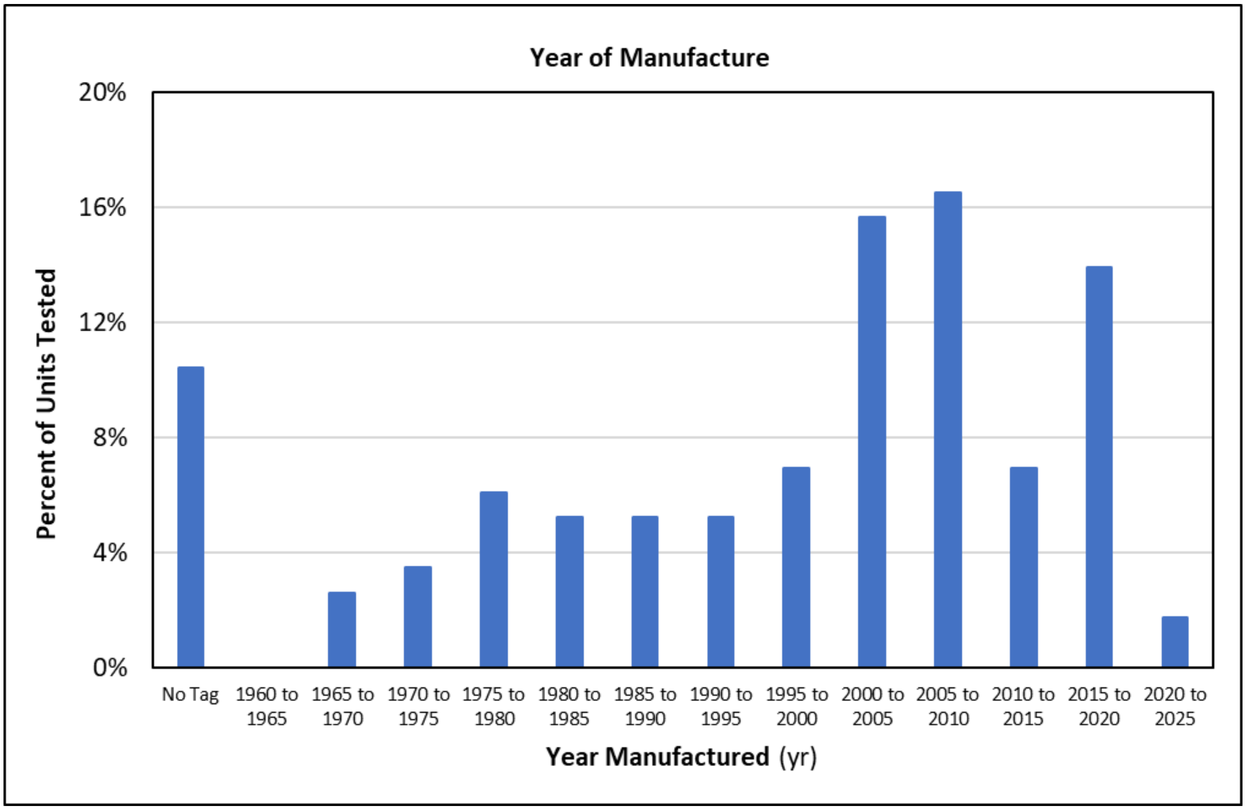

Figure 18 Distribution of the total number of engines in the sample according to the year of manufacture.

The total sample includes all combustion styles. The majority of the engines are built after 1995. Engine up to 58 years old are included in the sample. A comprehensive maintenance program allows stationary natural gas engines to operate virtually indefinitely, limited only by the availability of parts or the owner’s capability to fabricate parts.

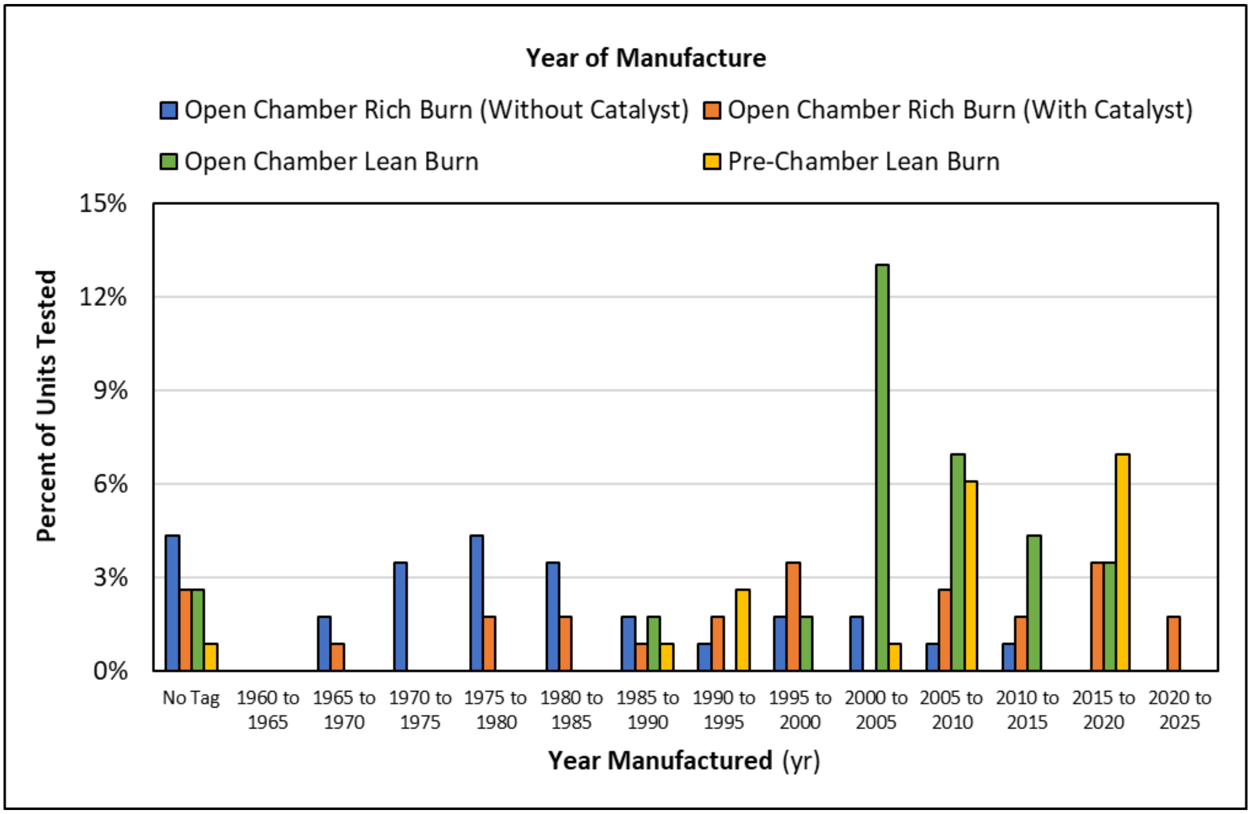

Figure 19 Distribution of the total number of engines in the sample according to the year of manufacture and the combustion style.

A further segmentation is provided by combustion style. Open chamber lean burn and pre-chamber lean burn engines are a more recent technology development. These combustion styles are available to address the NO_x regulatory limits. These regulations emerged in the mid-1990's. The requirement for catalysts to address NO_x emissions on open chamber rich burn engines coincides with those regulations.

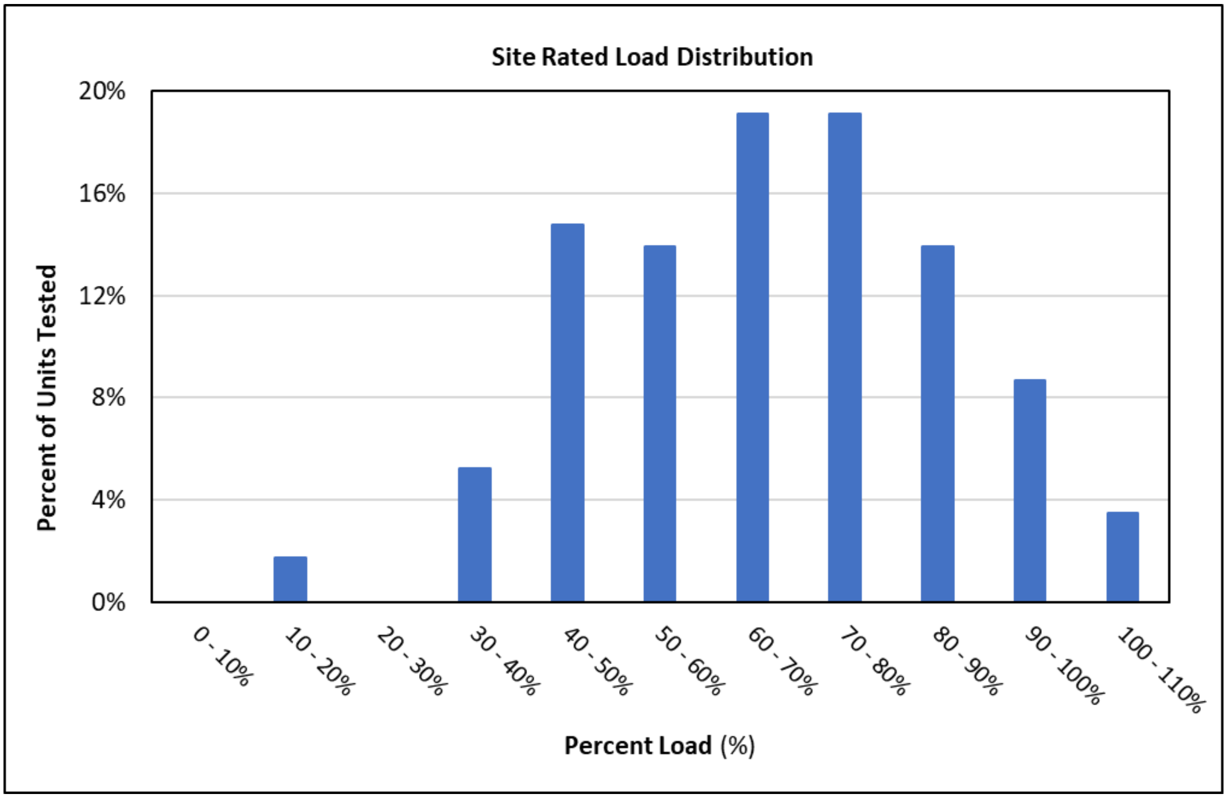

Figure 20 Distribution of the total number of engines in the sample according to the site rated load.

The total sample includes all combustion styles. The rated load is defined as the engine load required at the operating RPM. The rated load is directly proportional to RPM. Turbocharged engines are known to draw oil into the combustion chamber when the load is less than 60%. The figure shows that many of the engines are lightly loaded. Naturally aspirated engines can run at less than 60% load without contamination of the combustion air. Lightly loaded engines are normally the consequence of declining production volumes or low power demand at the time of the test.

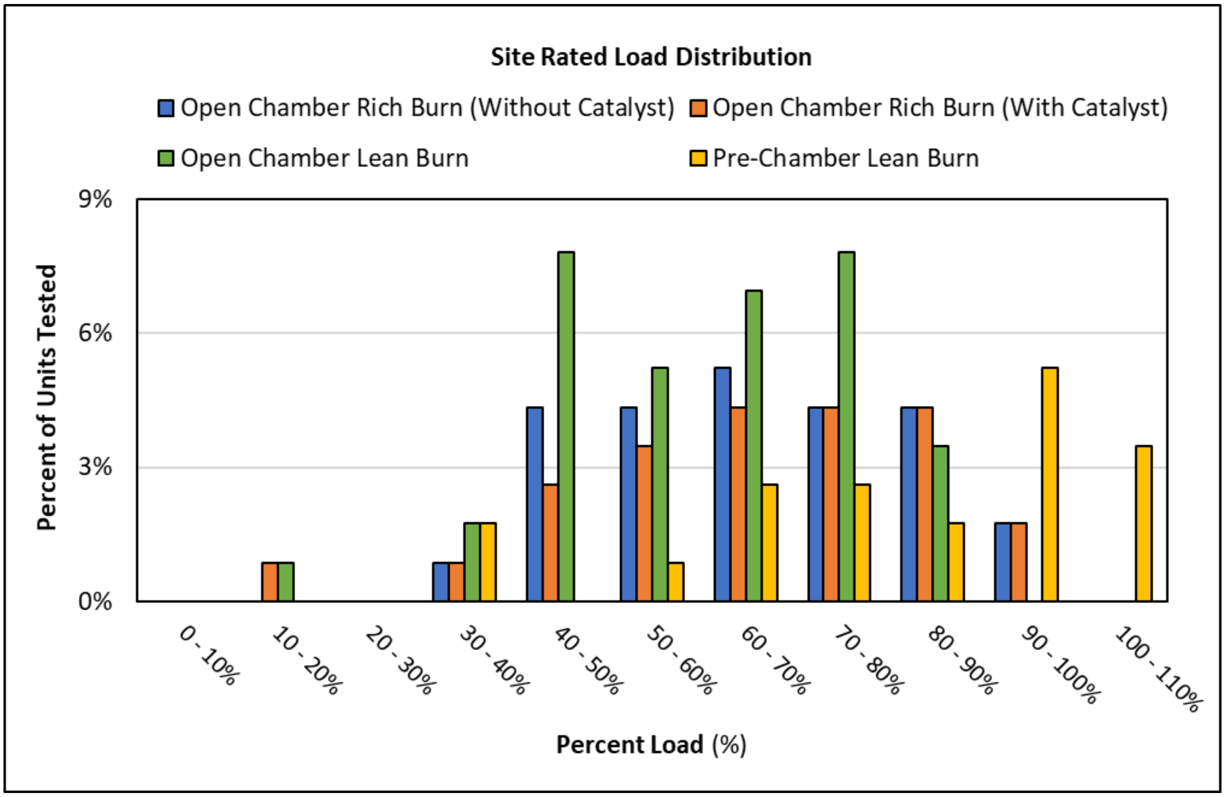

Figure 21 Distribution of the total number of engines in the sample according to the year of manufacture and the combustion style.

A further segmentation is provided by combustion style. The rated load is defined as the engine load required at the operating RPM. The rated load is directly proportional to RPM. Turbocharged engines are known to draw oil into the combustion chamber when the load is less than 60%. The figure shows that many of the engines are lightly loaded. Naturally aspirated engines can run at less than 60% load without contamination of the combustion air. Lean burn engines may be assumed to be equipped with turbochargers. Rich burn engines may be operated with or without turbochargers. Naturally aspirated engines are not equipped with turbochargers. Lightly loaded engines are normally the consequence of declining production volumes or low power demand at the time of the test.

3.2.3.2 GRAPHS DESCRIBING RELATIONSHIPS BETWEEN METHANE SLIP AND SELECTED VARIABLES

Most of the graphs did not reveal correlation to a best fit line. The following graphs are presented to show where the graphs support or diverge from expected results. The reason for the indicated behaviour is presented if possible. All of the graphs presented in the text also appear in the appendices with more detail on the equations for the best fit line and the correlation coefficients.

Engine models are not disclosed with statistics with the exception of the Caterpillar MSAPR tests. The quantity of the tests for each engine model is not sufficient to draw conclusions with statistical relevance. As such, the different models are collected into categories classified as groups. This generic approach avoids unsupported conclusions presented for specific engine models. The Caterpillar engines with MSAPR test data are presented in the text following the test data for this study to allow convenient comparison.

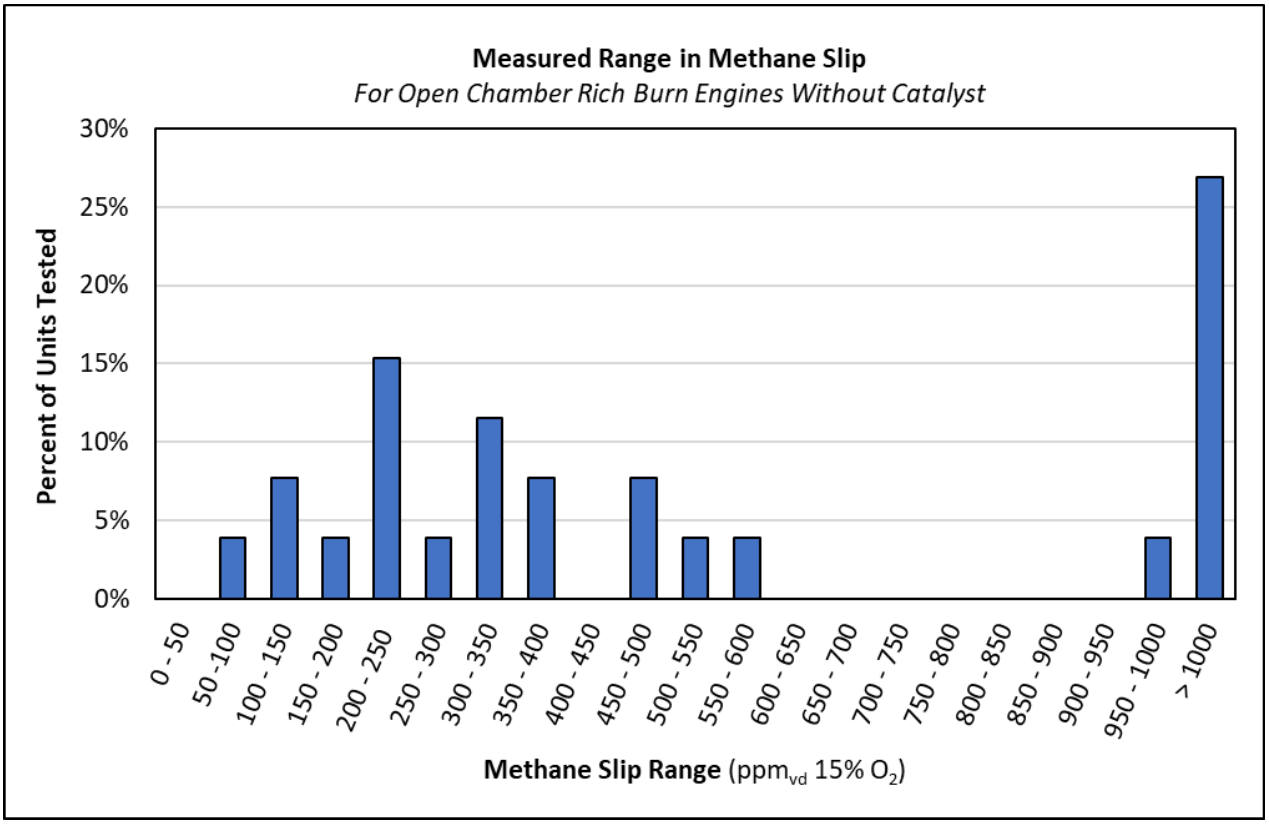

Figure 22 Measured range in methane slip for open chamber rich burn engines without catalyst

Roughly 10% of the open chamber rich burn engines without a catalyst are compliant with the Environment and Climate Change Canada (ECCC) proposed 1 g/kW-h limit (150 ppm_{vd} @ 15% O_2).

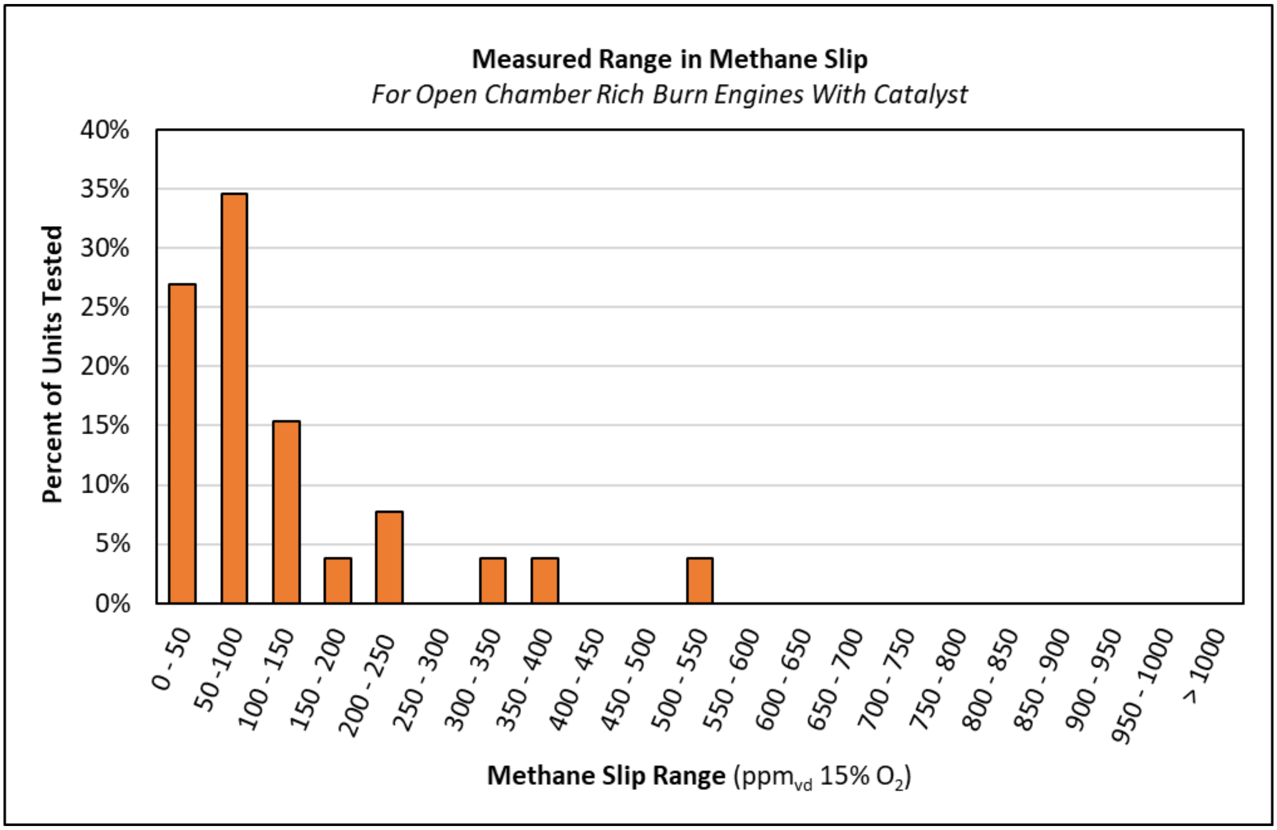

Figure 23 Measured range in methane slip for open chamber rich burn engines with catalyst

Roughly 60% of the open chamber rich burn engines with a catalyst are compliant with the ECCC proposed 1 g/kW-h limit.

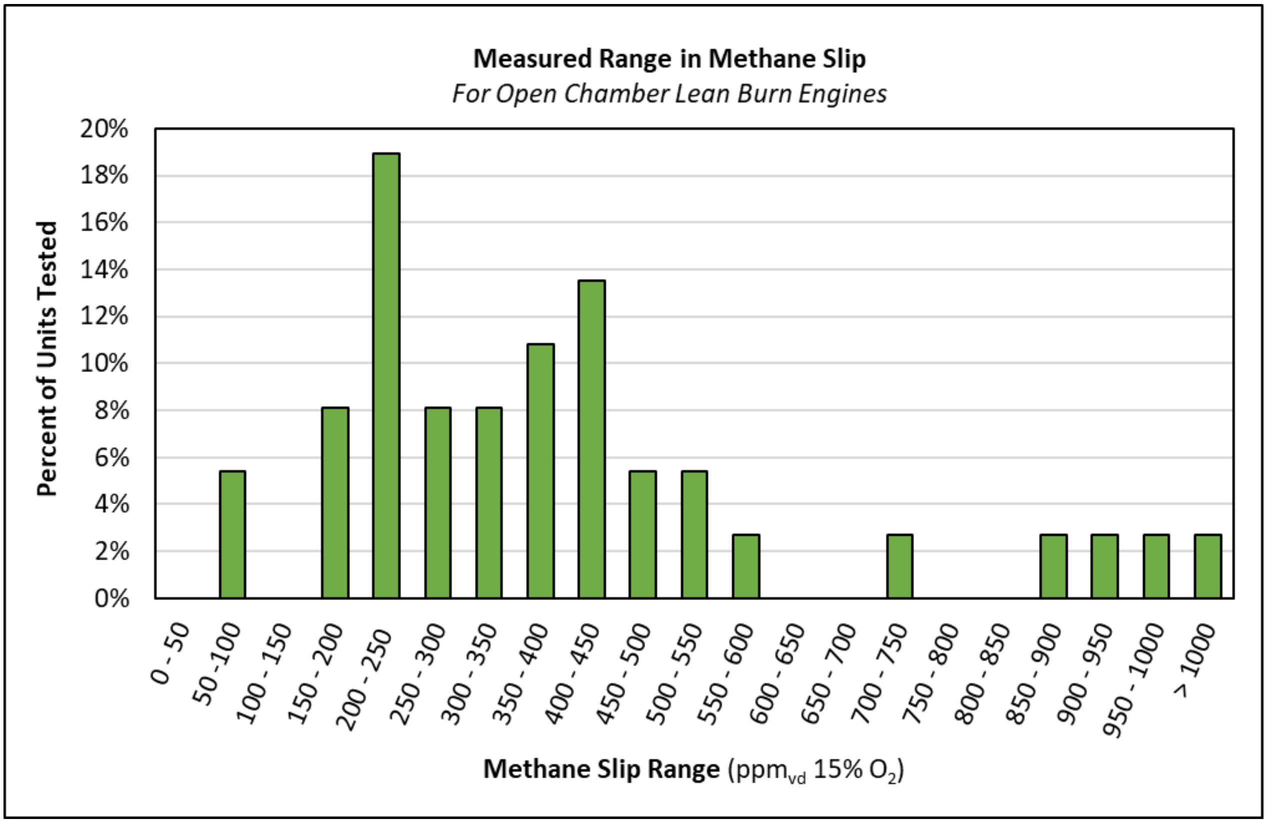

Figure 24 Measured range in methane slip for open chamber lean burn engines

Roughly 5% of the open chamber lean burn engines are compliant with the ECCC proposed 1 g/kW-h limit.

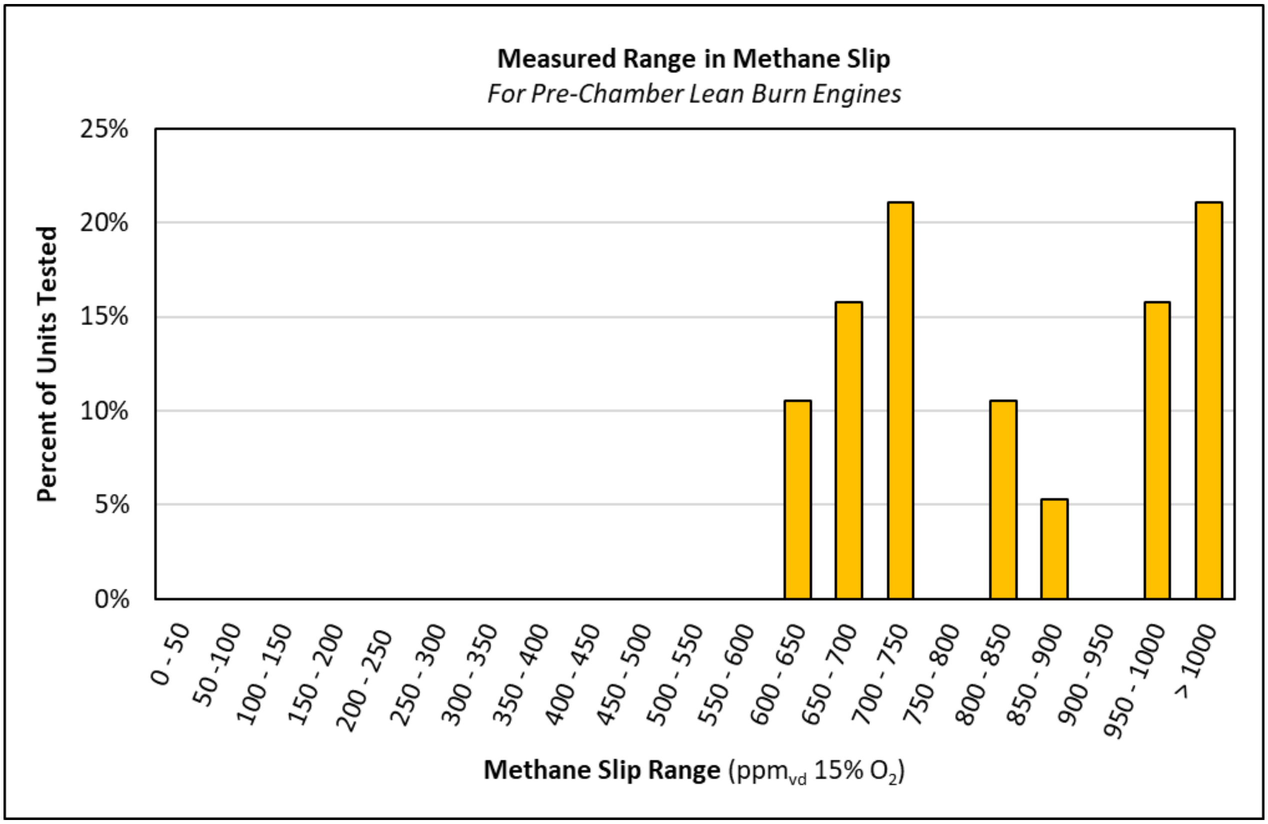

Figure 25 Measured range in methane slip for pre-chamber lean burn engines

No pre-chambered lean burn engines are compliant with the ECCC proposed 1 g/kW-h limit.

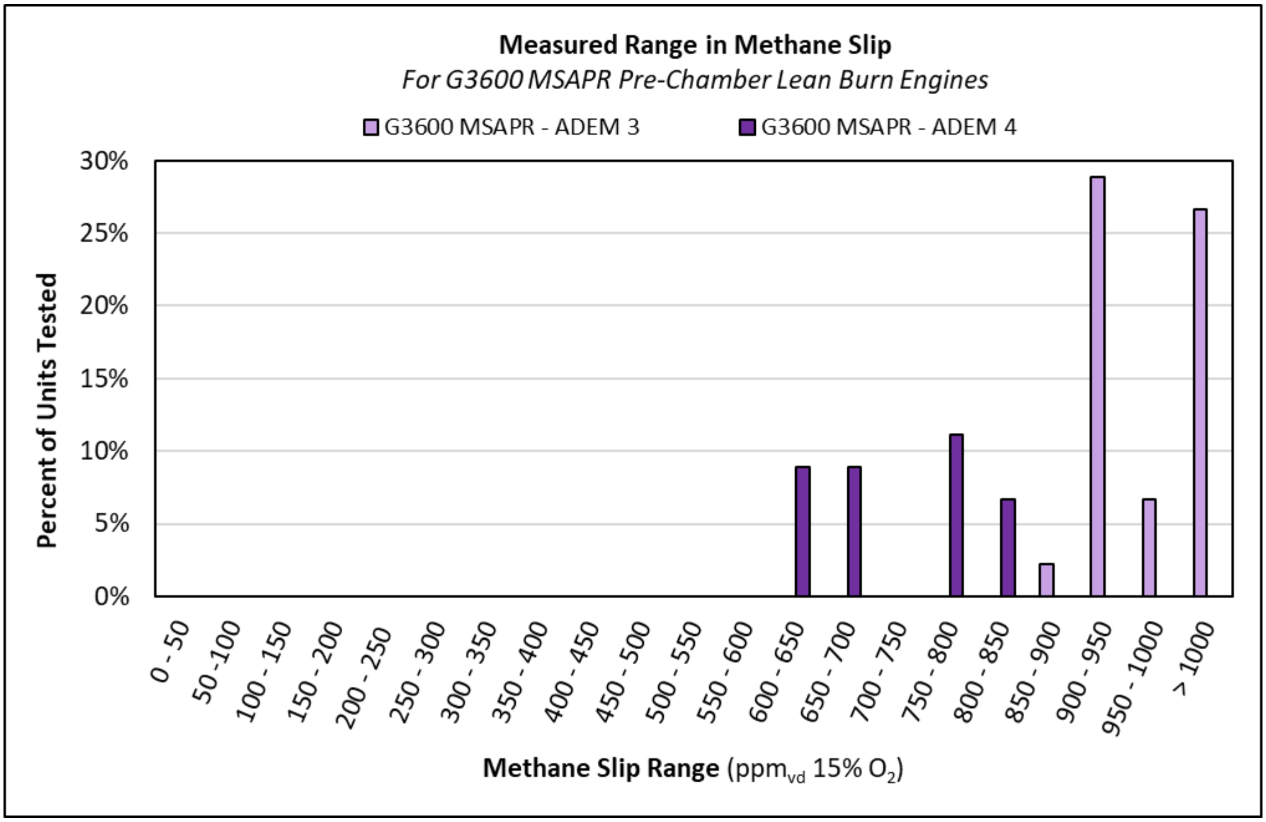

Figure 26 Measured range in methane slip for G3600 MSAPR tested pre-chamber lean burn engines

The Cat G3600 series engines are not compliant with the ECCC proposed 1 g/kW-h limit. The ADEM 4 engine management system is a newer model than the ADEM 3. The ADEM4 system appears to produce less methane slip than the ADEM 3, likely due to the enhanced adaptive controls on the ADEM 4 system. The standard deviation for these two groups indicates a limited spread on the sample data and good correlation.

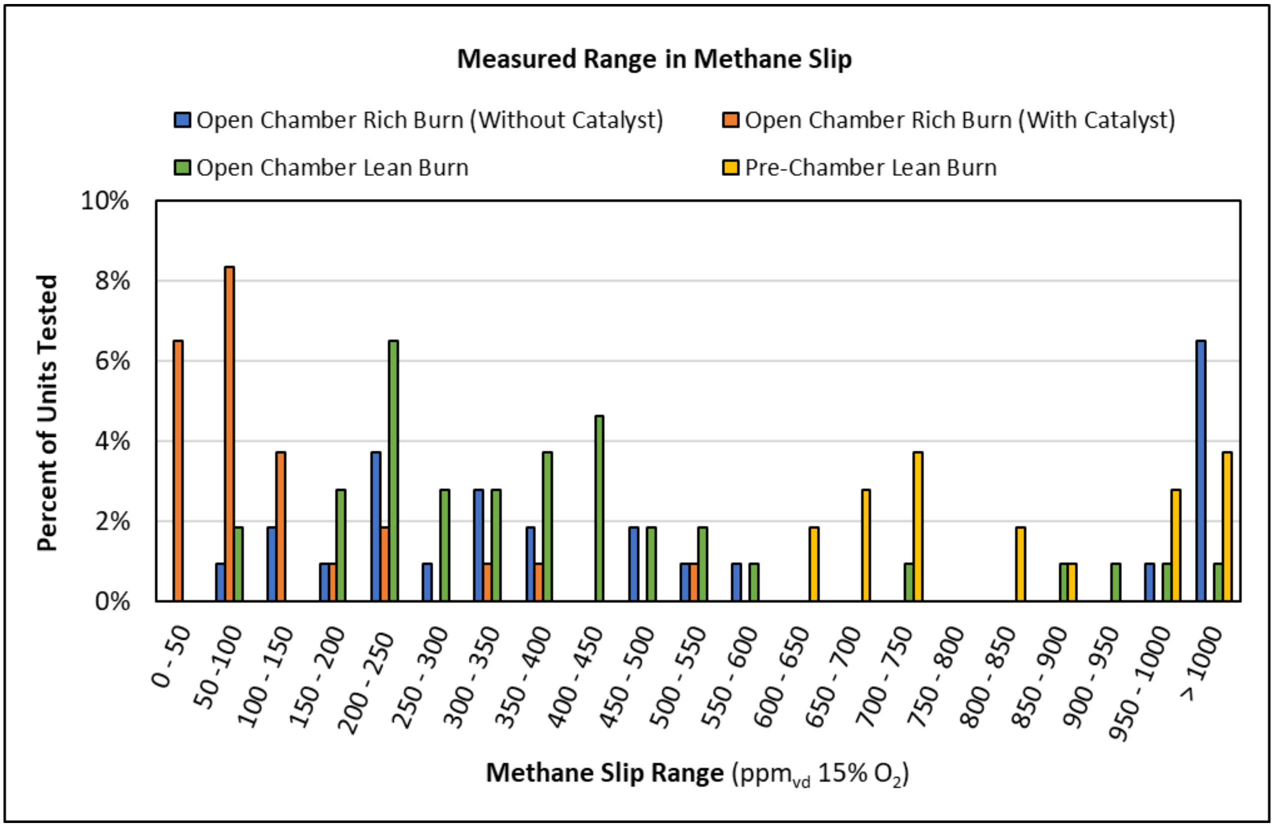

Figure 27 Measured range in methane slip for all engine combustion styles

Roughly 23% of all engines are compliant with the ECCC proposed 1 g/kW-h limit. The distribution of the data does not fit any recognized shape. The spread in the data is likely the result of different operating set points on the various engines. The various combustion styles also appear to be mutually independent.

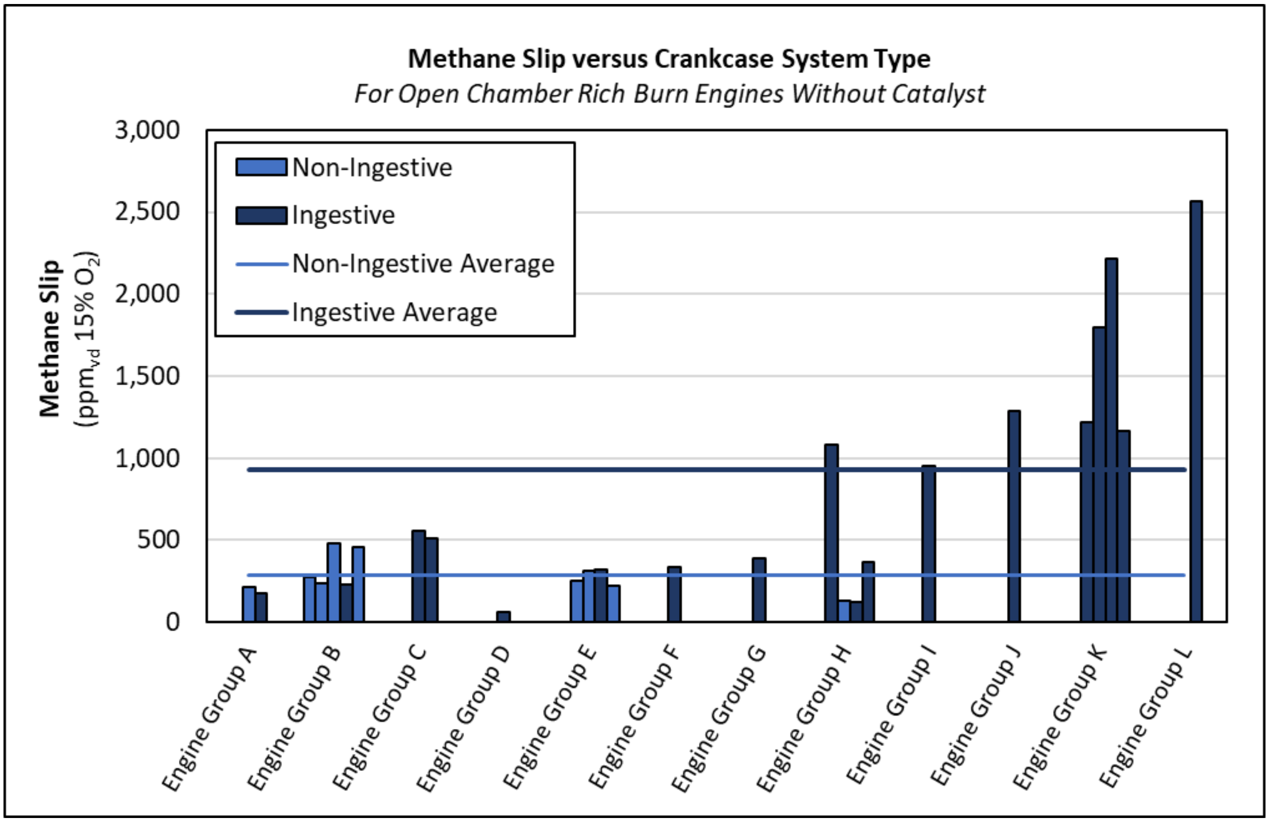

Figure 28 Methane slip versus crankcase evacuation system type for open chamber rich burn engines without catalyst

An ingestive crankcase evacuation system installed on an open chamber rich burn without a catalyst increases methane slip by 500 ppm_{vd} @ 15% O_2 above the average according to this data. That result is opposite to what theory would suggest. The tuning of these engines offered a wide range of air fuel ratio (rich and lean) and thus a wide dispersion of data. Engine groups are classified according to manufacturer.

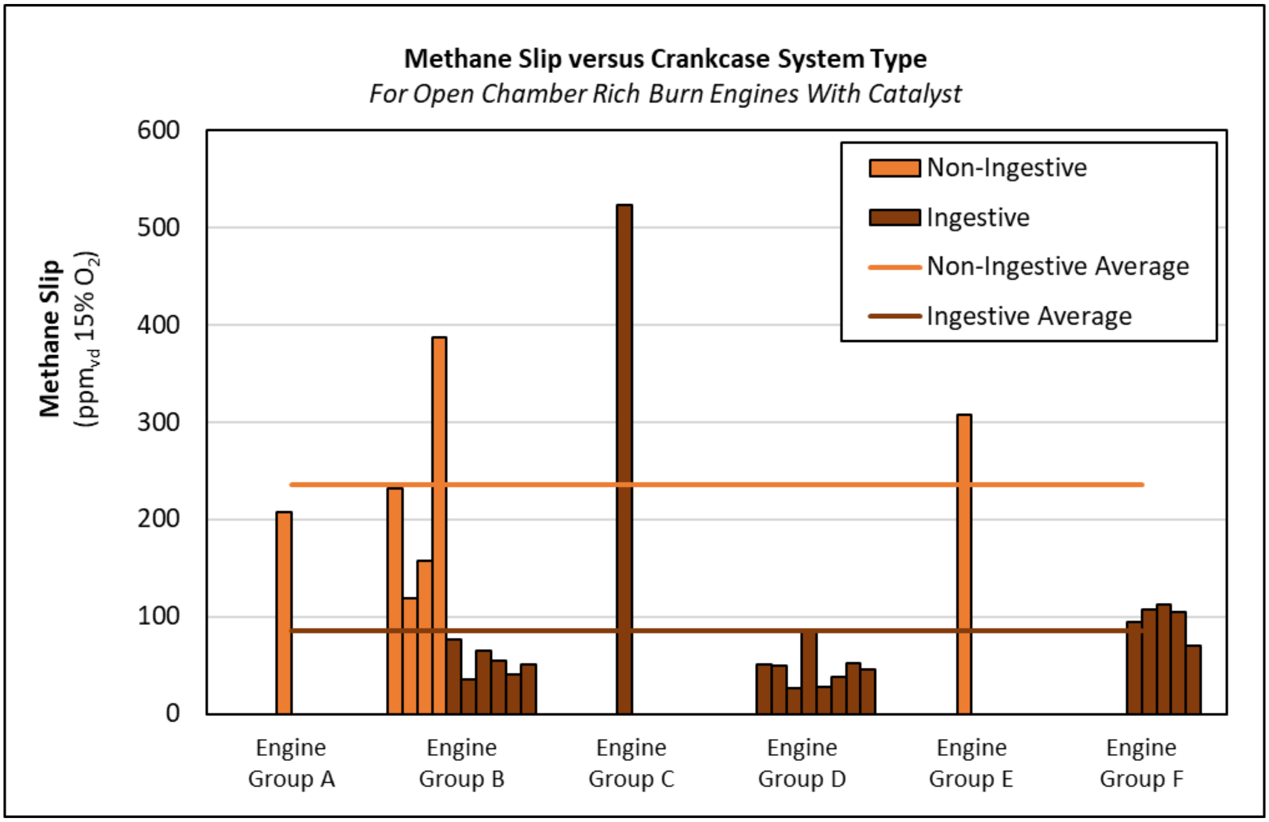

Figure 29 Methane slip versus crankcase evacuation system type for open chamber rich burn engines with catalyst

An ingestive crankcase evacuation system installed on an open chamber rich burn with a catalyst decreases methane slip by 150 ppm$_{vd}$ @ 15% O_2 below the average according to this data. That result follows what theory would suggest. The tuning of these engines offers a relatively narrow range of air fuel ratio (rich and lean) but a wide dispersion of data persists. Operating set points and load that differ is likely the cause of the spread in the data. Engine groups are classified according to manufacturer.

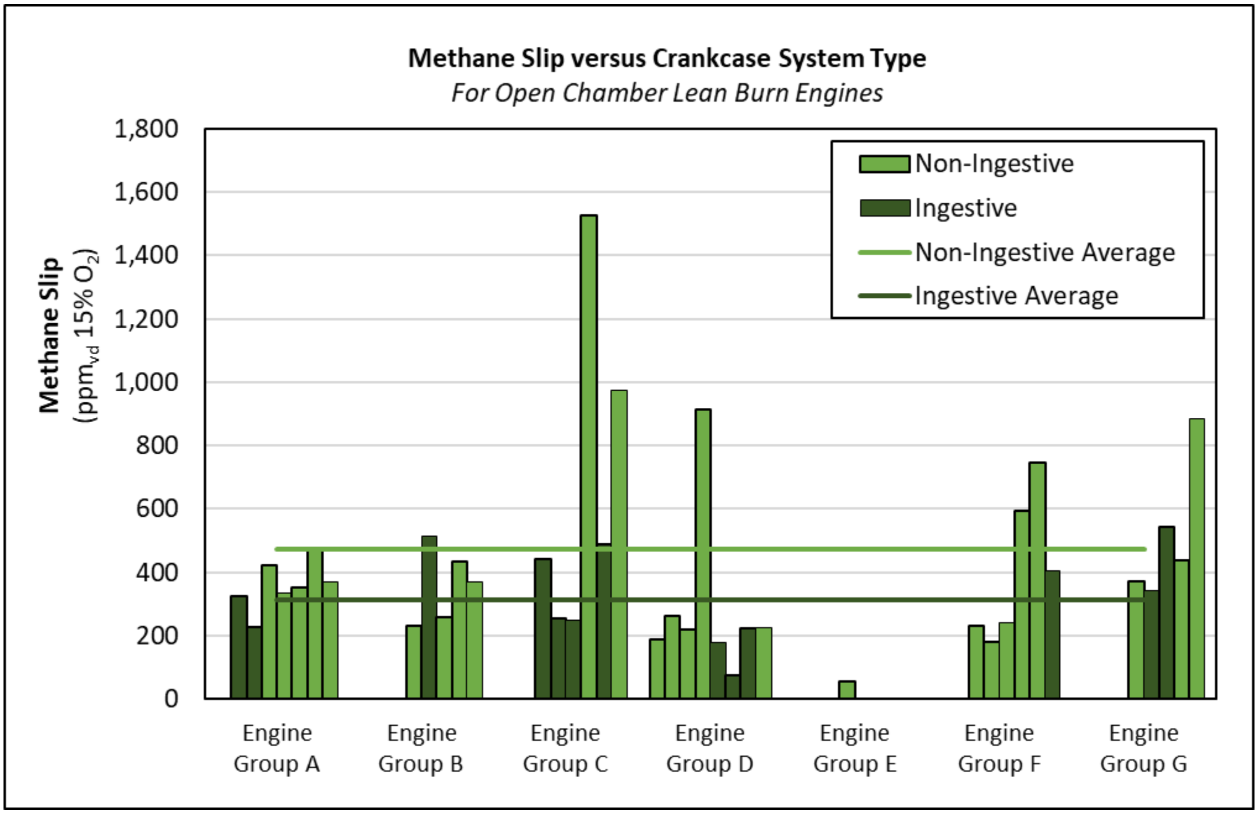

Figure 30 Methane slip versus crankcase evacuation system type for open chamber lean burn engines

An ingestive crankcase evacuation system installed on an open chamber lean burn engine decreases methane slip by 156 ppm$_{vd}$ @ 15% O_2 below the average according to this data. That result follows what theory would suggest. The tuning of these engines offers a relatively narrow range of air fuel ratio (rich and lean) but a moderate dispersion of data exists. Operating set points and load that differ is likely the cause of the spread in the data. Engine groups are classified according to manufacturer.

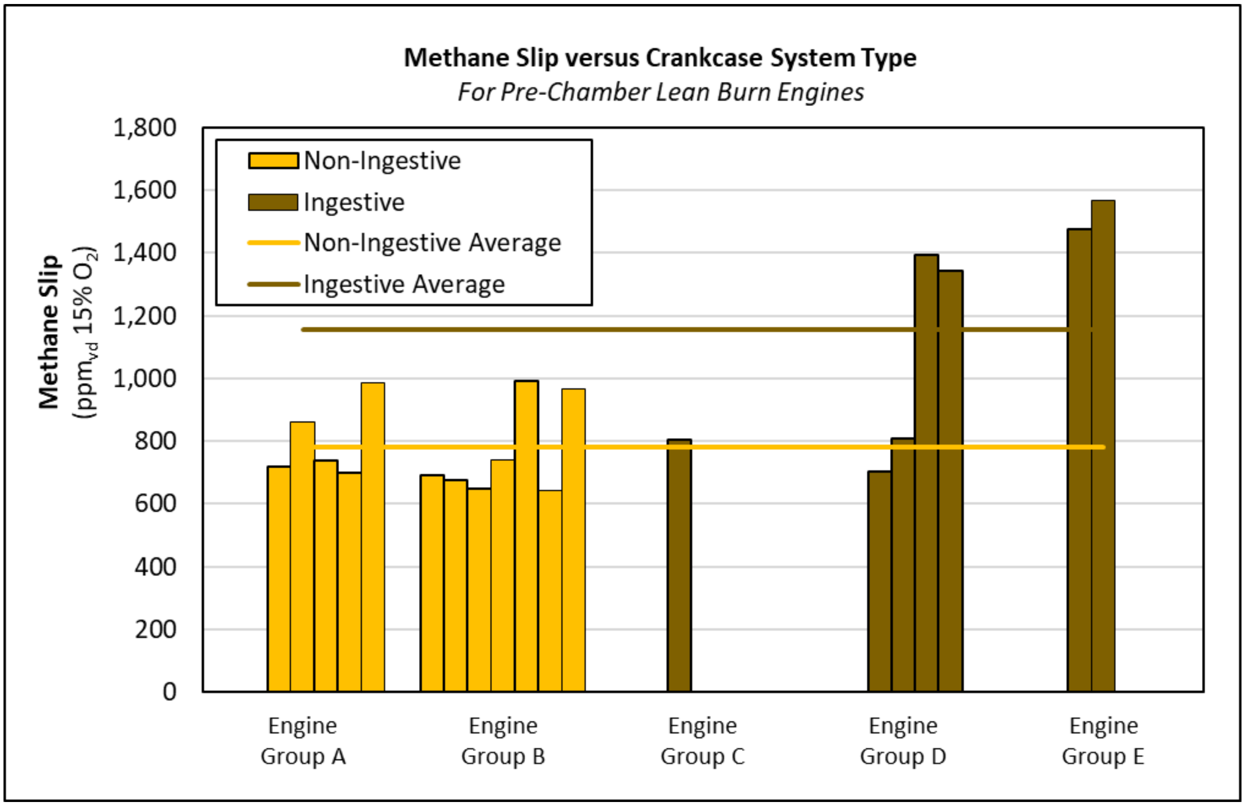

Figure 31 Methane slip versus crankcase evacuation system type for pre-chamber lean burn engines

An ingestive crankcase evacuation system installed on a pre-chamber lean burn engine increases methane slip by 377 ppm_{vd} @ 15% O_2 above the average according to this data. That result does not follow what theory would suggest. The tuning of these engines offers a relatively narrow range of air fuel ratio (rich and lean) and a limited dispersion of data exists. Operating set points and load that differ is likely the cause of the spread in the data. Groups C, D and E are legacy engine models with non adaptive controls which may not be tuned to limit CH_4 emissions without regardless of CCV. Engine groups are classified according to manufacturer.

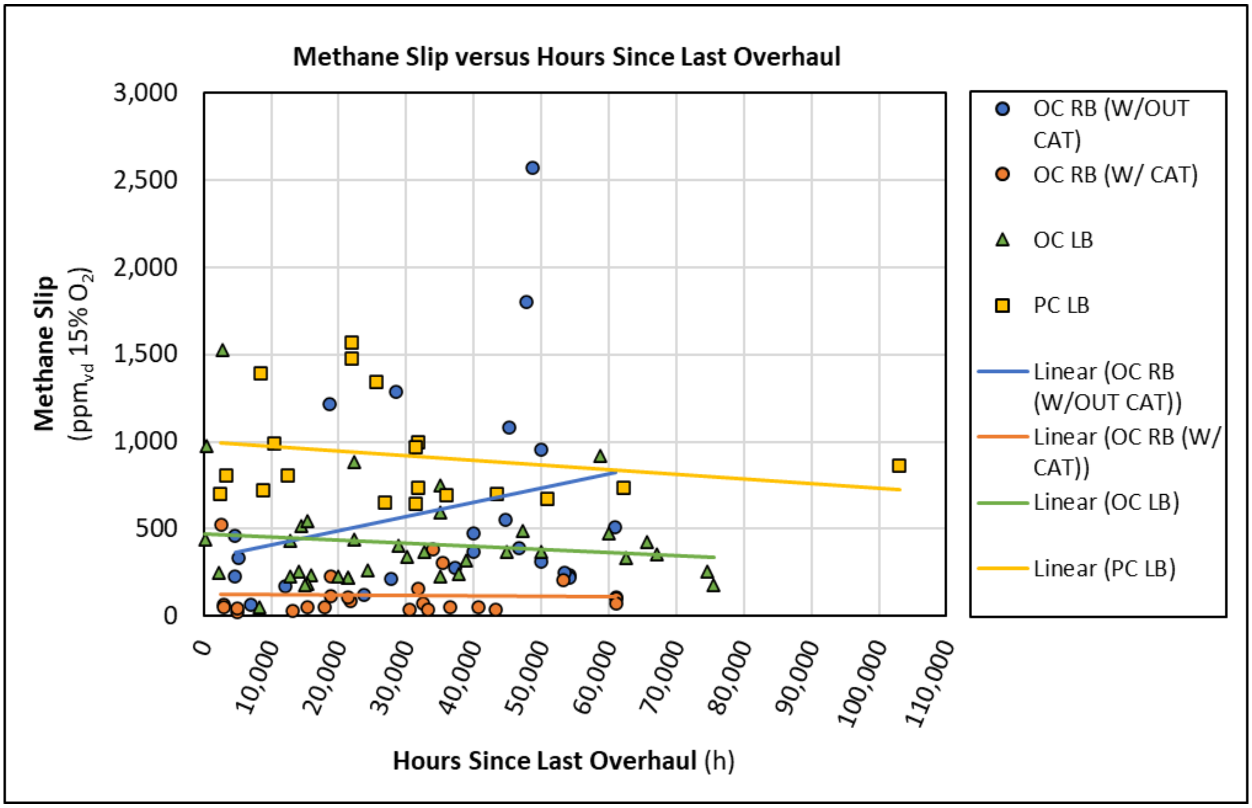

Figure 32 Methane slip versus hours since last overhaul for all engine combustion styles

No strong correlation is presented by comparing hours since last overhaul with methane slip for any of the engine combustion types. Clustering of the data suggests the trend follows O2% rather than hours since last overhaul. The data suggests a pattern that is counterintuitive to what theory should suggest. As the engine wears, crevices and tolerances should increase which should increase methane slip. That is not shown in this data set. Perhaps a more distinct correlation is evident if the crankcase vents are considered alone. A study of the crankcase vents separate from the exhaust emissions warrants further study.

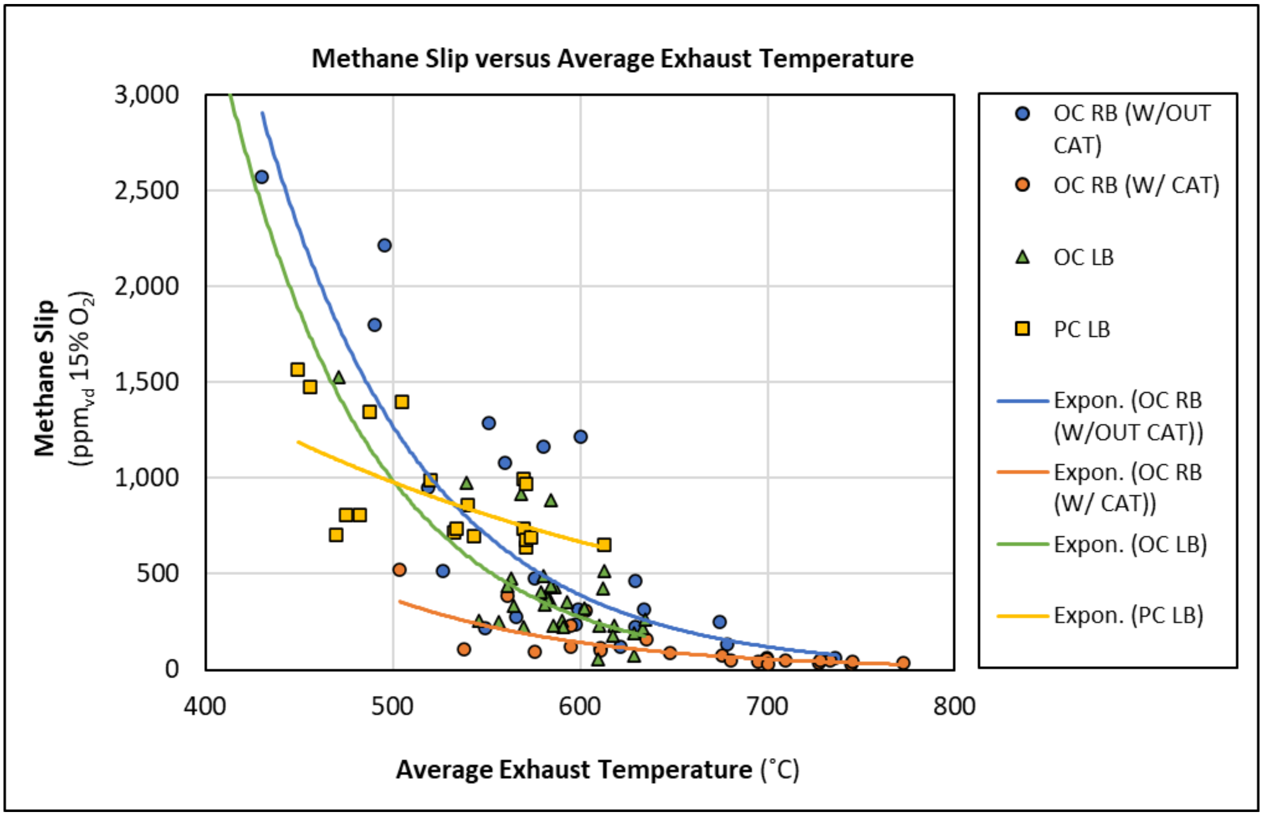

Figure 33 Methane slip versus average exhaust temperature for all engine combustion types

Average exhaust temperature follows an inversely proportional exponential best fit line with a strong correlation. Methane slip decreases exponentially as average exhaust temperature increases.

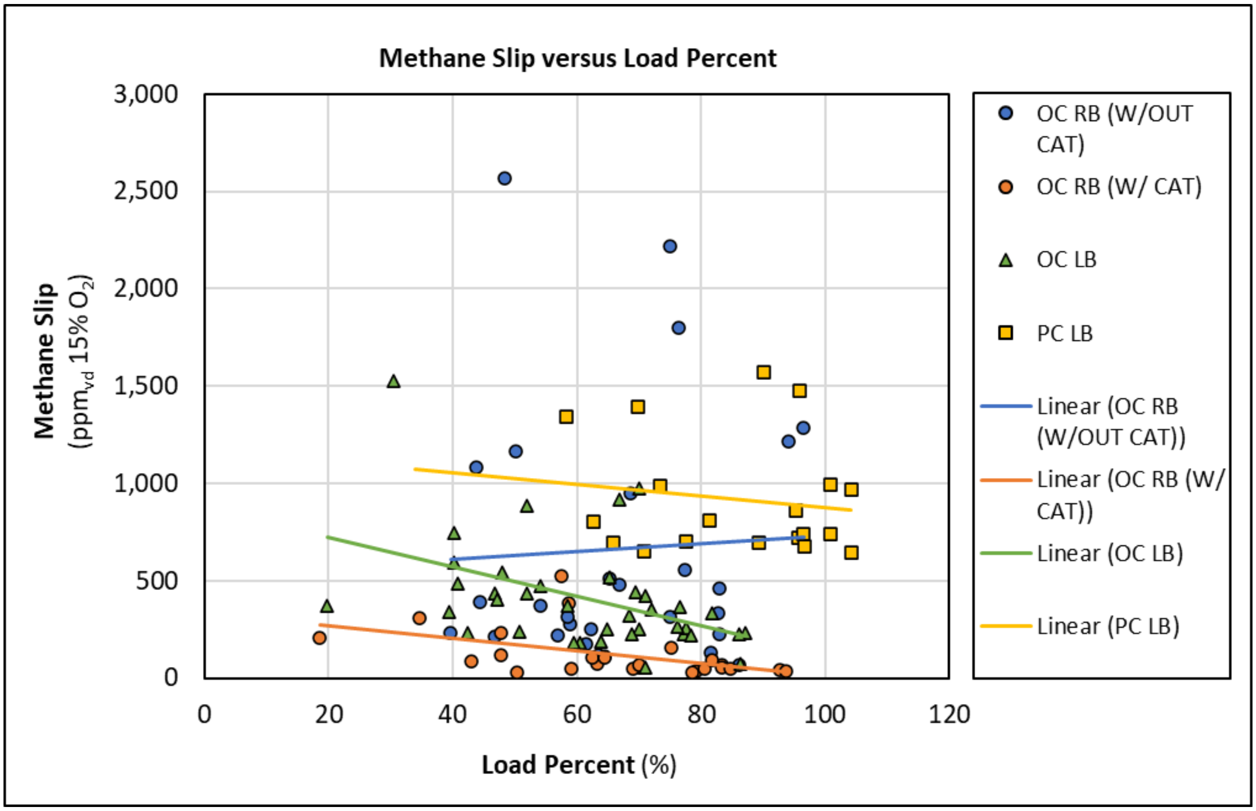

Figure 34 Methane slip versus load percent for all engine combustion types

Load percent is the actual engine load with reference to the rated load of the engine at that operating RPM. The rated load decreases with lower RPM. Thus, the rated load is always defined in the context of the operating speed. The data shows a wide dispersion and weak correlation. The trends indicated are both directly proportional and mostly inversely proportional. Theory suggests that methane slip might decrease with higher load since the head temperature increases. That trend is suggested in the data on all combustion types except rich burn combustion without a catalyst. Too many variables are in play to draw a conclusion on that one directly proportional trend.

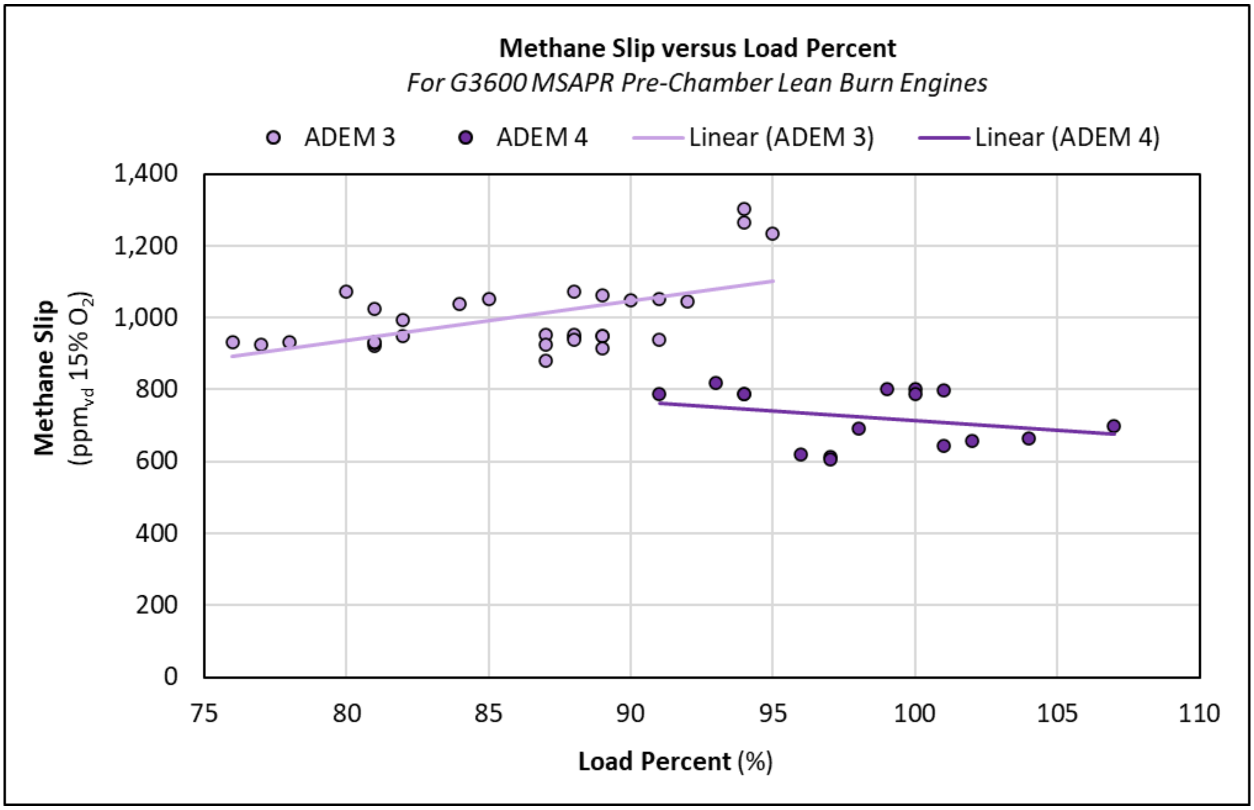

Figure 35 Methane slip versus load percent for G3600 MSAPR tested pre-chamber lean burn engines

The pre-chamber lean burn Caterpillar G3600 series engines follow the trend expected by theory for the ADEM 4 engine management system. That trend is not supported by the ADEM 3 engines. Correlation is limited for the two groups of engines but the data is grouped closer for these engines than in the remainder of the test samples. Tuning likely plays a part in the trends.

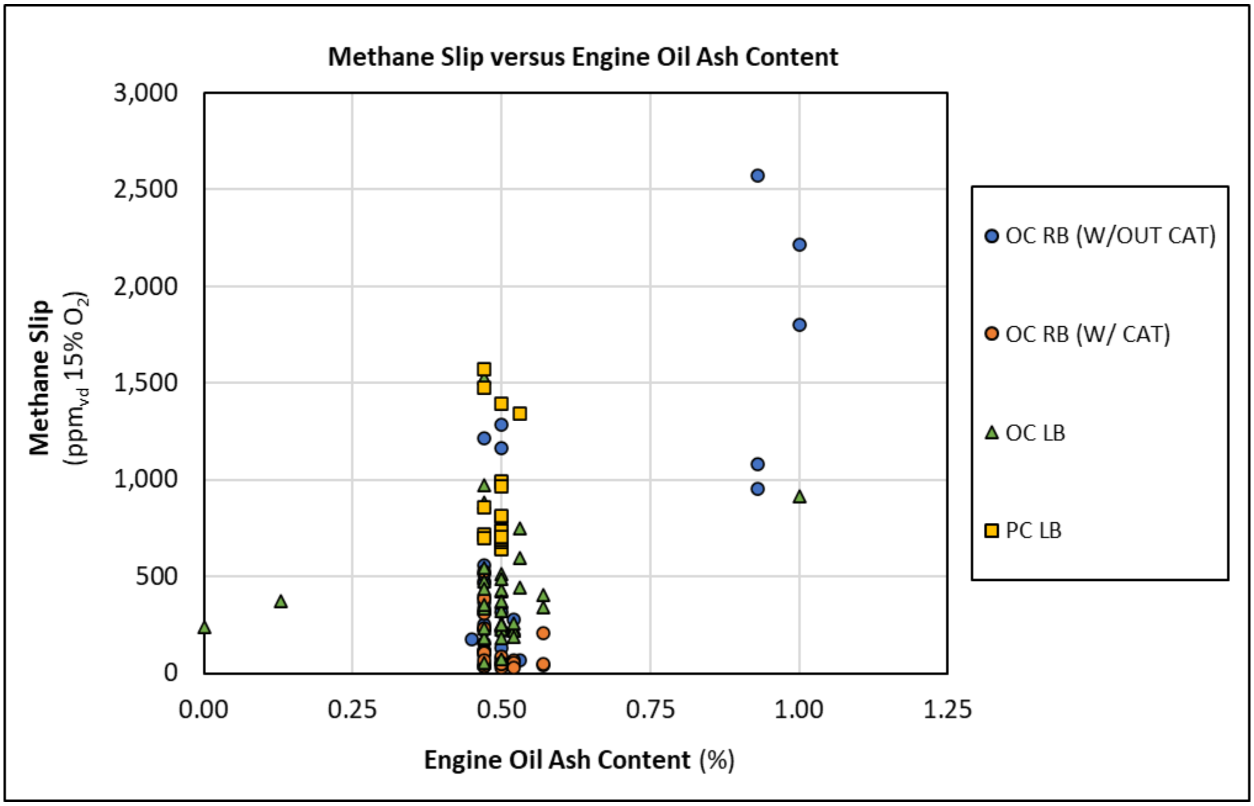

Figure 36 Methane slip versus engine oil ash content for all engine combustion types

No apparent trend is presented with respect to engine oil ash and methane slip. The data is clustered around the most common ash contents in commonly used oils. Sulphonated ash is thought to coat the interior surfaces of the combustion chamber and the valves where they seat in the cylinder head. That layer may reduce the crevice volumes or increase the trapped unburned methane in the surface layer. The two data points on the left of the graph suggest that lower methane slip might be associated with lower ash contents. Similarly, the cluster of data suggests a rising trend from lower left to upper right on the graph. That would also suggest lower ash yields lower methane slip. In addition, no correlation is presented by the plots of oil base number. These aspects deserve further study.

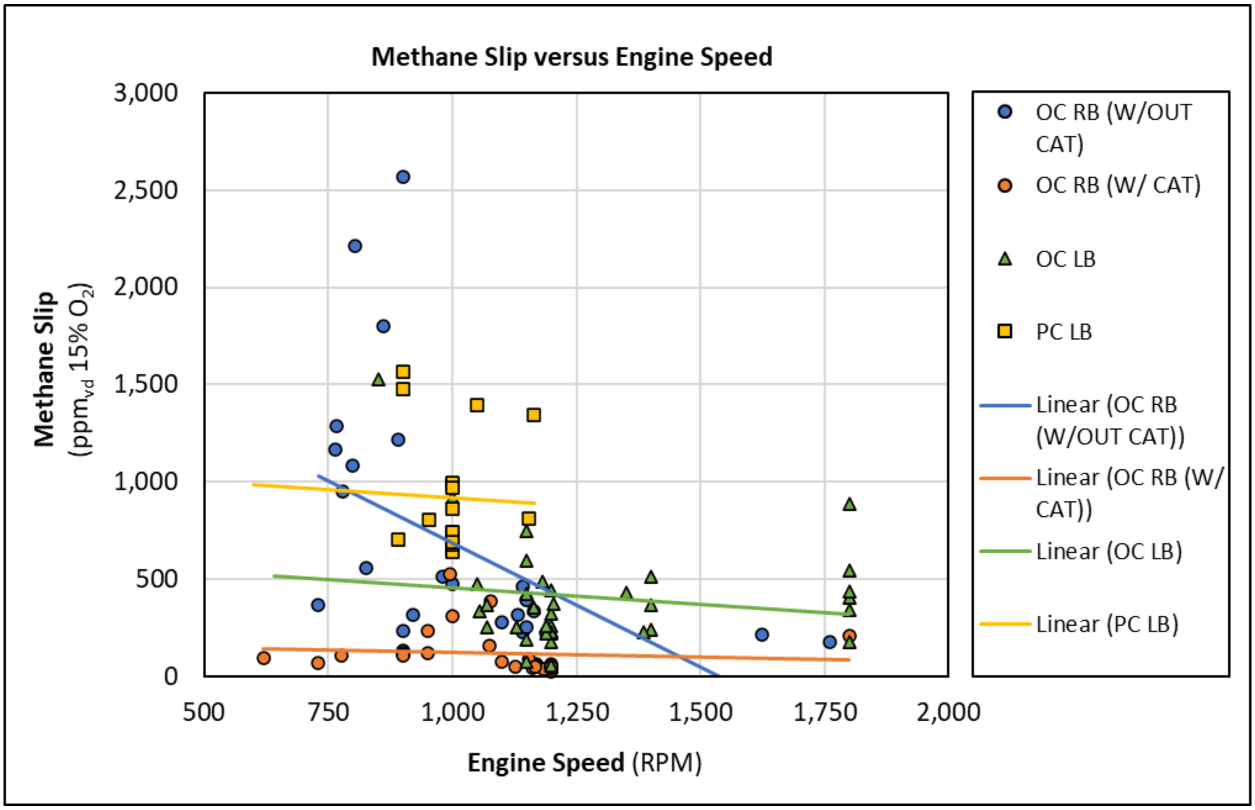

Figure 37 Methane slip versus engine speed for all engine types

No apparent correlation is apparent in the trends for methane slip versus engine speed. Theory suggests that methane slip should increase as RPM increases because the combustion event has less time to complete the burn. Timing of valves becomes more critical at higher speeds too. The opposite tends are suggested by the data.

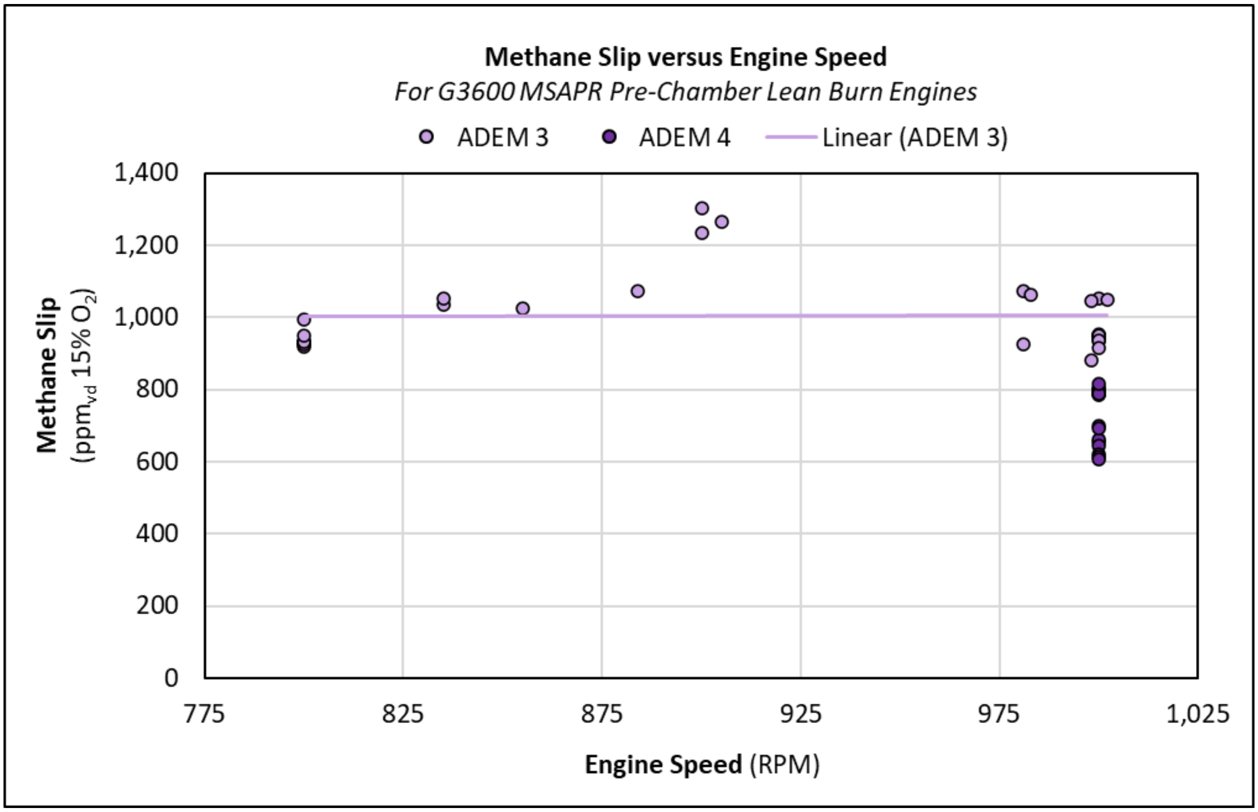

Figure 38 Methane slip versus engine speed for G3600 MSAPR tested pre-chamber lean burn engines

MSAPR test data for the Caterpillar G3600 series engines does not follow the trend expected by theory. Correlation for the ADEM3 data is also weak. The ADEM 4 data is a tighter group with all engines running at maximum speed which makes a best fit line vertical so the relationship is undefined. This data indicates that RPM does not affect methane slip in pre-chambered engines with adaptive control systems.

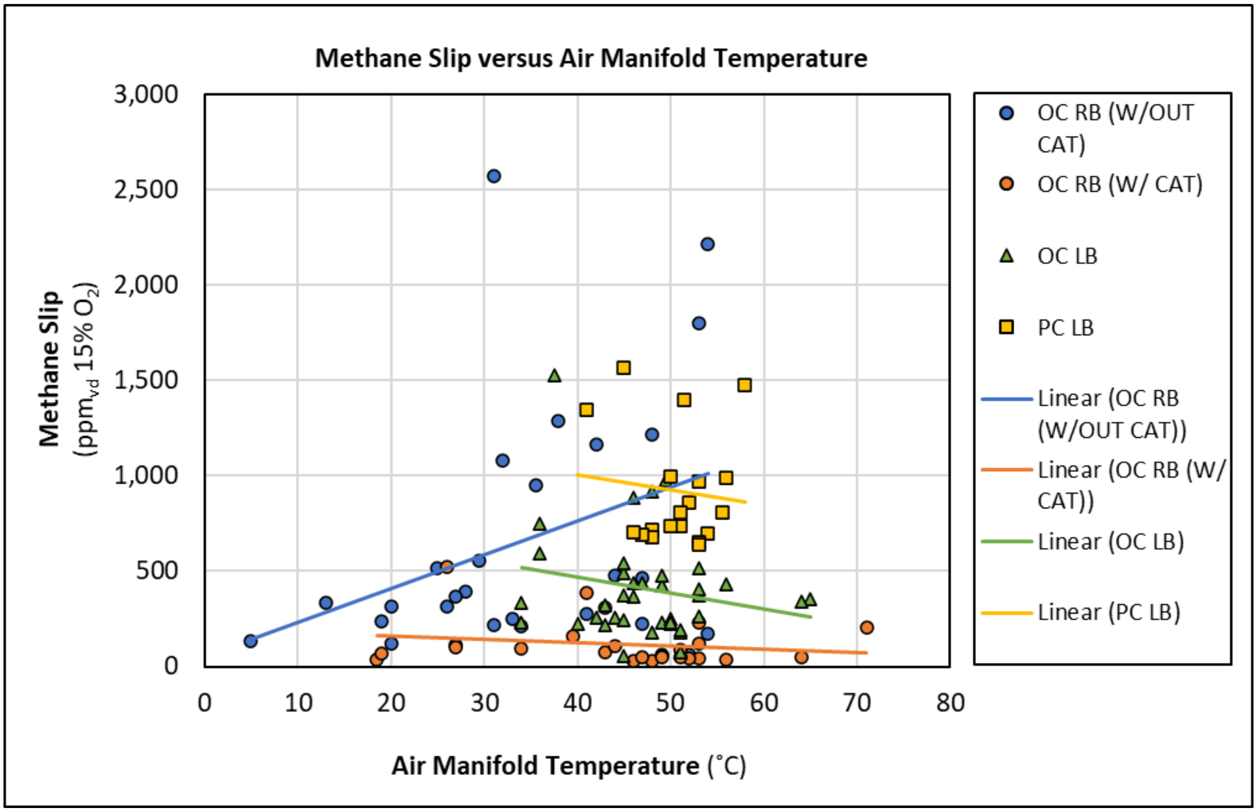

Figure 39 Methane slip versus air manifold temperature for all engine types

No apparent correlation is presented by air manifold temperature with respect to methane slip. The manifold temperature on turbocharged engines is conditioned by the auxiliary water circuit (SC on the data spreadsheet) to be relatively constant. Therefore, only the rich burn naturally aspirated engines would show any relevant trends. Viewing the graph above shows a wide dispersion of the open chamber rich burn engines without catalyst. No conclusion is presented by the data.

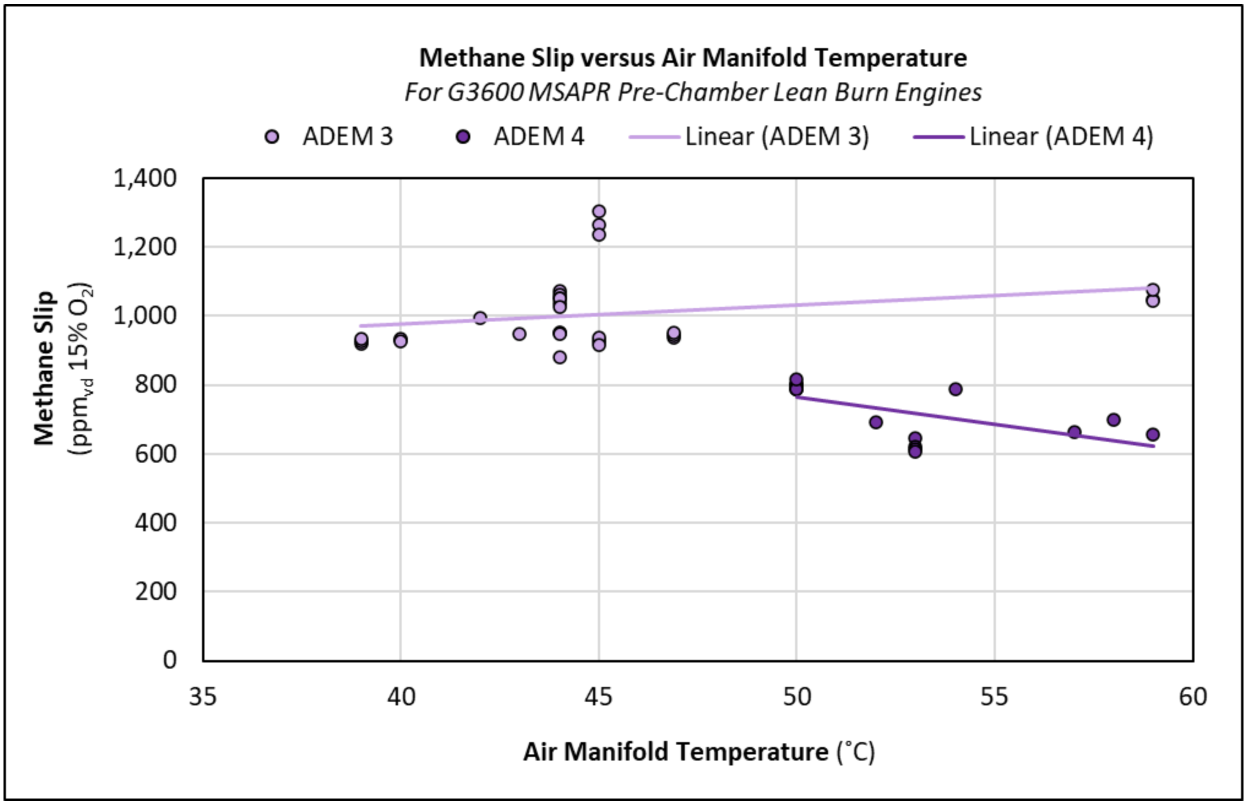

Figure 40 Methane slip versus air manifold temperature for G3600 MSAPR tested pre-chamber lean burn engines

No apparent correlation is presented by air manifold temperature with respect to methane slip. Correlation on both engine management systems is limited. The manifold temperature on turbocharged engines is conditioned by the auxiliary water circuit (SC on the data spreadsheet) to be relatively constant. Viewing the graph above shows a wide dispersion of data. The ADEM 4 data appears to mimic the trend line for all pre-chamber engines. That suggests that methane slip should decline with increasing combustion air temperature.

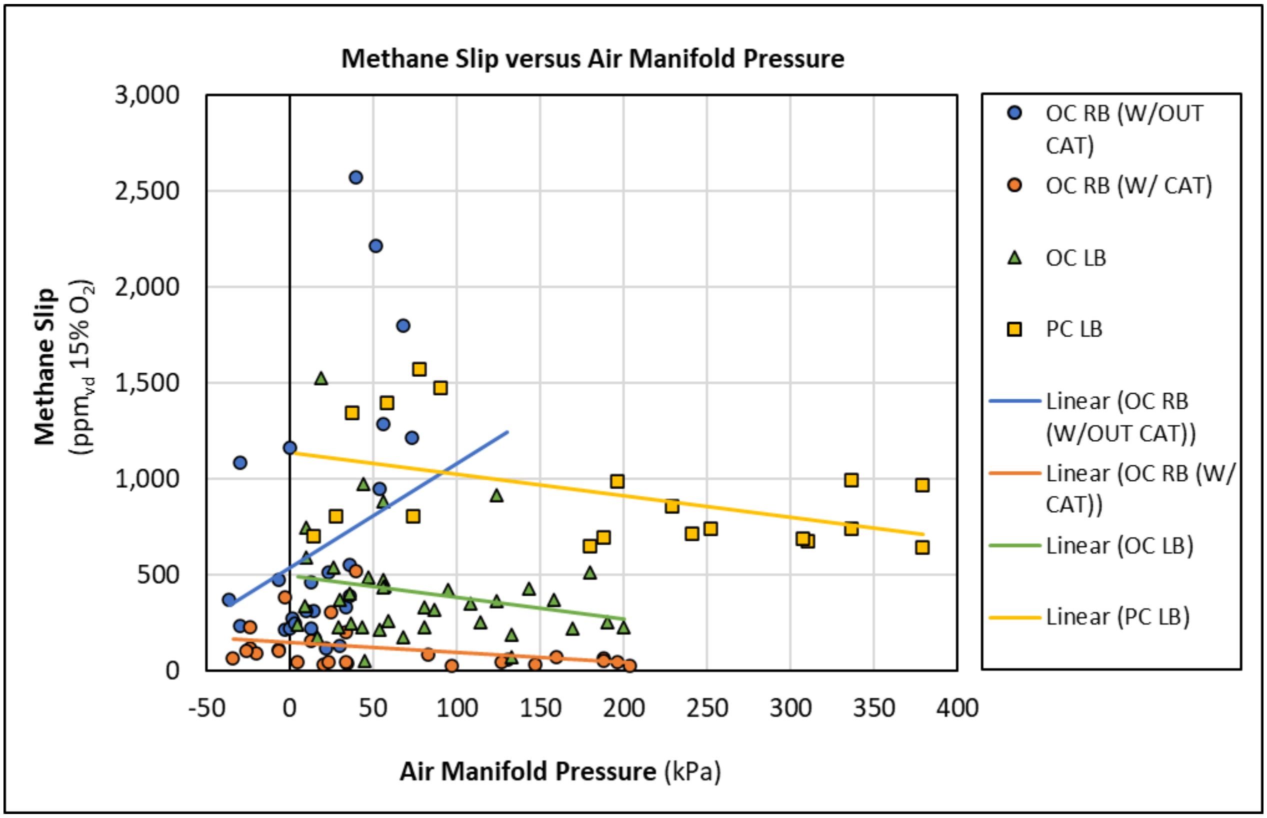

Figure 41 Methane slip versus air manifold pressure for all engine types

Air manifold pressure is an indicator of engine load. It follows that no correlation is then presented by manifold pressure either. Correlation is weak or slight. Theory would suggest that higher air manifold pressure would provide more air to mix with fuel and thus a higher charge for combustion. That should result in higher methane slip since more fuel is provided to the combustion chamber. That is not supported by the data. This aspect warrants further study.

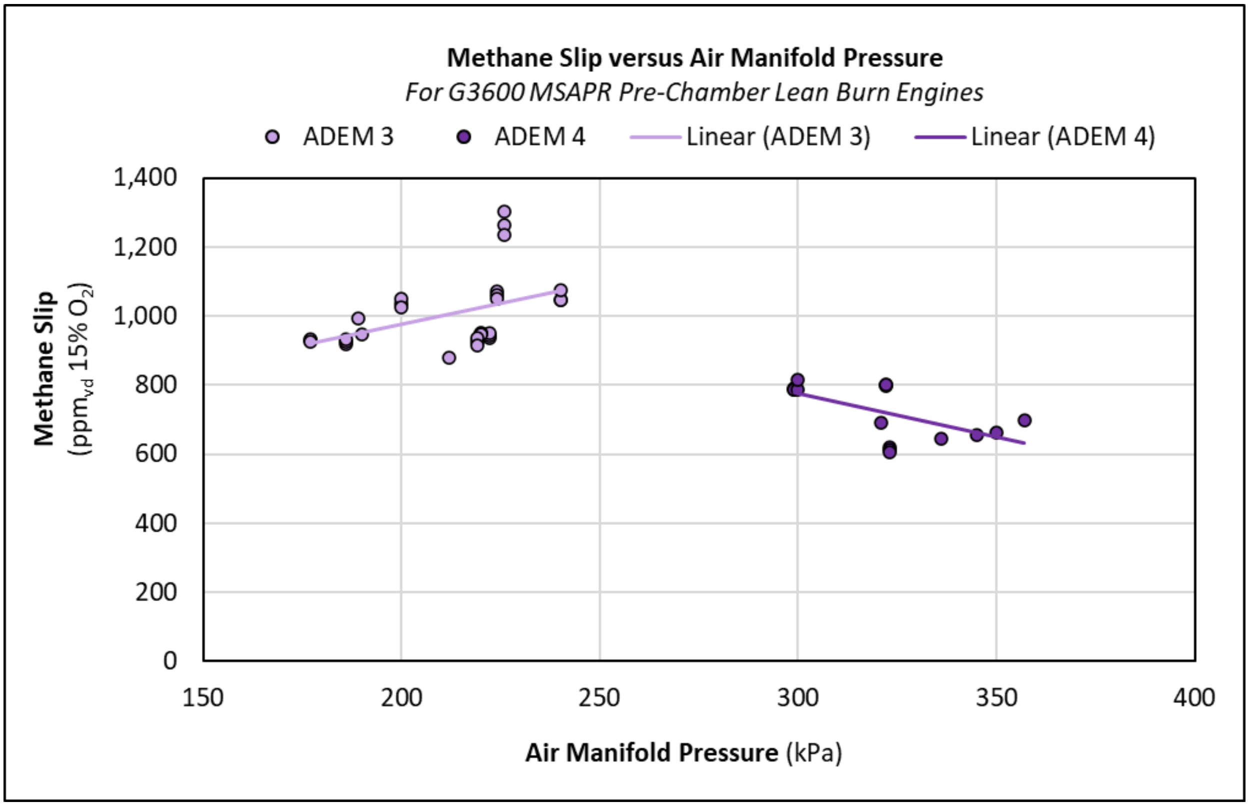

Figure 42 Methane slip versus air manifold pressure for G3600 MSAPR tested pre-chamber lean burn engines

Correlation is limited or moderate. Theory would suggest that higher air manifold pressure would provide more air to mix with fuel and thus a higher charge for combustion. That should result in higher methane slip since more fuel is introduced to the combustion chamber. That is not supported by the data for the ADEM 4 system. Enhanced adaptive controls on the ADEM 4 system may explain the divergence from theory. However, the ADEM 4 system trend line mimics the trend line for all engines with pre-chambered combustion style. This aspect warrants further study.

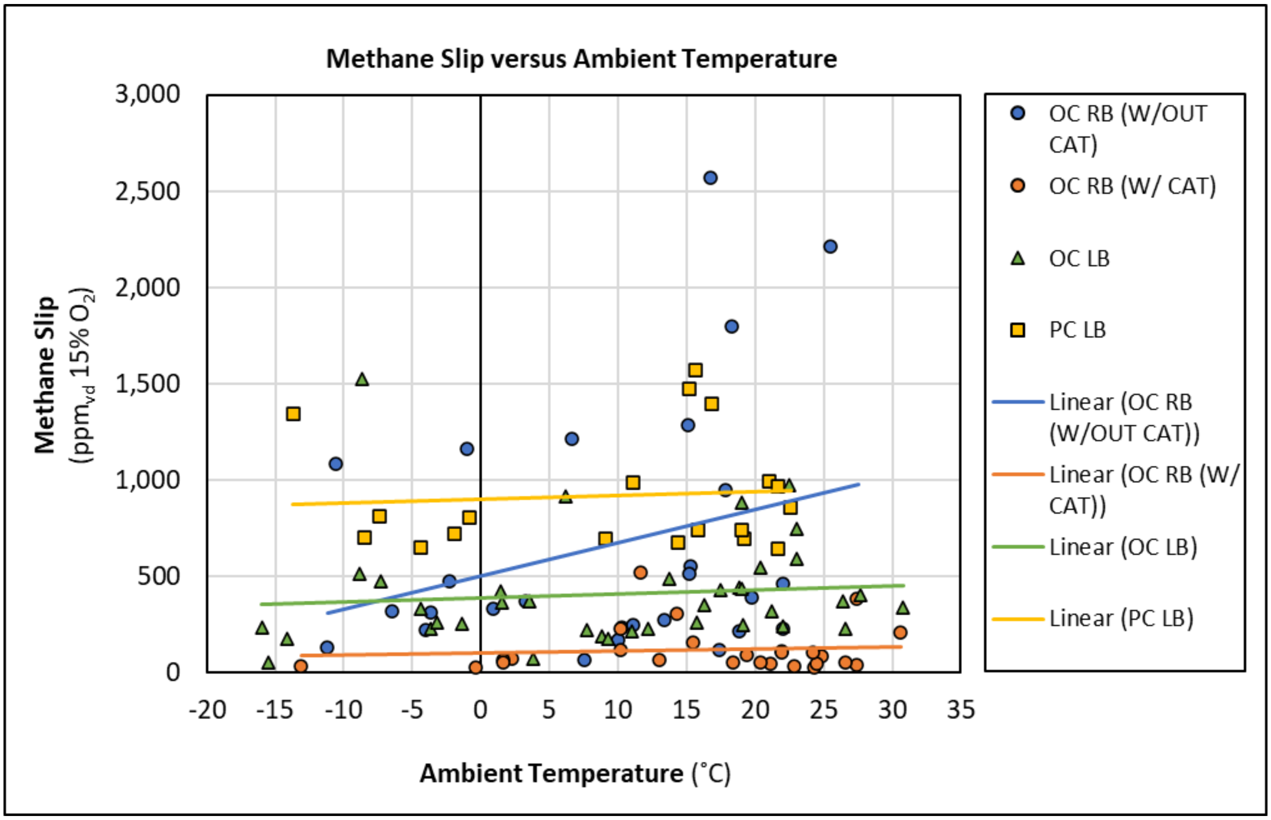

Figure 43 Methane slip versus ambient temperature for all engine types

Correlation for the trend lines is weak. The air manifold temperature is conditioned the auxiliary water circuit on turbocharged engines. The only combustion style that would see the ambient air temperature communicated to the combustion chamber is a naturally aspirated engine. The horizontal trend lines for the turbocharged engines advise that no relationship exists between changing the ambient temperature and methane slip.

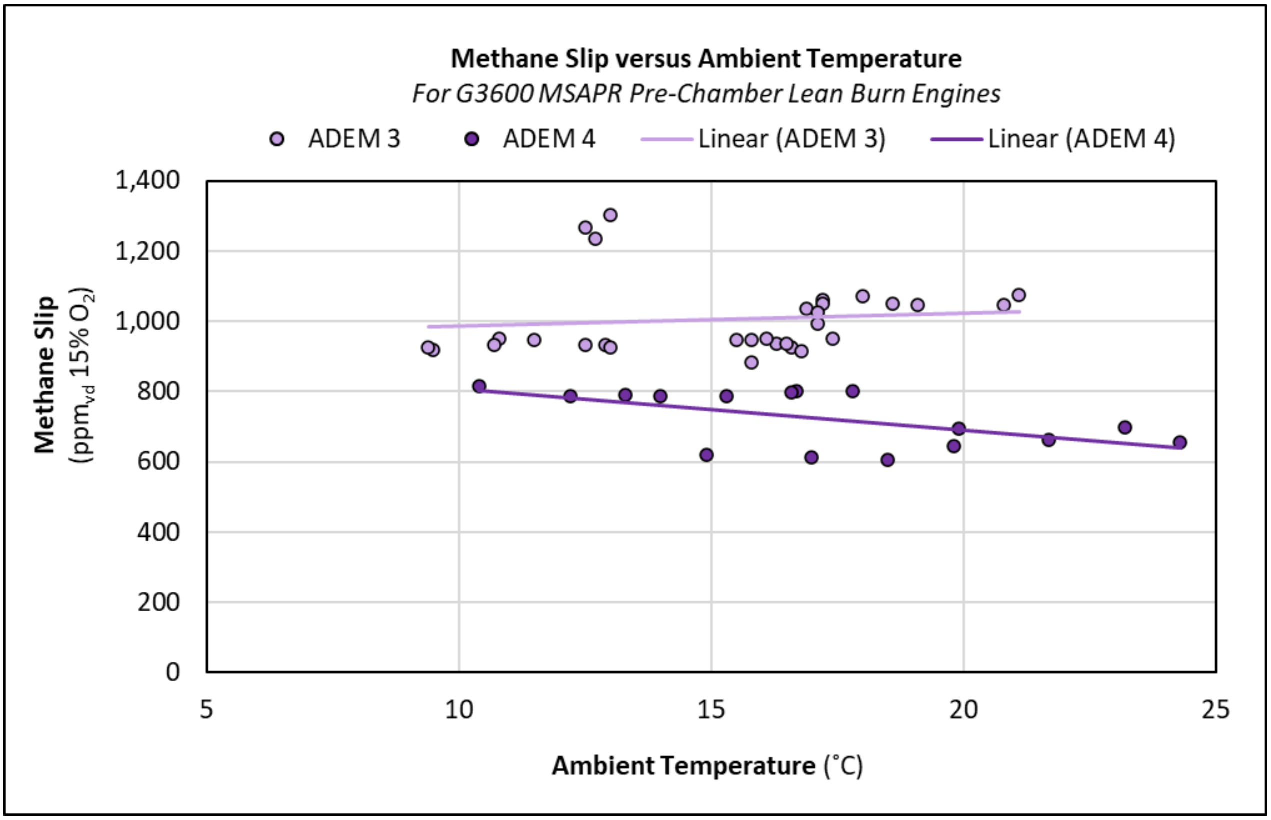

Figure 44 Methane slip versus ambient temperature for G3600 MSAPR tested pre-chamber lean burn engines

Correlation for the trend lines is weak. The air manifold temperature is conditioned the auxiliary water circuit on turbocharged engines. The near horizontal trend lines for the turbocharged engines advise that no relationship exists between changing the ambient temperature and methane slip.

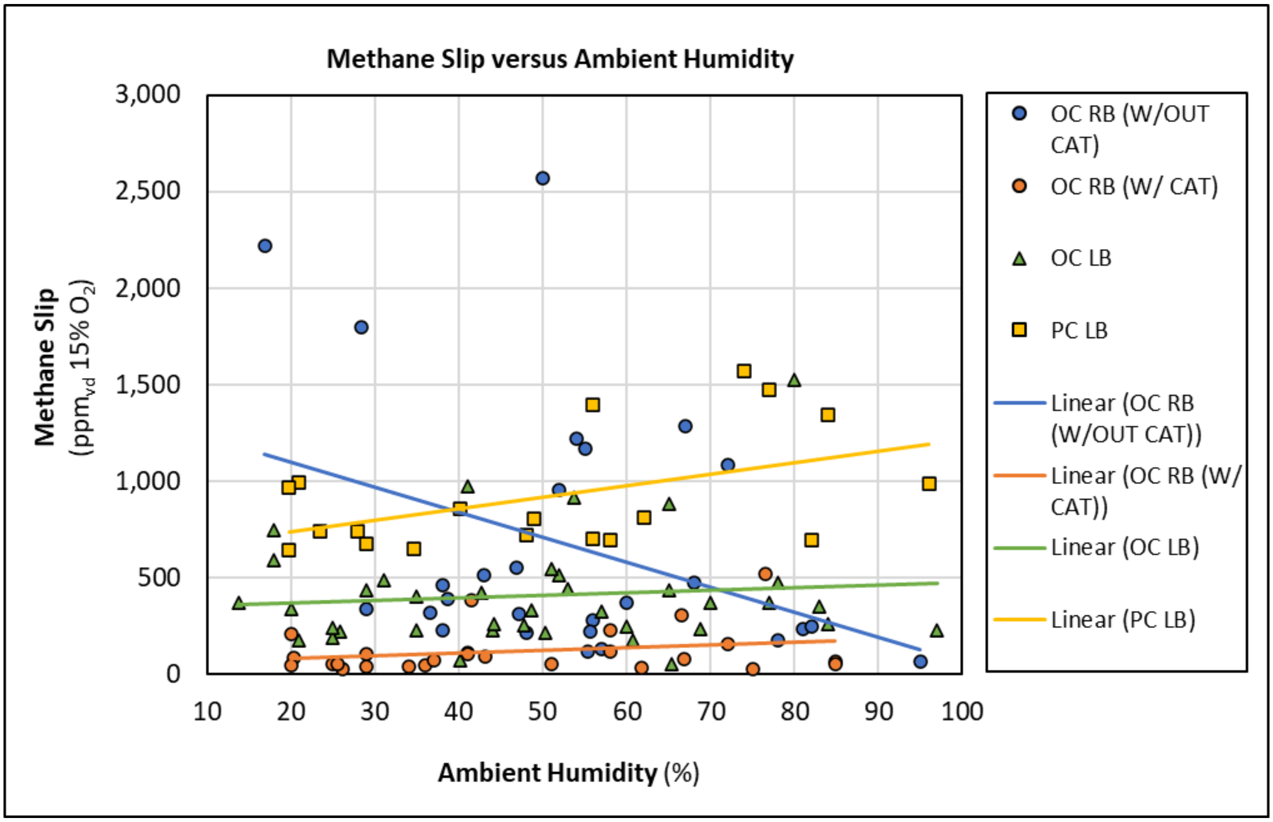

Figure 45 Methane slip versus ambient humidity for all engine combustion types

Water added to the combustion chamber is known to reduce operating temperatures and increase efficiency when the rate is controlled and mixing is optimum. Humidity will remain in a vapor state in the engine air intake on engines equipped with turbochargers since the auxiliary water circuit is designed to keep the inlet air at a temperature above the water dew point. Thorough mixing of the water vapor with the air-fuel mixture should be assured. Theory suggests that higher humidity should cool hot spots in the combustion chamber and result in increased methane slip. The trend lines associated with turbocharged engines suggest that to be true. The open chamber rich burn trend line shows a contrary trend to what is expected from the theory but the data is widely dispersed and that trend line is questionable.

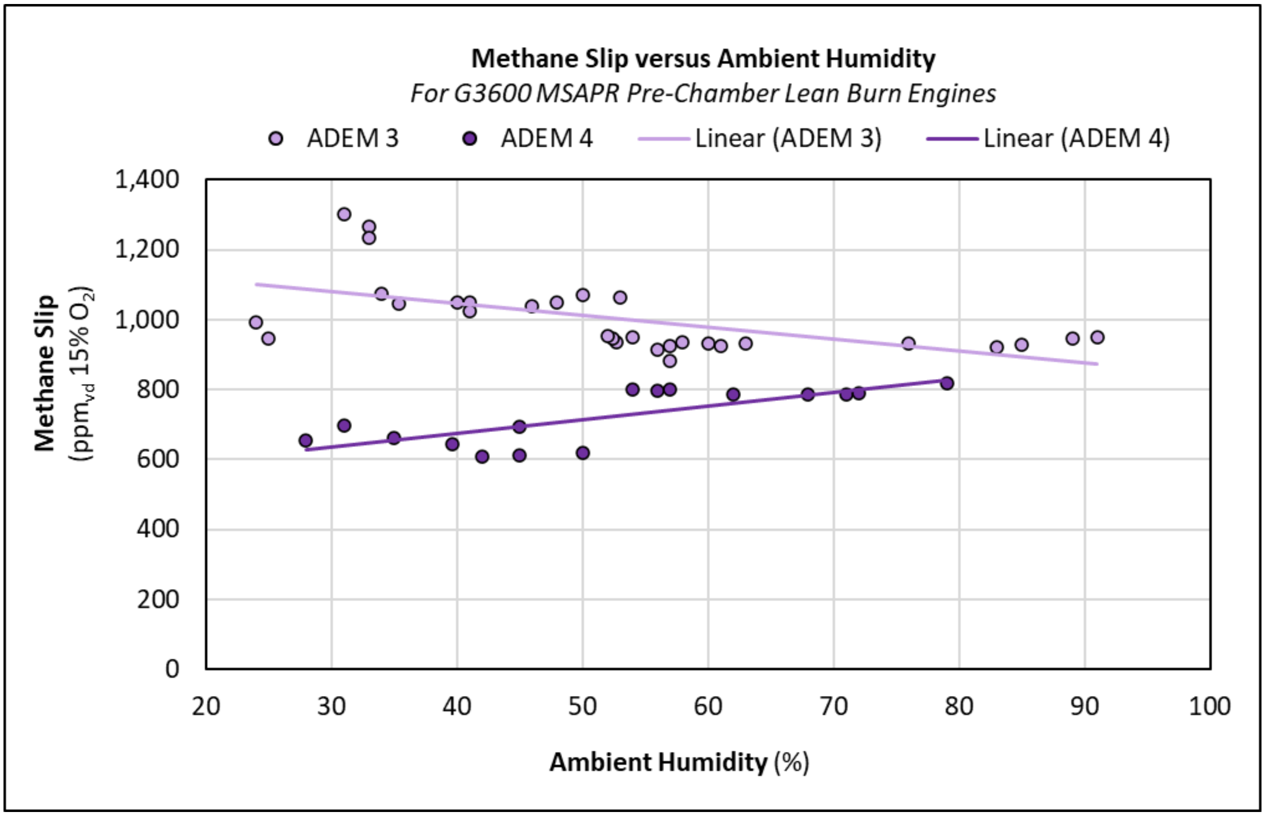

Figure 46 Methane slip versus ambient humidity for G3600 MSAPR tested pre-chamber lean burn engines

The auxiliary water circuit is designed to keep the inlet air at a temperature above the water dew point. Theory suggests that higher humidity should cool hot spots in the combustion chamber and result in increased methane slip. The trend lines associated with the ADEM 4 system suggest that to be true. The ADEM 3 trend line shows a contrary trend to what is expected from the theory. The correlation to the trend lines is limited for both engine models. The enhanced engine management system on the ADEM 4 engines may play a role in the slope of the trend line. Recall also that the operating speed of the ADEM 4 engines are higher than most of the ADEM 3 engines.

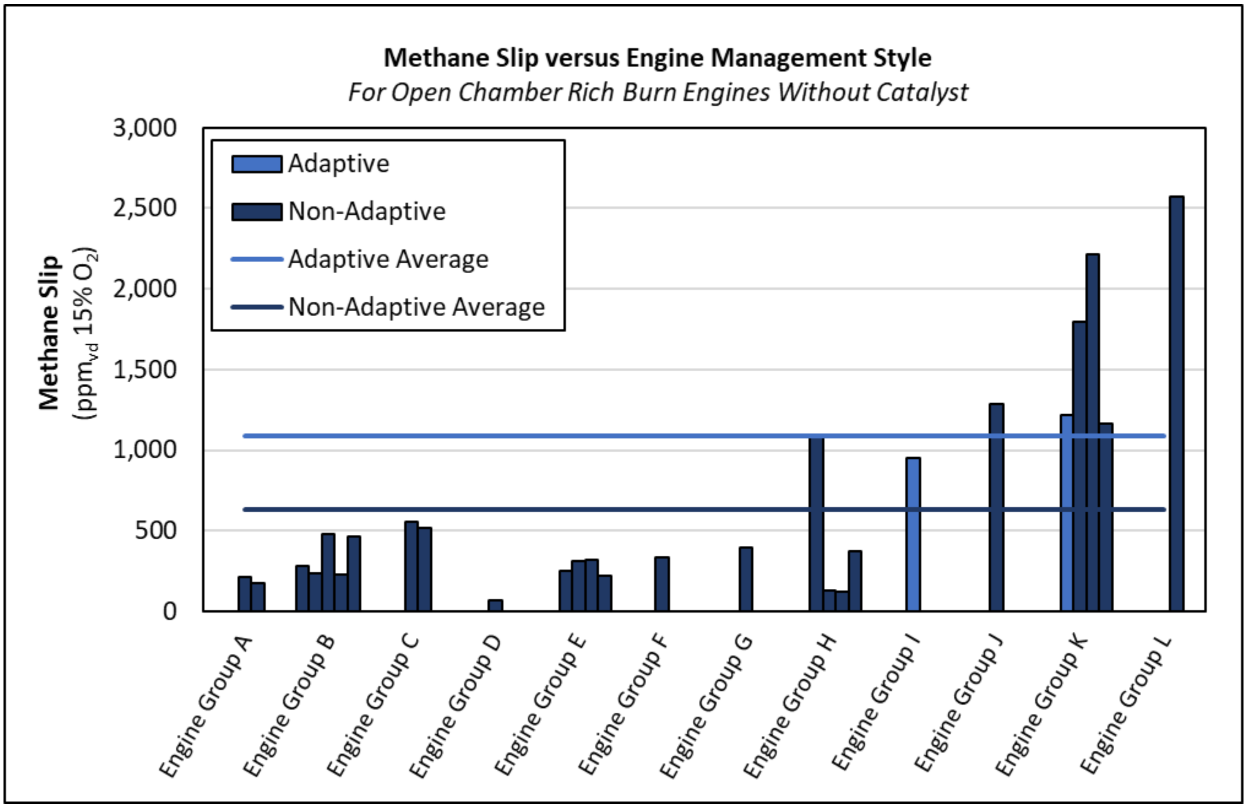

Figure 47 Methane slip versus engine management style for open chamber rich burn engines without catalyst

The average methane slip emissions for an open rich burn engine without catalyst is 453 ppm_{vd} @ 15% O_2 lower with a non-adaptive control system than an adaptive system. Theory suggests that the adaptive system should produce less methane slip. The data shows only two samples of engines with adaptive control systems versus 25 samples without adaptive controls. The subsequent averages will not be representative for the engines with adaptive control systems. The engine groups represent different engine models and manufacturers.

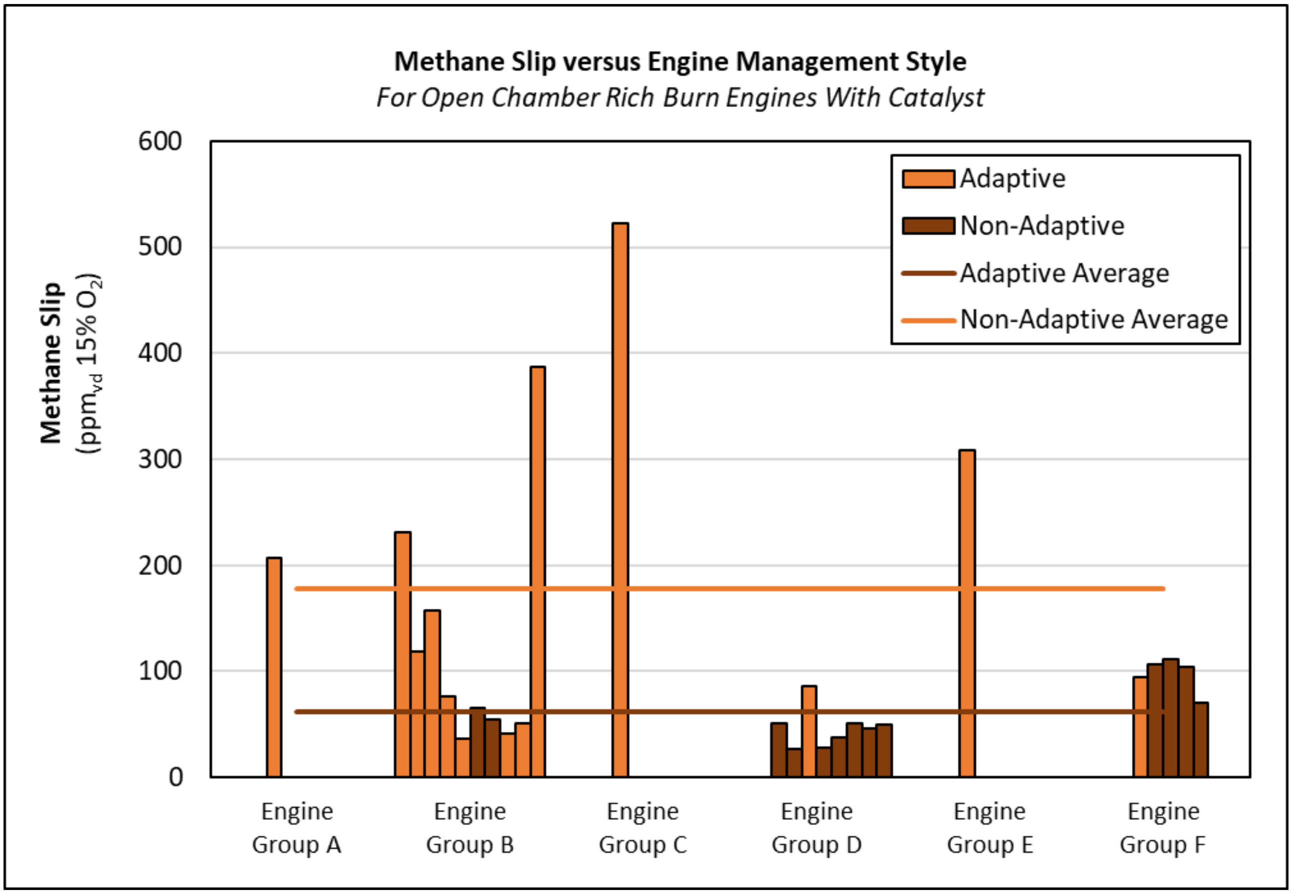

Figure 48 Methane slip versus engine management style for open chamber rich burn engines with catalyst

The average methane slip emissions for an open rich burn engine with catalyst is 117 ppm$_{vd}$ @ 15% O_2 lower with an adaptive control system than a non-adaptive system. Theory suggests that the adaptive system should produce less methane slip. The data shows equal sample sizes of engines with and without adaptive control systems. The subsequent averages will be representative. The engine groups represent different engine models and manufacturers.

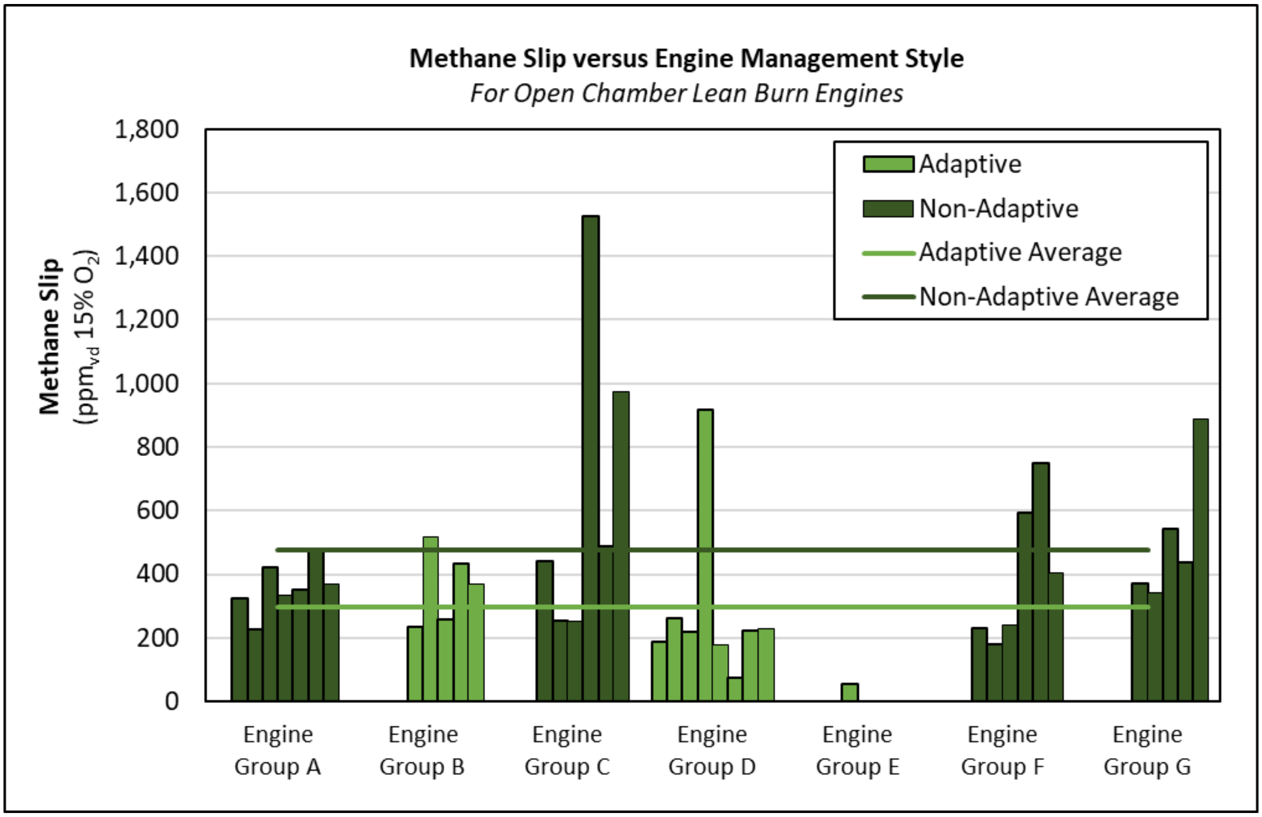

Figure 49 Methane slip versus engine management style for open chamber lean burn engines

The average methane slip emissions for an open chamber lean burn engine is 178 ppm_{vd} @ 15% O_2 lower with an adaptive control system than a non-adaptive system. Theory suggests that the adaptive system should produce less methane slip. The data shows similar sample sizes of engines with and without adaptive control systems. The subsequent averages will be representative. The engine groups represent different engine models and manufacturers.

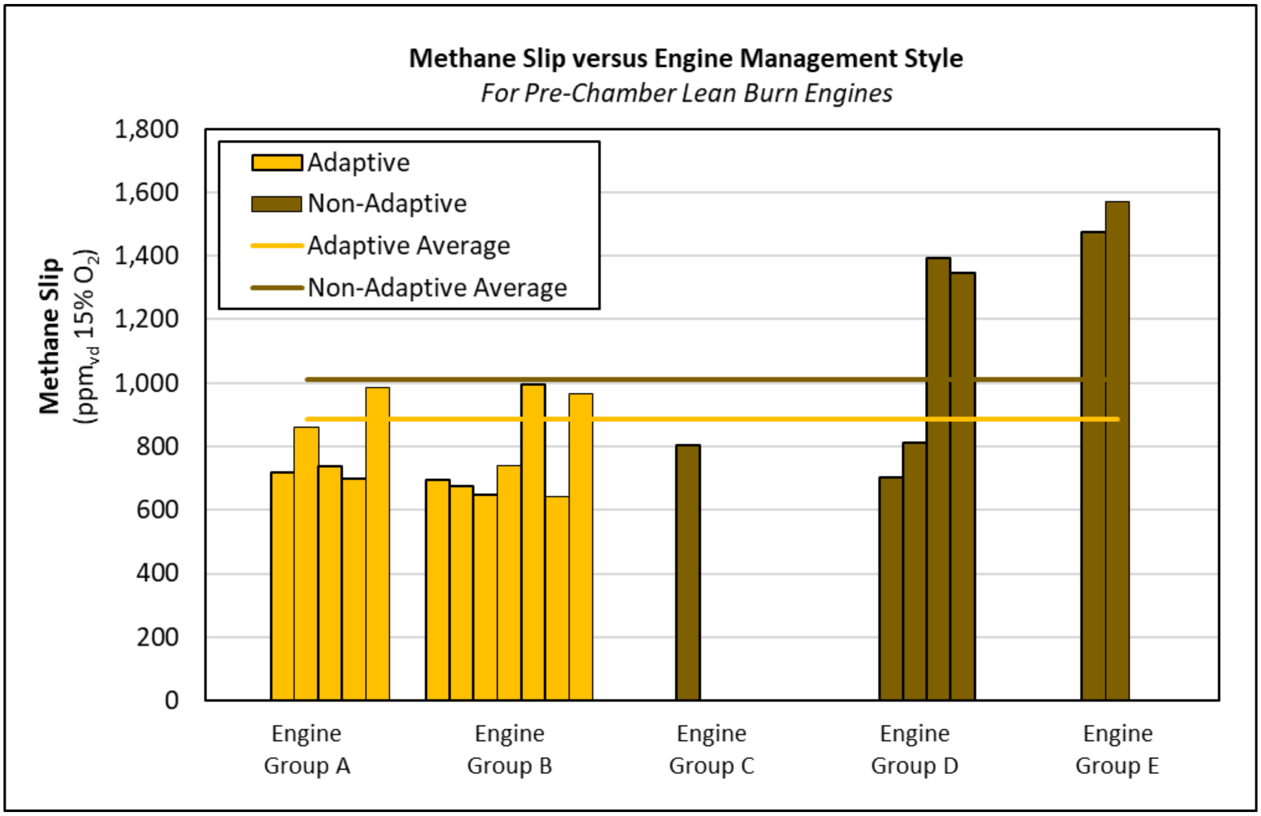

Figure 50 Methane slip versus engine management style for pre-chamber lean burn engines

The average methane slip emissions for an pre-chamber lean burn engine is 126 ppm$_{vd}$ @ 15% O_2 lower with an adaptive control system than a non-adaptive system. Theory suggests that the adaptive system should produce less methane slip. The data shows similar sample sizes of engines with and without adaptive control systems. The subsequent averages will be representative. The engine groups represent different engine models and manufacturers.

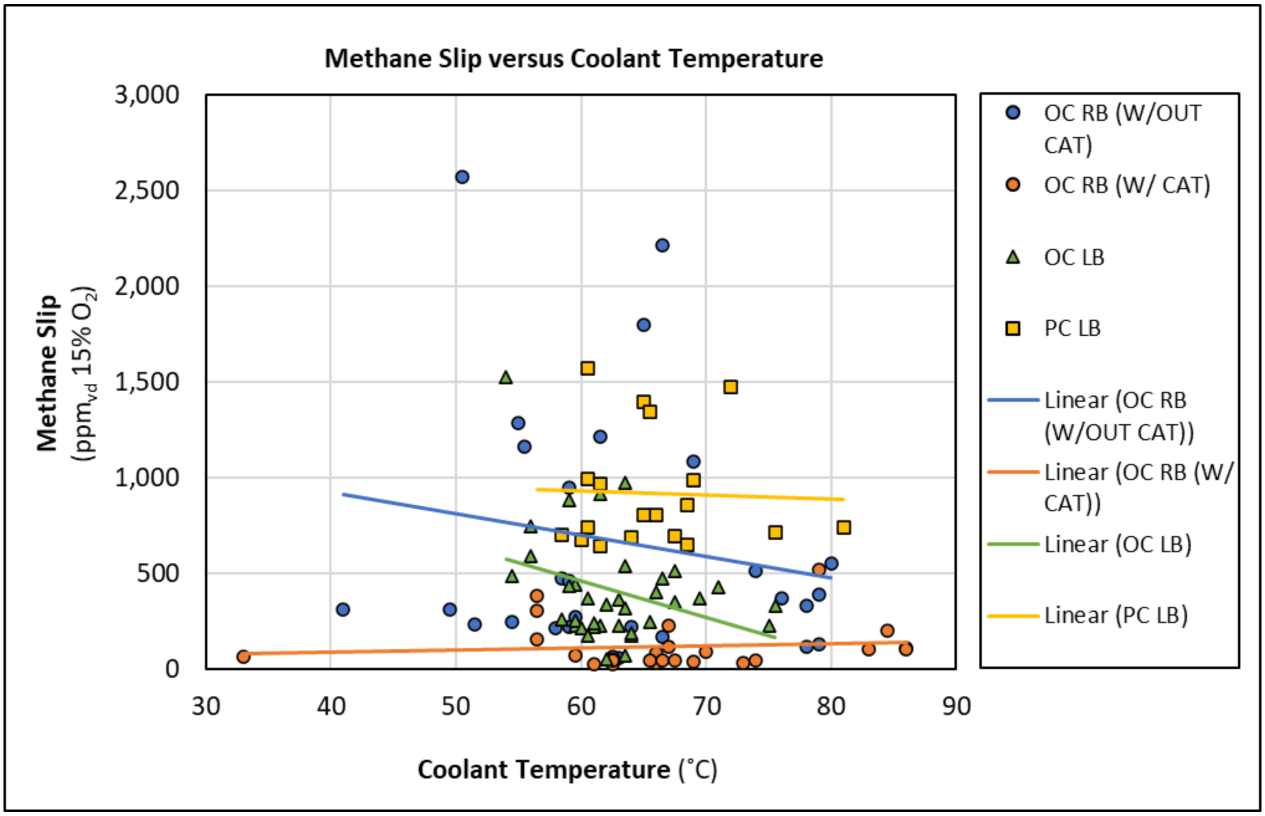

Figure 51 Methane slip versus coolant temperature for all engine combustion styles

Coolant is conditioned by thermostats and aerial cooler efficiency. The trend lines show weak correlation. Theory suggests that higher coolant temperature should result in lower methane slip emissions. The data does not suggest that trend.

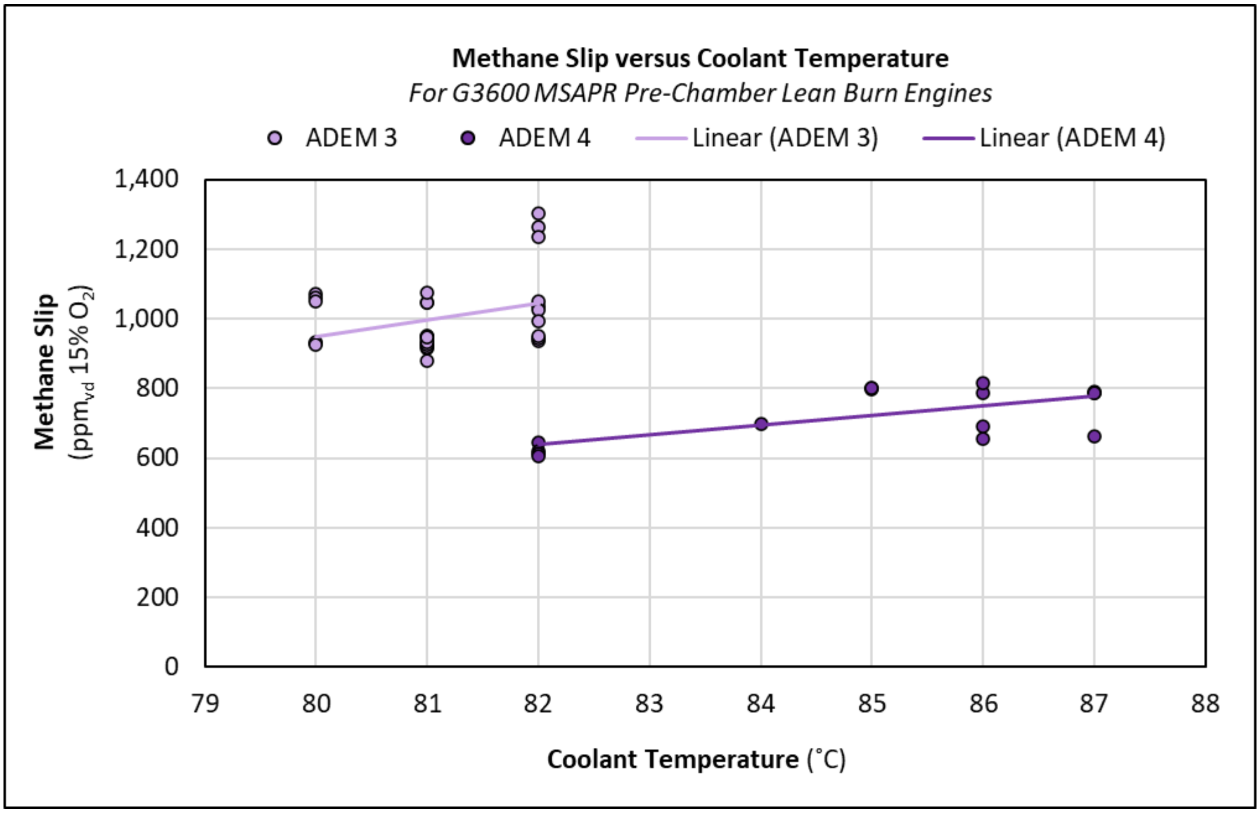

Figure 52 Methane slip versus coolant temperature for G3600 MSAPR tested pre-chamber lean burn engines

Coolant is conditioned by thermostats and aerial cooler efficiency. The trend lines show limited and moderate correlation. Theory suggests that higher coolant temperature should result in lower methane slip emissions. The data does not follow that trend. Furthermore, the Caterpillar G3600 series engine trend lines have the opposite slope to the trend line indicated for all pre-chambered engines.

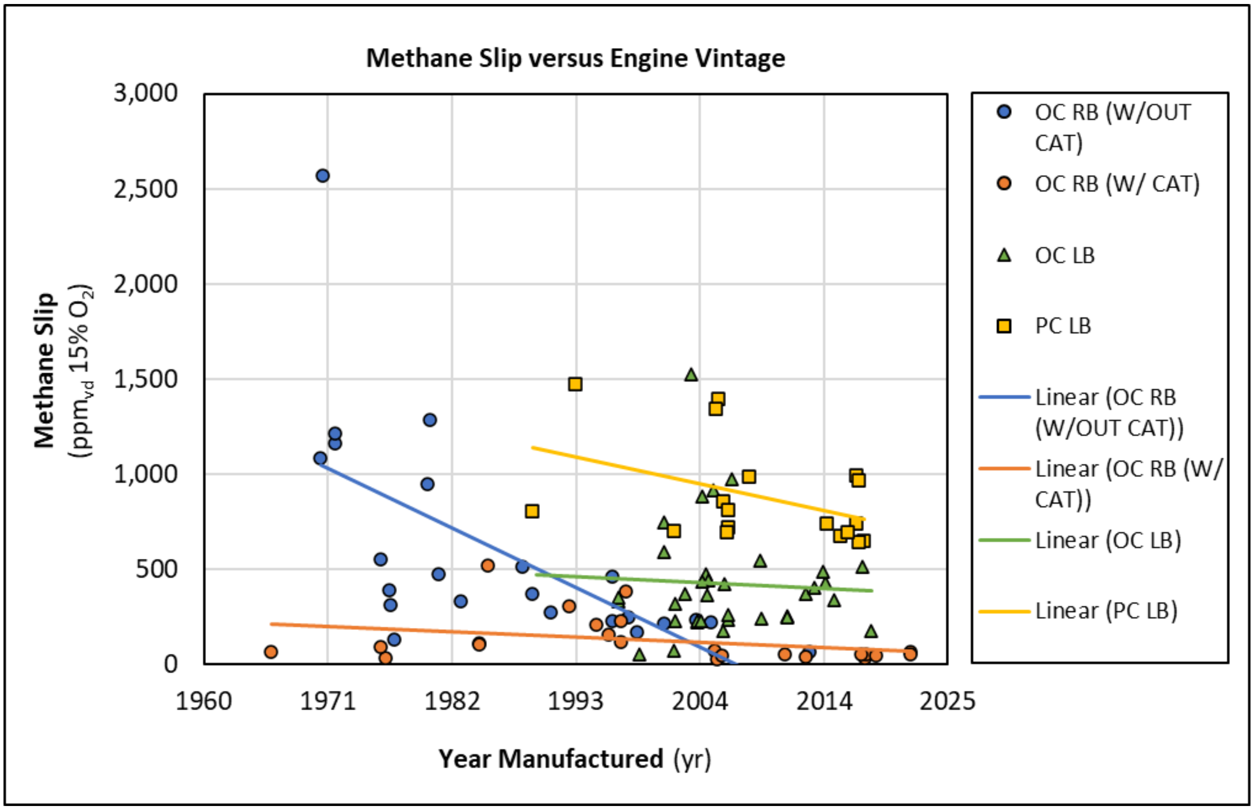

Figure 53 Methane slip versus engine vintage for all engine types

Newer engines appear to produce less methane slip. Correlation is weak for the trend lines indicated. The efforts of engine manufacturers to improve engine efficiency as new models emerge produce lower crevice volumes, higher compression ratios and enhanced combustion controls.

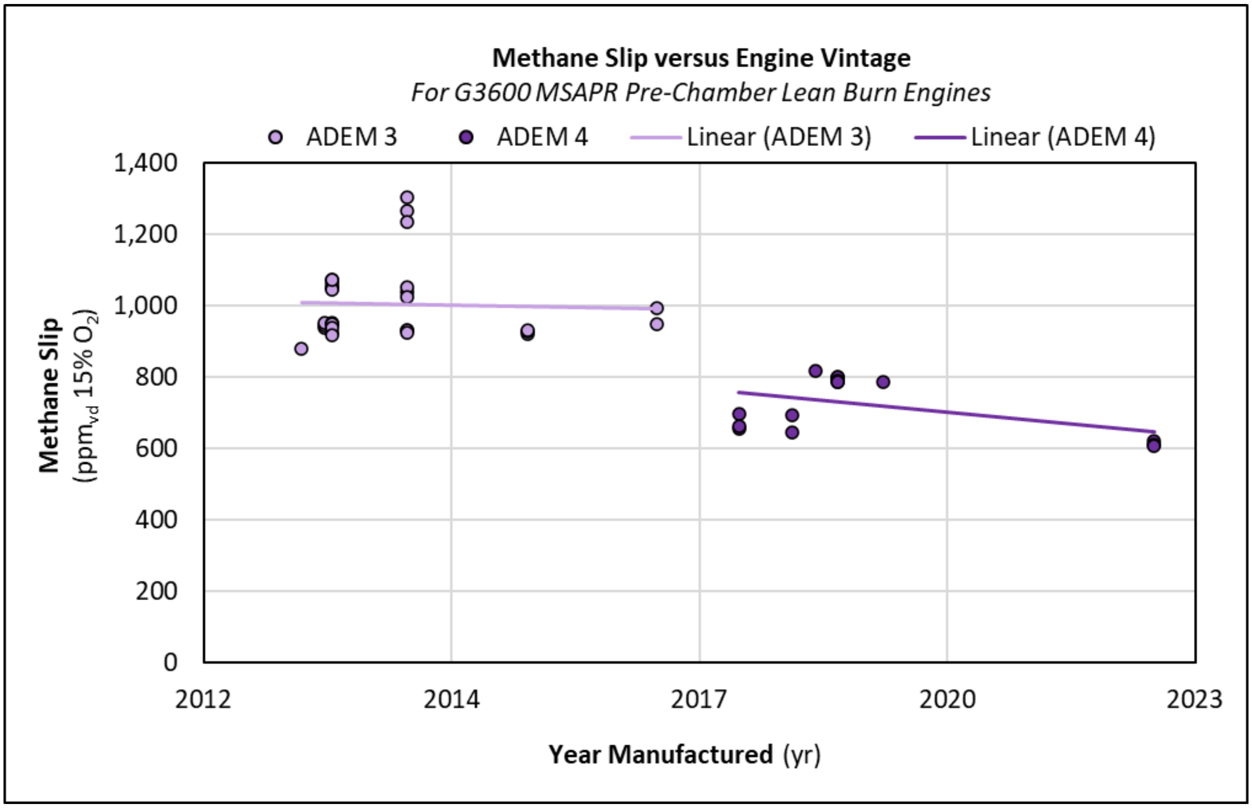

Figure 54 Methane slip versus engine vintage for G3600 MSAPR tested pre-chamber lean burn engines

The Caterpillar ADEM 4 engines are a newer model as indicated on the graph. Newer engines appear to produce less methane slip. Correlation is weak and limited for the trend lines indicated. The slope of the trend lines for these two engine series match the trend line slope for all pre-chambered engines. The efforts of engine manufacturers to improve engine efficiency as new models emerge produce lower crevice volumes, higher compression ratios and enhanced combustion controls. The data for the ADEM 3 and 4 systems follows what theory suggests.

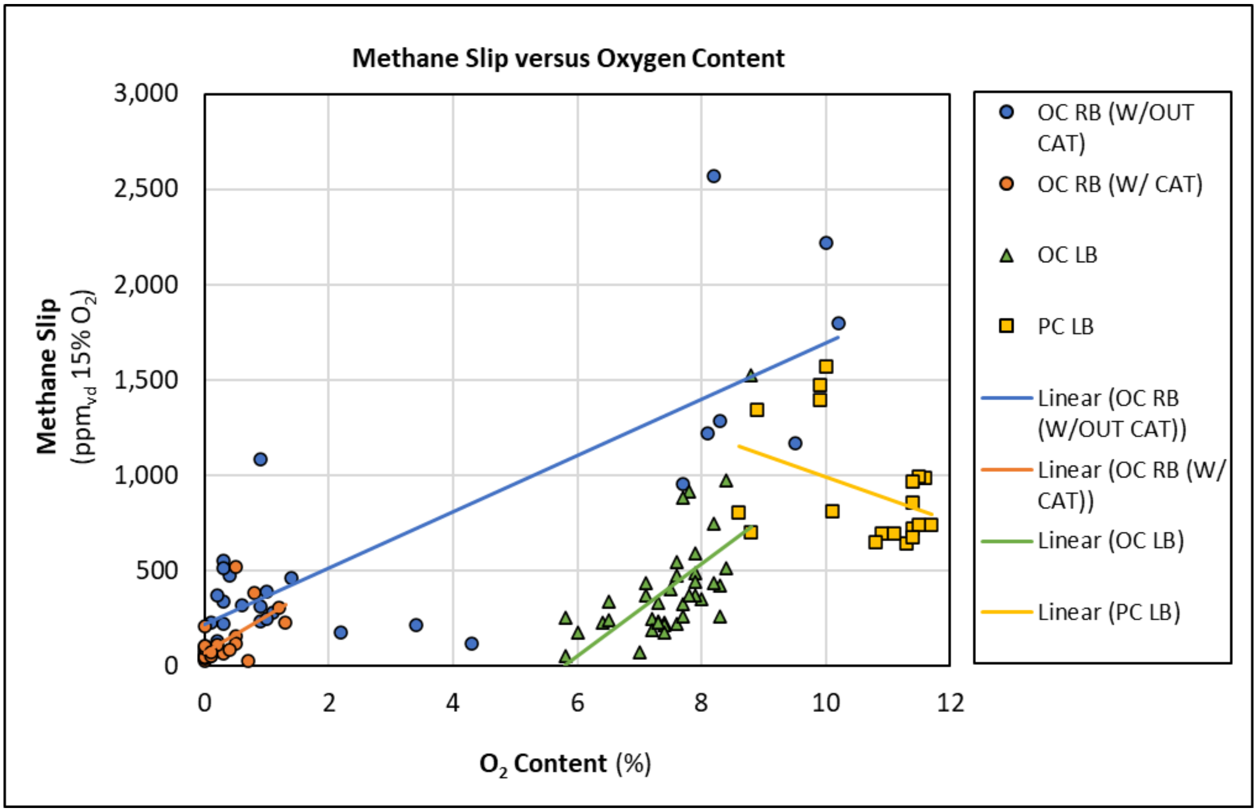

Figure 55 Methane slip versus oxygen content for all engine styles

Methane slip increases as O_2% increases. The correlation is moderate to strong. Pre-chamber combustion styles show a trend that is opposite to the other combustion styles. Tuning the pre-chamber combustion engines a little richer to enhance engine stability may explain why the trend for that line is inversely proportional. This aspect warrants more study.

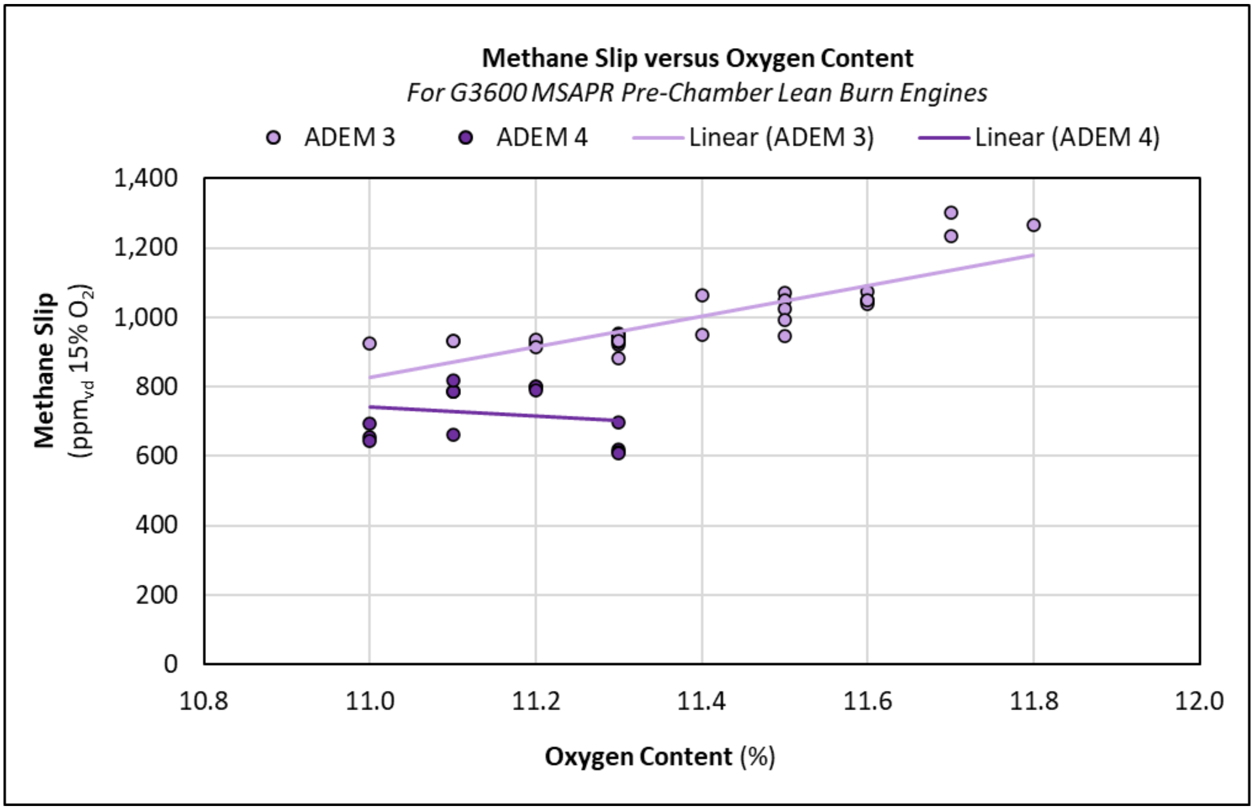

Figure 56 Methane slip versus oxygen content for G3600 MSAPR tested pre-chamber lean burn engines

Correlation to the trend line for the ADEM 4 system is weak. The correlation for the trend line for the ADEM 3 system is strong. The ADEM 3 system trend line follows what theory would suggest. The behaviour of the ADEM 4 trend line warrants more study.

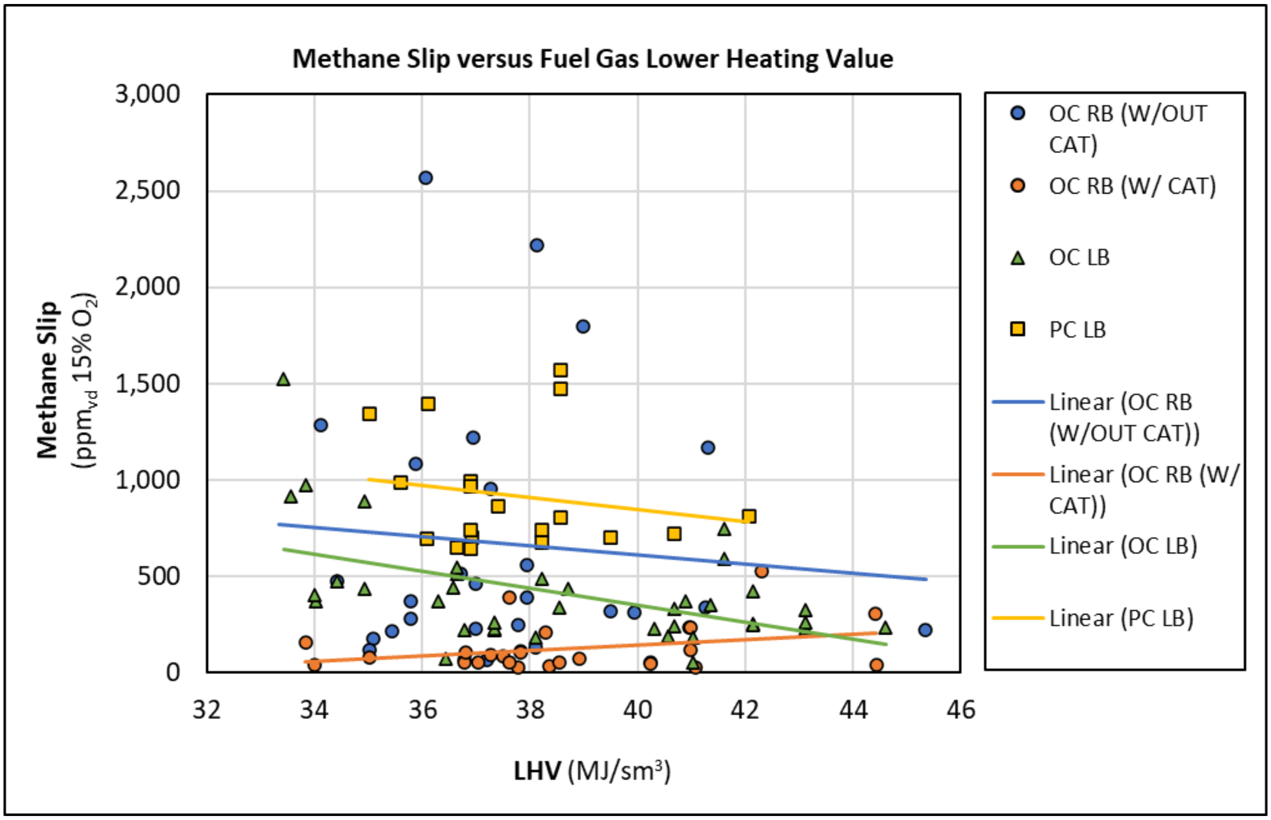

Figure 57 Methane slip versus fuel gas lower heating value for all engine combustion styles

Theory suggests that methane slip should decrease with increasing LHV. The trend lines agree with the theory except for the open chamber rich burn equipped with a catalyst. The dispersion of the data is relatively narrow for that engine combustion style with more data points for lower LHV values. The trend for the open chamber rich burn engines equipped with a catalyst questionable.

Specific gravity and LHV are related. The graphs are identical. The same comments apply to the specific gravity plots.

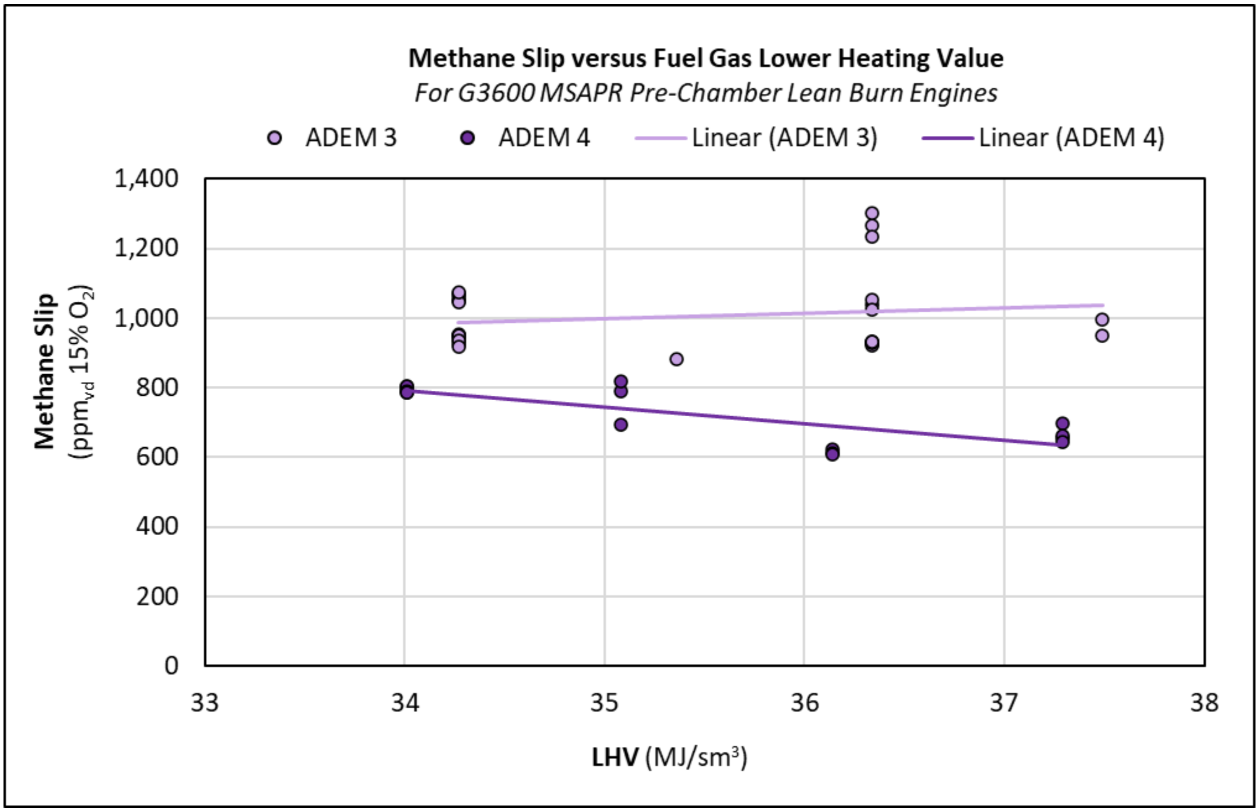

Figure 58 Methane slip versus fuel gas lower heating value for G3600 MSAPR tested pre-chamber lean burn engines

Theory suggests that methane slip should decrease with increasing LHV. The trend line for the ADEM 4 system agree with the theory. The ADEM 3 system trend line does not agree with the theory. More data points with a wider dispersion are available for the ADEM 3 engine with higher LHV. The trend might change if equal points for every LHV value is available. Correlation for the trend lines is weak or moderate.

Specific gravity and LHV are related. The graphs are identical. The same comments apply to the specific gravity plots.

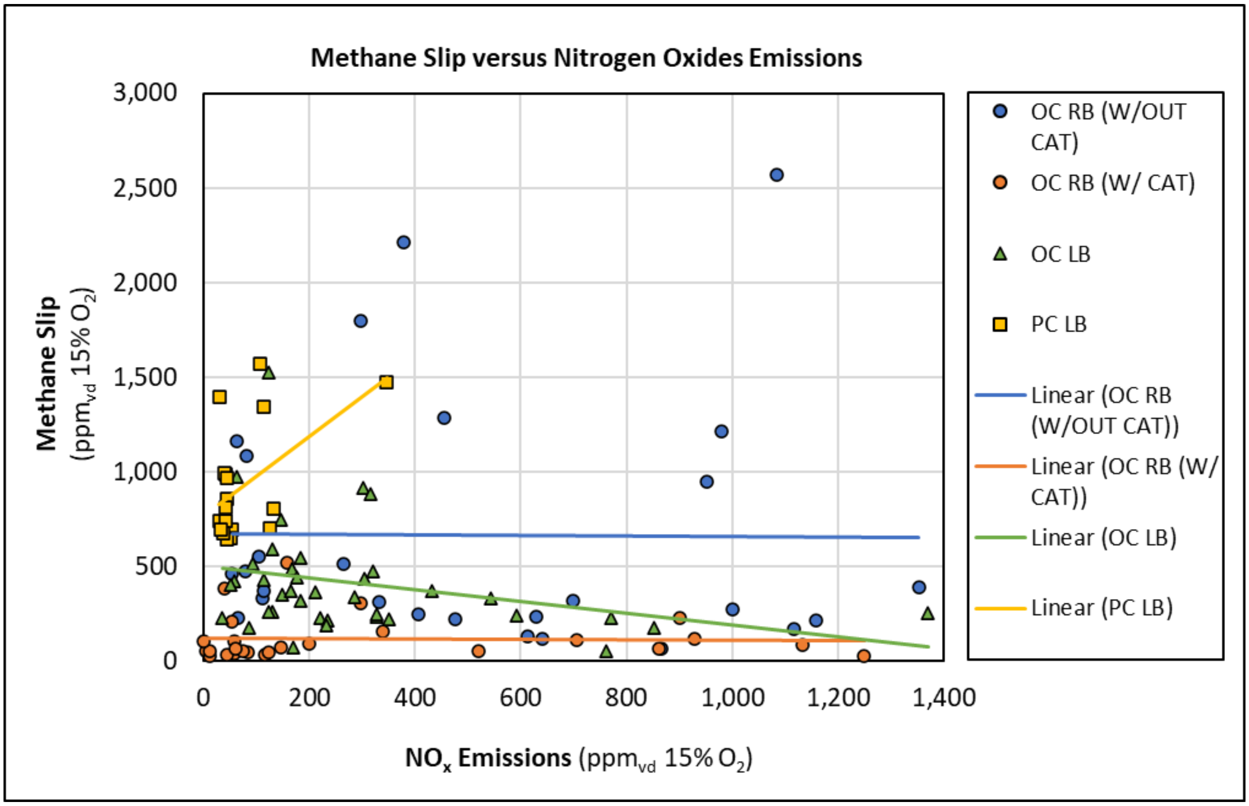

Figure 59 Methane slip versus nitrogen oxides emissions for all engine combustion styles

Methane slip increases as NO_x increases for the pre-chambered lean burn combustion style. This observation supports the notion that those engines are tuned richer (NO_x increases as O_2 decreases). Methane slip and NO_x are both linked to the excess O_2%. The clusters of data according to the combustion style shows the relationship that methane slip increases with increasing O_2 and generally decreases with increasing NO_x.

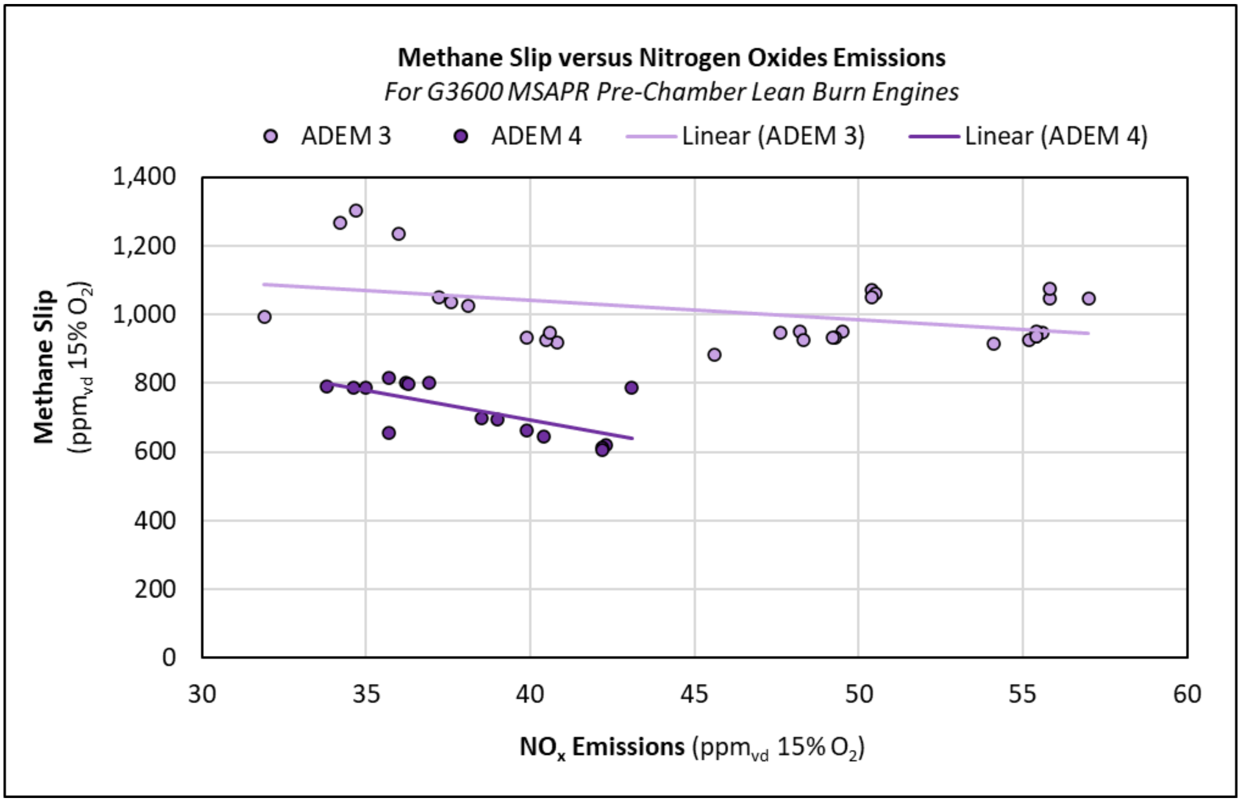

Figure 60 Methane slip versus nitrogen oxides emissions for G3600 MSAPR tested pre-chamber lean burn engines

The Caterpillar G3600 series engines does not mimic the trend line of all pre-chambered engines. The clusters of data according to the combustion style shows the relationship that methane slip increases with increasing O_2 and generally decreases with increasing NO_x. ADEM 3 systems have higher emissions of both methane slip and NO_x than the ADEM 4 systems.

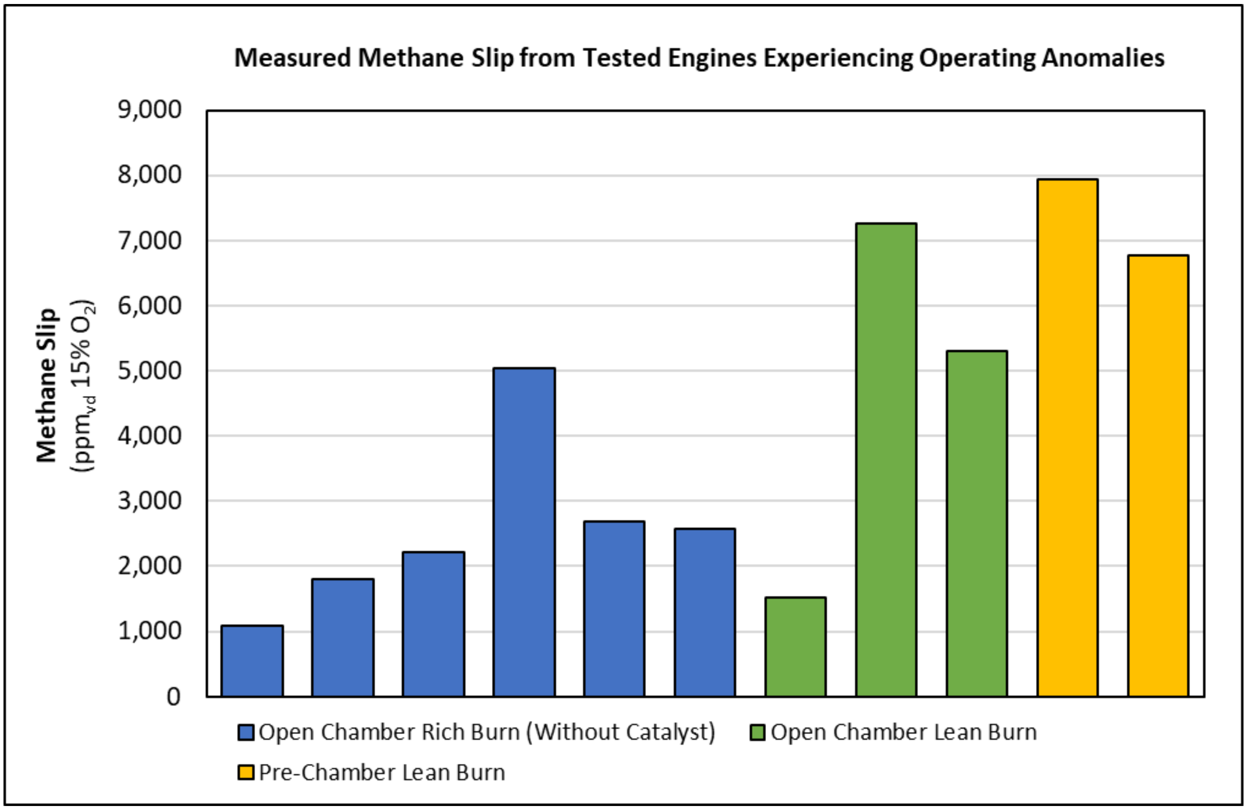

Figure 61 Methane slip for engines with operating anomalies

Methane slip is virtually doubled for engines with condition issues. The graph shows a few examples of three combustion styles. The condition issues are events like misfires or poor tuning. Clearly, engine condition and tuning is an important aspect to reducing methane slip. The details of engine condition are listed in the data tables in Appendix C.

3.2.3.3 SUMMARY OF FINDINGS IN THE GRAPHS

Table 24 summarizes the findings discovered in the plotting the graphs of all the variables with respect to methane slip. Table 25 provides a list of terms that describe the correlation strength used in Table 24**Error! Reference source not found.**. A list of the aspects found to support c orrelation and not support correlation follows Table 25.

Table 24 Relationships suggested by methane slip compared with engine operating parameters

Methane Slip possible relationships	Combustion Styles										Caterpillar MSAPR tests				
Methane Slip versus Variable	Open chamber rich burn		Open chamber rich burn		Open chamber lean burn		Pre-chamber lean burn		All combustion styles		Cat 3600 series ADEM 3		Cat 3600 ADEM 4 series		Comments
	Trend or Statistics	Correlation Strength	Trend or Statistics	Correlation Strength	Trend or Statistics	Correlation Strength	Trend or Statistics	Correlation Strength	Trend or Statistics	Correlation Strength	Trend or Statistics	Correlation Strength	Trend or Statistics	Correlation Strength	
% Units tested	average = 120 ppm, median = 73 ppm	standard deviation = 121 ppm (wide distribution)	average = 644 ppm, median = 370 ppm	standard deviation = 663 ppm (wide distribution)	average = 410 ppm, median = 347 ppm	standard deviation = 284 ppm (moderate distribution)	average = 919 ppm, median = 805 ppm	standard deviation = 302 ppm (moderate distribution)	average = 528 ppm, median = 537 ppm	standard deviation = 663 ppm (wide distribution)	average = 1004 ppm, median = 951 ppm	standard deviation = 951 ppm (wide distribution)	average = 528 ppm, median = 742 ppm	standard deviation = 742 ppm (wide distribution)	ADEM 3 > PCC; ADEM4 < PCC
Non-ingestive crankcase vent	average = 235 ppm, median = 219 ppm	standard deviation = 99 ppm (limited distribution)	average = 284 ppm, median = 250 ppm	standard deviation = 105 ppm (limited distribution)	average = 471 ppm, median = 370 ppm	standard deviation = 337 ppm (moderate distribution)	average = 780 ppm, median = 729 ppm	standard deviation = 134 ppm (limited distribution)	Not relevant	Not relevant	Not available		Not available		
Ingestive crankcase vent	average = 85 ppm, median = 53 ppm	standard deviation = 106 ppm (wide distribution)	average = 926 ppm, median = 754 ppm	standard deviation = 759 ppm (moderate distribution)	average = 315 ppm, median = 254 ppm	standard deviation = 137 ppm (limited distribution)	average = 1157 ppm, median = 1345 ppm	standard deviation = 368 ppm (wide distribution)	Not relevant	Not relevant	Not available		Not available		
Engine hours since last overhaul	IPL	weak	DPL	weak	IPL	weak	IPL	weak	normally IPL	weak	Not available		Not available		
Exhaust temperature	IPE	strong	IPE	strong	IPE	strong	IPL	moderate	IPL, IPE	normally strong	Not available		Not available		
Load percent	IPL	slight	DPL	weak	IPL	slight	IPL	weak	normally IPL	weak, slight	DPL	slight	IPL	slight	ADEM 4 matches PCC trend, ADEM 3 does not.
Engine defect: condition anomalies	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not available	Not available	Not available	Not available	
Engine oil ash content	U		U		U		U		U		Not available		Not available		
Engine oil total base number	IPL	slight	DPL	moderate	IPL	weak	DPL	weak	IPL, DPL	moderate, slight, weak	Not available		Not available		
RPM	IPL	weak	IPL	slight	IPL	weak	IPL	weak	IPL	weak	C	weak	U	weak	ADEM 4 is vertical line; ADEM 3 is horizontal line similar to PCC
Air manifold temperature	IPL	weak	DPL	slight	IPL	weak	IPL	weak	normally IPL	slight, weak	DPL	slight	IPL	moderate	ADEM 4 matches PCC trend, ADEM 3 does not.
Air manifold pressure	IPL	slight	DPL	weak	IPL	weak	IPL	slight			DPL	slight	IPL	moderate	ADEM 4 matches PCC trend, ADEM 3 does not.
Ambient temperature	DPL	weak	DPL	weak	DPL	weak	DPL	weak	DPL	weak	DPL	weak	IPL	slight	ADEM 3 matches PCC trend, ADEM 4 does not.
Ambient humidity	DPL	weak	IPL	slight	DPL	weak	DPL	slight	IPL, DPL	slight, weak	IPL	slight	DPL	slight	ADEM 4 matches PCC trend, ADEM 3 does not.
Non-adaptive engine management system	average = 178 ppm, median = 119 ppm	standard deviation = 149 ppm (wide distribution)	average = 644 ppm, median = 335 ppm	standard deviation = 677 ppm (wide distribution)	average = 475 ppm, median = 387 ppm	standard deviation = 301 ppm (moderate distribution)	average = 1012 ppm, median = 810 ppm	standard deviation = 330 ppm (moderate distribution)	U		U		U		
Adaptive engine management system	average = 61 ppm, median = 51 ppm	standard deviation = 30 ppm (moderate distribution)	average = 1084 ppm, median = 1084 ppm	standard deviation = 188 ppm (limited distribution)	average = 297 ppm, median = 230 ppm	standard deviation = 217 ppm (wide distribution)	average = 886 ppm, median = 739 ppm	standard deviation = 297 ppm (wide distribution)	U		average = 1004 ppm, median = 951 ppm	standard deviation = 951 ppm (wide distribution)	average = 528 ppm, median = 742 ppm	standard deviation = 742 ppm (wide distribution)	ADEM 4 matches PCC trend with lower values, ADEM 3 does not.
Coolant temperature	IPL	weak	DPL	weak	IPL	slight	IPL	weak	IPL, DPL	slight, weak	DPL	slight	DPL	moderate	ADEM 3 & 4 match expected trends, but PCC does not
Engine vintage (year built)	DPL	slight	DPL	moderate	DPL	weak	DPL	slight	DPL	moderate, slight, weak	IPL	weak	IPL	slight	ADEM 3 & 4 match expected trends, but PCC does not
O_2%	DPL	moderate	DPL	strong	DPL	moderate	IPL	slight	IPL, DPL	strong, moderate slight	DPL	strong	IPL	weak	ADEM 4 matches PCC trend, ADEM 3 does not.
Fuel gas LHV	DPL	slight	IPL	weak	IPL	slight	IPL	weak	IPL, DPL	slight, weak	DPL	weak	IPL	moderate	ADEM 4 matches PCC trend, ADEM 3 does not.
Fuel gas SG	DPL	weak	IPL	weak	IPL	slight	IPL	weak	IPL, DPL	slight, weak	DPL	weak	IPL	strong	ADEM 4 matches PCC trend, ADEM 3 does not.
NO_x	IPL	weak	IPL	weak	IPL	weak	DPL	slight	IPL, DPL	slight, weak	IPL	weak	IPL	moderate	ADEM 3 and 4 do not match PCC trend.
Legend:	**U = undefined**		**IPL = inversely proportional linear**			**DPL = directly proportional linear**			**CL = constant linear (horizontal line)**			**IPE = inversely proportional exponential**			**DPE = directly proportional exponential**

Table 25 Correlation Terms Definition

R-squared Value Range	Interpretation
< 0.1	Correlation is weak
0.1 - 0.3	Correlation is limited
0.4 - 0.6	Correlation is moderate
0.7 - 0.9	Correlation is strong
1	Correlation is exact

Observation of the trends indicated in the tables above suggest the following relationships contribute to methane slip.

- Adaptive control systems
- Exhaust temperature
- Fuel quality (LHV)
- Tuning
- Combustion style (O_2%)
- Ingestive crankcase evacuation systems
- Engine model age

Observation of the trends indicated in the tables above suggest the following relationships do not contribute to methane slip and do not follow the expected theory.

- Hours since last overhaul
- Oil ash content and TBN
- RPM
- Air manifold pressure
- Ambient temperature
- Ambient humidity
- Coolant temperature

4. Fuel Gas Meters

4.1. Goals of Fuel Gas Measurement

Fuel gas consumption is an indicator of engine efficiency. Engines that are designed with larger tolerances and crevice volumes will be less efficient. Also, engines in less than optimum operating conditions will use more fuel and likely emit higher methane slip emissions. An optimized engine will have more efficient combustion and, similarly, reduced methane slip. The authors' field experience has indicated that optimizing fuel consumption will result in a conservative 10% fuel savings.

Aerial and ground based tunable diode laser absorption surveys have recently been employed to identify elevated levels of methane slip in engine exhaust. This method allows a rapid assessment and identification of engines that deserve attention. Further investigation is then required to identify why an engine is apparently not optimized for fuel consumption. Measuring fuel consumption is a natural next step as part of a condition check to identify condition issues. The surveys are also only effective at the time of testing. Sustained efficient engine operation may be accomplished with fuel consumption monitoring. The reader must first gain an appreciation for engine fuel gas measurement and how the fuel and fuel consumption relate to the reciprocating engine aspects.

4.2. Efficiency and Brake Specific Fuel Consumption

The purpose of an engine is to provide mechanical power to the load. Efficiency is the fraction of the rate at which mechanical energy is produced (kW or HP) compared to the rate at which energy is used by the engine or motor.

For an engine the efficiency is the output in kW divided by the heat input in kW (1 kW = 1 kJ-s) of the fuel. The losses are the exhaust heat and friction. A more common rating for engines is the brake specific fuel consumption. Only some 30 to 40% of the fuel energy is converted to mechanical power in a natural gas engine. The remainder of the energy is given off as heat.

The rate of energy produced in an engine from combustion is a function of the heat content of the fuel. The heat content of the fuel is commonly measured per hour (h) in units of Btu/h or kJ/h. The ratio of this to the engine power output is (Btu/h)/HP = Btu/HP-h or kJ/kW-h. This ratio is known as the Brake Specific Fuel Consumption (BSFC). The lower heating value (LHV) of the fuel is used rather than the gross (or higher) heating value (GHV). The power delivered at the engine crank is commonly known as the Brake power.

Brake Specific Fuel Consumption varies dramatically for each size of engine and the nature of its combustion system. BSFC in units of Btu/BHP-h typically ranges from 6,500 to 11,000 depending on speed and load. These values are the lowest achievable fuel consumption based on lab test results by the engine manufacturers in ideal conditions.

Variable operating ranges and a variety of engine combustion systems do not offer a single target measure for fuel efficiency. Table 26 shows target BSFC values for various sizes of engines. The table represents natural gas fuel in reciprocating engines under full load and at full speed. We have imposed a 20% increase on the OEM (Original Equipment Manufacturer) values to determine the best possible fuel consumption in field conditions. This increase is based on field test results and our experience with field engines in large producers' fleets. Lab conditions are very difficult to reproduce in the field. Fuel consumption for engines in the field can easily be up to 30% higher than the ideal conditions. The affect of part load also increases normalized fuel consumption.

Table 26 Target BSFC in natural gas fuelled reciprocating engines

Engine Size and Combustion System	BSFC (Btu/BHP-h)
Large Naturally Aspirated Stoichiometric	9,240
Medium Naturally Aspirated Stoichiometric	9,480
Small Naturally Aspirated Stoichiometric	9,840
Large Turbocharged Stoichiometric	9,360
Medium Turbocharged Stoichiometric	9,120
Very Large Turbocharged Lean	8,040
Large Turbocharged Lean	8,760
Medium Large Turbocharged Lean	8,760

4.3. Engine Aspects

Engines are employed in upstream oil and gas applications to drive a variety of equipment. The selection of the driver is dictated by the lowest cost engine that fits the duty of the application. Considerations governing engine choice are speed (rpm), fuel quality, altitude, ambient temperature and the characteristics of the load.

Speed can be adjusted by gears to suit the requirements of the driven equipment (increase or decrease). The complexity of the gear box and torsional aspects add cost and maintenance requirements. Engine rated speed is also related to the size of the engine. Reciprocating engine speed varies between 1,800 RPM for the smaller engines (up to 1,000 HP) and 900 RPM for the larger models (up to 4,500 HP). The typical maximum operating speeds for the most popular reciprocating engine models in upstream applications is 1,800 RPM (80 to 600 HP), 1,200 RPM (700 to 1,800 HP) and 1,000 RPM (1,800 to 3,000 HP).

Fuel quality can dictate the choice of engine. Upstream oil and gas applications often take fuel from the process stream and it may not be sufficiently conditioned to meet the engine manufacturer's standard. Reciprocating engines are quite sensitive to fuel quality. The manufacturer will specify a power derate to accommodate hot fuels (higher in propane and butane). Limits on the H_2S content of the fuel are also imposed. They specify sweet, clean, dry fuel gas with a methane content of over 90% (typically at 900 Btu) for most engines to develop full nameplate power. The manufacturer will configure the engine differently to burn a wider range of heating value fuels as well as gas with much higher levels of H_2S content.

Elevation and ambient temperature play a large role in developing all the rated power for an engine. Increasing the ambient temperature of the combustion air will decrease the density of the air. Thus, less combustion air enters the engine to mix with the fuel than at the rated conditions (factory test cell). The engine manufacturers derate the nameplate power for warmer combustion air. Similarly, higher elevation has the same affect by reducing the air density. Turbochargers and superchargers will offset the affect of higher temperature or elevation on power de-rates by increasing the benchmark at which the manufacturer will apply the power reduction. The magnitude of power derate is specific to engine model and manufacturer. Power derate must be considered for the speed and demand of the load (driven equipment).

Engines can be used to drive portable or stationary equipment. Upstream applications are primarily stationary applications, albeit the equipment may be mounted on a mobile base. The equipment base is not intended to move during operation of the equipment. A variety of equipment may be driven by engines.

The reciprocating engine design allows for the conversion of a reciprocating motion from the up and down travel of the piston to a rotary motion using a lever action against a shaft that is placed at right angles to the input force. This conversion to rotary motion provides a constant force that is capable of spinning a driven member for the purpose of doing work. Appendix I provides a detailed discussion of engine design and fuel implications.

The first reciprocating engines incorporated an integral design with the compressor frame (known as a trunk style). These engines incorporated a large diameter cylinder bore and long piston stroke. The volume of the air-fuel mixture contained within the cylinder for combustion places limits on the speed at which the engine can operate. The greater the volume of the air-fuel mixture within the cylinder the more time required to complete the combustion process. The rate at which the flame front spreads through the air-fuel mixture to initiate and complete the combustion process limits the engine speed. The greater the volume of air-fuel within the cylinder consequently more time required to complete the burn process. High speed engines are designed with small bores and short strokes. The burn process is completed very quickly and can be repeated more often allowing for higher operating speeds.

The industry requirements expanded from large plant settings where gas was drawn from the fields for processing and compression to meet sales line requirements. The shift towards the installation of compression closer to the gas fields drove the development of equipment that is more readily installed and easily moved. The trunk style compressor approach did not offer the versatility required to meet the oil and gas industry needs.

The modern high speed natural gas fuelled engine design is capable of providing the same horsepower as the much larger integral design. The rotating components of the new high speed engine design are lighter in weight which reduces the parasitic engine horsepower loss related to maintaining inertia forces. The modern high speed engine provides smaller contact surfaces where the piston rings meet the liner bore, offers reduced areas of the crankshaft bearing areas, a smaller camshaft drive train and lighter cylinder head valve springing. The result is an engine design that delivers the same horsepower but in a much more efficient manner that provides the benefits of reduced fuel consumption.

Today the use of separable equipment is prevalent throughout the industry with a few exceptions that are designed to accommodate site specific applications. The focus of this study is therefore dedicated to the separable engine drivers. Appendix I provides descriptions of common engine models and their operating characteristics. The load characteristics also affect the fuel efficiency. Measuring the load will be part of any optimization exercise.

For a generator, the generator output may be measured in kW and multiplied by a factor 100/(100 – Effg) where Effg is the generator loss percentage to account for friction and heating. For a reciprocating gas compressor, the load may be measured with a compressor analyzer with an allowance for friction losses, or calculated from the measured process parameters and cylinder specifications. For a screw compressor, each manufacturer has load calculation software. As a note of caution, such software is normally valid for the slide valve position at 100%, and may be in error for slide valve positions less than 100%. Each pump manufacturer has a proprietary load calculation method.

The power consumed by the cooling fan operating at the rated speed is normally available from the manufacturer. If the fan pitch is unchanged, the fan load varies as (RPM). In the absence of details on the cooling fan a reasonable value is 3% to 4% of the rated engine load for an engine-compressor combination and 2% of rated engine load for a generator load. The power consumed by auxiliary equipment should also be estimated and included. These are relatively small (< 10 HP) and often not included. In special cases, items normally included in the engine package, such as the oil pump and main coolant pump are powered by electric motors.

4.4. Engine Ratings

A manufacturer normally supplies an engine rating for continuous use. Often there are temperature (coolant and ambient) and altitude de-rating factors. Check the manufacturer's manual to determine if these de-ratings apply for a particular site.

4.5. Part Load Efficiency

An engine has to power various engine components such as the water pump, oil pump, cam drives and overcome internal friction, no matter what the external load. At part loads, a larger fraction of the fuel input energy is used to power these engine components compared to full load operation. The graph below is an example of the reduction in engine efficiency, as defined by crankshaft output, at part loads.

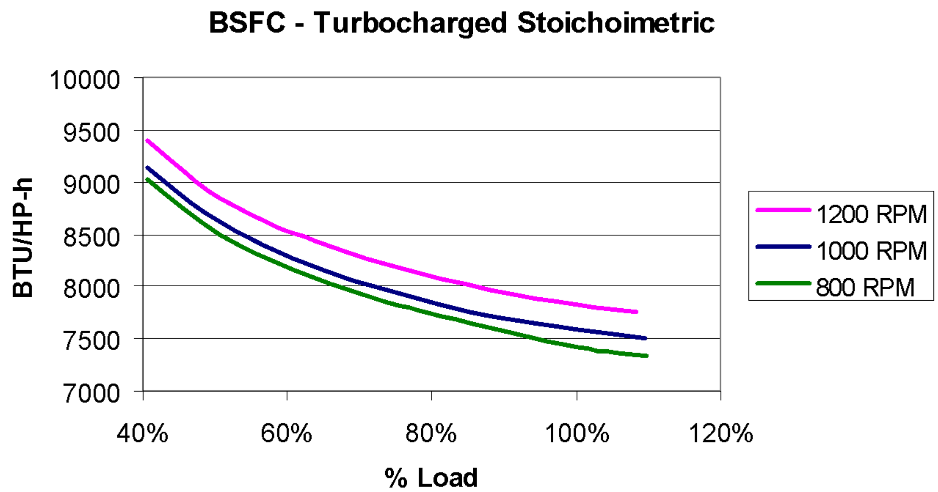

Figure 62 Part load reciprocating engine efficiency

The efficiency loss occurs for all engines at part load. The amount depends on the engine type and the BSFC curve for the engine.

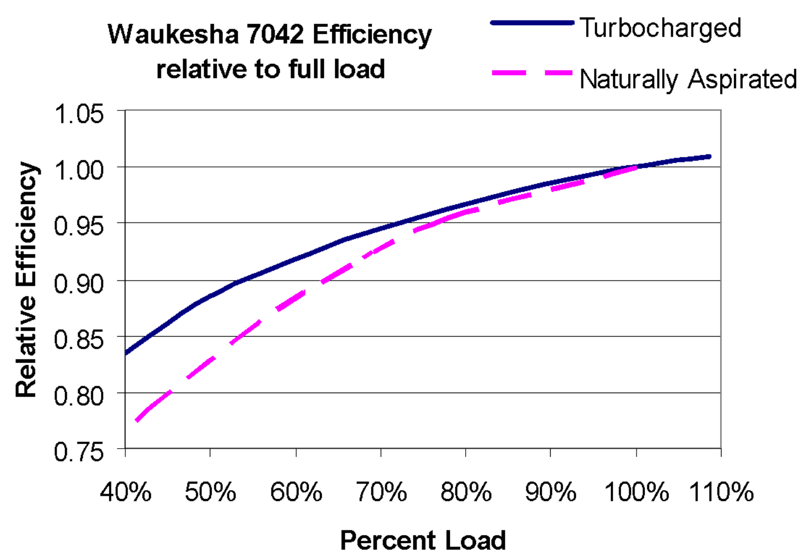

Figure 63 Efficiency loss for two engine types

4.6. Part Load Reciprocating Engine BSFC

The amount of power developed by an engine tends to be proportional to the RPM. Hence the rated output load also is proportional to the RPM. The power used by the engine components and friction also become smaller as the RPM becomes smaller. Hence, if the full engine output at the rated RPM is not required, it is more advantageous with respect to efficiency to operate an engine at reduced RPM but at a higher percentage load. This is shown in Table 27 by BSFC as a function of percent load (at that RPM) for a range of engine RPM values. For example, if the required output power required for the engine is 900 HP, the table below shows the expected BSFC for operating at 3 different speeds.

Table 27 Reciprocating engine BSFC at various speeds and loads

Engine Speed	% load	BSFC	Efficiency Comparison
800	91%	7550	Reference
1000	73%	8000	6% worse
1200	61%	8500	13% worse

If, for example, the clearances on the compressor cylinders can be adjusted to achieve the desired flow at reduced RPM, an engine efficiency improvement can be expected.

4.7. BSFC and Engine Type

The brake specific fuel consumption rating is valid for both 2 and 4 stroke cycle engines. It is a valuable way to compare the performance of different engines. The BSFC becomes smaller (engine is more efficient) as the displacement per cylinder becomes larger. Also, the air-fuel ratio control can affect BSFC and efficiency from differences in combustion completeness and heat loss during a combustion cycle.

An engine with lean combustion, excess air, will operate with a lower BSFC (more efficiently) than an engine with a stoichiometric air-fuel ratio. This occurs because the excess air with lean combustion ensures the fuel is fully combusted in the engine cylinder, whereas with a stoichiometric engine there is both some unburned fuel and carbon monoxide (CO) in the exhaust gases. These components are more fully combusted in the exhaust catalyst, producing heat in the catalyst. The BSFC of such engines are generally higher than for lean combustion engines.

If an engine uses a mechanically driven blower or super-charger for intake air compression, this reduces the crankshaft power available for the load. Such engines have a BSFC some 1500 to 2000 Btu/HP-h larger than the equivalent turbo-charged engine. An exhaust driven turbocharger does not increase the BSFC as an exhaust driven turbocharger gets its energy from the hot exhaust gases produced by the engine.

Pre-combustion chambers (PCC) are small volumes adjacent to the main combustion volume, where the spark plug ignites a richer mixture than is in the main chamber. The burning gases ejected from the PCC into the main chamber readily ignite the air-fuel mixture in the main chamber. PCCs are used on larger engines to overcome the difficulty in igniting a lean air-fuel mixture and the reduced flame speeds of lean mixtures. Since the relative volume of the PCCs is small relative to the main chamber, there is little effect on BSFC compared to open chamber designs with no PCCs.

4.8. BSFC for Different Reciprocating Engine Types and Sizes

The types of reciprocating engines are

- Naturally Aspirated
- Turbocharged Stoichiometric
- Turbocharged Lean

The sizes for purposes of this discussion are

- Small (bore < 4.0 inches)
- Medium (bore 4.5 to 6.5 inches)
- Large (bore 6.5 to 10 inches)
- Very large (bore > 10.1 inches)

4.8.1. Naturally Aspirated Engines

A naturally aspirated engine may be operated at stoichiometric, rich, or lean. Stoichiometric operation is required if the engine has a 3-way catalyst for NO_x and CO reduction. Rich operation is sometimes used to reduce NO_x without a catalyst, but with higher fuel consumption and high carbon monoxide (CO) emissions. Slightly lean operation (2% exhaust O_2) results in improved fuel efficiency but with increased NO_x and higher exhaust temperatures. Leaner operation (> 4% exhaust O_2) can result in improved fuel efficiency and reduced NO_x, but results in a maximum load de-rating.

The optimum RPM with regard to fuel efficiency depends on the engine design. Hence, operation at speeds different to the rated RPM may result in lower fuel efficiency. Information should be requested from the engine manufacturer.

4.8.2. Turbocharged Engines

A turbocharged engine uses an exhaust driven turbo-charger to increase the manifold air pressure and therefore the rated load. These engines may be operated at stoichiometric, rich, or lean. Stoichiometric operation is required if the engine has a 3-way catalyst for NO_x and CO reduction. Rich operation is sometimes used to reduce NO_x without a catalyst, but with higher fuel consumption and high carbon monoxide (CO) emissions. Slightly lean operation (2% exhaust O_2) results in improved fuel efficiency but with increased NO_x and higher exhaust temperatures. Leaner operation (> 4% exhaust O_2) can result in improved fuel efficiency and reduced NO_x, but results in a maximum load de-rating.

4.9. Fuel Selection

A fuel that is most readily deliverable or available to the site is usually the basis upon which an engine is selected. The type of fuel and its composition will determine the engine design selected. The fuel type will determine the combustion cylinder compression ratio, ignition timing, fuel delivery system and control system. Fuel supply management will address storage, conditioning, filtration, regulating supply and delivery pressure rates. The following aspects must be considered in fuel selection.

4.9.1. Heating Value

The internal combustion engine design is based upon the Btu; British thermal heating value of the fuel that will be consumed. The physical state in which the fuel is supplied for combustion purposes, i.e. gaseous or liquid and the stability of the fuel as determined by an octane or cetane rating, will determine the delivery system design.

4.9.2. Ignition Strategy

Dependant upon the fuel selected the engine designer will incorporate an ignition strategy. The natural gas or gasoline engine will employ a controlled electrical spark source of ignition. Diesel fuel oils will rely on auto-ignition. This is based upon the heat of compression generated within the combustion chamber as the piston travels towards top dead center compressing the air trapped above the piston.

4.9.3. Gaseous State Fuel

Natural gas is a methane based fuel in a gaseous state. The fuel either enters into a mixing chamber referred to as a carburetor or is injected directly into the cylinder to create an air-fuel ratio specific homogenous mixture that can be readily ignited within the combustion chamber by a timed ignition spark event.

4.9.4. Engine Compression Ratios

The Btu and composition of a fuel determines the combustion cylinder compression ratio options. The ratio of compression is determined by measuring the volume of the cylinder when the piston is at the bottom of it stroke, as compared to the volume of the cylinder when the piston is at the top of its stroke. Higher compression ratio engines produce more power per cylinder than lower compression ratio engines. The increased power output is related to the air fuel mixture within the cylinder being placed under an increased pressure during the compression stroke compounding the expansion pressures within the cylinder combustion chamber. A higher explosive expansion force is exerted upon the piston top which translates into an increase in overall horsepower.

4.10. Fuel Heating Value

The heating value is the amount of energy that a fuel produces for a unit of volume. The Btu heating value of natural gas may range from 400 – 1250 per cubic foot of gas. The Btu heating value of natural gas is dependant upon the source. The engine designer determines the horsepower rating by analyzing a sample of the fuel supply to determining heating value and establish the amount of energy that will be is created within the combustion chamber when the gas is combusted. A scenario in which the collected gas is emitted from the processing of organic waste products may be dealing with Btu value as low as 400 BTU per cubic foot of gas. Conversely natural gas contained within a well reservoir may have a heating value that exceeds 1250 BTU per cubic foot of gas. The heating value may be attributed to constituents contained within the gas source such as butane and hydrogen. A precise analysis of the fuel gas stream is required to ensure that the engine designs compatibility.

4.11. Engine Service Life

The internal combustion engine design must be rugged enough to ensure that its rotating forces can be controlled. Personnel safety and acceptable service life are the two major design considerations. The combustion process is an explosive event that generates useable energy and emits or radiates waste heat by-products. The engine cooling system design may utilize air to air or liquid to air heat transfer methods. Lubricating oils are selected to reduce frictional contact with moving parts, provide internal component cooling and to carry away any contaminates that form during operation. It is not unusual for an engine to consume some lubricating oils during normal operation. The rate of consumption is dependant upon the engine design, the severity of service and the lubricant selected. The oil supplier provides a specification and the operator of the engine is duty bound to select a lubrication product that has been approved for use by the engine designer. Over the service life of the engine assembly wear will occur that may lead to oil consumption. There is a range of formulated lubrication products within the industry that can be matched to the service duty of the equipment.

Engine designers and component manufactures utilize their knowledge base in selecting materials and development of a design to be compatible with the fuel(s) that will be consumed. The characteristics of the fuel during handling, metering and combustion are taken into consideration when designing monitoring and control systems. The primary objective by suppliers is to provide an engine that can be safely operated and will develop the horsepower that is required. Fuels that differ from the design intent will result in poor engine performance, a reduced service life of components and may contribute to the failure of the engine assembly.

4.12. Hot Fuel Management

The term hot fuels refer to the increased Btu values contained within a natural gas fuel source. Higher Btu values the greater the force that will be exerted against the top of the piston during the combustion process. If a hot mixture is ignited too early the resultant explosive expansion force is compounded and will affect engine performance and damage components.

The ignition of the air fuel mixture within the combustion cylinder is a controlled and precisely timed event. The point at which the ignition source is introduced and the duration of the ignition input is determined by the fuel type. Engine designers determined that the hotter the fuel the greater the increase in the rate of expansion and forces generated during the air fuel mixture combustion process.

Advanced ignition timing may either impede the pistons travel upwards during the compression cycle or increase the internal pressures within the cylinder bore. The result affects the engine's design performance. Advanced ignition timing may result in a compounding of the expansion forces within the cylinder. As the piston is traveling upwards compressing the air fuel mixture, the forces of inertia created by the engine flywheel and the other rotating components combine with the increased rate of expansion with the potential of over stressing components. The physical evidence of this damaging event is melted or fractured pistons, broken piston and oil control rings, bending of the connecting rods, excessively worn connecting rod and main bearings. If undetected the progressive engine damage may result in a catastrophic failure of the assembly. Engine designers often retard timing and de-rate the engine to compensate for hot fuels.

The octane rating of the fuel is a measure of the fuel's resistance to auto-ignite during this compression process. This is also referred to as fuel stability. As the piston travels upwards during its compression stroke the air fuel mixture is compressed into a smaller area and the internal temperature begins to rise. Engine control and monitoring systems capable of detecting and reacting to detonation or pre-ignition events have been developed and are available for installation on engines that may be at risk.

4.13. Natural Gas

Natural gas is a gaseous fossil fuel primarily consisting of methane and may include varying quantities of ethane, butane, propane, carbon dioxide, nitrogen, helium, hydrogen sulphide and water vapor. The approximant heating value of natural gas is 1000 Btu per standard cubic foot.

The use of natural gas as a fuel source within the oil and gas industry is based on its ready availability in a wide range of settings. These factors eliminate the need to source and manage the cost and risks associated with the transportation of other fuel types such as diesel or gasoline. The development of remote locations in restricted access locals has been made possible through the use of natural gas as a direct fuel source.

The quality of natural gas may be affected by the source and the process used to condition the fuel prior to use. The Btu values are dependant upon the amount of other hydrocarbon sources present in the stream. Wet gas (hot gas) will exhibit a higher Btu rating than gas that has been processed and stripped of excess hydrocarbons.

The incoming natural gas stream may also contain varying percentages corrosive elements such as carbon dioxide and hydrogen sulphide. These constituents contribute to the formation of acids when combined with the water. On occasion particulate matter may be transported within the gas stream and must be filtered out. The particulates act as an abrasive that will contribute to combustion chamber wear and contamination of lubricating oils.

4.14. Natural Gas Fuel Supply Sources

4.14.1. Utility Gas Pipeline

A utility gas pipeline provides access to a source of fuel gas that has been treated and can typically be counted on to deliver a consistent Btu value. This gas will have been processed. During processing the gas would have been passed through several phases of separation to remove hydrocarbon liquids and water vapour. A sample will be analyzed to confirm what constitutes may be present in the stream and to establish a Btu value that is used to determine the engine timing.

4.14.2. One Site Plant Process Source

Plant discharge gas is often selected as the primary source for fuel simply because it is readily available. The gas is usually moved through several phases of mechanical separation and or filtration medium to remove hydrocarbon liquids and water vapour. In addition to this the gas stream may have also been processed through a refrigeration process to further remove liquid hydrocarbons and water vapour. This gas would have passed through one or more stages of compression. It should be noted that during the compression stages the gas stream will pick up traces of compressor piston ring and piston rod seal packing box lubricating oils. The compressor lubrication rates are closely monitored to prevent excessive amounts from entering into the gas stream. The Btu value of the plant discharge gas is dependant upon the incoming gas stream constituents and level of processing that is applied within the plant prior to the gas been used as a source of fuel.

4.14.3. Wellhead Gas

Wellhead natural gas Btu values may vary widely and can be in a constant state of flux depending upon flow rates and contributing zones. Each of the reservoir zones will supply varying quantities of water, liquid hydrocarbons and in some fine particulate matter. The use of in water knock outs, separators and line heaters help to capture liquids and solids. While an effort is made to manage the incoming stream and render it as a usable fuel source an analysis of the fuel is required in order to identify the percentage of constituents, Btu value and ensure that any potential corrosive elements have been identified. The quality of well head gas varies by site and the relocation of equipment demands that a review of the equipment be undertaken to ensure compatibility with the new fuel source.

4.14.4. Unpredictable Fuel Quality Variances

To ensure that the performance and mechanical integrity of an engine is maintained, regularly scheduled gas analysis is performed. This approach will help to provide a record of the fuel source quality. Any shifts in the percentage composition of the fuel will be noted during a review of the gas analysis report and corrective action can be taken.

The gas field gathering systems are constantly in flux and subtle changes can occur in Btu values. Automated fuel management control systems have been developed that can monitor and respond accordingly. These systems ensure that the air-fuel mixtures are efficient and that levels of exhaust emissions are maintained within specifications.

4.15. Basic Improvement Strategy

The most significant elements of long-term operating efficiency are the application of best available technology, implementation of operating and maintenance systems and management commitment. Efficient operation of rotating equipment requires:

- knowing what each equipment element was designed to do and what it is currently required to do,
- the conduct of periodic checks and adjustments,
- routine testing and correction of abnormalities,
- assessment of opportunities to install upgrades and replacement of inefficient equipment, and
- retention of records.

4.16. Technology and Equipment

The first step in moving toward higher levels of fuel gas efficiency should always be to understand what the engine was designed to do and what modifications have been made since it was placed in service. This should provide an early indication of the suitability of the installed equipment for the service and if the equipment is likely to be able to meet the prescribed performance standards. Knowledge of the equipment will also help to identify what changes may be required to achieve higher levels of fuel gas efficiency. Following this, efforts should be made to bring the installation in line with manufacturer's specifications for the installation, use and maintenance of the equipment.

Proven processes and technology are available to both optimize and sustain optimized equipment operation. The important issue is to recognize an opportunity for application to the technology in this regard. More importantly is to consult with industry expertise to understand when the technology exists.

4.17. Improving Efficiency

Decisions to carry out adjustments or replace components should be made on an individual basis with consideration for health, safety, environmental and economic considerations. Where adjustments to existing systems are practical, these should be carried out at the time of testing. At that time, minor component replacements can also be undertaken. When equipment shut down is required to undertake improvements, the repair/replacement may be delayed until the next planned shutdown provided this does not pose any safety concern.

4.18. Training and Expertise

It is important to include training and education in any efficiency enhancing program. When an operating system is properly understood, correctly operated and adequately maintained the operations group will be in a better position to provide feedback. An understanding of the equipment and operating scenarios that may impact the operating efficiency is critical to identifying additional opportunities for improvement.

4.19. Inspection, Monitoring and Record-Keeping

Operators should have a record program to support the company's rotating equipment testing and improvement system. Proper record keeping should assist in ensuring that sub-optimal equipment is identified and that appropriate follow-up actions are implemented. This information will also assist in establishing the assessment frequency for each piece of equipment to achieve cost-effective fuel gas efficiency improvements.

Although each company will define its record keeping system, an effective program will include the following information:

- data sheets for each package,
- expected fuel gas consumption for each engine,
- records of changes for each unit that have been performed
- efficiency testing results and
- economic analysis performed on underutilized engines that have not been adjusted or modified.

Record keeping in support of a company's fuel gas estimates, where measurement is not provided, may be audited by the EUB to assess compliance. In addition, records need to be maintained to demonstrate compliance with EUB Directives related to NO_x and SO_X emissions.

4.20. Rapid Feasibility Assessment of Reciprocating Engine Components

Reciprocating engine operation requires the management of many variables. We will lead the worker through a discussion of the variables that affect fuel consumption. Good equipment condition is a critical element in reducing fuel consumption. This document is not intended to provide a detailed engine maintenance schedule. That task is considerable for each model of engine. It is best left to the equipment manufacturers. Metrics for evaluating fuel efficiency and how fuel efficient operation can be maintained are the focus of our discussion.

Operations personnel who understand the variables are better equipped to enhance equipment performance and maximize component service life. The engine condition and fuel consumption will vary with the following aspects.

4.20.1. Number of Operating Hours

Maintain records of when the equipment was installed, last overhauled or nearing a major maintenance milestone. Maintain records as to what items were checked, adjusted, repaired or replaced. Tired and worn equipment uses more fuel than new.

4.20.2. Ignition Type

The first generation ignition systems are far less efficient than modern systems. A modern, adaptive ignition system will reduce fuel consumption.

4.20.3. Fuel Composition and Quality

Changes in the fuel gas supply may occur during operation as wellhead gas supply streams co-mingle. Well flow adjustments or the introduction of new well flow will impact the fuel stream and fuel gas composition. Engine ignition timing may be affected by fuels with a higher energy value which may reduce the available power. Conditioning the fuel and installing an adaptive engine management system can help to restore full power to the engine and reduce fuel consumption.

4.20.4. Spark Plugs

Engines may be fitted with spark plugs originating from different suppliers. The service life of spark plugs will vary due to materials used in their manufacture, fuel composition, engine loading and engine speeds. Another factor to consider is the condition of the ignition system firing the plug. An often overlooked performance related problem is the spark plug installation procedure itself. The spark plug body will deform if over tightened during installation. Failure to use a torque wrench is the leading cause of this failure. An over-tightened sparkplug will allow combustion gases to escape up through the plug interior and cause overheating and voltage leakage as carbon trails develop. An improperly tightened spark plug is also a safety concern as it can separate from its casing and leaves the combustion chamber open to atmosphere. Plugs that are not seated properly will not transfer combustion process heat through the plug to the water cooled engine casting. Failure to achieve this heat transfer will result in poor engine performance. The use of precious metal spark plugs will increase the plug life. Using high quality spark plugs suitable for the application will reduce fuel consumption.

4.20.5. Engine Governor Control System Type

Mechanical governor systems are still in wide use as they are inexpensive, easy to maintain and simple to adjust. Mechanical governor systems are also prone to speed instability and the amplitude of instability will increase as the linkage wears. A means for improved and sustained speed stability is needed. An electronic governor system will provide that type of control. A number of electronic governor control systems are available for replacement of the existing equipment or on newer engines as factory installed equipment.

The purpose of an engine governor is to adjust engine speed to match the load. Over time, as the governor linkage wears, a wider range of speed variance will develop. The speed instability allowed by the worn linkage permits the engine to surge. The maximum speed attained during a surge event may exceed the high engine speed set point and shut the unit down. The operator will reduce the operating speed to avoid nuisance shut down events. The lower operating speed results in sub-optimal engine utilization.

A narrow speed control band will allow the engine to operate closer to the maximum or desired speed. Engine performance and the driven equipment production can also be optimized by having a tight range of speed control. Improved utilization of the existing equipment that avoids adding more power at the site will result in more efficient operation and less fuel consumption.

4.20.6. Dry Paper Element Air Filtration System

Research by manufacturers has caused a shift away from the oil bath filtration system towards the dry paper elements. The easily replaced or reusable chemically treated paper pleated air filter elements are proven by engine manufactures provide a 99.9% filtration capability. The high efficiency offers the best protection for the engine and is not impacted by ambient air temperatures as compared to oil bath filtration systems which call for seasonal oil changes. An optional feature is the air filter differential pressure sensor that will shut the engine down should the filter element restriction increase signalling that the filters require attention. A differential pressure increase across the paper element filters will result in poor engine performance, power loss and increased fuel usage.

4.20.7. Oil Bath Air Filtration

Oil bath air filtration systems have a long service history and remain in widespread use. Ensuring that these filters perform properly requires regular monitoring and maintenance. The oil reservoir oil level must be maintained within specifications and debris accumulations in the reservoir sump must be removed. An over-filled reservoir or an incorrect oil viscosity will result in oil being drawn into the intake manifold and being consumed within the combustion chamber. This will impact exhaust emissions. Failure to properly maintain the filter will allow airborne impurities to enter into the engine. Poorly maintained oil bath filters do not restrict the air flow rate but render the design characteristics of the oil bath system ineffective. The entrance of airborne dust and other debris such as insects has been shown to increase liner and piston wear rates. This increases the rate of oil contamination which leads to increased in engine wear. Deteriorating engine condition results in higher fuel consumption.

4.20.8. Exhaust System Backpressure

The amount of exhaust backpressure will vary among engine types and the individual installation design. Elevated backpressure in the engine crankcase will affect the engine performance. Engine manufacturers provide specifications to ensure that system design is within guidelines. Engines that begin to exhibit higher than normal backpressure need to be inspected for exhaust system restrictions or internal failures. Increased exhaust system pressure indicates inefficiencies which increase fuel consumption.

4.20.9. Inlet Air Variance

The temperature of the intake air, moisture content, and barometric pressure are constantly changing. Warmer inlet air may result in reduced engine power. Cooler air is denser and allows more air to enter the combustion chamber so the available power will increase. Extremely cold air may result in turbocharger surge on engines with more than one turbocharger (a warm air draw system is normally recommended for cold climates). Very warm inlet air temperature also reduces the efficiency of the engine and increases the fuel consumed to produce the same power.

4.21. Catalytic Convertor

A catalytic element treating the exhaust stream is required on stoichiometric engines when their emissions are higher than allowed by regulatory limits. Catalytic converters and the associated control systems also require the ongoing expense of maintenance and condition monitoring. Emissions treated by the catalyst are typically lower than those from a pre-chamber lean burn engine design at first but then increase over time. If a catalytic converter is used, the exhaust emissions will be reduced but without a savings in fuel gas consumption. The air-fuel ratio is maintained quite rich to maintain hot operating temperatures and a supply of unburned hydrocarbons for efficient catalyst performance. Running the engine using a richer air-fuel ratio setting will increase fuel consumption. Emission reduction is achieved but at a cost of higher fuel consumption.

It should be noted that turbocharged rich burn engines can be converted to operate with leaner air-fuel mixtures using certain engine management systems. This “rich to lean” conversion offers the benefits of lower fuel consumption (typically 10% to 18%) and emissions without the penalty of full lean burn problems. It also avoids the use of a catalytic converter and extends the service life of the engine. Details may be discovered in the PTAC report on the REMVue system qualification listed in the references.

4.21.1. Lean Air-Fuel Ratio

Lean burn engines use a very lean air-fuel mixture to reduce emissions. The air-fuel mixture is typically maintained at approximately 30:1 and this is so lean that a spark plug will not ignite the mixture. To overcome this problem, a pre-chamber attached to the main combustion chamber is filled with a stoichiometric mixture of air and fuel. The mixture in the pre-chamber is ignited by the spark plug and a flame front travels into the main combustion chamber to ignite the lean air-fuel mixture. Since their introduction, the lean burn engines have a reputation in the industry as being difficult to start and costly to maintain. Fuel consumption is reduced on lean burn engines compared with rich burn engines.

4.21.2. Engine Utilization

Low engine power utilization can affect engine reliability. Turbocharged engines in particular are susceptible to oil leaks and coking when loaded less than 60% of the power rating. Carbon deposits and head damage can also result when any engine is run at low speed and load. However, increasing the speed will consume more fuel than required for the application. Options should be considered for modification or replacement of the engine for circumstances where low loads affect engine reliability.

4.21.3. Engine Management System

Any engine will benefit from installing an engine management system. It provides adaptive control and, as a result, at least a savings in fuel consumption. The engine management system allows the operator to change the engine tuning from "best power" to "best fuel" and maintain stable engine operation. Engines tend to be more sensitive to load changes (and shut down) when run at leaner air-fuel ratios ("best fuel"). Factory installed engine controls are less refined and control best at one set point. Engines, however, are required to operate over a wide range of conditions, loads and speeds which incurs less efficient operation when the engine is not on the set point. Typically a 3% to 5% fuel consumption reduction is available due to more stable and adaptive engine control alone. An appropriate engine management system is required to maintain a leaner air-fuel ratio and reduce fuel consumption as much as possible.

Automatic engine control compensation capability eliminates the periodic adjustments that are required with other systems (i.e. on going carburetor adjustments to attain emission levels). Optimized operation is assured at all times with an adaptive control system. An additional benefit is that the engine speed and driven load are not set back to accommodate transient upset conditions. Incremental production gains can actually be achieved in this case. When linked to a compressor performance measurement system and process control valves, more sophisticated automatic compensation routines may be developed.

4.21.4. Operational Checks, Testing and Adjustments

The impact of performance and service requirements on efficiency necessitates the identification of what constitutes good performance for each piece of rotating equipment over the range of process conditions that are normally encountered. This may require a compromise to maintain the desired operation of one equipment element.

Attaining these levels of performance may not be possible in all cases especially when a unit is grossly oversized in its current application. Units that cannot meet the objective are candidates for upgrade or replacement. The variety of variables and components make fuel efficiency testing a complex effort.

We have constructed a logic diagram and engine checklist to help operations personnel sort through the various details to optimize an engine. The order of tasks is designed to make the process as efficient as possible. It leads the worker through the controls and capacity issues described above. It also identifies which conditions dictate a change in control or when physical parameters must be changed to accommodate a repair or replace option. The goal is to use only the engine fuel required to suit an optimized application.

4.21.5. Operational Checks

The first part of any fuel consumption efficiency effort is to understand how the equipment is operating. Indicators of efficient operation can be gleaned from engine power utilization, intake manifold pressure, cylinder temperatures, fuel quality and other aspects. However, these all require further analysis to allow the operator to understand how efficient that engine is running. A more accurate and intuitive measure of efficiency can be derived from monitoring the brake specific fuel consumption (BSFC) of the engine. Any change in engine efficiency or fuel quality will trigger an increase in the BSFC.

A checklist is shown in Table 28. The purpose of the checklist is primarily to ensure that the engine is operating properly. These checks can be performed during a site “walk around”. They require instrumentation installed on the equipment or portable measurement devices. They should be undertaken on daily basis depending on the availability of operating personnel. The time to carry out the visual checks is in the range of 30 to 60 minutes.

Efficiency tests are a formal survey of equipment performance. Such testing will establish the performance of the rotating equipment and identify where action needs to be taken to improve performance. The driven equipment is required to be optimized in order to optimize the engine. Another report identifies the steps necessary to optimize screw and reciprocating compressors.

An efficiency test may require several hours or days to perform. A worker must assess the results with adjustments and retesting to determine the affect of each change. The task can be overwhelming for large fleets in changing field conditions. An automated dynamic software tracking system is recommended to assist the operator with assessing equipment life and ranking the candidates deserving attention. The logic diagram helps to work through the efficiency test. Operations personnel may wish to add these parameters to their daily log data sheets.

Table 28 Engine condition checklist form

Site Location:		Date:	
Unit Number:		Time:	
Engine Model		Serial #:	
Driven Equipment Model:		Serial #:	
Unit In Service: (Y/N):		Outside Temp	

Item	Activity	Records
Hours from last major overhaul	Record hours	
Hours from last top end overhaul	Record hours	
Hours from last service	Record hours	
Fuel Pressure	Check pressure	
Fuel constituents	Take sample & cf last sample	
Ignition timing	Record set point	
Engine speed	Record RPM	
Speed control swings	Record ΔRPM (swing range)	
Engine misfiring	Yes, no?	
Air filter elements	Check condition and ΔP	
Oil Bath Air filter	Check condition and bypass	
Exhaust back pressure	Check engine crankcase P	
Catalytic Converter	Check condition and ΔP	
Air-Fuel ratio	Record mixture	
Engine management system	Active? Record settings	
Greenhouse Gas emissions	Attach exhaust analysis	
Driven equipment optimized	Yes, no (last check date)?	
Engine power utilization	Record power used	
Control valve position	Record position	
Adaptive controls active	Yes, no?	

General Observations and Conditions:

Operator:

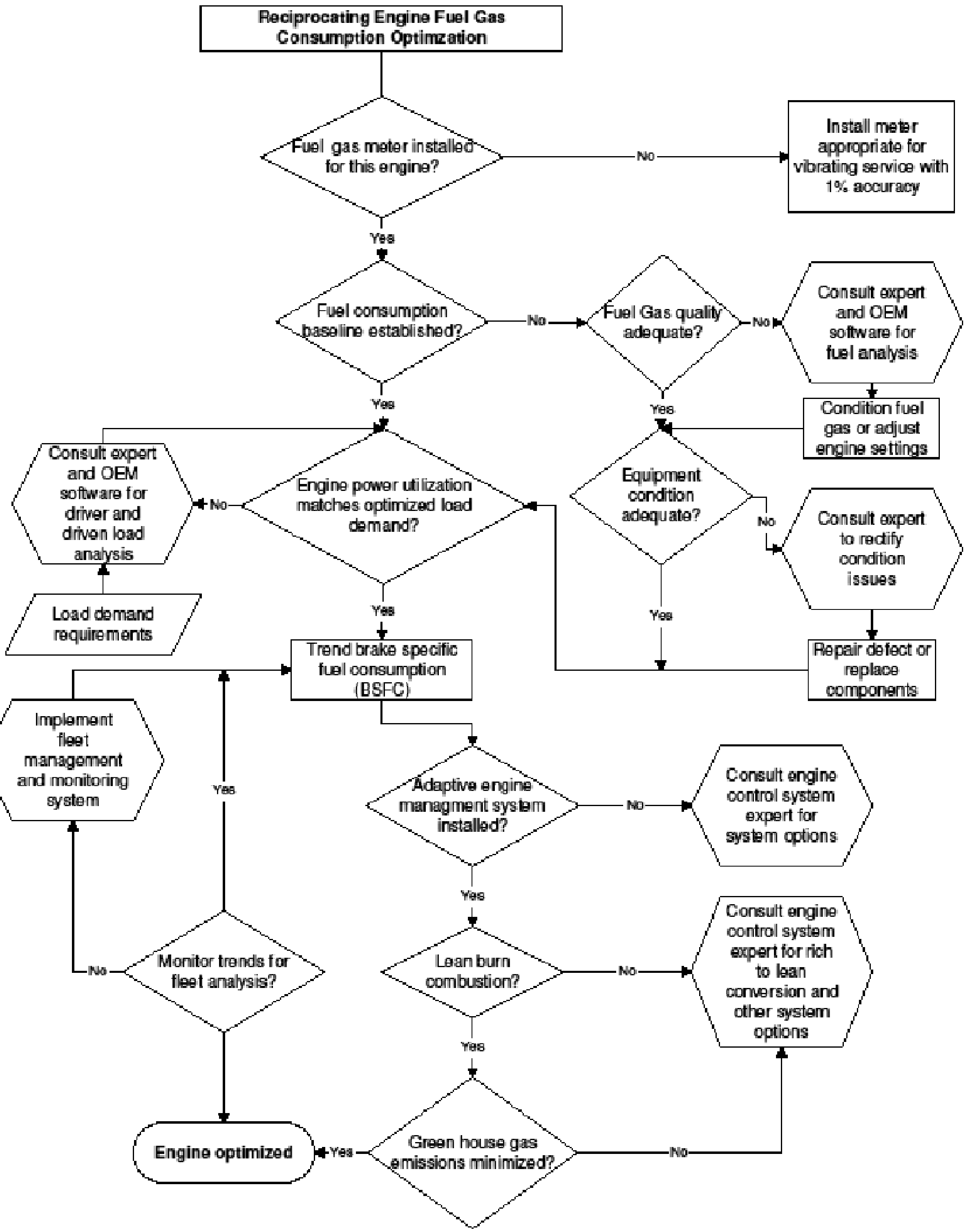

Figure 64 Engine optimization flow chart

4.22. Determining Brake Specific Fuel Consumption

BSFC is defined as Btu/(BHP*Hr). It is a convenient measure because it provides a uniform basis for comparison that includes power and the energy value of the fuel. In order to determine BSFC, the engine must be equipped with an individual fuel gas meter, gas property data, power and a means to perform the calculation. We have provided a table that will assist the worker with calculating the BSFC. A smaller BSFC number means lower fuel consumption.

The calculation requires fuel flow measurement that can be converted to the total energy consumed (Btu value of the gas must be known). The power used in the denominator is calculated based on power used at the time of the measurement. Several tools may be used to predict power but these must be calibrated against an actual measurement. A “recip trap” or similar diagnostic tool can determine the power used by a reciprocating compressor. The OEM (original equipment manufacturer) compressor software may then be tuned to produce the same results as the measured values. Screw compressors are not as easy to measure the actual power. A field torsional measurement may be used or the manufacturer can sometimes advise the accuracy of their software power predictions. In any event, the engine manufactures’ power predictions using manifold pressure are not sufficiently accurate. They advise that it should be used as a guide only.

It is important to measure the fuel consumption of each individual engine. Using one meter for a variety of engines will mask inefficiencies in individual engines. OEM fuel predictions from their test data is also virtually impossible to reproduce in the field. Actual fuel consumption can be as much as 30% higher than the factory predicted values. This is not to say that the manufacturer has fabricated the data. Test cell results by the manufacturers are achieved and reported for each individual engine. These results are used as the basis for the predicted values. Test cell parameters can be individually controlled to achieve the minimum fuel consumption each the engine. Field conditions can not be controlled to that extent. We included the information required to determine the OEM fuel predicted for comparison purposes. Knowledge of the typical deviation will allow using the OEM prediction as a guide for comparison of unfamiliar engines (i.e. new to the fleet, moved or replaced).

Field fuel consumption results may also vary between seemingly identical equipment models due to subtle mechanical design differences and load variables. Engine fuel gas streams may be derived from a single common source, blended at the header or from another source. The compressed gas stream is also subject to variables such as header inlet design, outlet pipe design and plant routing.

Site Location:		Date:	
Unit Number:		Time:	
Engine Model		Serial #:	
Driven Equipment Model:		Serial #:	
Unit In Service: (Y/N):		Outside Temp	

Item	Activity	Values
Fuel gas density	lb/scf from gas analysis	
OR (if gas density not stated)		
Fuel gas specific gravity	No units (SG; relative density)	
Density of air	lb/scf at standard conditions	0.0871
Fuel gas density	lb/scf = SG * 0.0871	
Fuel mass flow	lb/hr	
Fuel flow rate from mass flow	scf/h = mass flow÷gas density	
OR (if flow rate is stated on a volume basis)		
Fuel flow rate as volume flow	scf/h = volume flow rate	
Fuel gas heating value	BTU/scf from gas analysis	
Btu/h	Volume flow * heating value	
Power	Horsepower (calibrated calc)	
BSFC (calculated)	Btu/BHP*h = Btu/h÷Power	
Engine speed	Record RPM	
Power	Horsepower (calibrated calc)	
BSFC (theoretical)	Obtain from OEM data	
Actual vs OEM BSFC	Actual BSFC – OEM BSFC	

General Observations and Conditions:

Conversions:
1 Btu/HP-h = 1.414 kJ/kW-h
1 HP = 0.7457 kW
1 Btu = 1.05435 kJ

Operator:

Figure 65 BSFC calculation form

4.23. Monitoring Fuel Efficient Operation

Trending BSFC can show changes in the health of the engine or if other factors are changing engine performance. In order to trend BSFC, the engine must be equipped with an individual fuel gas meter and a means to perform the calculation. Refer to section 5.2 for a detailed method for manual calculation. A trend with decreasing BSFC means that fuel consumption is decreasing. The converse is true for increasing BSFC.

Workers should review the BSFC and efficiency of their engines each month. If time and resources do no permit a monthly review then a quarterly review should be undertaken as a minimum. If conditions for the driven equipment or the engine have changed then the BSFC should be reviewed again to determine a new baseline. Operations personnel should consider that this measure is as much an indicator of equipment condition as it is fuel consumption.

It takes a concerted effort to monitor engine performance and the influences that are inducing changes in its operating environment. Continuous vigilance is needed to maintain optimized operations. Operators of large fleets will recognize that this is daunting task. An automated software system approach to monitoring engine performance with an integrated operator interface is recommended.

The calculation can be incorporated in the control panel software. Gathering the fuel gas flow rates is made easier if the panel can log the data on a real time basis. Estimating load using predetermined algorithms is also easier when performed in the panel. It is imperative that engine manifold pressure is NOT used as the power prediction. Tests have proven that power can be substantially overestimated using that approach. REMVue panels produced by REM Technology Inc (A division of Spartan Controls) contain a proven algorithm that is calibrated to the actual measured power. It is accurate, reliable and scalable. Data from the panel can be incorporated into the log data collection system for review by operations personnel.

Another approach is to install a centralized software program that will calculate the parameters based on electronically communicated log data. Continuous monitoring is then possible with warnings when the BSFC drifts from the desired value. Fleet management software is available that present ranked operating and efficiency data for review. This is by far the most practical approach to trending unit and engine performance.

4.24. Fuel Gas Meter Requirements

To determine the efficiency of an engine, the fuel gas flow should be measured for each operating engine. It is not sufficient to use the gas meter for the entire site. A combination of individual engine fuel flow together with a site flow will enable the fuel gas usage by other components such as building heaters, instrument gas supplies, and leaks to be more easily assessed. Table 30 lists specifications for four types of fuel gas meters suitable for vibrating service.

A periodic fuel gas analysis is needed to determine the heat content of the fuel gas (see section on BSFC). The sampling and analysis frequency depends on the possibility of composition changes. Note that gas composition can change from well to well and also, if the fuel gas is from a gas treatment plant, the current status of the treatment plant (e.g. refrigeration unit may not be operating to specifications). Engines are often in vibrating service and the implications to the meter must be considered.

In natural gas fuelled engines, the amount of combustion air for good efficiency, exhaust emissions, and reliability depends on fuel flow. The heating value of the fuel can vary significantly depending on the hydrocarbon mix. The table below shows the lower heating value (*LHV*) per standard cubic foot (*scf*) for four components often found in engine fuel gas.

Table 29 Lower heating value per scf of typical components in engine fuel gas

GAS	**LHV – BTU/SCF**
Methane	912
Ethane	1622
Propane	2376
nButane	3020

Table 30 Comparison of four gas flow meter types suitable for engines in vibrating service

PROPERTY	VOLUMETRIC ORIFICE FLOW METER	VOLUMETRIC ROTARY FLOW METER	THERMAL MASS	CORIOLIS
Measuring principle	Volume	Volume	Specific heat	Mass
Temperature	Needs temperature measurement	Needs temperature measurement	Temperature compensated	Temperature compensated
Detect Fuel Quality Changes	Poor	Poor	Good	Best
Vibration effect	Low	Low	Low	High
Reliability	Good	Good	Good, see below	Good
“Dirty” gas influence	Some; increases apparent flow	Some; increases apparent flow	Some; decreases apparent flow	None
Differential Pressure	Low, depends on orifice size	Low	Very low; < 0.2 psi	1 to 20 psi depending on flow
Turndown ratio	Typically 10 to 1	68:1	Typically 100 to 1	Typically 10 or 20 to 1 for gases
Piping requirements	Straight pipe typically 38” before and 25” after	No piping limits; pipes must transmit minimal strain to the meter.	Typically no obstructions 10 pipe diameters upstream and 5 downstream	No piping limits; pipes must transmit minimal strain to the meter.
Installed Cost	$20,000	$5,700	$6,000	$20,000
Annual Maintenance Cost	$1,500	$100	$300	$1,500
Manufacturers	Daniel with Rosemount Transmitters	Roots 2M with Pulsar Communications Module	Fox Thermal Instruments model FT1A	1” MicroMotion

4.24.1. Measuring Principle

The orifice meter uses the pressure drop across an orifice plate in a straight pipe run to calculate volumetric flow. The pressure difference, the upstream or downstream pressure and the gas temperature must be measured. Some meters have significant piping requirements discussed in more detail below. A rotary meter uses two intermeshed rotors which are spun by the passing gas. The number of rotor rotations in a given time determine the flow rate. Volumetric meters measure volume flow, which may be converted to mass flow by multiplication by a pre-determined, user-entered density value. Changing gas properties will create inaccuracy flow measurements.

The Coriolis meter is based on the Coriolis effect and uses the transverse force created by a mass traveling in a curved path. It is a direct measurement of the mass flow. The thermal mass meter measures the thermal conductivity of the flowing gas. The thermal conductivity is very nearly proportional to mass flow. Thermistors measure the heat loss to a flowing gas.

Accuracy is less important as the operator is looking for changes in flow rate at the same operating condition. As long as the accuracy is the same for two measurements then that will be adequate for monitoring engine condition.

4.24.2. Temperature

The orifice meter requires a temperature measurement of the gas to calculate the flow. The thermal meter has internal temperature compensation while the Coriolis meter measures true mass flow and does not require a temperature adjustment. The volumetric meters are less sensitive to temperature fluctuations.

4.24.3. Fuel Changes

The fuel heating content may change in many applications. A volumetric meter cannot sense such a change. If the fuel consists mainly of hydrocarbons, then the thermal mass flow meter and the Coriolis meter provide a measurement that correlates well with heating value changes. The graph here, where other hydrocarbons are normalized to methane, shows the relative differences. A fuel meter based on a volumetric flow principle is not suitable for installations where significant changes in the fuel heating content are expected. If the fuel contains significant and changeable amounts (typically more than 5%) of inert gases such as argon, carbon dioxide, or nitrogen, a direct measurement of the fuel heating value may be required for any of these meters.

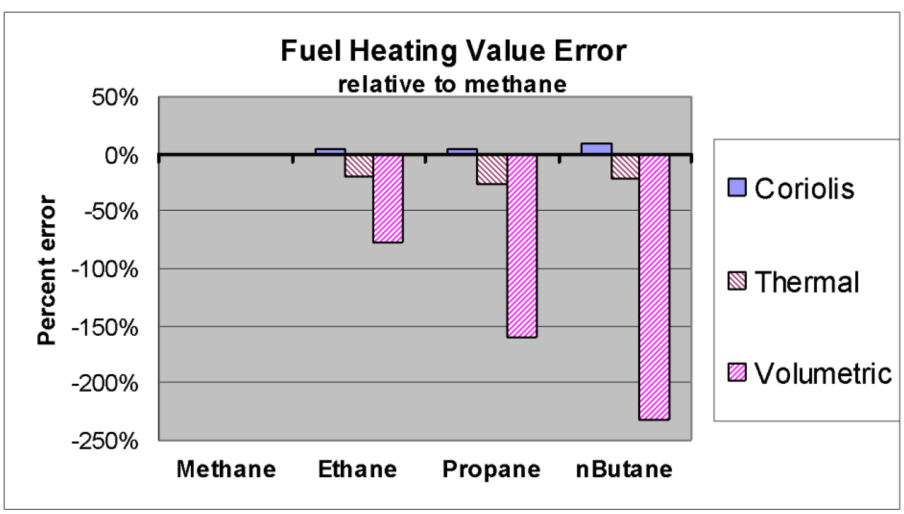

Figure 66 Fuel heating value error

4.24.4. Vibration Effects

Both the volumetric type and the thermal mass flow meters have low errors due to vibration while the Coriolis type is affected to a greater degree. Selection of location and vibration isolation should be used to minimize vibration induced flow signal noise with a Coriolis meter for engine fuel measurement. For smaller engines where the flow is low (poor signal to noise ratio), the other meters should be used. Table 31 shows some comparative measurements for meters in the same application where vibration is present. A longer averaging time for the thermal meter would further reduce the noise.

Table 31 Comparative measurements for meters in applications where vibration is present

METER TYPE	AVERAGING TIME(S)	PEAK TO PEAK SIGNAL NOISE %
Orifice	milliseconds	Depends on transmitter
Rotary	100 pulses/shaft revolution	undefined
Thermal (Fox)	0.25	± 2.5
Coriolis (MicroMotion)	12.8	± 5

4.24.5. Reliability

The reliability of each of the meter types is high and suitable for engine applications. Coriolis meter failures may occur when mounted with significant strain placed on the meter. In all cases, the reliability of fuel meters to determine engine air requirements far exceeds the reliability of exhaust oxygen sensors (an alternate method for engine air control).

4.24.6. "Dirty" Gas Influence

Engine fuel gas may contain particulate matter. Build-up of the particulate on the sensing elements may affect the readings of any of the meters. The Coriolis meter can be recalibrated when the flow is zero. Orifice plates may require cleaning as may the probe of the thermal meter.

4.24.7. Pressure Drop

The pressure drop of the Coriolis meter may be too large for applications where the fuel gas pressure is low. This graph shows the pressure drop versus flow for the Micromotion R50 Coriolis meter.

The pressure drop for the orifice plate meter is relatively low, depending on the orifice diameter relative to the pipe diameter and should be calculated where pressure loss is a concern. A rotary meter also offers low pressure drop. The pressure drop for the thermal mass flow meter is the lowest of all the meter types.

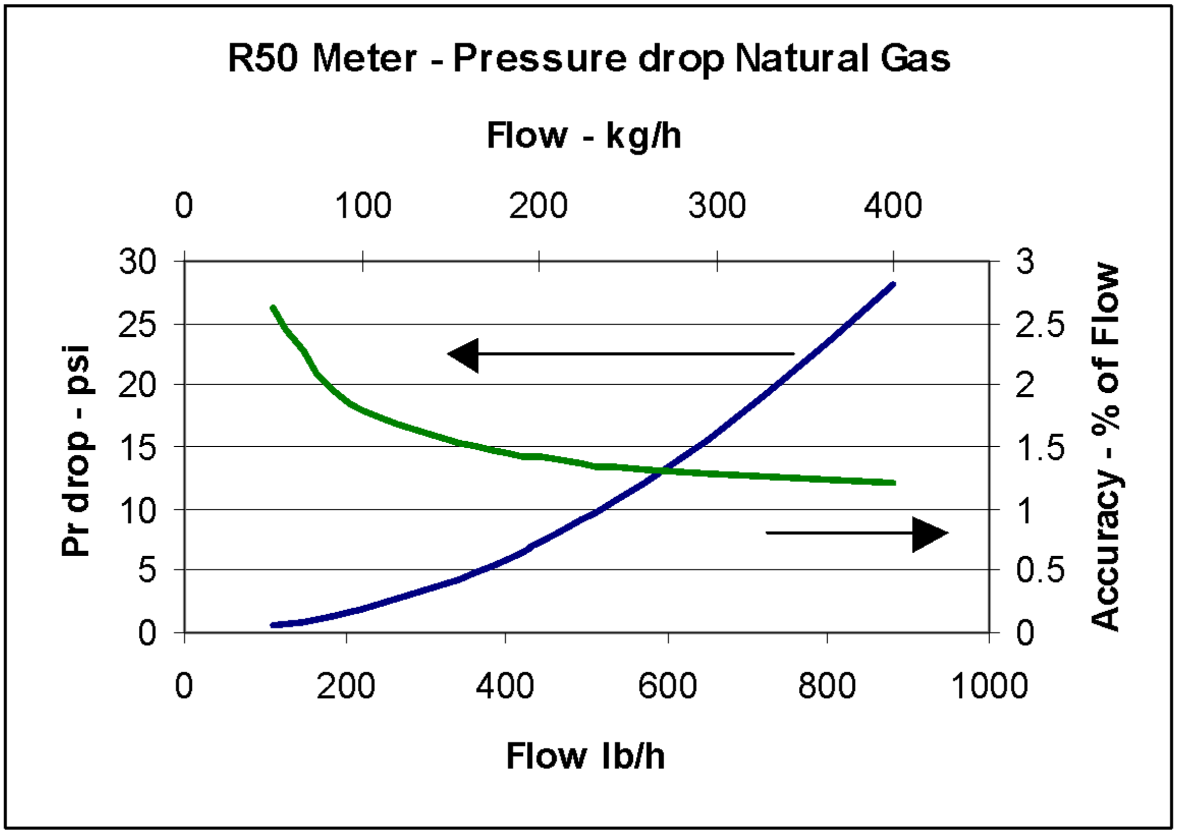

Figure 67 Pressure drop across an orifice plate meter

4.24.8. Turndown Ratio

The turndown ratio is defined by the signal to noise ratio for the application. The turndown ratios for the orifice and Coriolis meters are sufficient for most large engine fuel flow measurements. The thermal mass flow or rotary meter is recommended for smaller engines or for accuracy for low flow applications.

4.24.9. Piping Requirements

For best accuracy, the piping upstream and downstream of an orifice plate meter must be straight and uniform in diameter (about 20 diameters upstream and 10 to 15 downstream). The requirements are less stringent for the thermal mass flow meter (10 diameters upstream and 5 downstream). The Rotary and Coriolis meters have no such requirements except for those mentioned above in the Reliability section.

Micromotion ® Coriolis mass flow meter

Fox ® thermal mass flow meter

Daniel ® orifice meter run with Rosemount ® flow transmitter

Roots® rotary flow meter

Figure 68 Meter examples

4.24.10. Metering Accuracy

Flow measurements that rely on gas properties such as mass or specific heat properties scale better to the heating value of the fuel components in mainly hydrocarbon fuel. These devices are the Coriolis mass flow meter and the thermal mass flow meter. The graph shows the percentage error in measuring the heating value of the gas flowing through the meter according to meter type.

A volumetric meter should not be used where there is a possibility of a change to the gas composition. The best meter type is the Coriolis type due to the smallest errors with changes of gas mixture. The thermal mass flow meter is the best choice for applications where the fuel flow is small (*engines below about 500 HP*) or where vibration is significant. Fuel gas flow meters are not employed by any major OEM to control air fuel ratio. An exception is a REM*Vue*® engine control system that is the only system that uses a mass flow meter to operate their controls. As such, it is the only system that is dynamically adaptive to changes in fuel quality.

4.25. Cost Recovery of Fuel Gas Optimization by Installation of a Fuel Gas Meter

Continuous monitoring of fuel gas consumption allows the operator to identify the condition of the engine on a continuous basis. This process might be accomplished with periodic measurements and calculation of BSFC. However, that requires a significant effort. It is unlikely that such a program could be sustained. Installing a fuel gas meter and communicating the flow rate to the panel where computations are performed automatically allows direct monitoring with little additional effort. If a trend of increasing BSFC is noted, and the deficiencies are address during the next regular service, that behaviour promotes behaviour to reduce fuel gas consumption and the start of a predictive maintenance program. The predictive maintenance program offers additional benefits in savings of maintenance cost, reduction of downtime and reduced spare parts inventory (NIST.AMS.100-34 published by the USA government).

Table 32 shows an approximate cost recovery calculation. A fuel gas saving of 10% is estimated based on the expected improvement by optimizing the engine operation. The calculation shows that cost recovery can be justified based on fuel gas savings alone. The savings due to reduced downtime and maintenance costs are calculated using the percentages offered in the NIST study. They are encouraged by a predictive maintenance program. A continuous fuel consumption monitoring program may offer production personnel a tool to maintain optimized operation of their engines and document their pride of ownership.

Table 32 Cost recovery example for a Waukesha L7044GSI S4 demonstrating the benefits of fuel gas consumption monitoring

Cost recovery calculation for engine fuel gas monitoring benefits				
Engine model:	Waukesha L7044GSI S4			
Fuel Gas Required (BTU/BHP hr):				7,840
Gas Heating Value (BTU/scf):				1,050
Engine Power (HP):				1,680
Engine speed (RPM):				1,200
Fuel Gas Comsumption (scfd):				301,056
Premium for site service:				30%
Total fuel gas consumption (scfd):				391,373
Typical gas value ($/MSCF):				$3.70
OEM consumption cost of fuel gas per day:				$1,113.91
Actual consumption cost of fuel gas per day:				$1,448.08
Approximate Natural Gas Production (MMSCFD):				17
Downtime (hours/y):				130
Maintenance cost ($/h)				$20.00
Cost recovery per year				
Assume annual fuel savings:	10%	$52,855		
Reduction in annual downtime:	15%	$51,106		
Maintenance cost annual savings:	28%	$48,328		
Annual savings:		$152,289		
Approximate cost of fuel gas meter:			$20,000	
Cost recovery based on fuel savings alone:			4.54	Months
Cost recovery based on reduced maintenance and downtime:			1.58	Months

5. Best Management Practices

The following best management practices suggest opportunities to reduce methane slip. Each parameter is discussed and qualified for its effectiveness in reducing methane slip. The success of changing an individual parameter of an engine control system may present a limited opportunity. Adjustments to parameters may not be undertaken without consideration for how that change will affect the engine operation.

a. Ensure the engine is in good working condition and tuned for optimum operating characteristics at all times.

A concerted effort is required to ensure engine condition and tuning is optimized at all times. An optimal tuning set point must be defined and monitoring must be conducted to establish that the operating set point is optimized. This would ideally be accomplished by establishing key performance indicators and performing condition-based maintenance to maintain optimized operation. Condition-based maintenance adds the benefit of reducing maintenance, operating and inventory costs. Reduced downtime also yields production increases. And, of course, optimized engine condition.

Methane slip will be minimized when the engine condition is optimized. Engine condition that is eroded will emit more methane due to inefficient operation or combustion. Engines will run at a suboptimal point and emit more methane emissions in the exhaust when component wear increases and when set points drift from that required for the most efficient operation. The higher methane emission volumes result from incomplete combustion and blowby from worn engines.

b. Consider installing a fuel gas meter to ensure accurate fuel consumption measurements and to assist with determining engine health.

Fuel consumption is a key performance indicator of engine condition and efficiency. Increasing fuel consumption indicates that the engine operating conditions should be investigated. If the fuel consumption is not monitored then the engine can operate in a suboptimal condition for an extended time.

The fuel consumption may be determined by periodic checks and calculation of the brake specific fuel consumption. This effort is time consuming and arduous. A meter might also be installed. A meter offers the benefits of ease of use and visibility via the control system for remote monitoring.

This parameter is relatively easy to monitor with the addition of a fuel gas meter. Operators will gain the benefit visibility of their engine operating characteristics and correlate those to a need for service or investigation to determine the reason for the suboptimal performance.

Monitoring fuel consumption, and performing regular adjustments, is proven to reduce fuel consumption by at least 10%. A thermal mass flow meter will cost about $20,000 to install for a 1,150 kW engine. Cost recovery is achieved in about 4.5 months at this rate.

c. Consider optimizing the load of the equipment driven by the engine.

Driven equipment and adjustments for suboptimal operating conditions are sometimes configured and then not adjusted again to optimal settings. The equipment may continue to operate with setting that reduce the driven equipment output. Normally, running the engine for upset conditions will waste energy. The load of the driven equipment can be configured to use less power to do the same work.

This can involve reducing clearance in the gas compression chamber to reduce the engine speed while providing the same output from the driven equipment. Reciprocating compressor performance may be measured by installing indicator valves (Keine valves) in the compressor cylinder ports. Performance measurement will allow accurate measurement of reciprocating compressor flow, power, efficiency, and reliability. Reciprocating compressor valves and configurations may be adjusted to optimize the flow rate and the power required.

Screw compressors might be operated at reduced clearance to use less power at the same flow rate. Slide valves and Vi adjustments may be adjusted to suit upset conditions. Changing screw compressor settings is performed by theoretical analysis using the OEM performance software.

Generators operate at a single speed but the load is a function of the energy demand. Load banks artificially maintain a constant load on the engine. Generators are often operated with others to provide redundancy. Load sharing schemes are prepared to optimize load on the engines and provide a continuous supply of enough electrical power.

Detailed discussion of load optimization is beyond the scope of this study. However, operating the engine at higher speed and load than required for the service will normally increase methane slip emissions. Fuel gas consumption and maintenance costs will also increase.

d. Consider installing an adaptive engine management system.

The engine's operating environment is constantly changing, both during the day and over the seasons. The frequency of the adjustments to accommodate these changes must be practical and effective. Older engines are equipped with control systems and set points that are manually adjusted. This style of control system would require adjustment several times a day to ensure it remains optimally tuned. Clearly, control automation will assist with this task.

The current engine management systems and technology developments focus on reducing NO_x emissions. Control systems designed specifically to reduce methane slip are not currently available except from Caterpillar with their 3600 ADEM 4 Next Generation engine management system. Control of emissions is enhanced by adaptive engine management systems. These systems evolve with every new engine model. Control of the combustion process is key to managing the emissions. Any engine management system will meet emissions at the time of tuning. The trouble starts when the set points are not automatically adjusted to suit changing ambient, fuel quality and load conditions.

Older engines are designed to be set at one operating point. Changing operating conditions require the operator to tune the engine again. Such tuning normally occurs when quarterly oil changes are performed. It is unlikely that the engine remains in compliance with any regulatory emission limit in the interim period between tuning. Engine management systems evolve over time to accommodate changing regulations and owner needs for improved efficiency.

Most engines manufactured prior to 1995 are equipped with a rich burn combustion style. A catalyst is required to achieve NO_x compliance on rich burn engines. An array of sensors are employed to maintain the air-fuel ratio in conjunction with the catalyst operation. The first control systems are not adaptive. Frequent tuning is required to accommodate changing operating conditions. Reliability for these systems is generally poor.

Lean burn engines emerged to achieve NO_x compliance without the installation of a catalyst. The advent of lean burn combustion style engines revealed the need for more adaptive controls to promote operating stability at the leaner air-fuel ratios. The first generation of these adaptive controls are the product of development by Spartan Controls. Their conversion on rich burn engines with a rich to lean engine management system measured the engine parameters and responded to differences in fuel quality, ambient conditions and load. The result is a NO_x compliant engine without relying on a catalyst. The ignition is remotely adjustable to allow the engine management system to adapt to changing conditions.

Waukesha then launched the open chamber VHP LT engine model that mimicked the Spartan lean philosophy. However, Waukesha did not incorporate automatically adaptive controls at the time. Caterpillar's G3500 series engine models were always open chamber lean burn. The older models are not equipped with automatically adaptive control systems but newer models are equipped with ADEM 3 or ADEM 4 adaptive systems.

White Superior engines occupy a small portion of the market. The majority of these engines are rich burn combustion style with air introduced into the exhaust via valve overlap. The engine emissions cannot be controlled with a catalyst. Most of these engines are in service for over forty years and upgrades are typically limited to ignition systems. Cooper now offers pre-chamber conversions for the White Superior 825 series engines but no upgraded engines are in service in Alberta. Engine stability is always an issue with rich to lean upgrades.

Engine stability improved with more advanced adaptive engine management systems are offered by all engine manufacturers. Some are more adaptive than others but all are adaptive within a finite operating range. Wider ranges of operation with adaptive controls are now available from both Waukesha and Caterpillar. Waukesha offers their ESM2 engine control system with EmPact emission control and catalyst. Caterpillar offers the most sophisticated control system with the G3600 ADEM 3 and 4 by monitoring the flame front propagation in the cylinder and then adapting the operating set points to maintain consistent exhaust emissions. An array of sensors provides feedback to the engine management system to permit adaptive controls.

e. Consider engine upgrades that offer increased efficiency due to geometry changes.

Caterpillar has recently introduced their G3600 ADEM 3 and ADEM second Generation retrofit for in service engines. The upgrade replaces internal components to reduce internal crevice volumes. Field test results to qualify the effectiveness of this upgrade are not available at the time of this writing. Caterpillar advised that the cost of the retrofit should be trivial if done in conjunction with an overhaul. The operator should qualify this aspect. Most overhauls will employ rebuilt components for heads, pistons and liners with the same vintage as the engine. The geometry changes suggested by the ADEM 3 and 4 Next Generation retrofit suggest new parts with a different design would be provided. This change may add cost to the overhaul if OEM parts are not employed.

Waukesha claims their VHP GSI models with series 5 heads and ESM configurations is more efficient. The series 5 engine employs the Miller cycle which will reduce fuel consumption. However, our field measurements showed no difference in methane slip for the rich burn series 4 engine to the series 5 engine designs. Converting the series 4 engine design to a series 5 engine design will cost at least $200,000. Waukesha also offers a lean to rich conversion. The lean to rich field conversions will cost between $750,000 and $850,000. Waukesha also offers an engine replacement program to provide a rich burn engine that they call their Re-Up program. This program is more expensive because the engines must be removed and replaced in the field. Replacing a lean burn engine with a rich burn engine will reduce methane slip but at the expense of increased fuel consumption and the cost of the catalyst maintenance and installation.

Methane exhaust emissions are directly proportional to the excess oxygen in the exhaust stream. NO_x exhaust emissions are inversely proportional to the excess oxygen in the exhaust stream with lean air-fuel ratios. Reducing the two emissions at the same time to near zero emissions is not possible at this time. The technology does not exist to do so.

Regulating the methane emissions to a threshold of the proposed 1 g/kW-h will affect 77% of the engine fleet. Furthermore, the lean burn engines use 10% to 15% less fuel to operate the engine than a typical rich burn engine. The conversion of a lean burn engine to rich burn with a catalyst will embed the higher fuel consumption in the operating costs and the subsequent increase in CO2 emissions.

The offset of 700 to 1500 ppmvd @15% O2 methane slip associated with pre-chamber lean burn combustion represents the reduction of methane emissions. For example, consider a rich conversion of the G3612 ADEM4 engine in test report 100942 T2 operating at 96% of rated load at full speed. Converting the engine to rich burn will increase fuel consumption by at least 10%, or 78.5 kg/h. Reducing the methane exhaust emissions to near zero will save about 1500 g/kW-h, or about 27.96 kg/h. Clearly, the net reduction in methane exhaust emissions does not warrant retrofitting the lean burn engines with rich burn technology for the sole purpose of reducing methane slip.

f. Consider newer engines on greenfield projects with lower methane emissions in the exhaust.

New Caterpillar G3600 series and Waukesha VHP engines are equipped with ingestive crankcase emission systems. Caterpillar engines smaller than the G3600 series are not equipped with ingestive crankcase emission systems. However, Colorado State University is working with Caterpillar to develop an ingestive system for the G3500 series engines. Waukesha's VGF engines are equipped with ingestive crankcase emission systems. White Superior 825 series engines have always been equipped with ingestive crankcase emission systems.

Caterpillar has recently introduced their G3600 ADEM 4 Second Generation series engines with reduced internal crevice volumes. Waukesha claims their VHP GSI models with series 5 heads and ESM2 configurations are more efficient. These two examples show a different approach to reducing methane slip is offered.

Waukesha is promoting rich burn technology which is more expensive to maintain and with higher engine heads temperature which reduces the service life of the engine components. Caterpillar is improving on their pre-chambered lean burn technology to reduce methane slip while retaining the benefits of lean burn technology to reduce fuel consumption and extend the service life of engine components by running at cooler head temperatures. Both engine designs meet the currently regulated NO_x limits. Please refer to the discussion in the previous point for more detail.

g. Consider adopting modern and best available technology to minimize methane slip.

Changing the control system with the combustion style is a plausible method to reduce methane slip at the expense of engine component life and increased fuel consumption. Waukesha promotes this retrofit in their lean to rich conversions. These field conversions will cost between $750,000 to $850,000. Waukesha claims that their VHP series 5 engine design is more efficient. Our field tests did not observe a change in the methane slip compared with their series 4 design.

An ingestive crankcase vent capture system will reduce the fraction of methane slip from the crankcase. Caterpillar has produced a retrofit kit for G3600 series engines to change the engine geometry to reduce methane slip. Waukesha also offers ingestive crankcase volume retrofit options for their VHP models. Two popular third-party suppliers, namely Solberg and FleetGuard, also produce retrofit crankcase vent ingestive systems. Between them, they have options for all sizes and makes of natural gas fueled stationary engines. The captured crankcase methane flow rate in kg/h may be estimated as approximately 0.0017*kW.

The best technology solutions for methane slip reduction on an in-service engine is to adopt an adaptive engine management system. The next ingredient for reducing methane slip is to ensure the engine is operated in good condition. A predictive maintenance program will offer the most efficient method of ensuring good engine operating condition. Caterpillar's new G3600 ADEM4 Next Generation GHG ready engine model advertises a reduction in methane slip emissions of 40% due to tighter tolerances in the combustion chamber and other efficiencies. New technology is currently under development to help reduce methane emissions in the exhaust.

Methane catalysts are under investigation by various catalyst manufacturers and engine technology developers. Nanotechnology as a fuel supplement is also under investigation. Finally, hydrogen as a fuel source or blended with natural gas is under investigation. No conclusive information on the efficacy of these opportunities is available.

h. Consider installing more adaptive engine management systems components.

Engine management systems are comprised of several components to control ignition, air fuel ratio, operating speed, combustion air, exhaust flow and NO_x mitigation. These components work in concert, and the most effective controls are orchestrated to provide an adaptive control system. The individual elements will never be as effective as the sum of their parts. Changing individual components may improve reliability and perhaps reduce fuel consumption but it will not reduce the amount of methane slip.

Methane sensors are not currently available for engine management controls. Methane gas detectors use sensors specific to methane but their operating range and response time is too limited to serve in engine management control systems. Engine management systems rely on more robust sensors to monitor engine operating aspects. The following devices are common instrumentation found on engines.

- Pressure sensors for monitoring air manifolds, combustion chambers, oil galleries, fuel supply, turbochargers, water services, crankcase.
- Temperature sensors for monitoring air manifolds, exhaust manifolds, catalyst pre and post exhaust locations, combustion chambers, cylinder heads, oil galleries, fuel supply, turbochargers, water services.
- Oxygen sensors for monitoring pre and post catalyst exhaust locations, air manifolds, turbochargers, engine tuning.
- NO_x sensors for monitoring post catalyst exhaust gasses and engine tuning.

- Flame front monitoring using time of combustion event triggered by the spark plug firing and terminated by voltage measurement triggered by ionization of combusted gasses around the sensor.

The NO_x sensors are the latest technology introduced of the various sensors. They are improving in reliability. Oxygen sensors are also known for poor reliability. The reliability of these devices is also improving. Operators are tasked with constant checks to determine if the sensors continue to operate within specifications. Catalyst operating systems are reliant on sensors to maintain functionality. The system requires constant monitoring. NO_x sensors also provide similar reliability challenges.

i. Consider installing technology to increase the exhaust temperature.

Increased exhaust temperature does reduce methane slip. Exhaust temperature may be adjusted within a limited range for any combustion style by adjusting the air-fuel ratio to a richer setting. Doing so will change all other operating parameters for the engine and control adjustments may not be sufficient to compensate. Adjusting just the exhaust temperature alone will create more problems than produce any real benefit. A limited range of adjustment is available for each combustion style. A small adjustment will have little impact on the methane slip emissions. Converting lean engines to rich style combustion is the only feasible method to increase exhaust temperature with a stable control system. A lean to rich engine conversion engine is expensive and results in shorter component life and higher operating expenses.

j. Consider conditioning the engine fuel to increase the fuel heating value (LHV).

Theoretically, increasing the LHV of the fuel (hot fuel) should create a higher heat of combustion. Engine manufacturers adjust the operating configurations and ignition timing on engines to manage the combustion process. The design approach is to obtain the same power and engine performance with the hot fuel as it provided by their standard specified fuel. The ignition is retarded and the air fuel ratio is adjusted to have engine performance meet the original design operating points. Ignoring such adjustments will cause damage to the engine from uncontrolled combustion events and valve recession. Some adaptive control systems are able to compensate for LHV changes. To do so will require a mass flow meter or technology such as flame front propagation monitoring.

k. Consider adjusting the engine tuning to that specified by the operating condition.

The engine's operating environment is constantly changing, both during the day and over the seasons. The frequency of the adjustments to accommodate these changes must be practical and effective. Older engines are equipped with control systems and set points that are manually adjusted. This style of control system would require adjustment several times a day to ensure it remains optimally tuned. Clearly, control automation will assist with this task.

Engine manufacturers specify set points and other engine configurations specific to the operating conditions. These set points are influenced by regulatory emissions regulations. Engine tuning is also adapted to the engine condition. Maintaining good engine condition will permit optimal engine tuning. A primary finding in our study is that a wide range of engine performance for identical engine models was evident. Clearly this is influenced by the operating conditions for each site and each engine. However, it also indicates that engine condition is not consistent and may not be optimal.

l. Consider optimizing the engine air-fuel ratio.

Optimizing air fuel ratio will allow the engine to run at peak efficiency. The engine manufacturers specify setting for “best fuel” (lean air fuel ratio) and best power (rich air fuel ratio) and “catalyst” (if so equipped). These setting will change fuel consumption and create minor changes to the operating characteristics of the engine. Methane slip will not be significantly affected by these adjustments as the combustion style has not changed.

One exception to this statement is to adjust a rich burn engine without catalyst to an excessively rich setting. The very rich air fuel ratio set point is adjusted progressively richer until NO_x emissions are less than regulatory limits in Canada. The NO_x emissions are reduced by quenching the combustion chamber with excess fuel and cooling the exhaust gasses. The very rich tuning is accompanied by very high CO emissions. We suggest a CO concentration in the exhaust exceeding 5,000 ppm will indicate that the air fuel ratio is tuned very rich. A very rich set point floods the exhaust line with raw fuel, creating a high possibility of explosion in the exhaust with the accompanying personnel injury and engine damage. Current MSAPR regulation does not require monitoring of CO emissions nor does it restrict rich combustion without a catalyst.

m. Consider installing an ingestive crankcase vent system on in-service engines.

Both Waukesha and Caterpillar offer ingestive crankcase ventilation systems as OEM upgrades. Third party systems are also available. An ingestive crankcase vent capture system will reduce the fraction of methane slip from the crankcase. Caterpillar has produced a retrofit kit for G3600 series engines to change the engine geometry to reduce methane slip. Waukesha also offers ingestive crankcase volume retrofit options for their VHP and VGF models. Two popular third-party suppliers, namely Solberg and FleetGuard, also produce retrofit crankcase vent ingestive systems. Between them, they have options for all sizes and makes of natural gas fueled stationary engines. The captured crankcase methane flow rate in kg/h may be estimated as approximately 0.0017*kW. The installed cost of the retrofit crankcase vent ingestive systems vary between $5,000 for smaller engines to $90,000 for large engines. Fleet installation programs, if required, will have more impact to focus on larger engines first. White Superior 825 series engines have always been equipped with an ingestive crankcase vent system.

n. Consider driver electrification.

One method of reducing methane slip is to replace the engine with an electric motor. The authors have performed several analyses on the economics of performing such a retrofit. Normally, the reduced maintenance expense of the electric motor would offset capital cost of replacing the engine with a motor. However, electrical energy cost is high enough in Alberta to reverse that aspect. The feasibility of this alternative is not economically viable in Alberta. Programs for electrification of engine driven stationary equipment are exploited in other Provinces in Canada and in the USA. If applicable, methane use and emissions produced by generating the power for the electric motor should also be considered in the analysis. Electric motors do not produce any emissions directly by their operation.

o. Consider testing for CH_4 in emissions stack tests.

An emissions test could include measurements for CH_4 (methane). The measurement of the concentration of this element will allow operators to identify when methane slip may be increasing. It would also allow establishing a threshold value for an engine. Variables such as load and speed should be considered in determining a threshold value. A special CH_4 sensor and a CEMS monitoring system is required to obtain measurements of CH_4. Measuring THC (total hydrocarbons) is not an accurate representation of methane slip since it contains additional elements that will make identification of the methane component concentration difficult to quantify.

6. Future Work Suggestions

Discrepancies between the theory of how methane slip emissions behave and the graphical representation of the data are evident. These aspects suggest areas for future study with respect to methane slip:

- Air manifold pressure effect; especially on pre-chambered engines, to determine why the relationship between methane slip and air manifold pressure is normally inversely proportional.
- Hours since last overhaul effect; to determine why no directly proportional relationship with methane slip was observed.
- Crankcase emissions effect; to determine what relationship with methane slip is found with crankcase gas emissions alone.
- Oil ash content effect; to determine what relationship with methane slip is found with the ash content in engine oil.
- Oil ash content effect; to determine what relationship with methane slip is found with low ash content oils.
- Excess oxygen effect; especially on pre-chambered engines, to determine why this combustion style behaves contrary to theory.
- Engine coolant temperature effect; to determine why the relationship with methane slip is contrary to theory.

- Catalyst conversion efficiency effect; to determine how deterioration of the catalyst effects methane slip
- Low air manifold pressure effect; to determine how low manifold pressure causes ingestion of oil into combustion air and if it increases unburned hydrocarbons in the exhaust.

7. Conclusions

The testing program consists of samples from 100 engines and 116 tests. The objective is to gather as-found methane slip field test measurements. The sample contains the most common four cycle, natural gas fired engines in Alberta's natural gas production industry. The original test scope is five examples of each of 22 engine models. Site access and insufficient engine model quantity changes the number of site visits in the program to 100. Retesting seven engines with condition issues increases the test quantity to 108. Multiple tests on eight engines increases the test quantity to 116 tests. Finally, 22 Caterpillar G3600 series engine MSAPR tests from one producer offer test data from one operator and one engine type.

Four different engine combustion styles in the sample show characteristics that show they are mutually exclusive. The four combustion styles are rich burn without catalyst, rich burn with catalyst, open chamber lean burn and pre-chamber lean burn. The test data for each combustion style contain a wide spread of data. Graphs showing the data reveal possible correlation and identify relationships in the operating variables. The following operating aspects reduce methane slip emissions.

- More adaptive control systems,
- higher exhaust temperature,
- higher fuel lower heating value (LHV),
- engine tuning as specified by the operating condition,
- lower excess oxygen (O2%) for combustion,
- add ingestive crankcase evacuation systems, and
- newer engine model age.

Monitoring fuel consumption is recommended to identify when engine condition may be deteriorating. Poor engine condition is known to increase methane slip. For example, a spark plug that is not firing will cause raw methane to be introduced into the exhaust. Determining the brake specific fuel consumption will be the most efficient method for monitoring changes in fuel consumption. A manual method is provided which is shown to be detailed and complex. The installation of a fuel gas meter with remote monitoring simplifies the exercise and features cost recovery of about 4.5 months based on a fuel gas saving of 10%. Aerial and land based tunable diode laser absorption surveys of exhaust emissions using infrared surveys also offer an option to identify methane slip emissions.

Crankcase vent emissions are normally directed to the exhaust. These emissions constitute about 40% of the total methane slip. Assuming the crankcase vent volume is a function of the total methane slip is questioned. Howard Malm suggested that the mass flow (kg/h) of methane slip contributed by crankcase vent emissions may be estimated by 0.0017 * Engine power (kW). The relationship should be qualified with data from a larger sample. Capturing the crankcase vent emissions with and ingestive system will reduce the total methane slip.

Third party and OEM retrofit ingestive crankcase vent systems are available. The installed costs ranging from $20,000 to $80,000 depending on the engine model and the complexity of the system. Some new engine models are equipped with an ingestive crankcase system as standard equipment. Those engine modals are Waukesha VHP GSI and VGF as well as Caterpillar G3600 Next Generation series. White Superior 825 series engine models have always been equipped with ingestive engine crankcase vent systems.

The MSAPR engine data base provided by ECCC is employed to estimate fleet methane slip emissions. We estimated total methane slip emissions as approximately 182,500 T/y for Canada and approximately 127,800 T/y for Alberta. We estimated total Crankcase vent methane emissions as approximately 73,700 T/y for Canada and approximately 53,100 T/y for Alberta. These estimates could contain at least 40% error due to the assumptions made on the engine models, rated power, combustion style and the assumption that all engines are operating at full power. The emission factors used to the quantify the emission volumes are determined from our test data. Converting the methane slip concentration from ppmvd @ 15% O_2 to other units may offer a convenience in calculation but this compromises scientific rigor by introducing errors of 20% to 60%. Converting ppmvd @ 15% O_2 to g/kW-h will embed +/- 20% error. Converting ppmvd @ 15% O_2 to g/GJ will embed +/- 25% error. Converting ppmvd @ 15% O_2 to g/e3m3 will embed +/- 60% error. Adopting units of ppm is a direct measurement that avoids incorporating errors in measurements.

Technology is not currently available to specifically address methane slip. Modern engines are specifically designed to meet NO_x compliance. Caterpillar now offers their G3600 Next Generation series model and retrofit kits to reduce methane slip on pre-chambered lean burn engines. An open chamber rich burn engine equipped with a catalyst is capable of meeting NO_x compliance and the proposed 1 g/kW-h threshold proposed by Environment and Climate Change Canada (ECCC).

Imposing that threshold in regulations affects approximately 77% of the engines in the Alberta fleet. Converting lean burn engines to rich burn with a catalyst is the only current solution to meet methane slip regulations. The consequence of the solution is to increase fuel consumption by more than the reduction of methane slip. A tiered volume approach for the methane slip emissions according to the combustion style is more practical than one threshold value.

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APPENDIX A

Field Test Engine List

Engine Models Included in the Field Test Program and the G3600 MSAPR Tests

Engine Models Included in the Field Testing Program				
Combustion mode	**Engine Manufacturer**	**Engine Model**	**Number of engines**	**Number of tests**
Pre-chamber MSAPR (Refer to Appendix G of this report for more details)	Caterpillar MSAPR	G3608ADEM3	12	30
		G3608ADEM4	5	7
		G3612ADEM4	5	9
Pre-chamber (Refer to Table 8 of this report for more details).	Caterpillar	G3608ADEM3	5	5
		G3612ADEM4	5	7
	Waukesha	L7042GL	4	4
		L5790GL	1	1
	White Superior	8GTLB825	1	2
		8GTLE825	2	2
Open chamber Lean Burn (Refer to Table 7 of this report for more details).	Caterpillar	G3516TALE	5	7
		G3512ADEM3	5	5
	Waukesha (3rd party management system)	L7042GSI RB to LB	6	8
		L7044GSI RB to LB	1	1
	Waukesha	L5774LT	5	6
		H24GL	5	6
		F18GL	4	5
	White Superior	12VGT825	1	2
Open chamber Rich Burn with catalyst (Refer to Table 5 of this report for more details).	Caterpillar	G3408TA	1	1
	Waukesha	L7042GSI S2	3	4
		L7042GU S2	1	1
		L7042GSI S4	3	3
		L7042GSI S5	2	3
		L7044GSI S4	7	7
		L7044GSI S5	1	1
		F3521GSI	1	1
	White Superior	8G825	4	5
Open chamber Rich Burn without catalyst (Refer to Table 6 of this report for more details).	Caterpillar	G3408TA	2	2
	Waukesha	L7042GSI S2	4	5
		L7042GU S2	2	2
		L7044GSI S4	1	1
		F3521GSI	4	4
		F3521GU	1	1
		F2895GU	1	1
	White Superior	8G825	4	4
		12SGT825	1	1
		16SGT825	1	1
		8GTL825	5	5
		8GT825	1	2

APPENDIX B

Test Procedures

Emission Test Requirements (as provided by Signet Monitoring and Analysis)

1. Objective

The project requires in-situ emission tests on several common different models of stationary natural gas engines. The emission tests shall use CEMS analyzer(s) that detect the following gases: CH_4, NO_x, CO, CO_2, & O_2. Six of the emission tests need a grab sample to perform a laboratory analysis for corroboration of the measured field data. Ten of the engines will receive a second test, within 4 to 6 months following the initial test. Total hydrocarbons and VOC emissions will not be measured or estimated for the emission tests.

2. Measurement Requirements

Collect data for at least one 15-minute test run and record the data at an interval average of less than or equal to 1 minute. The test procedures must meet the following requirements.

2.1. All emissions data recorded must use a digital recorder or data logger with interval averages of less than or equal to 1 minute with timestamps for each measurement device.

2.2. All measurement devices must have proof of calibrations in accordance with the manufacturer's specifications.

2.3. Fuel consumption is measured using a mass/volumetric flow meter capable of ±2% measurement accuracy. The flow meter must have proof of calibrations according to manufacturer specifications. Optionally estimate the fuel flow rate from Brake Specific Fuel Consumption values provided by the OEM.

2.4. For the exhaust concentration of CH_4, use one of the following test methods.

a. USEPA Method 320 (or ASTM equivalent) for FTIR spectrometer analyzers

b. USEPA Method 25A for HFID analyzers

c. USEPA Method 25B for NDIR spectrometer analyzer

2.5. For the exhaust concentration of O_2, use USEPA Method 3A.

2.6. For the exhaust concentration of NO_x

a. USEPA Method 320 (or ASTM equivalent) for FTIR spectrometer analyzers

b. USEPA Method 7E for CEMS analyzers

c. USEPA Method 25B for NDIR spectrometer analyzers

2.7. For the exhaust concentration of CO_2, use USEPA Method 3A. It is an option to calculate CO_2 using carbon-mass balance based on the fuel consumption and gas analysis.

2.8. Use USEPA Method 19 to calculate the stack gas flow to determine the mass emission rates for CH_4 and NO_x in tonne/year.

3. Data & Calculations

3.1. Reports must contain a diagram of the flow meter location in relation to all downstream devices and equipment.

3.2. Calculate engine load consisting of the power to drive the reciprocating compressor plus auxiliary loads. It is optional to use OEM compressor software to calculate the load. The minimum input data are compressor RPM and the temperatures & pressures for the inlet and outlet of each compression stage. The load calculations must account for any auxiliary load(s). Do not include a parasitic load factor above those included in the compressor software.

3.3. Use a reciprocating compressor analyzer to collect once-per-turn engine vibration/performance data.

3.4. Calculate BSFC by dividing the fuel consumption (BTU/hour) by the engine power output (BHP).

3.5. Description of methods for collecting emission samples using sample ports compliant with USEPA Methods 1-4 or the Canadian MSAPR.

3.6. Determine N_2O by calculating 1.5% of NO_x (multiply the NO_x concentration by 0.015).

3.7. Natural gas composition analysis must include molar composition, LHV, HHV, and the method used.

3.8. Use a field data sheet to record the following data for each test run.

a. Engine Operating Conditions

i. Speed

ii. Fuel Flow Rate

iii. Air Manifold Pressure

iv. Air Manifold Temperatures

v. Ignition Timing

vi. Load (if available)

vii. Exhaust Temperature

b. Process Operating Conditions (if applicable)

i. Suction/Discharge Pressure

ii. Suction/Discharge Temperatures

iii. Variable Volume Control Pocket (VVCP) Settings (if applicable)

iv. Process Speed (if available)

v. Process Flow Rate (if available)

vi. Slide Valve Position (if applicable)

c. Generator/Alternator Operating Conditions (if applicable)

i. Output Power

ii. Efficiency (if available)

iii. Power Factor (if available)

3.9. The field data sheet must also include the following.

a. Engine Information

i. Serial Number

ii. Make & Model

iii. Date of Manufacture

iv. Rated Power

v. Rated Speed

vi. Hours at Start of Test

b. Elevation

c. Generator/Alternator (if applicable)

i. Rated Power

ii. Rated Speed

iii. Efficiency (if available)

iv. Power Factor (if available)

d. Gear Box Ratio (if applicable)

e. Screw Compressor's Volume Index (if applicable)

3.10. Information required with the report include the following.

a. Fuel Gas Composition

b. Compressor Gas Composition(s) (if applicable)

c. Maintenance History

i. Head Maintenance (hours since last head swing)

ii. Testing issues

iii. Engine condition issues

d. Oil Make & Type

e. Hours since the last Overhaul

f. Next Scheduled Overhaul

g. Ignition Make & Model

h. Ignition Coil Type

i. Spark Plug Make & Model

j. Air Fuel Ratio (AFR) Control Make & Model

3.11. If there are any dilutions into the exhaust stream, such as crankcase vents, complete the test with the dilution system connected and one disconnected.

3.12. If the engine has an outage at any point, complete a borescope exam and compression test.

3.13. If the engine has a catalyst, complete one test upstream and one test downstream of the catalyst. Please note if the emissions measurements are pre-catalyst or post-catalyst.

3.14. Make and model of the measurement equipment used for fuel flow, load, and emissions.

3.15. Perform calibrations in accordance with the applicable method. Include the EPA protocol calibration gas certificates of analysis in the report for each gas.

3.16. Measurement results for fuel consumption, speed, load, CH_4, NO_x, and O_2 emissions.

3.17. Additional measurement data from CEMS if it is available.

3.18. Date, time, and duration of pre- and post-measurements.

3.19. The individual and company that is collecting the measurements.

3.20. The individual doing QA/QC and peer-review of measurement collection.

4. Engine Conditions

4.1. If there is an AFR controller, it must be working and in control.

4.2. When possible, determine the engine's site-rated power using OEM specifications. OEM specifications are in OEM engine calculators or engine datasheets, which specify the effect of the elevation and temperature.

Site Data

Company Name					
Facility Name					
Location (LSD or BCNTS)					
Asset Number					
Field Technician(s)					
Date of Test			Elevation at Location [ft / m]		
Engine Manufacturer			Engine Model		
Engine Serial Number			Manufacture Date		
Rated Power [HP / kW]			Rated Speed [rpm]		
Engine Driven Fan?	☐		Fan Rated Load		
Total Engine Hours			Hours Recorded From		
Jacket Water Temp [°F / °C]			Aftercooler Water [°F / °C]		
Generator Rated Power [kW]			Generator Rated Speed [rpm]		
☐ Probe in Port ☐ Shephard's Hook Probe in Stack			Sample Probe Diameter		
Upstream Port Distance			Downstream Port Distance		
Stack Diameter [in / cm]			Sample Port Location Method		
Sample Line Length [ft / m]			Gear Box Ratio		
Volume Index (Port Setting)			Economizer?	☐	
Control Panel's Make Model					
Variable Volume Control	Throw #1		Throw #3		Throw #5
Pocket (VVCP) Setting	Throw #2		Throw #4		Throw #6

Maintenance History

Hours Since Service / Tune Up	
Hours Since Head Change	
Hours Since Overhaul	
Ignition Make & Model	
Ignition Coil Type	
Spark Plug Make & Model	

AFR Control Make & Model	
Engine Oil Make & Type	
Crankcase Breather Setup	

Test Runs

	Run 1		Run 2		Run 3	
Start of Test Time						
Ambient Temperature [°F / °C]						
Atmospheric Pressure ["Hg / kPa]						
Relative Humidity [%]						
Pre-Catalyst Temperature [°F / °C]						
Post-Catalyst Temperature [°F / °C]						
Engine Speed [rpm]						
Driven Equipment Speed [rpm]						
Ignition Timing						
Load						
Generator Load [kWe / kVA]						
Generator Power Factor						
Generator Efficiency [%]						
Left Bank & RB Air Manifold Press.	LB	RB	LB	RB	LB	RB
Left Bank & RB Air Manifold Temp.	LB	RB	LB	RB	LB	RB
Left & Right Bank Cylinder 1 Temp.	LB	RB	LB	RB	LB	RB
Left & Right Bank Cylinder 2 Temp.	LB	RB	LB	RB	LB	RB
Left & Right Bank Cylinder 3 Temp.	LB	RB	LB	RB	LB	RB
Left & Right Bank Cylinder 4 Temp.	LB	RB	LB	RB	LB	RB
Left & Right Bank Cylinder 5 Temp.	LB	RB	LB	RB	LB	RB
Left & Right Bank Cylinder 6 Temp.	LB	RB	LB	RB	LB	RB
Left & Right Bank Cylinder 7 Temp.	LB	RB	LB	RB	LB	RB
Left & Right Bank Cylinder 8 Temp.	LB	RB	LB	RB	LB	RB
Left & Right Bank Fuel Pressure	LB	RB	LB	RB	LB	RB
Main Fuel Gas Press. [psi / kPa]						
Main Fuel Temperature [°F / °C]						
Fuel Gas Flow Rate						

Process Flow Rate						
Fuel Gas Meter K-factor						
Rich Rail Fuel Pressure [inHg]						
Crank Case Pressure [inH_2O]						
Exhaust Back Pressure [inH_2O]						
Stack Temperature [°F / °C]						
Air-fuel Equivalence Ratio [λ]						
Slide Valve Position						
1st Stage Suction Press. & Temp.	P	T	P	T	P	T
1st Stage Discharge Press. & Temp.	P	T	P	T	P	T
2nd Stage Suction Press. & Temp.	P	T	P	T	P	T
2nd Stage Discharge Press & Temp.	P	T	P	T	P	T
3rd Stage Suction Press. & Temp.	P	T	P	T	P	T
3rd Stage Discharge Press. & Temp.	P	T	P	T	P	T
4th Stage Suction Press. & Temp.	P	T	P	T	P	T

APPENDIX C

Test Data Summaries Under Separate Cover

Folder Name: Test Data Summaries

Table of Test Data Summaries Enclosed Under Separate Cover

Work Order #	Tas	Engine mod	Comment
100086	1	G3516 TALE	
100086	2	L5774LT	
100087	1	L5790GL	
100140	1	G3516 TALE	
100140	2	G3608 ADEM 3	
100255	1	8G825	
100256	1	G3512 ADEM 3	
100257	1	L7042GSI	
100285	1	L7042GSI	
100285	2	L7044GSI	
100294	1	G3612 ADEM 3	
100294	5	G3512 ADEM 4	
100304	1	H24GL	
100311	1	G3512 ADEM 3	
100311	2	G3516 TALE	
100339	1	F3521GSI	
100340	1	F3521GU	
100341	1	L7042GL	
100342	1	F3521GSI	
100342	2	L7042GL	
100343	1	8GTL825	
100364	1	F3521GSI	
100450	1	L7044GSI	
100451	1	G3516 TALE	
100451	2	L7042GSI	
100452	1	8G825	
100463	1	L7042GSI	
100464	1	G3512	
100493	1	G3516 TALE	
100494	1	L7042GSI	
100501	1	L7042GL	
100502	1	L5774LT	
100503	1	8GT-825	
100503	2	8G-825	
100541	1	8GTL-825	
100543	1	L7042GSI	
100544	1	L7042GSI	
100544	2	L7042GSI S5	2 tests (pre and post catalyst)
100546	1	L7042GSI	
100630	1	L7042GL	
100685	1	12VGT825	
100686	1	12SGT825	
100686	2	8G825	
100751	1	L7044GSI	
100752	1	L7044GSI	
100755	1	H24GL	
100757	1	H24GL	2 tests (pre and post CCV)
100758	1	F18GL	
100796	1	8GTL825	
100797	1	8GTL825	
100809	1	L7044GSI	
100811	1	F3521GSI	
100812	1	L7042GU	
100813	1	8G-825	

Work Order #	Tas	Engine mode	Comment
100813	1	8G-825	
100814	1	I7042GU	
100814	4	F2895GU	
100815	1	F3521GSI	
100880	1	L7044GSI	
100916	1	L7042GL	
100917	1	L7042GU	
100938	1	G3512 ADEM 3	
100939	1	L7044GSI S5	
100939	2	L7044GSI S4	
100941	1	G3612 ADEM 4	2 tests (pre and post CCV)
100941	3	G3612 ADEM 4	2 tests (pre and post CCV)
100942	1	G3608 ADEM 3	
100942	2	G3612 ADEM 4	
100942	3	L5774LT	
100965	1	H24GL	
100965	2	L7042GSI	
100966	1	G3408	
100966	2	F-18GL	
100966	3	L7042GSI	
100967	1	8GTLB	
101042	1	G3608 ADEM 3	
101108	1	F18GL	
101109	1	L5774LT	
101110	1	F18GL	2 tests (pre and post CCV)
101112	1	G3608LE	
101141	1	H24GL	
101148	1	L7044GSI	
101176	1	8G825	
101177	1	G3408TA	
101178	1	L7044GSI	
101183	1	L7042GSI	2 tests (pre and post CCV)
101187	1	8GTL825	
101247	1	L5774LT	
101277	1	8G825	2 tests (pre and post catalyst)
101281	1	G3612 A4	
101282	1	G3408TA	
101292	1	8GTLE825	
101292	2	8GTLE825	
101296	1	L7042GSI	
101298	1	G3608 ADEM 3	
101299	1	16SGT825	
101353	1	L7042GSI	
101367	1	L7042GSI	
101368	1	L5774LT	Follow-up report 100086 T2
101477	1	G3516LE	Follow-up report 100140 T1
101478	1	G3516TALE	Follow-up report 100311 T2
101480	1	L7042GSI	Follow-up report 100543 T1
101481	1	L7042GSI	Follow-up report 100544 T1
101482	1	8GT825	Follow-up report 100503 T1
101505	1	8GTLB825	Follow-up report 100967 T1
101507	1	12VGTB825	Follow-up report 100685 T2
101580	1	8G825	
101647	1	L7042GSI	2 tests (pre and post CCV)
101664	1	L7042GSI	

APPENDIX D

Sample Test Data Full Report

Petroleum Technology Alliance Canada
Emissions Test Report

Make & Model: Caterpillar G3516
Work Order Number: 100140
Task Number: Task #1
Test Date: February 15, 2023

Prepared By:

Emission Test Role	**Name**
Quality Assurance	Ethan Clark
Quality Assurance	Dexter Gette
Emission Specialist	Rob Adams
Emission Technician	

Signet Monitoring & Analysis Inc.
102 – 8026 Edgar Industrial Crescent
Red Deer, Alberta
T4P 3R3

March 22, 2023

To Whom It May Concern:

Re: Engine Exhaust Emissions Test for Petroleum Technology Alliance Canada on a Caterpillar G3516

Signet Monitoring and Analysis Inc. was requested to provide an engine exhaust emissions test and analysis for NO_x, CO, O_2, CH_4 & CO_2 emission levels on a open chamber natural gas fueled Caterpillar G3516 lean-burn engine.

The purpose of the source testing conducted on February 15, 2023, was to demonstrate the emissions generated by a Caterpillar G3516. The data from this emissions test will help develop a comprehensive benchmark for emissions generated by stationary spark-ignited engines.

Emission Intensities:

The emission levels were averaged after one 15-minute run:

Measurement	**NO_x (g/kW-hr)**	**CO (g/kW-hr)**	**O_2 (%Vol.)**	**CH_4 (g/kW-hr)**	**CO_2 (g/kW-hr)**
Emission Intensity	*10.474	2.793	7.3	2.231	701.219

Notations: These notations are in the applicable tables throughout this report.

~ The CO_2 emissions surpassed the span gas value, and the emissions were estimated using carbon-mass balance.

* The emissions surpassed the span calibration gas, so the values do not comply with the gases specified USEPA Method.

> The emissions surpassed the analyzer's sensor range which is higher than the provided value for that gas.

Testing Protocols:

The attached emissions analysis report was generated using standard CEMS equipment and methodologies as required by EPA 40 CFR 60 (A) Protocol Methods 3A, 7E, 10, 19 & 25B.

Quality Assurance:

A complete review of the raw data and calculated results in this report have been conducted by the qualified officials whose signatures appear below. After performing the review, we are confident that the test results are accurate, and the testing was conducted in accordance with the procedures stated in the methods used. For questions or clarification on any information in this report, please contact Signet Monitoring & Analysis Inc.

Mechanical QA/QC:
Name: Ethan Clark
Title: General Manager
Phone Number: (403) 348-5251
Email: ethan.clark@signetma.com

Emissions QA/QC:
Name: Dexter Gette
Title: Emissions Engineer | EIT
Phone Number: (587) 876-4306
Email: dexter.gette@signetma.com

Environment and Climate Change Canada
Multi-Sector Air Pollutants Regulations
Emissions Check Report

Test Performed By:	Signet Monitoring & Analysis Inc.
Make & Model:	Caterpillar G3516
Emission Test Date:	February 15, 2023
Date of Report:	March 22, 2023

Table of Contents

Supporting Data

1. Introduction

The purpose of the emissions test on Caterpillar G3516 was to satisfy the requirements for an Emissions Test as set out by Petroleum Technology Alliance Canada. The total engine operating hours at the start of the testing was: 62518 hours as seen on the control panel.

One 15-minute duration emissions test run was performed to measure NO_x, CO, O_2, CH_4 & CO_2 stack exhaust concentrations and exhaust flow rates according to methodologies detailed in EPA 40 CFR 60 (A) Protocol Methods 3A, 7E, 10, 19 & 25B. Each of the test runs consisted of readings taken every 15 seconds.

1.1 Source Test Contractor

Test Contractor:	**Signet Monitoring & Analysis Inc.**
Address:	102 – 8026 Edgar Industrial Crescent Red Deer, Alberta T4P 3R3
Contact:	Ethan Clark
Phone:	(403) 348-5251
Fax:	(403) 348-5653
Email:	ethan.clark@signetma.com
Website:	http://www.signetma.com

Surveyed By: Signet Monitoring & Analysis Inc.

Personnel:

Emission Test Role	Name	Phone
Quality Assurance	Ethan Clark	(403) 348-5251
Quality Assurance	Dexter Gette	(587) 876-4306
Emission Specialist	Rob Adams	(403) 318-3952
Emission Technician		

2. Methods & Calculations

All EPA test methods used are listed below. The test method procedures are publicly available at www.ecfr.gov.

Method	Title	Compound	Description
USEPA 40 CFR 60 (A) Method 3A	Determination of Oxygen and Carbon Dioxide Concentrations in Emissions From Stationary Sources (Instrumental Analyzer Procedure)	O_2	Method 3A is a procedure for measuring oxygen (O_2) and carbon dioxide (CO_2) in stationary source emissions using a continuous instrumental analyzer.
USEPA 40 CFR 60 (A) Method 7E	Determination of Nitrogen Oxides Emissions From Stationary Sources (Instrumental Analyzer Procedure)	NO_x	Method 7E is a procedure for measuring nitrogen oxides (NO_x) in stationary source emissions using a continuous instrumental analyzer.
USEPA 40 CFR 60 (A) Method 10	Determination of Carbon Monoxide Emissions From Stationary Sources (Instrumental Analyzer Procedure)	CO	Method 10 is a procedure for measuring carbon monoxide (CO) in stationary source emissions using a continuous instrumental analyzer.
USEPA 40 CFR 60 (A) Method 19	Determination of Sulfur Dioxide Removal Efficiency and Particulate Matter, Sulfur Dioxide, and Nitrogen Oxide Emission Rates	Exhaust Flow	The data is correlated with the fuel gas composition and the measured exhaust gas Oxygen content to arrive at the overall exhaust effluent flow.
USEPA 40 CFR 60 (A) Method 25B	Determination of Total Gaseous Organic Concentration Using a Nondispersive Infrared Analyzer	CH_4	Method 25B is a procedure for measuring methane (CH_4) in stationary source emissions using a continuous instrumental analyzer.

2.1 Equipment Used

The following equipment was used in mobile emission testing Unit 221 for the emission test. Some equipment not mentioned in this list include a laptop, EPA Traceability Protocol© Calibration Gases, valves, regulators, and PTFE & stainless tubing.

Equipment	Make	Model	Serial Number	Specifications
Analyzer	Horiba	VA-5123	RV8MRHD8	Sensor Ranges: NO_x: 0-5,000 ppm CO: 0-10,000 ppm O_2: 0-25%
Analyzer	Horiba	VA-5111	W04UE3WE	Sensor Ranges: CH_4: 0-1% CO_2: 0-10%
Sampling Unit	Horiba	VS-5004	1C6K7FN3	
Flow Control Drawer	PermaPure	3300	N/A	
Gas Cooler	Perfect Sample Gas	MAK 6-2	N/A	
Diaphragm Pump	Thomas Pumps	107CAB	N/A	
Heated Sample Line	Clayborn Lab	50 ft	N/A	
Data Logger	Campbell Scientific	CR1000X	N/A	

2.2 Software Used

- Signet's Emission Processing Software
- Campbell Scientific's Real-Time Monitoring & Control Software
- Caterpillar's Gas Engine Rating Pro Web Version 2
- Cooper's PowerFlow™ Compressor Sizing Tool Version 1.17

3. Emission Test Results Summary

Please refer to the supporting data for listings of all raw data, calibration errors, system biases & drifts and calculations performed.

Test Run	NO_x (g/kW-hr)	CO (g/kW-hr)	O_2 (%Vol.)	CH_4 (g/kW-hr)	CO_2 (g/kW-hr)
1	*10.474	2.793	7.3	2.231	701.219

4. Engine Conditions During Testing

Please refer to the supporting data for listings of all the collected data and calculations.

Test Run	Test Period (hh:mm)	Speed (rpm)	Output (kW)	Load (%)	Stack Flow (dsm^3/s)
1	10:34-10:49	1,054	581	81.8	0.692

5. Stack Sampling Location

The sampling point location was in accordance with EPA Method 1. It was measured to determine it met the minimum of 2 diameters downstream and 1/2 of a diameter upstream of any flow disturbance. A 1/2" stainless-steel sampling probe was inserted into the center of the stack to extract the exhaust gases.

5.1 Sample Port Location

Probe Placement	Upstream Distance (inch)	Downstream Distance (inch)	Stack Diameter (inch)
Probe in Port	20	18	8

6. Quality Assurance

Analyzer pre- and post-calibration error checks, system leak checks and device conditions conformed to the requirements specified in EPA 40 CFR 60 (A) Methods 3A, 7E, 10, 19 & 25B.

7. Testing Protocol NO_2 Conversion

The attached emissions analysis reports were generated using standard CEMS equipment and methodologies as required by EPA 40 CFR 60 (A) Protocol Methods 7E. The NO_2 to NO Conversion Efficiency Test was performed to show that the converter catalyst was running with an efficiency greater than 90%.

Date of Test	NO_2 Calibration Gas	NO_x Analyzer Reading	Catalyst Efficiency
September 23, 2022	55.3 (±0.9) ppm	52.2 ppm	94.4%

8. Engine Brake Power Estimation Method

For the test, Cooper's PowerFlow software was used, to determine the driven load. Which is used to find the engine's driver load based on the recorded engine and compressor data during each emissions test run. The data for this can be found at the end of the supporting data section. Values for brake specific fuel consumption (BSFC) were estimated using the engine's data sheet from Caterpillar's GERP Web software, for the Caterpillar G3516 at the recorded operating conditions.

9. Engine Condition Notes

The engine was running rich for the tested load conditions.

The cylinder head high frequency vibration shows that there are early exhaust valve closure events on cylinders 4 and 5.
Early intake valve closures on 7 and 9. This indicates a slightly loose valve set.

SIGNET Monitoring & Analysis Inc.

Test Summary

Source: Caterpillar G3516
Site Rated BSFC (LHV): 7615 Btu/bhp-hr
Site Rated Power: 1085 HP
Site Rated Speed: 1200 rpm

Fuel Specifications			
Lower Heating Value	40.69 MJ/sm³	Lower Heating Value	1092.1 BTU/scf
Higher Heating Value	44.93 MJ/sm³	Higher Heating Value	1205.8 BTU/scf
Molecular Weight	19.720 kg/kg mol	Specific Gravity	0.6828
Gas Density	0.8350 kg/sm³	Gas Density	0.052130 lb/scf
EPA Fw Factor	316.9 sm³/GJ	EPA Fw Factor	10606 scf/MMBtu
EPA Fd Factor	259.5 sm³/GJ	EPA Fd Factor	8685 scf/MMBtu
Operating Parameters	**Unit**	**Run 1**	**Average**
Run Duration	Minutes	15	15
Ambient Air Temperature	°C	-4.4	-4.4
Barometric Station Pressure	kPa	88.69	88.69
Relative Humidity	%	48.6	48.6
Fuel Volumetric Flow Rate	sm³/s	0.043	0.043
Fuel Mass Flow Rate	kg/hr	129.63	129.63
Speed	rpm	1054	1054
Suction Pressure	kPa	274	274
Discharge Pressure	kPa	7119.0	7119.0
Load	kW	581	581
Load	bhp	779.4	779.4
Load	%	81.8	81.8
Available Power (Derated)	kW	711	711
Available Power (Derated)	bhp	953	953
BSFC (Based on LHV)	MJ/kWh	10.87	10.87
BSFC (Based on LHV)	Btu/bhp-hr	7681	7681
Dry Stack Flow Rate (EPA M19)	dscf/min	1466.3	1466.3
Dry Stack Flow Rate (EPA M19)	dsm³/s	0.692	0.692
Exhaust Gas Data			
H_2O (EPA M19)	Vol%	12.88	12.88
Oxygen (O_2)	Vol%	7.3	7.3
Nitrogen Oxides (NO_x)	ppmvd	*1258.3	*1258.3
	$ppmvd_{15\%O_2}$	*544.3	*544.3
	g/kW-hr	*10.47	*10.47
	tonnes/yr	*53.325	*53.325
Carbon Monoxide (CO)	ppmvd	551.1	551.1
	$ppmvd_{15\%O_2}$	238.4	238.4
	g/kW-hr	2.79	2.79
	tonnes/yr	14.220	14.220
Methane (CH_4)	ppmvd	768.7	768.7
	$ppmvd_{15\%O_2}$	332.5	332.5
	g/kW-hr	2.23	2.23
	tonnes/yr	11.360	11.360
Carbon Dioxide (CO_2)	ppmvd	79111	79111
	$ppmvd_{15\%O_2}$	34224	34224
	g/kW-hr	701.22	701.22
	tonnes/yr	3570.113	3570.1

SIGNET Monitoring & Analysis Inc.

Test Run
Minute Averages

Source: Caterpillar G3516 **Date**: 15/Feb/2023

Run 1

Date	Time	O_2 (%)	NO_x (ppmvd)	CO (ppmvd)	CO_2 (ppmvd)	CH_4 (ppmvd)
15/Feb/2023	10:34:45	6.59	2210.8	548.3	82939.6	715.0
15/Feb/2023	10:35:45	7.40	1164.5	545.9	79035.8	762.5
15/Feb/2023	10:36:45	7.84	563.9	527.7	75513.8	800.2
15/Feb/2023	10:37:45	7.32	1036.7	555.7	77700.9	762.4
15/Feb/2023	10:38:45	6.37	2464.8	548.7	83597.6	714.0
15/Feb/2023	10:39:45	6.43	2596.3	543.1	84662.6	717.8
15/Feb/2023	10:40:45	7.32	1182.8	556.0	79316.3	755.6
15/Feb/2023	10:41:45	7.65	741.8	544.5	76842.7	781.7
15/Feb/2023	10:42:45	7.40	1003.3	559.1	78221.1	758.6
15/Feb/2023	10:43:45	7.46	955.3	554.8	78026.9	762.1
15/Feb/2023	10:44:45	7.52	890.0	550.8	77692.7	763.5
15/Feb/2023	10:45:45	7.63	750.6	545.2	76913.2	774.4
15/Feb/2023	10:46:45	7.29	1100.0	559.8	78555.3	751.0
15/Feb/2023	10:47:45	7.20	1285.8	558.9	79557.1	742.4
15/Feb/2023	10:48:45	7.45	966.3	552.9	78070.0	761.8
Averages:	**15 min**	**7.26**	**1260.8**	**550.1**	**79109.7**	**754.9**

9

SIGNET Monitoring & Analysis Inc.

Calculation of Average Emissions

Source: Caterpillar G3516

Date: 15/Feb/2023

Gas Type	Calibration Gas Value	Initial Response	Final Response	Average
Zero O_2	0.00 %	0.00 %	0.02 %	0.01 %
Span O_2	19.13 %	19.16 %	19.06 %	19.11 %
Zero NO_x	0.0 ppm	0.2 ppm	1.7 ppm	0.94 ppm
Span NO_x	825.0 ppm	833.0 ppm	821.0 ppm	827.00 ppm
Zero CO_2	0.0 ppm	-11.0 ppm	19.8 ppm	4.37 ppm
Span CO_2	94,500 ppm	94,775 ppm	94,221 ppm	94,498 ppm
Zero CO	0.2 ppm	0.0 ppm	1.5 ppm	0.74 ppm
Span CO	1,206.0 ppm	1,203.7 ppm	1,202.6 ppm	1,203.1 ppm
Zero CH_4	0.0 ppm	-10.6 ppm	-22.2 ppm	-16.38 ppm
Span CH_4	2,979.0 ppm	2,979.9 ppm	2,965.2 ppm	2,972.5 ppm

Run 1

Gas	Emissions	Corrected	Emissions Based On O_2	
O_2	7.26 %	**7.26 %**		
NO_x	*1261 ppm	***1258 ppm**	***2.030 Lbs/mmBtu**	**13.42**
CO_2	79,109.7 ppm	**79,110.9 ppm**	**122.1 Lbs/mmBtu**	**807.16**
CO	550.1 ppm	**551.1 ppm**	**0.5414 Lbs/mmBtu**	**3.58**
CH_4	754.9 ppm	**768.7 ppm**	**0.4325 Lbs/mmBtu**	**2.86**

Bwa: 0.24% *Bws: 12.88%* *Fuel Flow: 91.367 scfm* *ISO Factor: 1.0869*

SIGNET Monitoring & Analysis Inc.

Calibration Tests

Source: Caterpillar G3516

Date: 15/Feb/2023

Analyzer Make & Model: HORIBA VA-5123 — **Serial Number: RV8MRHD8**

Gas Type	Cylinder Number	Test Method	Cylinder Gas Value	Direct Response	Direct Difference	Direct Calibration Error	System Initial Response	System Final Response	System Average Response	System Initial Bias	System Final Bias	System Total Drift
Zero O_2	EB0126458	Method 3A	0.00 %	0.00 %	0.00 %	0.01 %	0.00 %	0.02 %	0.01 %	0.01 %	0.10 %	0.09 %
Mid O_2	EB0001457	Method 3A	9.51 %	9.46 %	0.05 %	0.26 %	N/A	N/A	N/A	N/A	N/A	N/A
Span O_2	CC725988	Method 3A	19.13 %	19.14 %	0.01 %	0.05 %	19.16 %	19.06 %	19.11 %	0.10 %	-0.42 %	0.52 %
Zero NO_x	EB0126458	Method 7E	0.0 ppm	-0.2 ppm	0.2 ppm	0.03 %	0.2 ppm	1.7 ppm	0.94 ppm	0.05 %	0.23 %	0.18 %
Mid NO_x	CC279691	Method 7E	397.0 ppm	399.7 ppm	2.7 ppm	0.33 %	N/A	N/A	N/A	N/A	N/A	N/A
Span NO_x	CC169908	Method 7E	825.0 ppm	826.0 ppm	1.0 ppm	0.12 %	833.0 ppm	821.0 ppm	827.00 ppm	0.85 %	-0.61 %	1.45 %
Zero CO	EB0126458	Method 10	0.2 ppm	-0.5 ppm	0.7 ppm	0.06 %	0.0 ppm	1.5 ppm	0.74 ppm	0.04 %	0.17 %	0.12 %
Mid CO	CC279691	Method 10	607.0 ppm	623.2 ppm	16.2 ppm	1.34 %	N/A	N/A	N/A	N/A	N/A	N/A
Span CO	CC169908	Method 10	1,206.0 ppm	1,206.7 ppm	0.7 ppm	0.06 %	1,203.7 ppm	1,202.6 ppm	1,203.1 ppm	-0.25 %	-0.35 %	0.10 %

Analyzer Make & Model: HORIBA VA-5111 — **Serial Number: W04UE3WE**

Gas Type	Cylinder Number	Test Method	Cylinder Gas Value	Direct Response	Direct Difference	Calibration Error	System Initial Response	System Final Response	System Average Response	System Initial Bias	System Final Bias	System Total Drift
Zero CO_2	EB0126458	Method 3A	0.0 ppm	-27 ppm	27 ppm	0.03 %	-11.0 ppm	19.8 ppm	4.37 ppm	0.02 %	0.05 %	0.03 %
Mid CO_2	CC726061	Method 3A	47,300 ppm	46,389 ppm	911 ppm	0.96 %	N/A	N/A	N/A	N/A	N/A	N/A
Span CO_2	CC726085	Method 3A	94,500 ppm	94,549 ppm	49 ppm	0.05 %	94,775 ppm	94,221 ppm	94,498 ppm	0.24 %	-0.35 %	0.59 %
Zero CH_4	EB0126458	Method 25B	0.0 ppm	-4.1 ppm	4.1 ppm	N/A	-10.6 ppm	-22.2 ppm	-16.4 ppm	N/A	N/A	0.39 %
Low CH_4	CC279691	Method 25B	912.0 ppm	928.8 ppm	16.8 ppm	0.50 %	925.1 ppm	914.9 ppm	920.0 ppm	N/A	N/A	N/A
Mid CH_4	CC726061	Method 25B	1,451.0 ppm	1,484.8 ppm	33.8 ppm	1.16 %	1,488.8 ppm	1,474.2 ppm	1,481.5 ppm	N/A	N/A	0.49 %
High CH_4	CC169908	Method 25B	2,555.0 ppm	2,587.2 ppm	32.2 ppm	N/A	2,579.5 ppm	2,567.9 ppm	2,573.7 ppm	N/A	N/A	N/A
Span CH_4	CC726085	Method 25B	2,979.0 ppm	2,980.5 ppm	1.5 ppm	N/A	2,979.9 ppm	2,965.2 ppm	2,972.5 ppm	N/A	N/A	N/A

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SIGNET Monitoring & Analysis Inc.

Fuel Gas Analysis

Source: Caterpillar G3516

Date: 15/Feb/2023

Gas Analysis Per EPA M19 and ASTM D3588-98

Compound	Mole [%]	Norm. Mole [%]	x_j	$H^{id}_{m,j}$ [Btu/lbmol]	$H^{id}_{v,j}$ [Btu/ft^3]	M_j [lb/lbmol]	G^{id}_j	b_{ji} [psia^{-1}]	$x_j H^{id}_{m,j}$ [Btu/lbmol]	$x_j H^{id}_{v,j}$ [Btu/ft^3]	$x_j G^{id}_j$	$x_j b_j$ [psia^{-1}]
Hydrogen	0.0000	0.0000	0.00000	61022	324	0.00	0.070	0.0000	0.0	0.0	0.000	0.00000
Nitrogen	0.3500	0.3500	0.00350	0	0	0.10	0.967	0.0044	0.0	0.0	0.003	0.00002
Carbon Dioxide	0.0000	0.0000	0.00000	0	0	0.00	1.520	0.0197	0.0	0.0	0.000	0.00000
Methane	83.5500	83.5500	0.83550	23891	1010	13.40	0.554	0.0116	16238.8	843.9	0.463	0.00969
Ethane	10.1200	10.1200	0.10120	22333	1770	3.04	1.038	0.0239	3446.3	179.1	0.105	0.00242
Propane	3.6800	3.6800	0.03680	21653	2516	1.62	1.523	0.0344	1781.8	92.6	0.056	0.00127
i-Butane	0.5200	0.5200	0.00520	21232	3252	0.30	2.007	0.0458	325.4	16.9	0.010	0.00024
n-Butane	0.8200	0.8200	0.00820	21300	3262	0.48	2.007	0.0478	514.8	26.8	0.016	0.00039
i-Pentane	0.2400	0.2400	0.00240	21044	4001	0.17	2.491	0.0581	184.8	9.6	0.006	0.00014
n-Pentane	0.2300	0.2300	0.00230	21085	4009	0.17	2.491	0.0631	177.4	9.2	0.006	0.00015
n-Hexane	0.1900	0.1900	0.00190	20943	4756	0.16	2.976	0.0776	173.9	9.0	0.006	0.00015
Hexanes +	0.2900	0.2900	0.00290	20899	5129	0.27	3.218	0.0864	286.4	14.9	0.009	0.00025
Helium	0.0100	0.0100	0.00010	0	0	0.00	0.138	0.0000	0.0	0.0	0.000	0.00000
Total	**100.0000**	**100.0000**	**1.0000**			**19.72**			**23129.7**	**1201.9**	**0.681**	**0.01470**

b = Summation Factor
$_{da}$ = Dry Air
$_{dg}$ = Dry Gas
G = Molar Mass Ratio
H = Gross Heating Value
^{id} = Ideal Gas Value
j = property for component j
M = Molar Mass
$_m$ = per unit Mass
ρ = Density
$_{sa}$ = Saturated Air
$_{sg}$ = Saturated Gas
$_v$ = per unit Volume
x = Mole Fraction
Z = Compresibility

Z_{dg} = 0.9968
Z_{da} = 0.9996
$G_{dg,da}$ = 0.6828
$G_{dg,sa}$ = 0.6827
$H_v{}^{id}{}_{sg,da}$ = 1181.0 Btu/ft³
$G^{id}{}_{sg}$ = 0.6799
Z_{sg} = 0.9965
Z_{sa} = 0.9995
$G_{sg,da}$ = 0.6820
$G_{sg,sa}$ = 0.6819
$(H_v{}^{id}/Z)_{dg,da}$ = 1205.8 Btu/ft³
$(H_v{}^{id}/Z)_{sg,da}$ = 1185.2 Btu/ft³
ρ^{id} = 0.05196 lb/ft³
ρ = 0.05213 lb/ft³

Ultimate Fuel Analysis

Element	Mass Ratio
Carbon	76.5%
Hydrogen	23.0%
Oxygen	0.0%
Nitrogen	0.5%
Sulfur	0.0%
Total	**100.0%**

Total Carbon = 1.2557
Total Hydrogen = 4.5041
VOC = 34.68%

EPA Method 19 Constants

K_c = 1.53 scf·%/lb
K_{hd} = 3.64 scf·%/lb
K_o = 0.46 scf·%/lb
K_n = 0.14 scf·%/lb
K_s = 0.57 scf·%/lb
K_{hw} = 5.57 scf·%/lb
K_{cc} = 0.32 scf·%/lb
K = 1.0E+6 Btu/MMBtu
F_d = 8685 dscf/MMBtu
F_w = 10606 wscf/MMBtu
F_c = 1061 scf/MMBtu

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SIGNET Monitoring & Analysis Inc.

Exhaust Moisture

Source: Caterpillar G3516

Determination of Exhaust Moisture Content Per EPA M19 and ASTM D3588

	Stoichiometric Coefficients						Run 1 Exhaust Moles			
Compound	**C_xH_y**	**O_2**	**CO_2**	**H_2O**	**N_2**	**Stoich.**	**Excess O_2**	**H_2O**	**ExO_2***	**Actual Exhaust**
Methane	1	2.0	1	2	7.46	10.46	0.35	0.03	14.95	14.98
Ethane	1	3.5	2	3	13.05	18.05	0.35	0.06	26.04	26.10
Propane	1	5.0	3	4	18.64	25.64	0.35	0.09	37.13	37.22
I-Butane	1	6.5	4	5	24.24	33.24	0.35	0.11	48.22	48.34
N-Butane	1	6.5	4	5	24.24	33.24	0.35	0.11	48.22	48.34
I-Pentane	1	8.0	5	6	29.83	40.83	0.35	0.14	59.31	59.45
N-Pentane	1	8.0	5	6	29.83	40.83	0.35	0.14	59.31	59.45
Hexane	1	9.5	6	7	35.42	48.42	0.35	0.17	70.40	70.57
Hexane +	1	10.3	6.5	7.5	38.22	52.22	0.35	0.18	75.95	76.13
Heptane	1	11.0	7	8	41.02	56.02	0.35	0.20	81.50	81.69
Octane	1	12.5	8	9	46.61	63.61	0.35	0.22	92.59	92.81
Total Fuel Carbon Balance	**1**	**2.382**	**1.256**	**2.252**	**8.881**	**12.388**	**0.345**	**0.041**	**17.767**	**17.808**

*ExO_2 = Exhaust Considering Excess O_2

Constituent	Run 1
n^g_W, moles H_2O in Fuel	0.01775
n^a_W, moles H_2O in Air (B_{WA})	0.00243
n^v_W, moles H_2O in Products of Combustion	2.2521
n^l_W, moles H_2O that Actually Condense	0.0202
Stack Gas Moisture Content (B_{WS})	12.88%
Dry Combustion Products (moles)	15.515

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SIGNET Monitoring & Analysis Inc.

ISO Factors

Source: Caterpillar G3516 **Date**: 15/Feb/2023

Measurement		Run 1
Date of Run		15/Feb/2023
Start Time		10:34:45
Stop Time		10:49:45
Load		779.4 bhp
Ambient Temperature		24.1 °F -4.4 °C 268.8 K
Ambient Pressure		665.2 mmHg 26.19 inHg 88.69 kPa
Relative Humidity		48.6 %
Specific Humidity*		0.0014467 g/g
Combustor Correction Factor		1.0689
Humidity Correction Factor		0.9114
Temperature Correction Factor		1.1157
ISO Standard Correction Factor		1.0869
Water Vapor over Water	Water	6.091100
	Pvap Water	214.786009
	Rho Water	0.001732
	Dry Air Water	1.146718
	MW, Air, Wet	28.935988
	Air Pressure	88689.951
	Specific, Water	0.001510
	Vp Water	0.063426
Water Vapor over Ice	Ice	6.048358
	Pvap Ice	205.799135
	Rho Ice	0.001659
	Dry Air Ice	1.146834
	MW, Air, Wet	28.937098
	Specific, Ice	0.001447
	Vp Ice	0.060772

*Mass ratio of water to air

Specific Humidity Constants

C-1: -5.67454E+3	C-9: 1.39150E+0
C-2: 6.39252E+0	C-10: -48.64024E-3
C-3: -9.67784E-3	C-11: 41.76477E-6
C-4: 622.15701E-9	C-12: -14.45209E-9
C-5: 2.07478E-9	C-13: 6.54597E+0
C-6: -948.40240E-15	MW Air: 28.96250E+0
C-7: 4.16350E+0	MW Water: 18.01530E+0
C-8: -5.80022E+3	

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Fuel Gas
Lower Heating Value

Source: Caterpillar G3516

Date: 15/Feb/2023

Input Parameters

ρ, Gas Density = 0.052130 lb/scf
HHV, Higher Heating Value = 1205.8 Btu/scf
$H_2M\%$, Hydrogen Mass Percent = 0.2302%

H_2mol, Hydrogen Molar Mass = 2.02 lb/mol
H_2Omol, Water Molar Mass = 18.02 lb/mol
ΔHvap, H_2O Heat of Vaporization = 1059.9 Btu/lb
Reference Temperature = 15.6°C

Calculations for Fuel Gas

Variable	Description	Formula	Result
E	Energy with H_2O for 1lb of gas	$\frac{HHV}{\rho}$	23130.03 Btu
$H_2M\%$	Mass of H_2 for 1lb of gas	$1\text{lb} \times H_2M\%$	0.23 lb
$H_2mol\%$	mol of H_2 for 1lb of gas	$\frac{H_2M\%}{H_2mol}$	0.11 mol
$H_2Omol\%$	mol of H_2O for 1lb of gas	$H_2mol\% \times \frac{1\ mol\ H_2O}{1\ mol\ H_2}$	0.11 mol
$H_2OM\%$	Mass of H_2O for 1lb of gas	$H_2Omol \times H_2Omol\%$	2.06 lb
E_{H_2O}	Energy of water	$H_2OM\% \times \Delta Hvap$	2180.87 Btu
$E_{w/o\ H_2O}$	Energy w/o water	$E - E_{H_2O}$	20949.16 Btu
LHV	Lower Heating Value	$E_{H_2O} \times \rho$	1092.08 Btu/scf

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SIGNET Monitoring & Analysis Inc.

Humidity

Source: Caterpillar G3516 **Date**: 15/Feb/2023

Constants and Conversion Factors

Md, Molecular Mass of Dry Air = 28.965	A = 6.116441	1 lb = 7000 grains
Mw, Molecular Mass of Water = 18.015	C = 2.16679 kg/J	1 mmHg = 1.3332 hPa
Tc, Critical Temperature = 647.096 K	m = 7.591386	1 psi = 68.9476 hPa
Pc, Critical Pressure = 220640 hPa	T_n = 240.7263	

Calculations

Variable	Description	Formula	Run 1
T	Ambient Temperature	N/A	- 4.4 °C
P_b	Barometric Pressure	N/A	886.90 hPa
RH	Relative Humidity	N/A	48.6 %
M_g	Molecular Mass of Dry Gas	EPA Method 3	29.6 g/g-mol
T_d	Dew Point	$\frac{T_n}{\left[\frac{m}{^{10}\log\left(\frac{P_w}{A}\right)} - 1\right]}$	- 13.589 °C
B	Water Vapor per Dry Gas Mass	$\frac{M_w}{M_g} \times 7000$	4267 grains/lb
P_{ws}	Saturation Vapor Pressure	$A \times 10^{\left(\frac{m \times T}{T+T_n}\right)}$	4.42 hPa
P_w	Vapor Pressure	$P_{WS}(T) \times RH \div 100$	2.15 hPa
A	Absolute Humidity	$C \times P_W/T$	1.73 g/m³
X	Mixing Ratio	$\frac{B \times P_W}{P_{tot} - P_W}$	10.4 grains/lb
PPM_{vd}	Volume per Volume Dry	$\frac{P_w}{P_{tot} - P_w} 10^6$	2430
PPM_{md}	Mass per Mass Dry	$\frac{M_w P_w 10^6}{M_d(P_{tot} - P_w)}$	1481
PPM_{vw}	Volume per Volume Wet	$\frac{P_w}{P_{tot}} 10^6$	2424
PPM_{mw}	Mass per Mass Wet	$\frac{M_w P_w}{M_d P_{tot}} 10^6$	1477

Fuel Flow & BSFC Estimation

Source: Caterpillar G3516

Date: 15/Feb/2023

OEM Engine LHV BSFC Ratings [a]

Parameter	Load	LHV BSFC (btu/bhp-hr)
BSFC 100%	100%	7615
BSFC 75%	75%	7706
BSFC 50%	50%	8283

[a] Engine manufacturers report fuel-related specifications at 60°F and 14.696psi

Corrected LHV BSFC [b]

Parameter	Load	LHV BSFC (btu/bhp-hr)[a]
BSFC 100%	100%	7615
BSFC 75%	75%	7706
BSFC 50%	50%	8283

[b] Reference Conditions: 15.6°C & 101.325kPa

Engine Parameters

Rated Speed (rpm)	1200
Site Rated Power (HP)	1085
LHV (BTU/scf)	1092.08
Run Time (min)	15.00

Test Run	RPM	Run Time (min)	Load
1	1054	15	82%

Test Run	Derated Power (hp)	Calculated Power (bhp)	BSFC LHV (Btu/bhp-hr)
1	953	779	7681

Test Run	Energy Flow (Btu/hr)	Run Time (hr)	Total Energy (Btu)
1	5986809	0.25	1496702

Test Run	Gas Consumed (scf)	Fuel Gas Flow (scfm)
1	1370.5	**91.367**

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HORIBA

TEST REPORT

1. Specificatons

Model	VA-5123	Power requirement	115Vac @ 60Hz
HGS.No.	RV8MRHD8	Analog Output	4-20mA

Component	Measurement range			Range(Standard/Option)	Bench HGS No.	Cell length
1. O_2	0	~ 5/10/20/25	vol%	Standard	3C7LN8E0	-
2. CO	0	~ 500/1000/5000/10000	ppm	Standard	S8F8EN54	50mm
3. NO_x	0	~ 500/1000/2500/5000	ppm	Standard	TYW1L073	-
4. -	-	~ -	ppm	-	-	-

2. Inspection Results

1) Appearance and construction ... OK
2) Function and Operation ... OK
3) Leakage ... OK

4) Linearity ... OK
Criteria: Within +/- 1.0%FS (Range ratio over 10 times to 20 times: within +/- 2.0%FS)

Component	Minimum range				Maximum range			
	Error(%FS)		Test Range		Error(%FS)		Test Range	
1 O_2	-0.8	%FS	5	vol%	0.8	%FS	25	vol%
2 CO	-0.3	%FS	500	ppm	0.1	%FS	10000	ppm
3 NO_x	-0.7	%FS	500	ppm	-0.2	%FS	5000	ppm
4 -	-	-	-	-	-	-	-	-

5) Repeatability ... OK
Criteria: Within +/- 0.5%FS (SO_2 50 ppm range, CLA NOx less than 100ppm range : within +/- 1.0%FS)

Component	Span gas conc.		Gas mode	1st.	2nd.	3rd.	Average	Max.deviation	
1. O_2	5	vol%	ZERO	0.006	0.008	0.006	0.007	0.0	%FS
			SPAN	4.967	4.983	4.982	4.977	0.2	%FS
2. CO	500	ppm	ZERO	0.8	0.3	0.1	0.4	0.1	%FS
			SPAN	500.4	501.0	500.3	500.6	0.1	%FS
3. NO_x	484	ppm	ZERO	0.3	0.3	0.3	0.3	0.0	%FS
			SPAN	484.1	484.2	485.0	484.4	0.1	%FS
4. -	-		-	-	-	-	-	-	-
			-	-	-	-	-	-	-

6) Noise ... OK
Criteria: Within 1.0%FS (peak to peak) / 3min
[SO_2 50 ppm range, CLA NOx less than 100ppm range : within 2.0%FS(peak to peak)]

Component	Zero Noise				Span Noise			
1 O_2	0.014	vol%	0.3	%FS	0.017	vol%	0.3	%FS
2 CO	0.9	ppm	0.2	%FS	2.3	ppm	0.5	%FS
3 NO_x	0.1	ppm	0.0	%FS	0.6	ppm	0.1	%FS
4 -	-	-	-	-	-	-	-	-

7) Analog output ... OK
Criteria: Within +/- 0.02 mA or +/- 0.01V

Output scale		0%			100%		
CH	Assignment	Actual(mA)	Error(%FS)		Actual(mA)	Error(%FS)	
CH01	O_2	4.00	0.0	%FS	20.00	0.0	%FS
CH02	CO	4.00	0.0	%FS	20.00	0.0	%FS
CH03	NO_x	4.00	0.0	%FS	20.00	0.0	%FS
CH04	-	-	-	-	-	-	-

8) Response time (T_{90}) ... OK
Criteria: T_{90} is less than 30 sec

Component	Gas conc.		T_{90}(sec)
1. O_2	5	vol%	16
2. CO	500	ppm	21
3. NO_x	484	ppm	20
4. -	-	-	-

9) Interference of coexisting gas ... OK
Criteria: Refer to below criteria

Component	H_2O(5 deg.C Saturated)				CO_2(15vol%)				C3H8(1000ppm)				CO2 + NO(15vol% + 100ppm)			
	Reading		Criteria		Reading		Criteria		Reading		Criteria		Reading		Criteria	
1 O_2	-0.3	%FS	+/- 1.0	%FS	-0.4	%FS	+/- 1.0	%FS	0.4	%FS	+/- 1.0	%FS	-	-	-	-
2 CO	-0.2	%FS	+/- 2.0	%FS	-0.6	%FS	+/- 2.0	%FS	1.0	%FS	+/- 2.0	%FS	-	-	-	-
3 NO_x	-	-	-	-	-	-	-	-	-	-	-	-	2.0	%FS	+/- 3.0	%FS
4 -	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

10) Accessories check ... OK

Date: 2020/12/04 Tested by John Thompson Approved by Kcji Ishikawa

HORIBA

VA-5000 TEST REPORT

1. Specifications

Model	VA-5111	Power requirement	AC-100V-240V
HGS.No.	W04UE3WE	Output Signal	4-20mA
HGS.Date	July 12, 2022		

Component	Measurement range			Range(Standard/Option)	Bench HGS No.
1. CO_2	0 ~	5/10	vol%	Standard	UP2MSC73
2. CH_4	0 ~	1	vol%	Standard	P4EP1M5K
3. N_2O	0 ~	1000	ppm	Standard	FAVBXKH0
4. -	- ~	-	ppm	-	-

2. Inspection Results

1) Appearance and construction .... OK
2) Function and Operation .... OK
3) Leakage .... OK

4) Linearity .... OK

Criteria: Within +/- 1.0%FS (Range ratio over 10 times to 20 times: within +/- 2.0%FS)

Component	Minimum range				Maximum range			
	Error(%FS)		Test Range		Error(%FS)		Test Range	
1 CO_2	0.3	%FS	5.000	vol%	0.0	%FS	10.00	vol%
2 CH_4	-0.2	%FS	1.000	vol%	-	%FS	-	vol%
3 N_2O	-0.6	%FS	1000	ppm	-	%FS	-	ppm
4 -	-	%FS	-	ppm	-	%FS	-	ppm

5) Repeatability .... OK

Calibration range: CO_2 5 vol% | CH_4 1 vol% | N_2O 1000 ppm | - - ppm

Criteria: Within +/- 0.5%FS (SO2 50 ppm range, CLA NOx less than 100ppm range : within +/- 1.0%FS)

Component	Span gas conc.		Gas mode	1st.	2nd.	3rd.	Average	Max.deviation	
1. CO_2	5.000	vol%	ZERO	0.000	0.001	0.001	0.001	-0.1	%FS
			SPAN	5.000	4.996	4.996	4.997	0.1	%FS
2. CH_4	1.000	vol%	ZERO	0.000	0.003	0.003	0.002	-0.2	%FS
			SPAN	1.000	1.003	1.000	1.001	-0.1	%FS
3. N_2O	1000	ppm	ZERO	0	0	0	0	0.0	%FS
			SPAN	1000	998	1001	1000	-0.2	%FS
4. -	-	ppm	ZERO	-	-	-	-	-	%FS
			SPAN	-	-	-	-	-	%FS

6) Noise .... OK

Criteria: Within 1.0%FS (peak to peak) / 3min
[SO_2 50 ppm range, CLA NOx less than 100ppm range : within 2.0%FS(peak to peak)]

Component	Zero Noise				Span Noise			
1 CO_2	0.001	vol%	0.1	%FS	0.010	vol%	0.2	%FS
2 CH_4	0.002	vol%	0.2	%FS	0.002	vol%	0.2	%FS
3 N_2O	0	ppm	0.0	%FS	3	ppm	0.3	%FS
4 -	-	ppm	-	%FS	-	ppm	-	%FS

7) Analog output .... OK

Criteria: Within +/- 0.02 mA or +/- 0.01V

Output scale		0%			100%		
CH	Assignment	Actual(mA)	Error(%FS)		Actual(mA)	Error(%FS)	
CH01	CO_2	4.00	0.0	%FS	20.00	0.0	%FS
CH02	CH_4	4.00	0.0	%FS	20.00	0.0	%FS
CH03	N_2O	4.00	0.0	%FS	20.00	0.0	%FS
CH04	-	-	-	%FS	-	-	%FS

8) Response time (T_{90}) .... OK

Criteria: T_{90} is less than 30 sec

Component	Gas conc.		T_{90}(sec)
1. CO_2	5.000	vol%	17
2. CH_4	1.000	vol%	20
3. N_2O	1000	ppm	19
4. -	-	ppm	-

9) Interference acjustment check .... OK

Criteria: Refer to below criteria

Component	H_2O(5 deg.C Saturated)				CO_2(15vol%)				C_3H_8(1000ppm)				CO(1000ppm)			
	Reading		Criteria		Reading		Criteria		Reading		Criteria		Reading		Criteria	
CO_2	0.2	%	2.0	FS%	-	%	-	FS%	0.1	%	2.0	FS%	0.1	%	1.0	FS%
CH_4	0.1	%	1.0	FS%	1.0	%	2.0	FS%	-	%	-	FS%	0.7	%	1.0	FS%
N_2O	0.0	%	2.0	FS%	0.0	%	2.0	FS%	-	%	-	FS%	-0.1	%	2.0	FS%
-	-	%	-	FS%	-	%	-	FS%	-	%	-	FS%	-	%	-	FS%

10) Accessories check .... OK

Date: 2022/7/12 Tested by Jun Taya Approved by Kcji Ishikawa

Rev.A Doc.No.: QLTY-T-03-001

Making our world more productive

Linde Canada Inc.
9501 - 34th Street
Edmonton, AB T6B 2X6
Tel: 780-449-0778
Fax: 780-449-5302

Customer & Order Information:

LINDE PKG RED DEER AB HS
#4 7730 EDGAR INDUSTRIAL COURT,
RED DEER, AB T4P 4E3

Linde Order Number: **72253943**
Customer PO Number: **80259723**

Certificate Issuance Date: **10/31/2022**

Certification Date: **10/28/2022**
Lot Number: **206230033**
Part Number: **NI 5.5CE-AS**
DocNumber: **624323**
Expiration Date: **12/31/2027**

CERTIFICATE OF ANALYSIS

Nitrogen, 5.5 Continuous Emission Monitoring Zero

Analytes	Specification	Analytical Results	Analytical Reference	Analytical Uncertainty
Carbon Dioxide	**≤ 1 ppm**	**< 1 ppm**	**2**	**± 15 % rel**
Carbon Monoxide	**≤ 0.5 ppm**	**0.2 ppm**	**2**	**± 15 % rel**
Total Hydrocarbons	**≤ 0.1 ppm**	**< 0.1 ppm**	**1**	**± 0.1 ppm**
Oxides of Nitrogen	**≤ 0.1 ppm**	**< 0.001 ppm**	**5**	**± 0.01 ppm**
Oxygen	**≤ 0.5 ppm**	**0.4 ppm**	**3**	**± 0.5 ppm**
Sulfur Dioxide	**≤ 0.1 ppm**	**0.0006 ppm**	**6**	**± 0.01 ppm**
Water	**≤ 2 ppm**	**1.0 ppm**	**3**	**± 0.5 ppm**
Nitrogen	**≥ 99.9995 %**	**> 99.9995 %**	**4**	**N/A**

Cylinder Style: **AS**
Cylinder Pressure @ 21 C: **13,790 kPa**
Cylinder Volume: **4.01 M3**
Valve Outlet Connection: **CGA 580**
Cylinder Number(s): **EB0110176, CC139842, CC79011, CC413953**
Analyzed Cylinder Number(s): **EB0126458**

Fill Date: **10/27/2022**
Analysis Date: **10/28/2022**

Filling Method: **Pressure/Temperature**
Source Lot#: **N2062299**

QA Reviewer: **Alex Auty**

Key to Analytical Techniques:

Reference	Analytical Instrument - Analytical Principle
1	Beckman 400A - FID Total Hydrocarbon Analyzer
2	Horiba VIA 510 - NDIR
3	Meeco Gemini - Electrolytic Cell/Electrochemical
4	N/A - By Difference of Typical Impurities
5	TFS iQ Series 42 - Chemiluminescence
6	TFS iQ Series 43 - Emission Spectroscopy

This analysis of the product described herein was prepared by Linde Canada Inc. using instruments whose calibration is certified using Linde Canada Inc. Reference Materials which are traceable to the International System of Units (SI) through either weights traceable to the National Institute of Standards and Technology (NIST) or Measurement Canada, or through NIST Standard Reference Materials or equivalent where available.

Note: All expressions for concentration (e.g., % or ppm) are for gas phase, by mole unless otherwise noted. Analytical uncertainty is expressed as Absolute unless otherwise noted.

PRAXAIR
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DocNumber: 411562

Praxair Distribution, Inc.
5700 S. Alameda Street
Los Angeles CA 90058
Tel: 323-585-2154
Fax: 714-542-6689
PGVP ID: F22021

CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

Customer & Order Information

LINDE PKG RED DEER AB HS
#4 7730 EDGAR INDUSTRIAL COURT
RED DEER AB T4P 4E3

Certificate Issuance Date: 06/04/2021
Praxair Order Number: 71892352
Part Number: NI OX9.5E-AS
Customer PO Number: 79890311

Fill Date: 05/19/2021
Lot Number: 70086113902
Cylinder Style & Outlet: AS CGA 590
Cylinder Pressure and Volume: 2000 psig 140 ft3

Certified Concentration

Expiration Date:	06/03/2029	NIST Traceable
Cylinder Number:	EB0001457	Expanded Uncertainty
9.51 %	Oxygen	± 0.04 %
Balance	Nitrogen	

ProSpec EZ Cert

Certification Information: *Certification Date:* 06/03/2021 *Term:* 96 Months *Expiration Date:* 06/03/2029

This cylinder was certified according to the 2012 EPA Traceability Protocol, Document #EPA-600/R-12/531, using Procedure G1. Uncertainty above is expressed as absolute expanded uncertainty at a level of confidence of approximately 95% with a coverage factor k = 2. Do Not Use this Standard if Pressure is less than 100 PSIG.

Analytical Data: *(R=Reference Standard, Z=Zero Gas, C=Gas Candidate)*

1. *Component:* Oxygen

Requested Concentration: 9.5 %
Certified Concentration: 9.51 %
Instrument Used: Siemens Oxymat 6E S/N 7MB20211AA000CA1
Analytical Method: Paramagnetic
Last Multipoint Calibration: 05/14/2021

Reference Standard: Type / Cylinder #: NTRM / DT0010262
Concentration / Uncertainty: 9.875 % ±0.040 %
Expiration Date: 11/18/2022
Traceable to: SRM # / Sample # / Cylinder #: NTRM / 170701 / DT0010262
SRM Concentration / Uncertainty: 9.875% / ±0.040%
SRM Expiration Date: 11/18/2022

First Analysis Data: Date 06/03/2021

Z: 0	R: 9.88	C: 9.51	Conc: 9.5
R: 9.88	Z: 0	C: 9.5	Conc: 9.49
Z: 0	C: 9.53	R: 9.89	Conc: 9.52

UOM: % Mean Test Assay: 9.51 %

Second Analysis Data: Date

Z: 0	R: 0	C: 0	Conc: 0
R: 0	Z: 0	C: 0	Conc: 0
Z: 0	C: 0	R: 0	Conc: 0

UOM: % Mean Test Assay: %

Analyzed By Jose Vasquez Certified By Amalia Real

Linde — Making our world more productive

DocNumber: 491254

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PGVP ID: F22022

CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

Customer & Order Information

LINDE PKG RED DEER AB HS
#4 7730 EDGAR INDUSTRIAL COURT
RED DEER AB T4P 4E3

Certificate Issuance Date: 08/18/2022
Linde Order Number: 72120919
Part Number: NI OX19E-AS
Customer PO Number: 80124930

Fill Date: 08/08/2022
Lot Number: 70086222005
Cylinder Style & Outlet: AS CGA 590
Cylinder Pressure and Volume: 2000 psig 140 ft3

Certified Concentration

Expiration Date:	08/16/2030	NIST Traceable
Cylinder Number:	CC725988	Expanded Uncertainty
19.13 %	Oxygen	± 0.06 %
Balance	Nitrogen	

ProSpec EZ Cert

Certification Information:

Certification Date: 08/16/2022 *Term:* 96 Months *Expiration Date:* 08/16/2030

This cylinder was certified according to the 2012 EPA Traceability Protocol, Document #EPA-600/R-12/531, using Procedure G1. Uncertainty above is expressed as absolute expanded uncertainty at a level of confidence of approximately 95% with a coverage factor k = 2. Do Not Use this Standard if Pressure is less than 100 PSIG.

Analytical Data:

(R=Reference Standard, Z=Zero Gas, C=Gas Candidate)

1. *Component:* Oxygen

Requested Concentration: 19 %
Certified Concentration: 19.13 %
Instrument Used: Siemens Oxymat 6E S/N 7MB20211AA000CA1
Analytical Method: Paramagnetic
Last Multipoint Calibration: 07/18/2022

Reference Standard: Type / Cylinder #: GMIS / ND29287
Concentration / Uncertainty: 20.90 % ±0.02 %
Expiration Date: 09/01/2028
Traceable to: SRM # / Sample # / Cylinder #: SRM 2659a / 71-E-19 / FF22331
SRM Concentration / Uncertainty: 20.863% / ±0.021%
SRM Expiration Date: 08/23/2021

First Analysis Data:							Date	08/16/2022
Z:	0	R:	20.9	C:	19.17		Conc:	19.18
R:	20.88	Z:	0	C:	19.03		Conc:	19.04
Z:	0	C:	19.18	R:	20.9		Conc:	19.19
UOM:	%					Mean Test Assay:	19.13	%

Second Analysis Data:							Date	
Z:	0	R:	0	C:	0		Conc:	0
R:	0	Z:	0	C:	0		Conc:	0
Z:	0	C:	0	R:	0		Conc:	0
UOM:	%					Mean Test Assay:		%

Analyzed By: Courtney Zielke

Certified By: Henry Koung

Linde — Making our world more productive

DocNumber: 502436

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PGVP ID: F12022

CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

Customer & Order Information

LINDE PKG EDMONTON PLT 80206
5501 34TH ST
EDMONTON AB T6B 2X6

Certificate Issuance Date: 09/09/2022
Linde Order Number: 76559916
Part Number: NI CO600MN1E-AS

Fill Date: 08/18/2022
Lot Number: 700012230WE
Cylinder Style & Outlet: AS CGA 660
Cylinder Pressure and Volume: 2000 psig 140 ft3

Certified Concentration

Expiration Date:	09/09/2030	NIST Traceable
Cylinder Number:	CC279691	Expanded Uncertainty
607 ppm	Carbon monoxide	± 2 ppm
397 ppm	Nitric oxide	± 1 ppm
912 ppm	Methane	± 2 ppm
Balance	Nitrogen	

ProSpec EZ Cert

For Reference Only: NOx 400 ppm

Certification Information: Certification Date: 09/09/2022 Term: 96 Months Expiration Date: 09/09/2030

This cylinder was certified according to the 2012 EPA Traceability Protocol, Document #EPA-600/R-12/531, using Procedure G1. Uncertainty above is expressed as absolute expanded uncertainty at a level of confidence of approximately 95% with a coverage factor k = 2. Do Not Use this Standard if Pressure is less than 100 PSIG.

Analytical Data: *(R=Reference Standard, Z=Zero Gas, C=Gas Candidate)*

1. *Component:* Carbon monoxide

Requested Concentration: 600 ppm
Certified Concentration: 607 ppm
Instrument Used: Horiba VA-3000
Analytical Method: NDIR
Last Multipoint Calibration: 08/25/2022

Reference Standard: Type / Cylinder #: GMIS / ND24313
Concentration / Uncertainty: 1000 ppm ±3 ppm
Expiration Date: 02/01/2029
Traceable to: SRM # / Sample # / Cylinder #: 1681b / 1-K-42 / CAL015913
SRM Concentration / Uncertainty: 983.5 / ±3.0 PPM
SRM Expiration Date: 09/26/2021

First Analysis Data:						Date	09/02/2022
Z:	0	R:	1000	C:	607	Conc:	607
R:	1000	Z:	0	C:	607	Conc:	607
Z:	0	C:	607	R:	1000	Conc:	607
UOM:	ppm			Mean Test Assay:		607	ppm

Second Analysis Data:						Date	
Z:	0	R:	0	C:	0	Conc:	0
R:	0	Z:	0	C:	0	Conc:	0
Z:	0	C:	0	R:	0	Conc:	0
UOM:	ppm			Mean Test Assay:			ppm

2. *Component:* Nitric oxide

Requested Concentration: 400 ppm
Certified Concentration: 397 ppm
Instrument Used: Thermo-42i HL
Analytical Method: Chemiluminescence
Last Multipoint Calibration: 08/10/2022

Reference Standard: Type / Cylinder #: GMIS / XN017259B
Concentration / Uncertainty: 509 ppm ±1 ppm
Expiration Date: 03/27/2028
Traceable to: SRM # / Sample # / Cylinder #: 1687b / 41-L-20 / FF6081
SRM Concentration / Uncertainty: 985.3 ppm / ±2.1 ppm
SRM Expiration Date: 05/01/2020

First Analysis Data:						Date	09/02/2022
Z:	0	R:	509	C:	397	Conc:	397
R:	509	Z:	0	C:	397	Conc:	397
Z:	0	C:	396	R:	509	Conc:	396
UOM:	ppm			Mean Test Assay:		397	ppm

Second Analysis Data:						Date	09/09/2022
Z:	0	R:	509	C:	397	Conc:	397
R:	509	Z:	0	C:	397	Conc:	397
Z:	0	C:	399	R:	509	Conc:	399
UOM:	ppm			Mean Test Assay:		398	ppm

3. *Component:* Methane

Requested Concentration: 900 ppm
Certified Concentration: 912 ppm
Instrument Used: MKS 2031
Analytical Method: FTIR
Last Multipoint Calibration: 08/10/2022

Reference Standard: Type / Cylinder #: GMIS / DT0016021
Concentration / Uncertainty: 997 ppm ±2 ppm
Expiration Date: 04/03/2025
Traceable to: SRM # / Sample # / Cylinder #: RGM / N/A / CC364721
SRM Concentration / Uncertainty: 4965.6 PPM / ±9 PPM
SRM Expiration Date: 07/09/2021

First Analysis Data:						Date	09/02/2022
Z:	0	R:	997	C:	912	Conc:	912
R:	997	Z:	0	C:	911	Conc:	911
Z:	0	C:	912	R:	997	Conc:	912
UOM:	ppm			Mean Test Assay:		912	ppm

Second Analysis Data:						Date	
Z:	0	R:	0	C:	0	Conc:	0
R:	0	Z:	0	C:	0	Conc:	0
Z:	0	C:	0	R:	0	Conc:	0
UOM:	ppm			Mean Test Assay:			ppm

Analyzed By: Lloyd Knapp   Certified By: Edward E Zucal

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PGVP ID: F12022

DocNumber: 502483

CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

Customer & Order Information

LINDE PKG EDMONTON PLT 80206
5501 34TH ST
EDMONTON AB T6B 2X6

Certificate Issuance Date: 09/09/2022
Linde Order Number: 76559549
Part Number: NI CO.12MN1E-AS

Fill Date: 08/18/2022
Lot Number: 70001223OD2
Cylinder Style & Outlet: AS CGA 660
Cylinder Pressure and Volume: 2000 psig 140 ft3

Certified Concentration

Expiration Date:	09/09/2030	NIST Traceable
Cylinder Number:	CC169908	Expanded Uncertainty
2555 ppm	Methane	± 6 ppm
1206 ppm	Carbon monoxide	± 10 ppm
825 ppm	Nitric oxide	± 2 ppm
Balance	Nitrogen	

ProSpec EZ Cert

For Reference Only: NOx 831 ppm

Certification Information: Certification Date: 09/09/2022 Term: 96 Months Expiration Date: 09/09/2030

This cylinder was certified according to the 2012 EPA Traceability Protocol, Document #EPA-600/R-12/531, using Procedure G1. Uncertainty above is expressed as absolute expanded uncertainty at a level of confidence of approximately 95% with a coverage factor k = 2. Do Not Use this Standard if Pressure is less than 100 PSIG.

Analytical Data:

(R=Reference Standard, Z=Zero Gas, C=Gas Candidate)

1. Component: Methane

Requested Concentration: 2550 ppm
Certified Concentration: 2555 ppm
Instrument Used: MKS 2031
Analytical Method: FTIR
Last Multipoint Calibration: 08/09/2022

Reference Standard: Type / Cylinder #: GMIS / CC19172
Concentration / Uncertainty: 2522 ppm ±5 ppm
Expiration Date: 04/03/2025
Traceable to: SRM # / Sample # / Cylinder #: RGM / N/A / CC364721
SRM Concentration / Uncertainty: 4965.6 PPM / ±9 PPM
SRM Expiration Date: 07/09/2021

First Analysis Data:						Date	08/02/2022
Z:	0	R:	2224	C:	2253	Conc:	2555
R:	2224	Z:	0	C:	2253	Conc:	2555
Z:	0	C:	2253	R:	2224	Conc:	2555
UOM:	ppm			Mean Test Assay:		2555	ppm

Second Analysis Data:						Date	
Z:	0	R:	0	C:	0	Conc:	0
R:	0	Z:	0	C:	0	Conc:	0
Z:	0	C:	0	R:	0	Conc:	0
UOM:	ppm			Mean Test Assay:			ppm

2. Component: Carbon monoxide

Requested Concentration: 1200 ppm
Certified Concentration: 1206 ppm
Instrument Used: Horiba VA-3000
Analytical Method: NDIR
Last Multipoint Calibration: 08/25/2022

Reference Standard: Type / Cylinder #: GMIS / CC139535
Concentration / Uncertainty: 2526 ppm ±9 ppm
Expiration Date: 11/17/2025
Traceable to: SRM # / Sample # / Cylinder #: 2637a / 56-F-36 / CAL017141
SRM Concentration / Uncertainty: 2438 ppm / ± 5.1 ppm
SRM Expiration Date: 07/07/2022

First Analysis Data:						Date	09/02/2022
Z:	0	R:	2526	C:	1205	Conc:	1205
R:	2526	Z:	0	C:	1206	Conc:	1206
Z:	0	C:	1206	R:	2526	Conc:	1206
UOM:	ppm			Mean Test Assay:		1206	ppm

Second Analysis Data:						Date	
Z:	0	R:	0	C:	0	Conc:	0
R:	0	Z:	0	C:	0	Conc:	0
Z:	0	C:	0	R:	0	Conc:	0
UOM:	ppm			Mean Test Assay:			ppm

3. Component: Nitric oxide

Requested Concentration: 800 ppm
Certified Concentration: 825 ppm
Instrument Used: MKS 2031
Analytical Method: FTIR
Last Multipoint Calibration: 08/16/2022

Reference Standard: Type / Cylinder #: GMIS / EB0100672
Concentration / Uncertainty: 1028 ppm ±3 ppm
Expiration Date: 03/27/2028
Traceable to: SRM # / Sample # / Cylinder #: 1687b / 41-L-20 / FF6081
SRM Concentration / Uncertainty: 985 ppm / ±2.1 ppm
SRM Expiration Date: 05/01/2020

First Analysis Data:						Date	09/02/2022
Z:	0	R:	744	C:	597	Conc:	825
R:	744	Z:	0	C:	597	Conc:	825
Z:	0	C:	597	R:	744	Conc:	825
UOM:	ppm			Mean Test Assay:		825	ppm

Second Analysis Data:						Date	09/09/2022
Z:	0	R:	748	C:	600	Conc:	825
R:	748	Z:	0	C:	600	Conc:	825
Z:	0	C:	600	R:	748	Conc:	825
UOM:	ppm			Mean Test Assay:		825	ppm

Analyzed By: Lloyd Knapp

Certified By: Edward E Zucal

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DocNumber: 491048

Linde Gas & Equipment Inc.
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Fax: +1 (419) 729-2411
PGVP ID: F12022

CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

Customer & Order Information

LINDE PKG EDMONTON PLT 80206
5501 34TH ST
EDMONTON AB T6B 2X6

Certificate Issuance Date: 08/17/2022
Linde Order Number: 76474576
Part Number: NI CD4.75M1E-AS

Fill Date: 08/01/2022
Lot Number: 700012213UD
Cylinder Style & Outlet: AS CGA 350
Cylinder Pressure and Volume: 2000 psig 149 ft3

Certified Concentration

Expiration Date:	08/17/2030	NIST Traceable
Cylinder Number:	CC726061	Expanded Uncertainty
4.73 %	**Carbon dioxide**	**± 0.03 %**
1451 ppm	**Methane**	**± 7 ppm**
Balance	Nitrogen	

ProSpec EZ Cert

Certification Information: *Certification Date:* 08/17/2022 *Term:* 96 Months *Expiration Date:* 08/17/2030

This cylinder was certified according to the 2012 EPA Traceability Protocol, Document #EPA-600/R-12/531, using Procedure G1. Uncertainty above is expressed as absolute expanded uncertainty at a level of confidence of approximately 95% with a coverage factor k = 2. Do Not Use this Standard if Pressure is less than 100 PSIG.

Analytical Data:

(R=Reference Standard, Z=Zero Gas, C=Gas Candidate)

1. *Component:* Carbon dioxide

Requested Concentration: 4.75 %
Certified Concentration: 4.73 %
Instrument Used: Horiba VA-5000
Analytical Method: NDIR
Last Multipoint Calibration: 07/25/2022

Reference Standard: Type / Cylinder #: GMIS / ND3256
Concentration / Uncertainty: 6.59 % ±0.01 %
Expiration Date: 02/02/2029
Traceable to: SRM # / Sample # / Cylinder #: 1674b / 7-I-43 / FF58462
SRM Concentration / Uncertainty: 6.944% / ±0.013%
SRM Expiration Date: 01/12/2026

First Analysis Data:						Date	08/17/2022
Z:	0	R:	6.59	C:	4.73	Conc:	4.73
R:	6.6	Z:	0	C:	4.73	Conc:	4.73
Z:	0	C:	4.73	R:	6.6	Conc:	4.73
UOM:	%			Mean Test Assay:		4.73	%

Second Analysis Data:						Date	
Z:	0	R:	0	C:	0	Conc:	0
R:	0	Z:	0	C:	0	Conc:	0
Z:	0	C:	0	R:	0	Conc:	0
UOM:	%			Mean Test Assay:			%

2. *Component:* Methane

Requested Concentration: 1500 ppm
Certified Concentration: 1451 ppm
Instrument Used: MKS 2030
Analytical Method: FTIR
Last Multipoint Calibration: 08/05/2022

Reference Standard: Type / Cylinder #: GMIS / EB0044808
Concentration / Uncertainty: 2521 ppm ±5 ppm
Expiration Date: 04/03/2025
Traceable to: SRM # / Sample # / Cylinder #: RGM / N/A / CC364721
SRM Concentration / Uncertainty: 4965.6 PPM / ±9 PPM
SRM Expiration Date: 07/09/2021

First Analysis Data:						Date	08/17/2022
Z:	-3.8	R:	2676	C:	1543	Conc:	1453
R:	2687	Z:	1.09	C:	1542	Conc:	1452
Z:	-2.4	C:	1536	R:	2672	Conc:	1446
UOM:	ppm			Mean Test Assay:		1451	ppm

Second Analysis Data:						Date	
Z:	0	R:	0	C:	0	Conc:	0
R:	0	Z:	0	C:	0	Conc:	0
Z:	0	C:	0	R:	0	Conc:	0
UOM:	ppm			Mean Test Assay:			ppm

Analyzed By: Mike Monnette

Certified By: Edward E Zucal

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DocNumber: 491129

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PGVP ID: F12022

CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

Customer & Order Information

LINDE PKG EDMONTON PLT 80206
5501 34TH ST
EDMONTON AB T6B 2X6

Certificate Issuance Date: 08/18/2022
Linde Order Number: 76474697
Part Number: NI CD9.5M2E-AS

Fill Date: 08/01/2022
Lot Number: 70001221 3UA
Cylinder Style & Outlet: AS CGA 350
Cylinder Pressure and Volume: 2000 psig 149 ft3

Certified Concentration

Expiration Date:	08/18/2030	NIST Traceable
Cylinder Number:	CC726085	Expanded Uncertainty
9.45 %	Carbon dioxide	± 0.06 %
2979 ppm	Methane	± 7 ppm
Balance	Nitrogen	

ProSpec EZ Cert

Certification Information: Certification Date: 08/18/2022 Term: 96 Months Expiration Date: 08/18/2030

This cylinder was certified according to the 2012 EPA Traceability Protocol, Document #EPA-600/R-12/531, using Procedure G1. Uncertainty above is expressed as absolute expanded uncertainty at a level of confidence of approximately 95% with a coverage factor k = 2. Do Not Use this Standard if Pressure is less than 100 PSIG.

Analytical Data: (R=Reference Standard, Z=Zero Gas, C=Gas Candidate)

1. Component: Carbon dioxide

Requested Concentration: 9.50 %
Certified Concentration: 9.45 %
Instrument Used: Horiba VA-5000
Analytical Method: NDIR
Last Multipoint Calibration: 07/25/2022

Reference Standard: Type / Cylinder #: PRM / DT0032694
Concentration / Uncertainty: 19.99 % ±0.04 %
Expiration Date: 01/02/2028
Traceable to: SRM # / Sample # / Cylinder #: PRM#FF276163 / PRM#FF276163 / FF276163
SRM Concentration / Uncertainty: 20.008% / ± 0.028%
SRM Expiration Date: 04/01/2020

First Analysis Data:						Date	08/18/2022
Z:	0	R:	19.99	C:	9.45	Conc:	9.45
R:	19.99	Z:	0	C:	9.45	Conc:	9.45
Z:	0	C:	9.45	R:	20	Conc:	9.45
UOM:	%			Mean Test Assay:		9.45	%

Second Analysis Data:						Date	
Z:	0	R:	0	C:	0	Conc:	0
R:	0	Z:	0	C:	0	Conc:	0
Z:	0	C:	0	R:	0	Conc:	0
UOM:	%			Mean Test Assay:			%

2. Component: Methane

Requested Concentration: 3000 ppm
Certified Concentration: 2979 ppm
Instrument Used: MKS 2030
Analytical Method: FTIR
Last Multipoint Calibration: 08/05/2022

Reference Standard: Type / Cylinder #: GMIS / DT0016090
Concentration / Uncertainty: 5052 ppm ±10 ppm
Expiration Date: 04/03/2025
Traceable to: SRM # / Sample # / Cylinder #: RGM / N/A / CC364721
SRM Concentration / Uncertainty: 4965.6 PPM / ±9 PPM
SRM Expiration Date: 07/09/2021

First Analysis Data:						Date	08/18/2022
Z:	0	R:	5385	C:	3171	Conc:	2974
R:	5384	Z:	0	C:	3180	Conc:	2982
Z:	0	C:	3179	R:	5391	Conc:	2981
UOM:	ppm			Mean Test Assay:		2979	ppm

Second Analysis Data:						Date	
Z:	0	R:	0	C:	0	Conc:	0
R:	0	Z:	0	C:	0	Conc:	0
Z:	0	C:	0	R:	0	Conc:	0
UOM:	ppm			Mean Test Assay:			ppm

Analyzed By Mike Monnette

Certified By Edward E Zucal

Making our world more productive

DocNumber: 464761

Linde Gas & Equipment Inc.
5700 S. Alameda Street
Los Angeles CA 90058
Tel: 323-585-2154
Fax: 714-542-6689
PGVP ID: F22022

CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

Customer & Order Information

LINDE PKG GRAND PRAIRIE AB HS
11530 97TH AVE UNIT 100
GRAND PRAIRIE AB T8V 6R8

Certificate Issuance Date: 05/23/2022
Linde Order Number: 71970886
Part Number: NI NX55MO4E-AS
Customer PO Number: 79972883

Fill Date: 05/11/2022
Lot Number: 70086213106
Cylinder Style & Outlet: AS CGA 660
Cylinder Pressure and Volume: 2000 psig 140 ft3

Certified Concentration

Expiration Date:	05/23/2023	NIST Traceable
Cylinder Number:	CC2839	Expanded Uncertainty
55.3 ppm	Nitrogen dioxide (as NOx)	± 0.9 ppm
3.64 %	Oxygen	± 0.02 %
Balance	Nitrogen	

ProSpec EZ Cert

Certification Information: Certification Date: 05/23/2022 Term: 12 Months Expiration Date: 05/23/2023

This cylinder was certified according to the 2012 EPA Traceability Protocol, Document #EPA-600/R-12/531, using Procedure G1. Uncertainty above is expressed as absolute expanded uncertainty at a level of confidence of approximately 95% with a coverage factor k = 2. Do Not Use this Standard if Pressure is less than 100 PSIG.

Analytical Data:

(R=Reference Standard, Z=Zero Gas, C=Gas Candidate)

1. Component: Nitrogen dioxide (as NOx)

Requested Concentration: 55 ppm
Certified Concentration: 55.3 ppm
Instrument Used: MKS 2 MultiGas 2031 FTIR
Analytical Method: FTIR
Last Multipoint Calibration: 04/27/2022

Reference Standard: Type / Cylinder #: GMIS / GN0009586
Concentration / Uncertainty: 51.45 ppm ±0.82 ppm
Expiration Date: 06/07/2022
Traceable to: SRM # / Sample # / Cylinder #: C1901910.02 / PRM/ D685026
SRM Concentration / Uncertainty: 50.0 ppm / ±0.5 ppm
SRM Expiration Date: 10/16/2021

First Analysis Data: Date 05/16/2022

Z: 0	R: 51.3	C: 55.2	Conc: 55.3
R: 51.5	Z: 0	C: 55.5	Conc: 55.6
Z: 0	C: 55.4	R: 51.4	Conc: 55.5

UOM: ppm Mean Test Assay: 55.4 ppm

Second Analysis Data: Date 05/23/2022

Z: 0	R: 51.7	C: 55.4	Conc: 55.3
R: 51.4	Z: 0	C: 55.1	Conc: 55
Z: 0	C: 55.2	R: 51.5	Conc: 55.1

UOM: ppm Mean Test Assay: 55.1 ppm

2. Component: Oxygen

Requested Concentration: 3.6 %
Certified Concentration: 3.64 %
Instrument Used: Siemens Oxymat 6E S/N 7MB20211AA000CA1
Analytical Method: Paramagnetic
Last Multipoint Calibration: 05/11/2022

Reference Standard: Type / Cylinder #: GMIS / CC163512
Concentration / Uncertainty: 4.97 % ±0.02 %
Expiration Date: 07/17/2029
Traceable to: SRM # / Sample # / Cylinder #: SRM 2658a / 72-D-28 / CAL016862
SRM Concentration / Uncertainty: 9.918% / ±0.022%
SRM Expiration Date: 02/03/2024

First Analysis Data: Date 05/16/2022

Z: 0	R: 4.97	C: 3.64	Conc: 3.64
R: 4.97	Z: 0	C: 3.65	Conc: 3.65
Z: 0	C: 3.65	R: 4.98	Conc: 3.65

UOM: % Mean Test Assay: 3.64 %

Second Analysis Data: Date

Z: 0	R: 0	C: 0	Conc: 0
R: 0	Z: 0	C: 0	Conc: 0
Z: 0	C: 0	R: 0	Conc: 0

UOM: % Mean Test Assay: %

Analyzed By Henry Koung

Certified By Lissette Morales

SIGNET Monitoring & Analysis

PTAC Emissions Field Data Sheet: Engine

Site Data

Company Name	WO 100140		
Facility Name	Task 1		
Location (LSD or BCNTS)			
Asset Number			
Field Technician(s)	Rob Adams,		
Date of Test	Feb 15 2023	Elevation at Location [ft / m]	3647'
Engine Manufacturer	Catepillar	Engine Model	G3512
Engine Serial Number		Manufacture Date	
Rated Power [HP / kW]	1085	Rated Speed [rpm]	1200
Engine Driven Fan?	☒	Fan Rated Load	43
Total Engine Hours	62518	Hours Recorded From	Panel.
Jacket Water Temp [°F / °C]		Aftercooler Water [°F / °C]	
Generator Rated Power [kW]		Generator Rated Speed [rpm]	
☒ Probe in Port ☐ Shephard's Hook Probe in Stack		Sample Probe Diameter	1/2"
Upstream Port Distance	20"	Downstream Port Distance	18"
Stack Diameter [in / cm]	8"	Sample Port Location Method	Method 1
Sample Line Length [ft / m]	50'	Gear Box Ratio	
Volume Index (Port Setting)		Economizer?	☐
Control Panel's Make Model			

Variable Volume Control	Throw #1	2"	Throw #3	1.75"	Throw #5	
Pocket (VVCP) Setting	Throw #2	0"	Throw #4	0"	Throw #6	

Maintenance History

Hours Since Service / Tune Up	
Hours Since Head Change	30842 hrs
Hours Since Overhaul	62518 hrs.
Ignition Make & Model	Caterpillar
Ignition Coil Type	Caterpillar Transformer
Spark Plug Make & Model	Champion 5B 77 WPCC
AFR Control Make & Model	N/A
Engine Oil Make & Type	Petro Can LP3000
Crankcase Breather Setup	Stock Breathers on valve Covers piped to stack Tip with a venturi

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SIGNET Monitoring & Analysis

PTAC Emissions Field Data Sheet: Engine

Test Runs

	Run 1		Run 2		Run 3	
Start of Test Time	10:341					
Ambient Temperature [°F / °C]	21°F					
Atmospheric Pressure ["Hg / kPa]	26.19"Hg					
Relative Humidity [%]	52%					
Pre-Catalyst Temperature [°F / °C]						
Post-Catalyst Temperature [°F / °C]						
Engine Speed [rpm]	1054					
Driven Equipment Speed [rpm]						
Ignition Timing						
Load						
Generator Load [kWe / kVA]						
Generator Power Factor						
Generator Efficiency [%]						
Left Bank & RB Air Manifold Press.	LB 24"Hg	RB	LB	RB	LB	RB
Left Bank & RB Air Manifold Temp.	LB 34°C	RB	LB	RB	LB	RB
Left & Right Bank Cylinder 1 Temp.	LB 580	RB 583	LB	RB	LB	RB
Left & Right Bank Cylinder 2 Temp.	LB 554	RB 473	LB	RB	LB	RB
Left & Right Bank Cylinder 3 Temp.	LB 578	RB 580	LB	RB	LB	RB
Left & Right Bank Cylinder 4 Temp.	LB 577	RB 566	LB	RB	LB	RB
Left & Right Bank Cylinder 5 Temp.	LB 578	RB 574	LB	RB	LB	RB
Left & Right Bank Cylinder 6 Temp.	LB 558	RB 558	LB	RB	LB	RB
Left & Right Bank Cylinder 7 Temp.	LB 568	RB 568	LB	RB	LB	RB
Left & Right Bank Cylinder 8 Temp.	LB 579	RB 562	LB	RB	LB	RB
Left & Right Bank Fuel Pressure	LB 4"H_2O	RB	LB	RB	LB	RB
Main Fuel Gas Press. [psi / kPa]	220 kpa					
Main Fuel Temperature [°F / °C]						
Fuel Gas Flow Rate						
Process Flow Rate						
Fuel Gas Meter K-factor						
Rich Rail Fuel Pressure [inHg]						
Crank Case Pressure [inH_2O]						
Exhaust Back Pressure [inH_2O]	-1"H_2O					
Stack Temperature [°F / °C]	1"H_2O					
Air-fuel Equivalence Ratio [λ]						
Slide Valve Position						
1st Stage Suction Press. & Temp.	P 274 kpa	T 8°C	P	T	P	T
1st Stage Discharge Press. & Temp.	P 964 kpa	T 90/90°C	P	T	P	T
2nd Stage Suction Press. & Temp.	P	T 32°C	P	T	P	T
2nd Stage Discharge Press & Temp.	P 2425 kpa	T 99°C	P	T	P	T
3rd Stage Suction Press. & Temp.	P	T 29°C	P	T	P	T
3rd Stage Discharge Press. & Temp.	P 7119 kpa	T 107°C	P	T	P	T
4th Stage Suction Press. & Temp.	P	T	P	T	P	T
4th Stage Discharge Press. & Temp.	P	T	P	T	P	T

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G3516
NON-CURRENT

GAS ENGINE SITE SPECIFIC TECHNICAL DATA

CATERPILLAR®

GAS COMPRESSION APPLICATION

ENGINE SPEED (rpm):	1200	RATING STRATEGY:	STANDARD
COMPRESSION RATIO:	8	RATING LEVEL:	CONTINUOUS
AFTERCOOLER TYPE:	SCAC	FUEL SYSTEM:	HPG IMPCO
AFTERCOOLER WATER INLET (°F):	130	**SITE CONDITIONS:**	
JACKET WATER OUTLET (°F):	210	FUEL:	
ASPIRATION:	TA	FUEL PRESSURE RANGE(psig): (See note 1)	35.0-40.0
COOLING SYSTEM:	JW+OC, AC	FUEL METHANE NUMBER:	58.4
CONTROL SYSTEM:	EIS	FUEL LHV (Btu/scf):	1093
EXHAUST MANIFOLD:	ASWC	ALTITUDE(ft):	3647
COMBUSTION:	LOW EMISSION	INLET AIR TEMPERATURE(°F):	77
NOx EMISSION LEVEL (g/bhp-hr NOx):	2.0	STANDARD RATED POWER:	1085 bhp@1200rpm
SET POINT TIMING:	27		

			MAXIMUM RATING	SITE RATING AT MAXIMUM INLET AIR TEMPERATURE		
RATING	**NOTES**	**LOAD**	**100%**	**100%**	**75%**	**50%**
ENGINE POWER (WITHOUT FAN)	(2)	bhp	1085	1085	814	543
INLET AIR TEMPERATURE		°F	77	77	77	77
ENGINE DATA						
FUEL CONSUMPTION (LHV)	(3)	Btu/bhp-hr	7615	7615	7706	8283
FUEL CONSUMPTION (HHV)	(3)	Btu/bhp-hr	8405	8405	8506	9142
AIR FLOW (@inlet air temp, 14.7 psia) (WET)	(4)(5)	ft3/min	2282	2282	1693	998
AIR FLOW (WET)	(4)(5)	lb/hr	10119	10119	7508	4427
FUEL FLOW (60°F, 14.7 psia)		scfm	126	126	96	68
INLET MANIFOLD PRESSURE	(6)	in Hg(abs)	61.6	61.6	47.3	29.8
EXHAUST TEMPERATURE - ENGINE OUTLET	(7)	°F	894	894	872	914
EXHAUST GAS FLOW (@engine outlet temp, 14.5 psia) (WET)	(5)(8)	ft3/min	6213	6213	4540	2798
EXHAUST GAS MASS FLOW (WET)	(5)(8)	lb/hr	10510	10510	7805	4640
EMISSIONS DATA - ENGINE OUT						
NOx (as NO2)	(9)(10)	g/bhp-hr	2.00	2.00	2.60	4.20
CO	(9)(10)	g/bhp-hr	2.68	2.68	3.13	2.83
THC (mol. wt. of 15.84)	(9)(10)	g/bhp-hr	2.72	2.72	2.63	1.94
NMHC (mol. wt. of 15.84)	(9)(10)	g/bhp-hr	0.91	0.91	0.88	0.65
NMNEHC (VOCs) (mol. wt. of 15.84)	(9)(10)(11)	g/bhp-hr	0.47	0.47	0.46	0.34
HCHO (Formaldehyde)	(9)(10)	g/bhp-hr	0.29	0.29	0.32	0.34
CO2	(9)(10)	g/bhp-hr	536	536	542	582
EXHAUST OXYGEN	(9)(12)	% DRY	7.7	7.7	7.2	6.6
HEAT REJECTION						
HEAT REJ. TO JACKET WATER (JW)	(13)	Btu/min	35589	35589	28932	25798
HEAT REJ. TO ATMOSPHERE	(13)	Btu/min	4554	4554	3795	3037
HEAT REJ. TO LUBE OIL (OC)	(13)	Btu/min	5627	5627	4575	4079
HEAT REJ. TO AFTERCOOLER (AC)	(13)(14)	Btu/min	7313	7313	4708	982
COOLING SYSTEM SIZING CRITERIA						
TOTAL JACKET WATER CIRCUIT (JW+OC)	(14)	Btu/min	45900			
TOTAL AFTERCOOLER CIRCUIT (AC)	(14)(15)	Btu/min	7679			

A cooling system safety factor of 0% has been added to the cooling system sizing criteria.

CONDITIONS AND DEFINITIONS

Engine rating obtained and presented in accordance with ISO 3046/1, adjusted for fuel, site altitude and site inlet air temperature. 100% rating at maximum inlet air temperature is the maximum engine capability for the specified fuel at site altitude and maximum site inlet air temperature. Maximum rating is the maximum capability at the specified aftercooler inlet temperature for the specified fuel at site altitude and reduced inlet air temperature. Refer to product O&M manual for details on additional lower load capability. No overload permitted at rating shown.

For notes information consult page three.
WARNINGS ISSUED FOR THIS RATING CONSULT PAGE 3

PREPARED BY: Rob Adams, Signet Monitoring and Analysis Inc.
Data generated by GERP Web Version 2.4.1.25
Ref. Dta Set DM0107-12-001, Printed 21Mar2023

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GAS ENGINE SITE SPECIFIC TECHNICAL DATA

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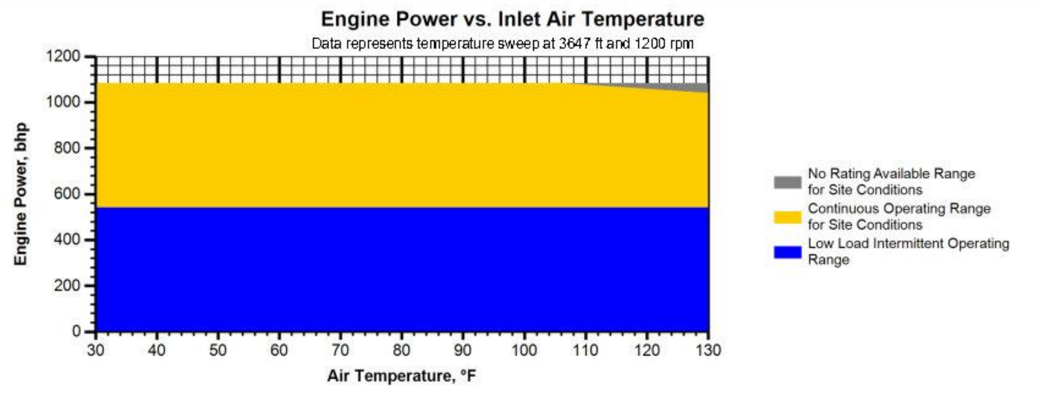

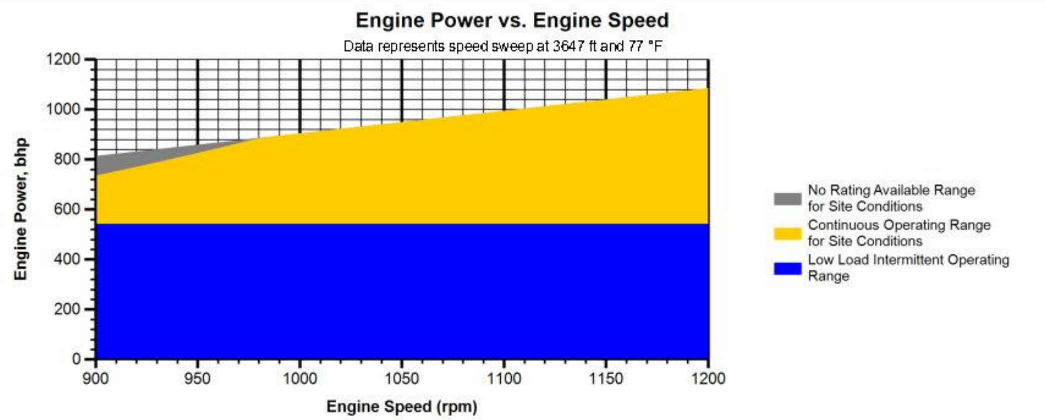

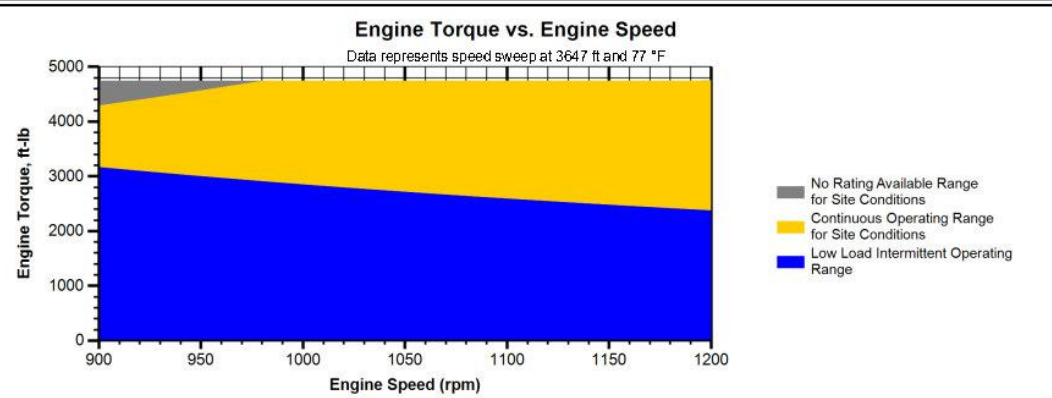

Note:
At site conditions of 3647 ft and 77°F inlet air temp., constant torque can be maintained down to 985 rpm. The minimum speed for loading at these conditions is 900 rpm.

PREPARED BY: Rob Adams, Signet Monitoring and Analysis Inc.
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G3516
NON-CURRENT

GAS ENGINE SITE SPECIFIC TECHNICAL DATA

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NOTES:

1. Fuel pressure range specified is to the engine fuel pressure regulator. Additional fuel train components should be considered in pressure and flow calculations.

2. Engine rating is with two engine driven water pumps. Tolerance is ±3% of full load.

3. Fuel consumption tolerance is ± 3.0% of full load data.

4. Air flow value is on a 'wet' basis. Flow is a nominal value with a tolerance of ± 5 %.

5. Inlet and Exhaust Restrictions must not exceed A&I limits based on full load flow rates from the standard technical data sheet.

6. Inlet manifold pressure is a nominal value with a tolerance of ± 5 %.

7. Exhaust temperature is a nominal value with a tolerance of (+)63°F, (-)54°F.

8. Exhaust flow value is on a "wet" basis. Flow is a nominal value with a tolerance of ± 6 %.

9. Emissions data is at engine exhaust flange prior to any after treatment.

10. Emission values are based on engine operating at steady state conditions, adjusted to the specified NOx level at 100% load. Fuel methane number cannot vary more than ± 3. NOx values are set points and will vary with operating conditions. All other emission values listed are higher than nominal levels to allow for instrumentation, measurement, and engine-to-engine variations. They indicate "Not to Exceed" values. THC, NMHC, and NMNEHC do not include aldehydes. Part load data may require engine adjustment.

11. VOCs - Volatile organic compounds as defined in US EPA 40 CFR 60, subpart JJJJ

12. Exhaust Oxygen level is the result of adjusting the engine to operate at the specified NOx level. Tolerance is ± 0.5.

13. Heat rejection values are nominal. Tolerances, based on treated water, are ± 10% for jacket water circuit, ± 50% for radiation, ± 20% for lube oil circuit, and ± 5% for aftercooler circuit.

14. Aftercooler heat rejection includes an aftercooler heat rejection factor for the site elevation and inlet air temperature specified. Aftercooler heat rejection values at part load are for reference only. Do not use part load data for heat exchanger sizing.

15. Cooling system sizing criteria are maximum circuit heat rejection for the site, with applied tolerances.

WARNING:

1. The lower heating value of the fuel is higher than or equal to 1050 Btu/scf and lower than 1300 Btu/scf. May require on-site adjustment or tuning of the fuel system and up to two 7E-1569 valve washers per carburetor mixer to lean out part load operating points.

RECOMMENDED ACTION

For additional information please contact your Caterpillar engine dealer.

PREPARED BY: Rob Adams, Signet Monitoring and Analysis Inc.
Data generated by GERP Web Version 2.4.1.25
Ref. Dta Set DM0107-12-001, Printed 21Mar2023

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GAS ENGINE SITE SPECIFIC TECHNICAL DATA

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Constituent	Abbrev	Mole %	Norm
Water Vapor	H2O	0.0000	0.0000
Methane	CH4	83.5500	83.5500
Ethane	C2H6	10.1200	10.1200
Propane	C3H8	3.6800	3.6800
Isobutane	iso-C4H10	0.5200	0.5200
Norbutane	nor-C4H10	0.8200	0.8200
Isopentane	iso-C5H12	0.2400	0.2400
Norpentane	nor-C5H12	0.2300	0.2300
Hexane	C6H14	0.1900	0.1900
Heptane	C7H16	0.2900	0.2900
Nitrogen	N2	0.3500	0.3500
Carbon Dioxide	CO2	0.0000	0.0000
Hydrogen Sulfide	H2S	0.0000	0.0000
Carbon Monoxide	CO	0.0000	0.0000
Hydrogen	H2	0.0000	0.0000
Oxygen	O2	0.0000	0.0000
Helium	HE	0.0100	0.0100
Neopentane	neo-C5H12	0.0000	0.0000
Octane	C8H18	0.0000	0.0000
Nonane	C9H20	0.0000	0.0000
Ethylene	C2H4	0.0000	0.0000
Propylene	C3H6	0.0000	0.0000
TOTAL (Volume %)		100.0000	100.0000

Fuel Makeup:

Unit of Measure: English

Calculated Fuel Properties

Caterpillar Methane Number:	58.4
Lower Heating Value (Btu/scf):	1093
Higher Heating Value (Btu/scf):	1207
WOBBE Index (Btu/scf):	1325
THC: Free Inert Ratio:	276.78
Total % Inerts (% N2, CO2, He):	0.36%
RPC (%) (To 905 Btu/scf Fuel):	100%
Compressibility Factor:	0.997
Stoich A/F Ratio (Vol/Vol):	11.36
Stoich A/F Ratio (Mass/Mass):	16.66
Specific Gravity (Relative to Air):	0.682
Fuel Specific Heat Ratio (K):	1.290

CONDITIONS AND DEFINITIONS
Caterpillar Methane Number represents the knock resistance of a gaseous fuel. It should be used with the Caterpillar Fuel Usage Guide for the engine and rating to determine the rating for the fuel specified. A Fuel Usage Guide for each rating is included on page 2 of its standard technical data sheet.

RPC always applies to naturally aspirated (NA) engines, and turbocharged (TA or LE) engines only when they are derated for altitude and ambient site conditions.

Project specific technical data sheets generated by the Caterpillar Gas Engine Rating Pro program take the Caterpillar Methane Number and RPC into account when generating a site rating.

Fuel properties for Btu/scf calculations are at 60F and 14.696 psia.

Caterpillar shall have no liability in law or equity, for damages, consequently or otherwise, arising from use of program and related material or any part thereof.

FUEL LIQUIDS
Field gases, well head gases, and associated gases typically contain liquid water and heavy hydrocarbons entrained in the gas. To prevent detonation and severe damage to the engine, hydrocarbon liquids must not be allowed to enter the engine fuel system. To remove liquids, a liquid separator and coalescing filter are recommended, with an automatic drain and collection tank to prevent contamination of the ground in accordance with local codes and standards.

To avoid water condensation in the engine or fuel lines, limit the relative humidity of water in the fuel to 80% at the minimum fuel operating temperature.

WARNING:
1. The lower heating value of the fuel is higher than or equal to 1050 Btu/scf and lower than 1300 Btu/scf. May require on-site adjustment or tuning of the fuel system and up to two 7E-1569 valve washers per carburetor mixer to lean out part load operating points.

RECOMMENDED ACTION
For additional information please contact your Caterpillar engine dealer.

PREPARED BY: Rob Adams, Signet Monitoring and Analysis Inc.
Data generated by GERP Web Version 2.4.1.25
Ref. Dta Set DM0107-12-001, Printed 21Mar2023

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COOPER MACHINERY SERVICES

PowerFlow - Compressor Performance Report

Ver. 1.17.4.0 Page 1 of 2

Customer/End-user:		Quote #::	RA
Site Location:		Case #:	N/A
Engineer:		Date:	3/21/2023, 10:38 AM

Application Data		High Speed FE650D-4		Driver Data		Site Data	
Unit Flow	3.89 MMscfd	Rated Power	2400.0 HP	Manufacturer	Caterpillar	Elevation	3647.0 ft
Load per Flow	189.38 HP/MMscfd	Stroke	6.000 in	Model	G3516 LE	Atm. Pressure	88.66 KPaA
Lubrication	Lubed	Rated Speed	1200 RPM	Rated Power	1150.0 HP	Ambient Temp	26.7 ° C
		Rod Diameter	2.000 in	Rated Speed	1200 RPM	Gas Method	AGA8
Unit Load	736.4 HP	Max Rod Load Comp	32500.0 lbf	Avail. Power	1107.0 HP	Base Pressure	101.325 KPaA
Avg. Piston Vel.	1200.00 ft/min	Max Rod Load Tens	30000.0 lbf	Derate	0.00 %	Base Temp.	15.6 ° C
Type	Gathering	Max Rod Load Gas	32500.0 lbf	Run Speed	1200 RPM	Auxiliary Load	43.0 HP
CONCERNS							
Project Notes							
Case Notes	N/A						
Order Status							

Stage/Service Data

		Stage 1	Stage 2	Stage 3
Flow Rate	MMscfd	3.890	3.890	3.890
Load	HP	266.30	219.20	218.90
Specific Gravity	-	0.682	0.682	0.682
K Value (Cp/Cv)	-	1.2453	1.2376	1.2371
Zs	-	0.9880	0.9715	0.9296
Zd	-	0.9844	0.9659	0.9227
Suction Press.	KPaG	274.00	1035.09	2590.67
Ps@Flange	KPaG	270.37	1035.09	2590.67
Pd@Flange	KPaG	1068.81	2644.26	7191.08
Discharge Press.	KPaG	1035.09	2590.67	7119.00
Compress. Ratio	-	3.2238	2.4319	2.7170
Ts/Adiba. Temp.	° C	8.0/80.9	32.0/88.8	29.0/92.8
Cooler Temp.	° C	32.0	29.0	48.9

Cylinder Data

		Throw-1	Throw-2	Throw-3	Throw-4	Throw-5	Throw-6
Model	-	06 Series	95 Series	06 Series	06 Series		
Operating Mode	-	D/A Cyl	D/A Cyl	D/A Cyl	D/A Cyl	BLANK	BLANK
Head End	Serv#/Stg#	1/1	1/3	1/1	1/2		
Bore	in	10.500	5.500	10.500	7.500		
MAWP	KPaG	8618.45	24821.13	8618.45	12410.56		
RDP	KPaG	7832.44	22566.54	7832.44	11279.82		
Tail Rod Dia	in	0.000	0.000	0.000	0.000		
Tsi / Est. Td	° C	11.3/97.6	31.1/105.2	11.3/97.6	34.1/102.7		
VVCP Open	in / Turns	2.00 : 16	0.00 : 0	1.75 : 14	0.00 : 0		
Base Clr	%	20.95	33.06	20.95	23.68		
Added Clr	%	14.82	0.00	12.97	0.00		
Total Clr	%	35.76	33.06	33.91	23.68		
Vol. Eff. Ps / Pd	% / %	40.44/15.74	54.29/24.04	43.12/16.79	70.01/33.96		
Q-Value Ps / Pd		7.19/6.56	5.20/4.56	7.19/6.56	7.82/6.87		
Flow	MMscfd	0.76	2.07	0.81	1.98		
Crank End	Serv#/Stg#	1/1	1/3	1/1	1/2		
Bore	in	10.500	5.500	10.500	7.500		
MAWP	KPaG	8618.45	24821.13	8618.45	12410.56		
RDP	KPaG	7832.44	22566.54	7832.44	11279.82		
Tsi / Est. Td	° C	11.3/97.6	31.1/105.2	11.3/97.6	34.1/102.7		
Base Clr	%	19.43	32.96	19.43	20.70		
Added Clr	%	0.00	0.00	0.00	0.00		
Total Clr	%	19.43	32.96	19.43	20.70		
Vol. Eff. Ps / Pd	% / %	64.08/24.95	54.42/24.10	64.08/24.95	72.97/35.39		
Q-Value Ps / Pd		6.67/6.09	3.92/3.44	6.67/6.09	6.74/5.93		
Flow	MMscfd	1.16	1.80	1.16	1.91		
Valve Spacers	HE#/CE#	0 / 0	0 / 0	0 / 0	0 / 0		
Rod Loads							
Gas-Compress.	%	34.8	58.6	35.0	41.3		
Gas-Tension	%	33.3	43.0	33.3	34.7		
Combined-Comp.	%	49.3	47.6	49.4	55.5		
Combined-Tens.	%	71.5	50.2	71.5	70.3		
Pin Reversal	Deg/Mag%	152/75	142/97	154/75	158/86		
Throw Loading	HP	131.4	218.9	134.9	219.2		

BOLD = *Out of Limit*

APPENDIX E

Test Data Summary in Excel Spreadsheet Under Separate Cover

File Name: Appendix E Test Data Summary

APPENDIX F

Test Data Plots Under Separate Cover

File Name: Appendix F Test Data Plots

LIST OF FIGURES FOR PLOTS OF TEST DATA UNDER SEPARATE COVER

APPENDIX G

G3600 Series MSAPR Test Data Under Separate Cover

File Name: Appendix G G3600 MSAPR Test Data Summary

APPENDIX H
G3600 Series MSAPR Test Plots

File Name: Appendix I G3600 MSAPR Test Data Plots

LIST OF FIGURES FOR G3600 MSAPR TEST PLOTS UNDER SEPARATE COVER

APPENDIX I

STAIONARY NATURAL GAS ENGINE DESCRIPTIONS AND OPERATING ASPECTS

I. Engine Design

The oil and gas industry utilized modified diesel engines to drive gas compression equipment, refrigeration compressors and to power electrical generators. The term gasification describes the process of converting an engine from diesel or gasoline fuels to natural gas. The ruggedness of the diesel engine design provided a benefit to the industry in the form of reliability and exceptional major component life. The move towards the development of what is termed a pure natural gas engine design was a combination of the need for a wider range of engine drivers, diesel engine conversion costs and an opportunity to reduce overall costs as the diesel engine components were over designed for natural gas service.

The engine manufacturers responded to the increasing and diverse needs of the industry. They expanded the range of products to ensure that horsepower output could be closely matched to needs. This enabled the user to select the best possible combination of operating speeds, operating ranges, horsepower ratings, fuel compositions, engine ignition systems and engine control and monitoring systems to meet specific site requirements.

The natural gas engines used today are fully capable of 24/7 continuous operation, deliver the full rated horsepower and are controlled and monitored by fully automated systems. Technological advances in the areas of ignition systems, speed control, loading, and exhaust emission reduction have improved starting and run time reliability.

The natural gas engine provides components are physically lighter in weight and dimensionally smaller than what the diesel engine conversions offered. The lightening of materials is due to the lower Btu energy forces that are created with the combustion of natural gas fuels within the combustion chamber. The reduction in the overall mass of the engine components provides reduced mechanical forces, lower overall casting weight and physical dimensions. The reduction in mechanical forces and casting weight also allows for a reduction in the amount of structural support and foundation support required.

Engine design and fuel delivery systems vary substantially. The following descriptions provide a brief orientation of engine design aspects.

I.1. Two Stroke Design

The two stroke engine design has seen limited use in the oil and gas industry. The design is suited to scenarios where the fuel gas supply contains traces of hydrogen sulphide gas that exceed levels acceptable to the manufacturers of separable four stroke engine designs.

The sequence of the two stroke engine operation begins with the piston moving downwards in the cylinder bore during its power stroke. On its travel downwards the top of the piston will pass an exhaust port and the pressurized exhaust gases will exit. The piston continues downwards in its travel. During this phase it compresses the air-fuel-oil mixture within in the crankcase. The top of the piston then passes a transfer port and the compressed crankcase charge is allowed into the cylinder and the remaining exhaust is forced out.

The compression stroke begins with the air-fuel-oil mixture charge in the cylinder. As the piston begins to move upwards the compression charge in the cylinder draws a vacuum in the crankcase, pulling in more air, fuel, and oil from the carburetor. The compressed charge is then ignited by a spark plug and the resultant explosion of the air-fuel-oil mixture drives the piston downwards in the cylinder and the process is repeated.

The two stroke design uses the space below the piston for air intake and compression. This allows the area above the piston to be used for the power and exhaust strokes. The design offers an advantage in that there is a power stroke for every revolution of the crank, instead of every second revolution as in a four-stroke engine.

I.2. Four Stroke Design

The four stroke engine design is the most prevalent within the industry. The sequence of operation starts with the piston being positioned at the top dead center (TDC). This means that the piston position is now furthest away from the crankshaft. The travel of the piston in the cylinder bore downwards from the TDC position is referred to as the intake of the piston (first stroke). As the piston travels down the cylinder bore a vacuum is created and the air-fuel mixture is drawn into the cylinder aided by the atmospheric pressure or forced into the cylinder by a turbocharger. The intake valve closes as the piston begins it travel upwards compressing the air-fuel mixture within the cylinder bore.

As the piston nears the top of its compression travel (second stroke) the air-fuel mixture is ignited by the spark plug. The combustion process that then takes place results in a rapid expansion of the ignited gases and the piston is driven down into the bore delivering its power (third stroke). At the bottom of its stroke the piston begins its return journey and expels the burnt combustion gases out of the cylinder past the exhaust valve (fourth stroke).

I.3. Naturally Aspirated Engine with Stoichiometric Air-Fuel Mixture

The naturally aspirated engine design relies on the atmospheric pressure differential created when the piston moves downwards in the cylinder bore to draw in the air-fuel mixture. The term stoichiometric refers to the perfect ratio of air to fuel (16.8:1) that matches the oxygen and hydrocarbon molecules so as to create a complete combustion process; the exhaust stream analysis would show that there are no unburned hydrocarbons or free oxygen exiting the combustion chamber.

I.4. Turbocharged Engine with Stoichiometric Air-Fuel Mixture

The turbocharged engine design utilizes the exhaust stream thermal flow energy to drive an impeller fitted to a shaft that is fitted with a turbine wheel that forces air into the intake manifold of the engine building a pressurized air reserve that is of sufficient quality so as to force the air-fuel mixture under pressure into the cylinder bore. This process is capable of increasing engine horsepower by approximately 30% over the same cubic inch displacement that a naturally aspirated version of the same engine would be capable of producing.

As is the case with the naturally aspirated engine design the term stoichiometric refers to the perfect ratio of air to fuel (16.8:1) that matches the oxygen and hydrocarbon molecules so as to create a complete combustion process; the exhaust stream analysis would show that there are no unburned hydrocarbons or free oxygen exiting the combustion chamber.

I.5. Turbocharged Engine with Lean Burn Technology

The turbocharged lean burn engine design utilizes the exhaust stream thermal flow energy to drive an impeller fitted to a shaft that is fitted with an over sized turbine wheel capable of delivering approximately 80% more air than a standard turbocharger equipped engine. This forces more air into the intake manifold of the engine building a much higher reserve of air. The net result is that the ratio of air-fuel mixture entering under pressure into the cylinder bore may range from 25:1 to 32:1 dependant upon engine design. As is the case with the standard turbocharger design this process is capable of increasing engine horsepower by approximately 30% over the same cubic inch displacement that a naturally aspirated version of the same engine would be capable of producing. Lean burn engines with the lower air fuel ratios may be designed with an open chamber that is also standard for naturally aspirated engines. Lean burn engines may also be built with a pre-chamber design.

Engines operating with ultra-lean air fuel mixtures will require additional energy to ignite the air fuel mixture. It is too lean to ignite with a spark plug. This energy is created with a device called a pre-chamber. The pre-chamber is a sperate chamber that is vented into the main combustion chamber. A stoichiometric air fuel ratio is introduced into the pre-chamber and that is ignited with a spark plug. The flame front that advances into the main combustion chamber is called a plasma jet. The plasma jet ignites the ultra lean air fuel mixture in the combustion chamber.

The exhaust gas stream is measured for the percentage of free oxygen as a means of setting the air fuel ratio of the engine. The excess oxygen forced into the cylinder ensures that the combustion process is fully completed prior to exiting into the exhaust manifold.

I.6. Supercharged Engine with Mechanical Forced Air Induction Design

The supercharged engine design utilizes a mechanically driven rotary meshing impeller design to force air into the intake manifold. The mechanical drive approach provides an even response to changes in speed and loads as it not reliant upon the thermal energy generated by the exhaust stream to drive an impeller. The engine design may be open chamber or pre-chamber as the only difference with a supercharged engine is the motive power for the combustion air compressor.

I.7. Engine Operating Speed Ranges

The speed ranges of the natural gas fuelled spark ignited reciprocating engines typically range from 600 to 1800 rpm. The lean burn designed engines are the exception as their oversized turbocharger capacity requires a specific amount of thermal heat energy to drive the turbine wheel shaft. The speed range of these engines is limited. If the engine is to be operated at a lower rpm a low speed turbocharger cartridge is installed to match the thermal energy level that is being generated by the engine.

I.8. Separable Engine and Compressor Design

The term separable defines the engine driver and the driven components are individual rotating elements connected by couplings. This allows mixing and matching of a wide range of drivers, driven equipment, gearboxes and accessories. One engine model could be used to drive a compressor, a water pump, an electrical power generator or other rotating elements.

I.9. Integral Reciprocating Engine and Compressor Design

The integral design incorporated a low speed, long piston stroke approach to generate horsepower and to compress natural gas. The combination of the engine and compressor into a single unit eliminated the need for drive belts, gear box drives or clutch assemblies that would manage the transfer of engine power to the driven component. At the time, industrial equipment was evolving and the designers working in that period of time offered a modern approach to moving large volumes of natural gas. The design utilized a single casting combining the engine power cylinders with the compression cylinders.

The industry has steadily phased out the use of the integral design over the years due to manufacturers' obsolescence issues, the resultant difficultly in sourcing of replacement parts and the emergence of the separable concept that offers features and benefits that greatly improved the economics of plant and field development and ongoing operations.

The integral engine-compressor designers created a number of models and variations. The power cylinders were typically arranged in the vertical plain or in a "V" configuration. The number of power cylinders would vary from 1 to 16, dependant upon its design philosophy. The compression portion of the design incorporated varying numbers of cylinders and methods of attachment. The dimensions of the units would vary widely based upon the design of the crankcase and the oil sumps. It was not unusual for a plant to provide a basement located below floor level that would accommodate a secondary filtration set up so as to facilitate engine filter and oil changes without having to shut down the engine. The fuel selection process, fuel management systems, ignition strategy and monitoring and control systems are comparable to the separable engine design. Surviving integral installations are represented by a number of different manufacturers and utilize a variety of monitoring and control systems.

II. Pre-Chamber Lean Burn Engines

The engines considered in this report are pre-chambered, lean burn engine models. The most popular engine models we considered are as follows.

- Caterpillar 3600 series ADEM 3
- Caterpillar 3600 series ADEM 4
- Waukesha VHP GL
- Waukesha AT GL

- White-Superior GTLA-825 Lean Burn
- White-Superior GTLB-825 Lean Burn

Pre-chambered lean burn engines employ an additional chamber that contains a stoichiometric fuel mixture and a spark plug. The pre-chamber is open to the main combustion chamber containing a very lean air fuel mixture. The mixture is so lean that it will not ignite with the energy provided by a spark plug alone. The mixture in the pre-chamber is ignited instead and that introduces a jet of combusted fuel, called a plasma jet, into the combustion chamber. The plasma jet ignites the lean mixture in the combustion chamber. The benefit of the using a pre-chamber is that the advantages of lower NO_x and fuel consumption may be enjoyed during normal operation. An adaptive engine management system that temporarily richens the primary air fuel mixture is recommended to allow for upset operating conditions of load and ambient conditions. The test cell data of the amounts of air and fuel consumed as well is needed as the operating air-fuel ratio for the various engines under consideration in this report are detailed in Table I1.

Table I1 Test Cell AFR by Engine

Actual AFR for Lean burn (pre-chamber) engines by OEM definition						
MODEL	HP	SPEED	Flow (scfm) @ 100% load		RATIO	OEM REFERENCE
			Fuel	Air		
CATERPILLAR						
G3606A3	1775	1000	224	4719	21.0	DM8605-07
G3608A3	2370		270	6177	22.9	LEHW0040-02
G3612A3	3550		433	9358	21.6	LEHW0041-02
G3616A3	4735		576	12294	21.3	LEHW0042-03
G3606A4	1875	1000	235	4586	19.5	EM0555-07
G3608A4	2500		315	6252	19.8	EM1410-04
G3612A4	3750		470	9251	19.7	EM0755-09
G3616A4	500		624	12136	19.4	EM1426-04
WAUKESHA						
F3524GL	738	1200	100	1569	15.6	EngCalk 05/01/23
L7042GL	1480	1200	199	3699	18.6	7005 1211 GEA-18912
L5790GL	1215	1200	163	2740	16.8	S6124-45; C976-16
P9390GL	1980	1200	262	4890	15.0	EngCalk 05/01/23
12V275GL+	3625	1000	437	9762	22.4	7264 0711 GEA-18930
16V275GL+	4835	1000	579	12411	21.4	7116 0711 GEA-18931
12V275GL+ AFR2	3750	1000	433	9978	23	EngCalc07/10/22
16V275GL+ AFR2	5000	1000	575	12877	22.4	EngCalc07/10/22
WHITE SUPERIOR						
6GTLA/B	825	900	109	1885	17.4	A-S CB 111/1-89
8GTLA/B	1100	900	144	2621	18.2	A-S CB 211/1-89
12GTLA/B	1650	900	223	3934	17.6	A-S CB 411/1-89
16GTLA/B	2200	900	298	5050	17.0	A-S CB 611/1-89
8GTLE	1100	900	155	2521	16.3	A-S TC(LE) 211A/6-89
8SGTB	1350	900	177	3246	18.4	A-S CB 311/1-89
12SGTB	2000	900	263	4590	17.4	A-S CB 511/1-89
16SGTB	2650	900	347	5970	17.2	A-S CB 711/1-89
12SGTD	2000	900	262	4895	18.7	SPE20012 08/2020
16SGTD	2650	900	347	6526	18.8	SPE20012 08/2020

The air-fuel ratio determines the concentrations of NO_x and other components of combustion. The values in the table illustrate the change in concentration with respect to O_2%. Please note that the oxygen content for this style of combustion normally exceeds 11% and NO_x concentrations can be much less than 1 g/kW-hr. Pre-chambered engines will provide the lowest NO_x concentrations without additional treatment of the exhaust emissions. Pre-chambered engines will be compliant with NO_x regulation limits and offer the lowest fuel consumption.

OEM engine management systems have traditionally been designed to operate at one point and adjustments made on the day of tuning are expected to remain unchanged. Thus, adaptive controls, especially on OEM engines older than five years, should not be expected. Operating conditions are always changing so this assumption by the engine manufacturers is rarely valid.

Pre-chambered engines require sophisticated devices and controls to manage stable operation. Reliability of these components varies with the various engine models. Factory trained technicians are often necessary to monitor the behaviour of the engines and maintain reliable operations. The control systems on the latest models of factory supplied pre-chambered engines are now sufficiently adaptive to maintain regulatory compliance at any time.

The advent of the MSAPR regulations provided the expectation that the NO_x emissions should be managed at all times during engine operation. The frequency of regulatory testing reflects the ability of the engine managements system to maintain emissions within the required limits. A pre-chambered engine management system has the best chance of performing in that fashion.

Caterpillar's G3600 series ADEM 3 and ADEM 4 systems offer the most adaptive solution from the OEM's on their G3600 series engines. Both engines use a fuel delivery system that terminates at each cylinder. A fuel valve supplies a metered supply to a needle valve for the pre-chamber and an admission valve for the combustion chamber. Air is introduced separately into the combustion chamber to produce in an ultra-lean mixture when mixed with the fuel. Air from the combustion chamber is also introduced into the pre-chamber where a rich mixture is created with the fuel supply from the needle valve. The system is not fuel injected. Both engines also monitor the flame front and pressure and temperature in the combustion chamber. This monitoring allows adapting engine performance to fuel quality and load. Both engine series control turbo speed with a wastegate and air manifold pressure with a butterfly valve. The ADEM control systems manage combustion and timing and safety shut downs. The ADEM 3 and ADEM 4 engines differ significantly in compression ratio, top end design and the sophistication of the control systems. The ADEM 4 system has a NO_x sensor that provides feedback to the control system. A CAT certified technician is required to set up and tune these engines.

Waukesha legacy VHP GL engines use a CEC ignition system along with a carburetor and pre-chamber fuel valve that is delivered with pneumatically balanced regulators. Spring return admission valves admit a rich air fuel mixture into the pre-combustion chamber. The lean fuel mixture is introduced into the combustion chamber via the intake valves. The turbo speed is controlled by a wastegate with spring loaded plates. The air manifold pressure is controlled with a butterfly valve prior to the carburetor that helped to deliver more air pressure held in reserve when the engine demanded more load.

Waukesha's 275 series and legacy AT are different engines. The AT engine use carburetors and pre-chambers with pneumatically balanced regulators. The 275 series uses Waukesha's advanced ESM control system to manage turbo speed and air fuel ratio. A NO_x sensor provides feedback to the control system to manage engine performance automatically. Waukesha claims to be able to adapt to changing fuel quality but the control system description does not offer sufficient monitoring to do so. Inlet air heaters and complex systems for cooling and lubrication require frequent adjustment.

The first generations of the ESM systems employed a stepper motor to provide a lean air fuel mixture to the intake manifold with rich fuel delivered separately to the pre-chambers. The ESM 2 system now employs a butterfly valve for air fuel ratio control with NO_x and O_2 sensors to provide feedback to the control system. Waukesha also provided a learning capability in their control system on the first 275GL models to allow the engine to adapt to changing operating or engine conditions. Early versions of this system were problematic.

White-Superior 825 series pre-chambered engines employ their Clean Burn control systems. They are fuel injected with a fuel valve on each cylinder head that is actuated by a dedicated camshaft. The air intake and exhaust valves are also actuated by dedicated camshafts. Air and fuel mixing occurs in the combustion chamber and at the pre-chambers. Exhaust and air manifold control is accomplished with local control valves on the engine. The air manifold pressure controls the air fuel ratio control. These engines are known for valve overlap that allows air to sweep the combustion chamber.

Two factory versions of the White-Superior 825 series pre-chambered designs are historically available as GTLA or GTLB models. These designations indicate the first and second generation of Superior pre-chambered engine control systems. The current version of their pre-chamber technology is called SGTD. Engine management systems on White-Superior Superior engines have demonstrated chronic hard starting and reliability issues. The mechanical construction of the engines is robust and many have been in service for several decades.

III. Open Chamber Lean Burn Engines

The engines considered in this report are open chamber lean burn engine models. The most popular engine models we considered are as follows. White-Superior 825 series engines were not equipped with an open chamber lean burn design.

- Caterpillar G3500 TALE series lean burn
- Caterpillar G3500 A3 series lean burn
- Caterpillar G3500 J series lean burn
- Caterpillar G3400 C LE series lean burn

- Waukesha VHP LT lean burn
- Waukesha VGF GL lean burn

Open chamber lean burn engines employ a conventional fuel delivery system and combustion chamber using a spark plug to ignite the air fuel mixture. Excess air is provided for leaner than stoichiometric combustion. Higher capacity turbochargers and intercooler capacity are required to delivery the increased air volume. Open chamber lean burn engines require a larger auxiliary water and smaller jacket water cooling capacities than a rich burn turbocharged engine of the same model. Lower head temperature and extended service intervals deliver lower operating costs when compared with open chamber rich burn engines.

The benefit of an open chamber lean burn is that the advantages of reduced NO_x and fuel consumption may be enjoyed during normal operation. The open chamber design offers less complexity than the engine equipped with the pre-chambered combustion style. An adaptive engine management system that temporarily richens the primary air fuel mixture is recommended to allow for upset operating conditions of load and ambient conditions. The test cell data of the amounts of air and fuel consumed as well as the operating air-fuel ratio for the various engines under consideration in this report are detailed in Table I2.

Table I2 AFR Test Cell Data

Actual AFR for Lean burn (open chamber) engines by OEM definition						
MODEL	HP	SPEED	Flow 100% load, scfm		RATIO	OEM REFERENCE
			Fuel	Air		
CATERPILLAR						
G3408CLE	425	1800	55	843	15.3	LEHW0031-02
G3412CLE	637	1800	90	1358	15.1	LEHW0033-00
G3512LE	860	1200	117	1850	15.8	LEHW0035-01
G3516LE	1150	1200	155	2453	15.8	LEHW0036-00
G3512B ULB	1035	1400	138	2337	16.9	LEHW0095-01
G3516B ULB	1380	1400	185	3126	16.9	LEHW0037-00
G3512J	1035	1400	141	2309	16.4	EM4557-00
G3516J	1380	1400	187	3110	16.6	EM1495-05
WAUKESHA						
F18GL	400	1800	55	860	15.5	7071 1211 GEA-19029
H24GL	530	1800	70	1139	16.4	7073 1211 GEA-19031
L5774LT	1280	1200	179	2822	15.7	IWK-119009-EN
L5794LT	1450	1200	201	3169	15.8	8023 1211 GEA-189

Test Cell OEM and measured field emission levels for these engines are detailed in Table . The air fuel ratio determines the concentrations of NO_x and other components of combustion. The values in the table illustrate the change in concentration with respect to O_2%. Please note that the oxygen content for this style of combustion normally exceed 8% and NO_x concentrations are much less than 3 g/kW-hr (usually less than 2.7 g/kW-hr). Open chambered engines will provide the NO_x concentrations that are less than a stoichiometric engine (without catalyst) and more than a pre-chambered lean burn combustion style. Open chamber lean burn engines do not require additional treatment of the exhaust emissions to be NO_x compliant in Alberta.

Open chamber engines require less sophisticated devices and controls to manage stable operation than an engine with a pre-chambered combustion style. Reliability of the engine management system components is normally higher than the pre-chambered combustion style. Plant mechanics with standard industry training are qualified to monitor the behaviour of the engines and maintain reliable operations.

OEM engine management systems have traditionally been designed to operate at one point and adjustments made on the day of tuning are expected to remain unchanged. Thus, adaptive controls, especially on OEM engines older than five years, should not be expected. Operating conditions always change so this assumption by the engine manufacturers is rarely valid.

The advent of the MSAPR regulations provided the expectation that the NO_x emissions should be managed at all times during engine operation. The frequency of regulatory testing reflects the ability of the engine management system to maintain emissions within the required limits. The control systems on the latest models of factory supplied open chamber engines are now more adaptive and less frequent regulatory testing is specified to ensure regulatory compliance over time.

Caterpillar’s G3500 series engines have been equipped with their TALE combustion systems for decades. Cat has been running this open chamber lean burn system long before it became popular for NO_x emission compliance. It is robust and reliable. The original versions did not provide adaptive controls. That is now achieved with the ADEM 3 system. The ADEM 3 system offers the most adaptive solution from the OEM’s on open chamber lean burn engine models. The ADEM 3 system may also be configured for a catalyst or other exhaust treatment if desired. A lean air fuel ratio will not provide enough fuel to ignite an oxidation catalyst. Different equipment will be required to change the engine controls to a rich burn configuration.

Waukesha created an open chamber lean model called the LT by blending components from their GSI and GL models. The first models used a CEC ignition system along with a carburetor and higher capacity turbochargers. Later versions were equipped with ESM modules and stepper valves for fuel delivery devices. The turbo speed is controlled by a wastegate with spring loaded plates. The air manifold pressure is controlled with a butterfly valve prior to the carburetor that could deliver more air pressure (called the reserve) when the engine demanded more load. Air intake manifolds matched those used on the GL engines to accommodate higher air flow volumes.

IV. Open Chamber Rich Burn Engines

The characteristics of engines with rich burn combustion styles, with and without catalysts, are presented. The term "rich" means an air fuel ratio that contains more fuel than lean burn engines. The air fuel ratio is stoichiometric for engines without catalysts. Engines equipped with catalysts must be set richer than stoichiometric in order to provide excess fuel to ignite in the catalyst.

Table I3 shows factory test cell data of air fuel ratios for rich burn engines. The values shown are without catalyst. An engine operating at stoichiometric conditions will exceed NO_x regulatory limits. Furthermore, engines are set to “best power” or “best fuel economy.” The best fuel economy setting is leaner than the best power. Setting the carburetor to best power offers more flexibility to accommodate variable load conditions. Cooper does not provide air - fuel ratio data for the White-Superior Superior engines.

A catalyst or a modification to support reliable operation at much leaner air fuel ratios is required to meet NO_x emission regulatory limits. The purpose of the catalyst or engine combustion style modifications is to treat the engine exhaust to reduce the NO_x concentration in the emissions. Note that air fuel ratios at stoichiometric on factory equipped engines are typically above 10:1 by volume for natural gas engines.

Table I3 AFR Test Cell Data

Actual AFR for Rich burn engines by OEM definition						
MODEL	HP	SPEED	Flow (scfm) 100% load		RATIO	OEM REFERENCE
			Fuel	Air		
CATERPILLAR						
G3304 NA	95	1800	14	150	10.7	LEHW0019
G3306 NA	145	1800	21	225	10.7	LEHW0027
G3306 TA	203	1800	30	320	10.7	LEHW0027
G3306 ATAAC	220	1800	31	329	11	LEHW0027
G3406 NA	215	1800	31	342	11	LEHW0028
G3406 TA	325	1800	43	459	10.7	LEHW0029
G3408 TA	400	1800	53	559	10.5	LEHW0030
G3412 TA	600	1800	81	843	10.4	LEHW0032
CG137-08	400	1800	55	531	9.7	EM3829-05
CG137-12	600	1800	84	801	9.5	EM4986-01
G3512TA	790	1200	109	1162	10.6	TM9502-02
G3516TA	1050	1200	145	1554	10.7	DM5208-00
G3516TA A4	1380	1400	186	1827	9.8	EM1440-00
WAUKESHA						
F18GSI	400	1800	55	590	10.6	7013 1211 GEA-18916
F18GSI SE	400	1800	56	613	10.9	EngCalc07/10/22
H24GSI	530	1800	73	780	10.7	7014 1211 GEA-18917
H24GSI SE	530	1800	74	817	11.0	EngCalc07/10/22
F3514GSI	740	1200	111	1108	10.0	EngCalc 01/05/23
F3521GSI	740	1200	107	1090	10.2	C 248-J
F3524GSI	840	1200	124	1237	9.9	EngCalc 01/05/23
F3521G	515	1200	70	741	10.7	7008 1211 GEA-19025
L5790G	845	1200	116	1234	10.6	EngCalc 01/05/26
L5794GSI	1380	1200	195	2001	10.3	7058 1211 GEA-18928
L7042GSI	1480	1200	214	2275	10.7	7011 1211 GEA-18914
L7042GSI S5	1500	1200	194	2043	10.5	EngCalc07/10/22
L7044GSI	1680	1200	244	2424	9.9	7011B 1211GEA-18926
L7044GSI S5	1900	1200	242	2544	10.5	EngCalc07/10/22
P9390GSI	1980	1200	289	3081	10.7	EngCalc 01/05/23
P9394GSI S5	2500	1200	312	3274	10.5	EngCalc07/10/22
WHITE SUPERIOR						
6G-825	600	900	86	944	11.0	A-S NA 111/1-89
8G-825	800	900	114	1186	10.4	A-S NA 211/1/89
12G-825	1200	900	171	1890	11.0	A-S NA 311/1-89
16G-825	1600	900	228	2387	10.5	A-S NA 411/1-89
6GT-825	825	900	118	Unavailable	Unavailable	Cooper Machinery Services.
8GT-825	1100	900	157	Unavailable	Unavailable	Superior engine exhaust
6GTL-825	825	900	112	1640	14.7	A-S TC 111/1-89
8GTL-825	1100	900	150	2170	14.5	A-S TC 211/1-89
12GTL-825	1650	900	225	3080	13.7	A-S TC 411/1-89
16GTL-825	2200	900	299	4200	14.1	A-S TC 611/1-89
8SGT-825	1350	900	182	2570	14.1	A-S TC 311/1-89
8SGT-825	1500	1000	205	2885	14.1	A-S TC 311/1-89
12SGT-825	2000	900	267	3575	13.4	A-S TC 511/1-89
16SGT-825	2650	900	354	4900	13.8	A-S TC 711/1-89

IV.1. Open Chamber Rich Burn Engines Without Catalysts

- Open chamber Caterpillar G3500 TA series stoichiometric
- Open chamber Caterpillar G3400 TA series stoichiometric
- Open chamber Waukesha VHP GSI series 2 stoichiometric
- Open chamber Waukesha VHP G stoichiometric
- Open chamber Waukesha VHP GSI series 4 stoichiometric
- Open chamber Waukesha VGF GSI stoichiometric
- Open chamber White-Superior G-825 stoichiometric
- Open chamber White-Superior GT-825 stoichiometric
- Open chamber White-Superior GTL-825 stoichiometric
- Open chamber White-Superior SGT-825 stoichiometric

IV.2. Open Chamber Rich Burn Engines With Catalysts

- Open chamber Waukesha VGF GSI stoichiometric
- Open chamber Waukesha VHP G stoichiometric
- Open chamber Waukesha VHP GSI series 4 AFR2
- Open chamber Waukesha VHP GSI series 5 AFR2
- Open chamber White-Superior G825 stoichiometric
- Open chamber Caterpillar G3500 TA series stoichiometric
- Open chamber Caterpillar G3400 TA series stoichiometric
- Open chamber Caterpillar GC137

The traditional industry solution for exhaust gas conditioning during the 1990's and early 2000's was to install aftermarket air fuel ratio controls along with a catalyst on a rich burn engine. The catalyst and the control system were often not produced by the same manufacturer. Obtaining consistent quality in the adaptive nature of the control systems and the quality of the catalytic elements was difficult. The engine packager would select the least cost alternative. Control systems were not adaptive and the oxygen sensor provided a short service life.

Modern engines from Caterpillar and Waukesha both offer emission control solutions from the factory. Caterpillar offers their "Clean Air system" with 0.38 to 0.75 g/kW-hr (0.5 and 1 g/bhp-h) NO_x output. Waukesha offers an "emPact system" with 0.11 to 0.75 g/kW-hr (0.15 and 1 g/bhp-h) NO_x output. The factory supplied solutions include a catalyst and the associated control systems. Modern engine management systems provided by the manufacturer can be adaptive and the reliability of the instrumentation is improving.

Note that the evolution of emissions regulations in the USA required control of carbon monoxide and volatile organic compounds in addition to NO_x in stationary natural gas engine exhaust emissions. Selective catalytic converters are required to mitigate the expanded assortment of emissions components. Waukesha responded to these requirements by making their pre-chambered VHP GL engine models obsolete. At present only VHP LT and VHP GSI models are available as new models. Factory conversions focus on changing previous lean burn engine models to rich burn configurations. A catalyst is assumed to be installed on these engines once they are converted to rich burn.

Higher cylinder head operating temperature resulting in shorter service life of some components, increased fuel consumption and catalyst service all contribute to higher operating costs than required for the pre-chambered or open chambered lean burn engines. Upgrades of existing rich burn engines using Waukesha's latest technology offerings will reduce operating costs to due improved efficiency and enhanced cylinder head cooling. However, these upgrades may not affect NO_x reductions since that is achieved by the installation of a 3-way catalyst.

White-Superior 825 series open chambered engines employ typical ignition systems. The naturally aspirated G series engine are carbureted and the turbocharged models are fuel injected with a fuel valve on each cylinder head that is actuated by a dedicated camshaft. The air intake and exhaust valves are also actuated by dedicated camshafts. The fuel is admitted to the individual cylinder air intake ducts while the cylinder intake valve is open. Some air-fuel mixing occurs in the air intake ducts and some mixing occurs in the combustion chamber during the compression stroke. Exhaust and air manifold control is accomplished with local control valves on the engine. The air manifold pressure and wastegate are controlled independently of the air fuel ratio control. The GT model may have a pulsed turbocharger while the GTL and SGTL have different sizes of turbochargers according to the engine vintage. The turbochargers nozzle rings may have been changed on many of the engines to increase or decrease the desired air flow. The mechanical construction of the engines is robust and many have been in service for several decades.

White-Superior engines are known for valve overlap that sweeps the cylinder of exhaust gasses with air, a process known as scavenging. The air-to fuel ratio is controlled by the pressure of the fuel up-stream of the fuel valves. Increasing the ratio of the fuel pressure relative to the air pressure supplied by the turbocharger(s) to the cylinders controls the air-to fuel ratio. Scavenging causes the exhaust gases to have a higher oxygen content. The trapped air-fuel ratio in the combustion chamber is the actual air-fuel ratio that is subject to combustion. The trapped air-fuel ratio may be rich, stoichiometric or lean. The trapped air- fuel ratio for GT and SGT engine models is rich or stoichiometric. The trapped air-fuel ratio mixtures for the GTL and engines with pre-combustion chambers is lean. The exhaust stream then contains high levels of excess oxygen provided by the valve overlap combined with high NO_x values associated with the stoichiometric (or near stoichiometric) air fuel ratio. The level of excess oxygen in the exhaust stream exceeds the MSAPR limit defining lean burn combustion. Thus, this engine is classified as lean burn by the MSAPR definition due to the high excess oxygen levels in the exhaust despite the high NO_x values not normally associated with a lean burn engine.

White Superior engine management systems on 825 series engines have demonstrated chronic hard starting and reliability issues. A REMVue or REACTT air fuel ratio control will help to manage control of the air manifold pressure, the wastegates and the air fuel ratio to enable easier starting and improve engine reliability. However, in the case of the SGT model, the tuning of the engine is very specific and offers a narrow operating range. Spartan technicians are required to make periodic adjustments for seasonal variations or operating load changes. NO_x compliance to MSAPR can be achieved with GT, SGT or GTL engine models by adjustment of air fuel ratio. Combustion in a NSCR (3-way) catalyst is not supported because the excess oxygen in the exhaust is too high.

V. Engine Models Comprising Less Than 5% of the Alberta Fleet

The styles of engine and their vintage present significant variety. Engine types represented in this category are four stroke or two stroke, separable or integral, high speed or low speed. The engine management systems offer similar variety depending on the age of the engine and what upgrades have been installed. Engines that fall into the following general categories listed in order of the most frequently listed.

- Large slow speed Integral (trunk type) compressors made by Cooper Bessemer, Worthington, Clark, Ingersoll Rand, Chicago-Pneumatic (legacy machines),
- Separable medium speed engines made by White-Superior Superior (early 825 series), Waukesha (early VHP series), Caterpillar (G-300 series) (legacy machines), Worthington (legacy machines), Delval-Enterprise (legacy machines), Fairbanks-Morse MEP,
- Integral compressors made by Ajax, Ariel,
- Separable higher speed engines that did not gain popularity made by Arrow, Cummins, Admiralty, Superior 2400 series, Jennbacher J series,
- Larger modern separable engines made by Caterpillar (GCM, MWM), Waukesha (ATGL, 275 GL series), Wartsila,
- High speed, modern separable engines that are unpopular, discontinued or below the MSAPR power ratings made by Superior (2400 series), Caterpillar (G3520LE, G3500 B series, G3400 NA series, G3400 TALE series, G3300 NA series, G3300 TA series), Waukesha (VSG GL series, VSG GSI series), and White-Superior SGTD-825 series.

V.1. Large Slow Speed Integral Compressors

Integral engine models were popular up to the 1980's. They are massive and slow speed. One crankshaft is used for power pistons and compressor pistons. The compressor cylinders are normally arranged horizontally and the power cylinders are arranged vertically in a line or a vee configuration. Fuel delivery systems are typically injected. Turbochargers and superchargers became more popular in later models. Operating speeds are typically between 300 and 450 RPM. They operate indefinitely with good maintenance. The integral engines are common in both pipeline and gathering networks. They are found producing natural gas and in gas plants in mature fields.

Parts for most of these engines can be obtained from the OEM or third party suppliers. Mechanics with the skills to maintain the intricate engine management systems and the large cast iron engine blocks are becoming rare. All of these engines were manufactured as rich burn engines in either two stroke or four stroke configurations. The engine design is robust and often requires special tools and skills to tune and maintain.

Two stroke engines often incorporate oil in the fuel or air delivery system. This oil entrainment will damage a catalyst so that alternative is not available for two stroke engines. Low NO_x systems are produced by some OEM's using pre-chambers or an open chamber lean burn system.

Maintenance costs for these engines will be high simply because the components are very large and a supply of new parts will be limited. The population of these engines is declining and that does not support developing new supply networks or product development. Combining the high cost of maintenance, upgrades and declining production profiles produces unfavorable economics. The benefit of replacing the units may offer a more attractive option.

V.2. Separable Medium Speed Engines

Separable medium speed legacy engines by Waukesha and White-Superior emerged in the 1960's. They are coupled to compressors that were designed for the operating speed of the engines at 900 or 1,000 RPM. The first engines were naturally aspirated with rudimentary fuel delivery systems using pneumatic controls and magneto powered ignition systems. It is rare to find one of these engines currently operating in the same configuration. Most of them have been upgraded with more modern components. The economics are assisted with the following upgrade options.

- Increase operating speed (if possible),
- Zero hour engine rebuilds (refurbished engine brought up to current modern design standards),
- Exhaust treatment or rich to lean conversions,
- Modern ignition systems, and
- Adaptive engine management control systems.

The life of these engines is extended by the availability of modification options from both the OEM and third party suppliers. These engines included in the category of less popular models because those without the ability to increase the operating speed (due to compressor or driven equipment restrictions) have not been upgraded.

Medium speed separable engines by Delaval-Enterprise and Fairbanks Morse (MEP) fall into two categorises. The first, Delaval-Enterprise was manufactured in the early 1970's and is no longer produced. Operating speeds for these separable compressors are between 450 and 630 RPM. The size of the engine and compressor is larger than the high speed machines. Cooper Machinery Services produces parts for these engines. Upgraded control systems with pre-chambers are available.

The second is the Fairbanks Morse opposed piston engine. These engines are two stroke, operate at 900 RPM and are arranged with a crankshaft at the top and bottom of the engine crankcase. The pistons travel toward each other vertically to meet at the center of the engine where combustion is initiated. The two stroke configuration makes it unsuitable for application of a catalyst for exhaust NO_x treatment. The MEP is a diesel engine (submarine service) retrofit for natural gas service of the Fairbanks Morse OP engine model. The OP engine is available as a new natural gas fuelled engine. Several MEP engines remain in service. Low NO_x engine management systems are available. The engine is equipped with turbochargers or superchargers or both. Fuel is injected at the center of where the pistons meet.

V.3. Integral Compressors Made by Ajax, Ariel

Another alternative of integral compressors that gained little popularity are the Ariel JGS compressor. This was a small integral compressor with two models that Ariel Corporation developed in the 1970's. The power limit is below what MSAPR requires for emissions compliance. Ariel continues to support this compressor. Ariel does not produce the JGS except by special order.

Ajax integral compressors have been manufactured since 1958. The product line offers a variety of sizes. The engines are two stroke and thereby not candidates for exhaust treatment using a catalyst. Low NO_x combustion systems offered by the manufacturer are available to be compliant to MSAPR requirements. The older models will require upgrading the ignition system. Ajax power cylinders have the reputation of burning virtually any quality of fuel but that will also affect the emissions. The engine often has a rhythm like a galloping horse which memorable to those who operate them. Ajax machines continue to be available as a new product.

V.4. Separable Higher Speed Engines

Arrow and Cummins produce smaller, high speed natural gas engines. Arrow engine offers four model series designed for pump jacks and small compressors. All of these engines fall below the MSAPR power threshold. Arrow engines did not find a substantial market in Canada because their ignition and control components did not meet Canadian regulatory requirements. The engines are rich burn and NO_x emission exhaust treatment can be achieved by use of a catalyst.

Admiralty engines are rebuilt diesel engines used for submarine and marine service. Natural gas conversion models have not been available for decades. Some were used for pumps and generators and may be providing emergency capacity. The combustion configuration for the natural gas converted engines could not be determined. Aging military applications continue to operate diesel models as 1400 kW generators.

Superior produced their 2400 series engine based on a Mitsubishi design. The engine is configured with 6, 8, 12 or 16 cylinders producing between 900 and 2400 kW. 2400 series engine employ pre-chambers and utilize the Superior Clean Burn engine management system They are compliant with MSAPR regulations as a modern engine. The engines demonstrated unreliable service due to unstable operating characteristics. Continuous maintenance attention is required to keep them on line. These engines are being retired from service.

Cooper has updated their 825 series engines with their SGTD models. These models are pre-chambered and equipped with the latest Cooper engine management system. They achieve less than 1 g/kW-hr NO_x according to Cooper's specifications. They are compliant with MSAPR regulations as a modern engine. The SGTD models are available in 8, 12 and 16 cylinder configurations. The reliability and performance of the engine is unknown to the authors. No SGTD models are installed in Alberta.

Jennbacher J series (now Type 2 engines) are used as mechanical drive units in limited applications. Jennbacher offers a wider range of models that produce between 235 kW and 9350 kW with most engines in power generation. Their engine management systems are advanced, adaptive and contain pre-chambers. They will be compliant with MSAPR regulations. These engines are high performance and thus require more frequent service intervals, especially under variable load conditions. The engine is relatively new to North America and operators tend to shy away from unfamiliar products.

V.5. Larger Modern Separable Engines

Caterpillar produces two large separable engines that define the top end of their power range. The GCM engine is pre-chambered, very large and operates at medium speed. Caterpillar's engine management systems are normally reliable so this engine will likely perform as advertised. The large physical size of this engine makes transportation difficult. A few might be running in Canada and perhaps in Alberta.

Caterpillar's MWM engine is a product they purchased from a German Manufacturer. A few are in service in Alberta and Canada. They employ an open chamber lean burn combustion style that is complicated to operate and run at higher speeds. Due diligence by the Producer is recommended if these engines are in consideration. Technical support for the MWM engines offers incomplete technical data and frustrating exercises working with the representatives. Both these engine series offer engine management systems that will be compliant with MSAPR regulatory limits for modern engines.

Waukesha introduced the AT25GL engine series in the early 1990's which was later upgraded to the AT27GL series. These models were unreliable due to unstable control systems and required constant tuning. A mechanic certified by the OEM was required for that tuning and this requires an ongoing expense with mechanics that were few. Many Producers abandoned the engines. Installing an AFR control like the REMVue system can solve the reliability issues. The AT platform was updated to the 275GL series with electronic engine management controls. This, too, presented reliability issues with unstable engine operation but the stability issues were different than the AT engine. The latest version of this engine is the 275+ which employs updated adaptive engine controls to reportedly offer more stable operations. The authors do not have personal experience with these engine models so the operator should exercise due diligence if this engine is in consideration. The engine provides higher rated power and those applications are fewer so the quantity of operating engines are also fewer.

V.6. Separable Higher Discontinued and Small Engines

Caterpillar engine models that have been discontinued are as follows;

- G3520LE,
- G3400 NA series,
- G3400 TALE series,
- G3300 NA series, and
- G3300 TA series).

These very popular engine models remain in service in large quantities and operate at speeds up to 1800 RPM. The models were discontinued because the engine management systems will not be compliant with MSAPR regulations. Most of the G3300 and G3400 series engine models produce less than the MSAPR regulatory lower power limit. Rich burn models can be upgraded with a catalyst to be compliant. Caterpillar has reworked the engine designs so that all models are compliant with lower NO_x limits. The Caterpillar G3500 B series remains available but did not win any sales in Alberta.

Waukesha's VSG GL series and GSI series have been retired from their product line. VSG series engine are characterized by 1800 RPM operating speeds in a six cylinder design producing between 90 and 180 kW. These engine models continue to operate with parts available. The engines are configured as rich burn combustion. Emissions from these engines will not be compliant with MSAPR NO_x regulations without the addition of a catalyst.

APPENDIX J

FIELD EXHAUST SAMPLE LAB TESTS WITH COMPARISON TO CEMS DATA

OEM and Test Emissions vs. Analytical Lab Results

Engine Data			Emissions Level										Operating conditions			Reference	
Make	Model	Combustion Style	CH4					CO2					O2			Signet Report Number	Lab File
			OEM		Lab	Test		OEM	Lab		Test		OEM	Lab	Test		
		Description	g/kW-hr	ppmvd 15%O2	ppmvd 15%O2	g/kW-hr	ppmvd 15%O2	g/kW-hr	ppmvd	ppmvd 15%O2	g/kW-hr	ppmvd 15%O2	%				
Caterpillar	G3608	Lean	6.85	1226	832	6.14	987	589	55500	34965	563	33007	11.7	12.9	11.6	101298 T1	CEN-10-36-#4
Caterpillar	G3612	Lean	4.82	879	564	4.11	693	562	58500	35100	524	32244	11.4	12.3	11.1	101281 T1	TOU-07-09-K-603
Caterpillar	G3408	Rich	2.98	460	160	1.26	174	616	112000	35840	661	33193	2.0	3.2	2.2	101282 T1	TOU-02-17-K-201
Waukesha	L7042GSI S2	Rich	1.70	243	165	2.03	234	650	120000	35400	735	30895	1.4	1.8	0.9	101296 T1	PAR-14-29-K-220
White Superior	16SGT825	Rich	Not Avail.	Not Avail.	1180	8.18	1287	Not Avail.	75900	35673	584	33457	Not Avail.	9.5	8.3	101299 T1	CEN-01-08-K-102
White Superior	8GTLE825	Lean	Not Avail.	Not Avail.	1458	10.31	1569	Not Avail.	65600	35424	592	32820	Not Avail.	11.4	10.0	101292 T1	NOR-11-26-1

Lab tests do not indicate if samples are wet or dry

APPENDIX K

Methane Emissions in Engine Blowby

Methane Emissions in Engine Blowby for Common Stationary Engine Models Based on an Inventory List from ECCC's MSAPR Engine Database

Make	Model Designation as described in ECCC MSAPR list	Total number of engines		Assumed Engine Models	Nameplate power (kW) (estimated)	Blowby Rate (GEM Data for worn engine)	Individual Methane Emissions in Engine Blowby (worn engine)				Total Methane Emissions in Engine Blowby (m3/h) (worn engine)							
							CSU Data (3% of GEM Blowby Rate)	GEM Emission Factor (20% of Total GEM Predicted Methane Slip)	Accurata Estimate (40% of Total Methane Slip Based on Emission Factors applied to MSAPR list)	Howard Malm Estimate (kW*0.0017/0.9)	CSU Data (3% of GEM Blowby Rate)		GEM Emission Factor (20% of Total GEM Predicted Methane Slip)		Accurata Estimate (40% of Total Methane Slip Based on Emission Factors applied to MSAPR list)		Howard Malm Estimate (kW*0.0017/0.9)	
		Canada	Alberta			m3/h	m3/h				Canada	Alberta	Canada	Alberta	Canada	Alberta	Canada	Alberta
	8LAT27GL	8	3		1370	102	5.1	5.5	5.8	5.0	24	13	26	16	51	19	24	13
	12V AT25GL	9	1		1940	135	4.6	2.6	4.7	5.7	41	3	25	3	45	3	55	4
	12V AT27GL	6	4	Pre-chamber LB	2535	135	4.6	4.8	5.7	4.4	28	18	29	19	34	25	26	18
	16V AT27GL	1	1		3375	204	6.1	7.0	8.5	6.4	6	6	7	7	8	8	6	6
	16V275GL	3	0		5536	204	6.1	5.1	8.2	6.5	51	0	15	0	41	0	52	0
	L7042GL/GLS/GL FSM	413	323	Pre-chamber LB	1105	156	4.1	1.5	2.7	2.1	1,691	1,324	625	488	1,119	876	863	677
	L7042GSI/GSI U/GSI D/S4/GSI RSM/GSI L	507	403	Rich burn	1105	156	4.1	0.5	1.5	2.1	2,096	1,650	230	200	671	556	1,056	844
	L7042GSI S4	38	35	Rich burn	1105	156	4.1	0.7	0.2	2.1	155	154	27	25	7	6	79	69
	L7042GSI S5	37	29	Rich burn, modern	1119	156	4.1	0.2	0.2	2.1	151	118	8	6	7	6	78	61
	L7044GSI/GSI RSM/G	305	255	Rich burn	1235	156	4.1	0.6	1.3	2.4	1,253	930	170	150	436	330	717	531
	L7044GSI S4	5	5	Rich burn	1235	156	4.1	0.8	0.2	2.4	12	12	2	2	1	1	7	7
	L7044GSI S5	24	24	Rich burn, modern	1417	156	4.1	0.5	0.5	2.7	98	98	6	6	6	6	64	64
	P9390GSI/GSI U	24	24	Rich burn	1476	170	5.1	0.7	1.8	2.8	122	122	16	16	45	45	67	67
	P9394GSI	12	10	Rich burn	1476	170	5.1	0.9	1.8	2.8	61	51	11	9	21	18	33	28
	P9390GL/AFM	17	17	Pre-chamber LB	1476	170	5.1	2.0	3.6	2.8	87	87	34	34	61	61	47	47
	P9394GSI S5	1	1	Rich burn, modern	1364	170	5.1	0.5	0.4	3.3	3	3	0	0	0	0	4	4
Waukesha	F3521GSI/GU/GSI U/GSI C/G/HA, F3524GSI	255	196	Rich burn	351	63	2.0	0.2	0.7	1.0	520	399	55	41	169	130	263	204
	F3521GL	53	40	Pre-chamber LB	351	63	2.0	0.7	0.9	1.0	108	82	40	30	48	36	55	42
	F3514GSI/GSI FSM/GU	25	19	Rich burn	352	63	2.0	0.2	0.7	1.0	51	39	5	4	17	15	26	20
	F2895GU/GSI U/GSI	58	44	Rich burn	435	63	2.0	0.1	0.3	0.9	118	90	8	6	32	24	50	38
	F2895G	11	11	Rich burn	514	63	2.0	0.1	0.4	0.6	22	22	1	1	4	4	7	7
	F2895GL/GL FSM	6	6	Lean burn	435	63	2.0	0.6	0.7	0.9	12	12	4	4	4	4	5	5
	L5790GU/GSI U	38	28	Rich burn	949	156	4.1	0.5	1.1	1.8	155	114	11	8	45	32	68	50
	L5790G	11	8	Rich burn	650	156	4.1	0.2	0.8	1.2	45	33	3	2	8	6	13	10
	L5790GL	46	39	Pre-chamber LB	906	156	4.1	1.2	2.2	1.7	187	159	57	48	102	86	79	67
	L5774LT/LT/LTF/LT RSM, L5794LT/RSM/LTF	103	76	Lean burn	934	156	4.1	1.0	1.6	1.8	440	310	106	75	163	113	193	137
	L5794LT/RSM/LTF	136	96	Lean burn	1031	156	4.1	1.1	1.8	2.0	554	391	131	107	242	171	278	196
	H24GL/GLD/GL LCR/GL NRC	350	263	Lean burn	400	16	0.5	0.3	0.7	0.8	158	127	102	82	217	174	249	200
	H24GSI/H2475G	9	9	Rich burn	400	16	0.5	0.1	0.5	0.8	4	4	1	1	4	4	7	7
	F18GL/GL LCR/GL NCR/	254	202	Lean burn	300	12	0.4	0.2	0.5	0.6	94	75	54	47	115	100	155	114
	F18GSI/SI/GSID	4	5	Rich burn	300	12	0.4	0.1	0.4	0.6	1	1	0	0	1	1	2	2
	L36GL/GL NCR/GL LCR, F48GL	37	37	Lean burn	600	24	0.7	0.5	1.0	1.1	41	27	26	17	56	37	65	42
	F48GL	38	49	Lean burn	300	52	1.0	0.6	1.5	1.3	56	44	56	23	76	61	83	70
	L36GSI/GSID, F48GSI	4	4	Rich burn	600	24	0.7	0.2	0.7	1.1	5	5	1	1	5	5	3	3
	F48GSI	1	1	Rich burn	300	52	1.0	0.5	1.0	1.3	1	1	0	0	1	1	2	2
	G3606/TA W/TALE/TA/LE/CC TA	82	56		1524	35	1.6	2.0	5.2	2.5	150	89	166	114	265	181	205	140
	G3606 A4	6	6		1417	37	1.7	1.6	3.5	2.7	10	10	9	9	21	21	16	16
	G3608/TA WLE/TA W/LE/SITA	302	178		1767	71	2.1	2.7	4.5	5.5	640	377	817	482	1,304	769	1,003	594
	G3608 A4	19	19	Pre-chamber LB	1364	73	2.2	2.1	4.6	5.5	42	42	39	39	87	87	67	67
	G3612/TA W/TA/SITA/LE/A3	152	80		2647	106	5.2	4.1	6.5	5.0	485	254	616	324	984	518	760	400
	G3612 A4	2	2		2796	112	5.4	5.1	6.8	5.5	7	7	6	6	14	14	11	11
	G3616/TA LE/A1 RC/TA/LE/CC	79	41		3351	141	4.2	3.4	8.6	6.7	333	174	427	222	682	354	527	275
	G3616A DFM4	2	2		3729	149	4.5	4.1	9.1	7.0	9	9	8	8	18	18	14	14
	G3516TALE/A1 RC/LE/B/C	418	305	Lean burn	858	54	1.0	0.7	1.4	1.6	430	312	289	210	590	428	677	491
	G3516TA	54	54	Rich burn	809	52	1.0	0.5	1.0	1.3	55	55	9	9	55	55	72	72
	G3516HA	9	7	Rich burn	492	20	0.6	0.5	0.6	0.9	5	4	5	2	5	4	8	7
	G3520/LE/B LE/TALE/H/C/H EE TA LE/B1 S4	40	33	Lean burn	1104	44	1.5	0.9	1.8	2.1	55	44	56	29	75	60	85	69
	G3512/TA/TA W/SITA	37	28	Rich burn	589	24	0.7	0.2	0.7	1.1	26	20	7	6	26	20	41	31
	G3512TALE/A1 RC/LE/B	310	240	Lean burn	642	26	0.8	0.5	1.1	1.2	259	183	161	124	327	235	376	291
	G3512HA	10	5	Rich burn	591	16	0.5	0.2	0.5	0.7	5	2	2	1	5	2	7	4
	G3508TALE/TAW LE/LE	23	18	Lean burn	500	20	0.6	0.4	0.8	0.9	13	11	10	7	21	13	24	17
Caterpillar	G3508/TA, SITA	4	4	Rich burn	391	16	0.5	0.1	0.5	0.7	2	2	1	1	2	2	3	3
	G379TA	4	3	Rich burn	239	10	0.5	0.1	0.5	0.5	1	1	0	0	1	1	2	1
	G398 TA/TAW/SITA	13	11	Rich burn	548	14	0.4	0.1	0.4	0.7	5	5	1	1	5	5	9	7
	G398 HA	9	9	Rich burn	272	11	0.5	0.1	0.5	0.5	5	5	1	1	5	5	5	5
	G399 TA/TAW/SITA	4	4	Rich burn	318	21	0.6	0.1	0.6	1.0	2	2	1	1	2	2	4	4
	12-CG137	4	4	Rich burn	447	18	0.5	0.4	0.5	0.8	2	2	1	1	2	2	3	3
	8-CG137	1	1	Rich burn	298	12	0.4	0.2	0.4	0.6	0	0	0	0	0	0	1	1
	G3408TA/TAW	96	74	Rich burn	298	12	0.4	0.2	0.4	0.6	34	26	18	14	34	26	54	42
	G3408 LE/CLE/C	30	11	Lean burn	298	12	0.4	0.2	0.5	0.6	11	4	6	2	13	5	17	6
	G3412TA/TAW/SITA	96	76	Rich burn	448	18	0.5	0.5	0.5	0.8	52	41	29	25	52	41	81	64
	G3412HA	2	2	Rich burn	272	11	0.5	0.2	0.5	0.5	1	1	0	0	1	1	1	1
	G3412LE/C/CLE/TA LE/A1 RC	36	27	Lean burn	448	18	0.5	0.2	0.7	0.8	20	13	14	7	41	20	47	25
	G3406HA	4	4	Rich burn	160	6	0.2	0.1	0.2	0.5	1	1	0	0	1	1	1	1
	G3406TA	18	10	Rich burn	242	10	0.5	0.1	0.5	0.5	5	5	2	1	5	5	8	5
	G3306/B/BTA/TA/AT AAC	19	16	Rich burn	149	6	0.2	0.0	0.2	0.5	5	5	0	0	5	5	5	5
	G3306HA	2	2	Rich burn	108	4	0.1	0.0	0.1	0.2	0	0	0	0	0	0	0	0
	6G825	26	21	Rich burn	447	18	0.5	N/A	0.6	0.8	14	11	N/A	N/A	15	15	22	18
	8G825	78	71	Rich burn	597	24	0.7	N/A	0.8	1.1	56	51	N/A	N/A	62	57	88	80
	12G825	13	13	Rich burn	895	36	1.1	N/A	1.2	1.7	16	16	N/A	N/A	18	18	23	23
	16G825	18	18	Rich burn	1193	48	1.4	N/A	1.6	2.3	26	26	N/A	N/A	29	29	41	41
	8GT/GTL	81	65	Rich burn	820	55	1.0	N/A	2.9	1.5	80	62	N/A	N/A	236	184	123	98
White Superior	12SGT	4	4	Rich burn	1491	60	1.8	N/A	5.3	2.8	7	7	N/A	N/A	21	21	11	11
	16GT/GTL	6	6	Rich burn	1641	66	2.0	N/A	5.8	3.1	12	12	N/A	N/A	35	35	19	19
	16SGT	18	10	Rich burn	1976	79	2.4	N/A	7.0	3.7	43	24	N/A	N/A	126	70	67	37
	8GTLE/B/X	9	9	Pre-chamber LB	820	55	1.0	N/A	5.6	1.5	9	9	N/A	N/A	55	55	14	14
	12SGTLE/SGTB/	3	3	Pre-chamber LB	1491	60	1.8	N/A	6.6	2.8	9	3	N/A	N/A	55	20	14	8
	16SGTB/SGTD	19	17	Pre-chamber LB	1976	79	2.4	N/A	8.8	3.7	45	40	N/A	N/A	167	149	71	63
						Total estimated Methane Emissions in blowby (m^3/h)					11,307	8,472	4,586	3,106	9,261	6,483	9,345	6,739
						Total estimated Methane Emissions in blowby (m^3/y)					99,048,758	74,212,581	40,172,703	27,206,670	81,122,821	56,790,267	81,860,215	59,030,366
						Total estimated Methane Emissions in Blowby (Tonnes/h) based on 0.9 kg/m^3					10	8	4	3	8	6	8	6
						Total estimated Methane Emissions in blowby (Tonnes/y) based on 0.9 kg/m^3					89,144	66,791	36,155	24,486	73,011	51,111	73,674	53,127
Notes																Total Fleet Methane Slip (Tonnes/y)	132,500	127,300