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Development of Quantification Methodology for Methane Emission through Venting in Alberta

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Development of Quantification Methodology for Methane Emission through Venting in Alberta Oil and Gas Industry

by

Shin Roey Tan

A RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

GRADUATE PROGRAM IN SUSTAINABLE ENERGY DEVELOPMENT

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Abstract

Methane emission accounts for a huge proportion of the total GHG as it is 25 times more potent than CO₂. New requirements through Directive 60 from AER mandate producers to quantify and report on the methane emissions from the facilities. This research focuses on the quantification methodology on methane emission via venting processes in Alberta oil and gas industry to achieve compliance as there is a limit imposed on the annual venting. This research is conducted through literature review, interviews with industry SMEs, and seminars on related technologies. Two quantification models are identified; measurement and estimation, and these models are analyzed to most appropriately establish their suitability and economics under different conditions. Proper design and implementation of either model will ensure the effectiveness in the quantification and reduction of methane emissions in the oil and gas industry and meeting the target set out by ACLP.
Acknowledgement

The Sustainable Energy Development program at University of Calgary is prompted by the need to re-discover my love and passion for sustainability after a decade of employment in the oil and gas industry. Through the duration of my study of this program, there are many people who have supported, encouraged, and inspired me on this journey.

To my research supervisor, Dr. Anil Mehrotra, I would like to express my sincere gratitude for the sage advice and guidance given and not forgetting for giving me the space to progress through the research at my own pace, which may not necessarily be according to the timeline. I would also like to extend my gratitude to Dr. Irene Herremans who provided the assistance on this program from the beginning to the end; she has been truly helpful on all the advices and tips provided in order for me to complete the research project without hiccups. Also, not forgetting Dr. Matt Rahimi from Canadian Standards Association (CSA), also an adjunct professor at the Haskayne School of Business at the University of Calgary, who contributed to such a wonderful idea for research project; a topic that meets the requirements of the program and being so significant to me on a personal level. This has indeed been a serendipity for me.

Besides the academic team that has supported me, there is also a team of industry people I am be grateful for. To my mentor, Doug Koroluk, you have been an inspiration and fountain of knowledge in my journey not only to this program but also to this country as a newcomer. To Ian Kuwahara from AER and Roy Meyer from Imperial Oil, I would like to express my sincerest gratitude for their time and expertise in coaching and guiding me through topics that I am not well-versed in. That knowledge and information have been tremendous in the completion of this
research project. Not forgetting Spartan Controls, and especially Dane Etwaroo for willing to provide help to a complete stranger via email. I must admit that I have never cold-called prior to this and I have to agree that it isn’t a bad thing after all. You have given me a wonderful experience, not just through the information but also through the contact with other subject matter experts in Spartan and for registering me to the Spartan University Day. I look forward to many more University Days to gain further knowledge and hone my rusty instrumentation knowledge. To all the above, I would not have been able to accomplish it without your help.

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Abbreviations

acf       Actual cubic feet

ACLP      Alberta Climate Leadership Plan

AER       Alberta Energy Regulator

AGA       American Gas Association

ANSI      American National Standards Institute

BTEX      Benzene, Toluene, Ethylbenzene, and Xylene

CAPP      Canadian Association of Petroleum Producers

CCAL      Canadian Centre for Advanced Leadership in Business

CDP       Carbon Disclosure Project

CFD       Computational Fluid Dynamics

CO₂       Carbon dioxide

CO₂e      Carbon dioxide equivalent

CSA       Canadian Standards Association

EEMS      Environmental Emissions Monitoring System

EPA       Environmental Protection Agency

ERA       Emissions Reduction Alberta

ESDV      Emergency Shut Down Valve

FERC      Federal Energy Regulatory Commission

GDP       Gross Domestic Product

GHG       Greenhouse Gas

H₂S       Hydrogen Sulphide

ISO       International Organization for Standardization
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>LDAR</td>
<td>Leak Detection and Repair</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-governmental Organization</td>
</tr>
<tr>
<td>PDE</td>
<td>Partial Differential Equation</td>
</tr>
<tr>
<td>PHAST</td>
<td>Process Hazard Analysis Software Tool</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per million</td>
</tr>
<tr>
<td>ppm-m</td>
<td>Parts per million-meter</td>
</tr>
<tr>
<td>PTAC</td>
<td>Petroleum Technology Alliance Canada</td>
</tr>
<tr>
<td>scf</td>
<td>Standard cubic feet</td>
</tr>
<tr>
<td>SEDV</td>
<td>Sustainable Energy Development</td>
</tr>
<tr>
<td>sm$^3$</td>
<td>Standard cubic meter</td>
</tr>
<tr>
<td>SME</td>
<td>Subject Matter Expert</td>
</tr>
<tr>
<td>TDL</td>
<td>Tunable Diode Laser</td>
</tr>
<tr>
<td>TEG</td>
<td>Triethylene Glycol</td>
</tr>
<tr>
<td>UDM</td>
<td>Unified Dispersion Modelling</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compound</td>
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Chapter 1. Introduction

The Alberta Climate Leadership Plan (ACLP) was introduced following the Pan Canadian Framework on Climate Change which is a result of the ratification of Paris Accord by Canada. Its aim is to reduce manmade activities that resulted to the release of greenhouse gas (GHG) in an attempt to keep the global temperature rise this century well below 2°C above the pre-industrial level (UNFCCC, 2018). One of the objectives of the ACLP is to reduce methane emissions within the province by 45% by 2025 (Alberta Government, 2018a). The focus on methane reduction is since methane is considered a highly potent GHG which is 70 times more than carbon dioxide (CO$_2$) (Environment and Climate Change Canada, 2018). The largest source of methane emissions in Alberta is from the oil and gas industry accounting for 70% of methane emission in the province and hence targeting this industry would be crucial to meeting the overall objective as set out by ACLP.

Flaring and venting processes are regulated by Alberta Energy Regulator (AER) through Directive 60 – Upstream Petroleum Industry Flaring, Incinerating and Venting. Venting is typically performed as an alternative to flaring, to maintain safe operating conditions, such as direct blowdown through the equipment when there is operational upset. Another cause might be there is no redirection of natural gas to the flare header, which is often seen in older production facilities as designs in the earlier years do not cater to such requirements.

The changes to Directive 60 in March 2018 have focused on the targets set out by the ACLP in reducing methane emissions. It has now introduced a new requirement to venting, which differs from its predecessor, in that it is now required for the oil and gas producers to reduce venting,
and where it is not possible and venting must be performed, it must be limited to a certain amount, either annually or monthly.

1.1 The Research Problem

Prior to the changes to Directive 60 in March 2018, there was never a need to measure and quantify the release of methane through venting process. Hence, any producer who wishes to conduct the venting process would only need to apply for a permit from AER. The new requirements from Directive 60 has resulted in technical developments in the elimination, reduction, and measurement of methane gas through the venting process. As this was never practised before, producers will undoubtedly be faced with the challenge of complying with the new requirements to ensure that they are operating within the law.

AER recognizes this issue and under Section 8.2 in Directive 60, it has been mentioned that ‘Manual XXX (publication forthcoming)’ will provide guidance on how to estimate vent gas and fugitive emissions. However, such manual has yet to be published and provided to the producers for guidance.

A procedure or guideline is crucial in achieving the target of methane reduction as it will provide a standardized quantification and reporting protocol for all producers in Alberta to submit to AER. This will ensure that the error margin from the quantification will be consistent throughout for all producers. Furthermore, Alberta government has also pledged to transition to carbon competitive system in its greenhouse gas emissions in Jan 2018. This system will allow for a facility to receive performance credits if their greenhouse gas emissions are less than the amount freely permitted (Alberta Government, 2018c). It will therefore require accurate quantification
that is verified to ensure that any initiative undertaken to reduce methane emissions is captured and reported and subsequently its performance credits are evaluated accordingly.

1.2 The Purpose of the study

This research project is focused on the development of the quantification methodology of methane emission through venting in Alberta oil and gas industry. The main objective of this study is to determine and define the required parameters in methane venting measurement to complement AER’s Directive 60 requirements. The focus of the study will be limited to only intentional release of methane, i.e. venting, and will exclude fugitive emission, which is defined as the uncontrolled release or leaks from valves, pumps, or flanges. This study is important as it will allow for standardization measurement and reporting within Alberta and comply with the requirements from AER Directive 60.

The methane venting quantification can be uploaded on ‘real-time’ to the AER’s website for ‘live’ inventory and provide the AER with a better management tool. This management tool can be developed through established reporting system that provides both quantification and reporting platform. Oil and gas producers will benefit from this management tool as it can benefit from the monitoring and devise an initiative to improve on its operational efficiencies. This will also align the provincial direction with the federal one through Environment and Climate Change Canada where it has proposed for a regulation on the restriction of venting unless it is for emergency venting and utilizes current provincial reporting activities (Environment and Climate Change Canada, 2018).
This research on the study of parameters definition on methane quantification is useful for the oil and gas industry as it will first and foremost provide the producers with compliance to the regulations and continue its operation without suspension and be less damaging to the environment. Secondly, it would also provide standardization on procedural development on the quantification and reporting of methane emission to the AER which will simplify its job for verification purposes. Lastly, it would serve to provide a framework platform for the committee that would oversee the development of the procedure.

This study is anchored in three dimensions of sustainability: the energy, the environment, and regulatory compliance of methane venting. The environment pillar focuses on the climate change resulting from methane emission, which is a potent GHG contributor. Any reduction or elimination of methane emission is crucial to combatting climate change. The energy pillar is centered on the oil and gas sector which is core to the provision of energy for the society at large. The oil and gas industry are the largest industry in Alberta accounting for 17% of its annual Gross Domestic Product (GDP) and hence, the research focusing on the oil and gas industry in Alberta would essentially be focusing on the largest energy provider in the province (Alberta Government, 2018b). Coupled with the fact that the largest source of methane emissions in Alberta is directly resulted from the oil and gas operation, it would seem vital that the focus be put on this industry. The last pillar focuses on regulatory compliance from the requirements of Directive 60. The development of the guidance on measurement and estimation models would provide a better planning and execution to meeting the requirements of Directive 60 and being compliant of the regulation.
The research methods primarily focus on literature research, interviews with industry experts, and attending seminars on new technologies and innovations that are relevant to the quantification development.
Chapter 2. Literature Review

2.1 Background

Canada is a signatory country to Paris Agreement, which is the continuation of the Kyoto Protocol that seeks to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2°C above pre-industrial level (UNFCCC, 2018). As such the focus will be on the control and management of GHG which the main contributor to climate change is. This signatory is ratified in 2016 and sets out domestic actions and works with provinces and territories to establish a Pan-Canada framework on climate change. This framework will ensure that the provinces have the flexibility to implement climate policies while working together to achieve Canada’s national emission reduction targets (Government of Canada, 2018).

Alberta has since introduced the ACLP in response to the federal framework and listed four key aspects as part of the GHG emission reduction commitment. One of the key aspect is addressing the methane emission reduction with a target of 45% reduction by year 2025 (Alberta Government, 2018a). This is a strategic component to the reduction of GHG emission over other aspects as methane is 70 times more potent than carbon dioxide as a GHG over a 20-year period to trap heat (Environment and Climate Change Canada, 2018).

Currently in Alberta, the largest source of methane emission is the oil and gas industry and accounts for 70% of the province emissions in 2014 (Alberta Government, 2018d). Flaring is the controlled burning of natural gas as part of production and processing to maintain operational efficiency and avoid production upset and downtime. Venting is the controlled release of natural
gas directly into the atmosphere as part of regular operation. Any uncontrolled release of natural gas as part of the operation such as leak, or malfunction equipment is known as fugitive emission (AER60, 2018). Canadian Association of Petroleum Producers (CAPP) reported that 48% of methane emission is from direct venting from equipment which is intentional emission, and 46% from fugitive emission (CAPP, 2018).

2.2 Methane Emissions

Methane is a considerable source of climate change due to its high greenhouse gas potential, 25 times higher than carbon dioxide over a period of 100 years. Alberta government has provided funding to address methane emissions in Alberta back in 2016. The focus areas on the proposal are (ERA, 2018):

- Methane emissions detection and quantification
- Reduction of methane emissions from oil and gas, agriculture, waste and other sources.

Methane emissions might be coming from sources such as incomplete combustion of natural gas through flaring, fugitive emissions from oil and gas sector, agriculture, waste, and venting from oil and gas sector. Venting of methane emissions is of considerable spotlight as it is intentional and makes up the highest percentage of the total methane emissions in the province (Alberta Government, 2018d).

Historically, natural gas derived through oil and gas production is not as valued as the oil produced and considered a by-product to which it is disposed off. Hence, the philosophy of the facility design does not integrate the conservation of natural gas and it is simply just redirected to the flare for combustion. As facilities grow to accommodate new processes, retrofitting might
be done minimally to be cost-effective and has neglected to consider the need to redirect natural gas flow to the flare header and subsequently constituting for the need to vent. As venting is done to prevent operational upset, it can be carried out continuously or intermittently, at source or redirected to a vent stack, with or without metering.

The flow diagram below shows the sources of methane emission in an oil and gas facility.

Figure 1. Sources of Methane Emissions

Source: (AER60, 2018)

There are two distinct sources of methane emissions; venting and fugitive. Routine venting is considered continuous or intermittent process on a regular basis as part of a normal operation. This is typical for the equipment listed below on the diagram as this equipment are usually operating continuously. Non-routine venting is usually intermittent and infrequent and can be
categorized into two sections; either planned or unplanned. Planned non-routine venting is typically associated with maintenance, shutdown, or pipeline depressurizing. Un-planned non-routine venting is either due to an upset in the facility such as pressure buildup requiring blowdown or an emergency. Fugitive emission is defined as leak and is considered unintentional release.

In order to combat methane emissions reduction, a committee made up of key players such as regulators, producers, and environmentalists, is formed in 2016 to develop recommendations and options to inform cost-effective regulations for new and existing facilities in the oil and gas sector. This approach is considered to be collaborative and focuses on a multi-stakeholder engagement. These recommendations will include the detection technologies and quantification methodology of methane emissions.

2.3 Regulations at both Provincial and Federal Level

AER has published a draft version of Directive 60: Upstream Petroleum Industry Flaring, Incinerating and Venting in April 2018 that incorporated the ACLP objectives of methane reduction. A review of the previous directive published in 2016 to the current draft highlights the changes to the directive significantly for venting process and fugitive emission. Currently, AER does not allow for venting to be performed at the facility; however, the producer may apply for a permit to justify venting. This venting process may be performed without any requirement to quantify nor to report it to AER (AER60, 2016). The changes to the draft now incorporate that all venting process and fugitive emissions will need to be eliminated, if possible, or reduced. All sources of methane emissions will now be required to be quantified and reported to AER.
Additionally, there is a limit imposed monthly on venting amount by AER to 15,000 Sm$^3$ in a month and must be quantified and reported to AER on an annual basis. Besides the overall vent limit from all sources, there are limits specified specifically for different types of equipment and fugitive emissions. Please refer to Appendix A – Directive 60 Summary of Vent Gas Limits and Fugitive Emission Survey Requirements for more information on the breakdown on the limits imposed for different vent source. Producers are required to start complying with this regulation once the directive is finalized unless an exemption is approved, to which the requirements are only valid starting 2023. Methane emissions may be quantified via continuous metering, periodic testing, or even estimates.

At the federal level, the Minister of Justice has published a draft issue of the Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector) in June 2018. This is in response to the Pan Canadian Framework on climate change. In general, the requirements on venting are similar to Directive 60. The key difference is on the venting limit of 15,000 Sm$^3$ annually instead of monthly. This is crucial information to producers who operate between provinces as these requirements would now be applicable too. Please refer to Appendix B – Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector) for more information on the breakdown on the limits imposed for different vent source.

2.4 Quantification and Reporting Model

To successfully develop the methane emissions methodology, a quantification and reporting model would have to be established.
The quantification model would be based on 2 criteria:

- Direct measurement at source using metering devices;
- Estimation based on empirical data or prediction simulation.

Direct measurement quantification utilizing metering devices is the most direct and simple methodology to be used. These metering devices are accepted in the oil and gas industry for measurement of the oil and gas production and can be adapted to meet the venting parameters. This quantification type will be discussed further in Section 6 below.

Estimation quantification can be done either by empirical analysis or prediction simulation. Empirical analysis is conducted via previous data through an inductive approach. The aim is to generate an emissions factor coefficient that is aligned to the production parameter to infer to the amount of venting released. Prediction analysis, on the other hand, relies on algorithmic software tool to analyze and predict the future release rate of vent gas based on certain parameters. This quantification type will be discussed further in Section 7 below.

Any emission reporting done via estimation is verified with direct measurements at interval and the algorithms are modified to reflect on its most accurate portrayal. Currently, all oil and gas producers are reporting to AER via the Petrinex webpage and this reporting model can be replicated to equip the regulator with the management control with the aim of methane emission monitoring and reduction (Petrinex, 2018).
Chapter 3. Methodology

A gap analysis has been conducted to identify the necessary updates required to understand the requirements on the quantification model. This will also determine how the quantification methodology can be developed to align to the AER’s current direction using previous successful cases. Key documents reviewed are:

- AER Directive 60 – Upstream Petroleum Industry Flaring, Incineration and Venting – approved on March 22, 2016. This will provide the basis on the research approach and direction;

- Environment and Climate Change Canada – Proposed Methane Regulations – published June 2017. This regulation will focus on how the provincial requirements will be directed as we proceed towards meeting the targets; and

- UK Environmental Emissions Monitoring System (EEMS) – last updated Nov 13 2017. This successfully implemented system used in UK for the oil and gas industry can provide a reference as to how the quantification methodology can be replicated in Alberta, with tweaks to ensure that the guidelines remain appropriate and applicable to Alberta’s unique industrial environment.

3.1 Scope

The scope of the research study focuses on:

- Alberta province, Canada only; and

- Limited to only intentional release of methane through venting.
3.2 Parameters

The parameters initially identified for further studies are:

- Volumes of natural gas vented;
- Composition of natural gas;
- Processes associated with venting;
- Continuous vs intermittent venting;
- New vs old facilities;
- Measurement device types;
- Measurement devices’ threshold;
- Calibration and verification of measurement devices;
- Estimation, when measurement is unavailable; and
- Any other parameters yet to be identified.

3.3 Data Collection Procedure

The data collection on the parameters identified for this research study will be conducted through:

- Survey/input from Industry stakeholders such as AER and producer’s association. This will determine the limitations and what the stakeholders’ expectations might be.
- Interview with scholars and subject matter experts (SME). The interview will focus on
  a) parameters that will define the quantification methodology;
  b) Technology available in the market and their advantages and limitations; and
  c) Current operational processes and how it can be improved to reduce venting process.
Assumptions associated with the study.

3.4 Ethical Considerations

This research study will adhere to the ethical guidelines of the Conjoint Faculties Research Ethics Board (CFREB). This includes the basic five principles of ethical considerations outlined below (Laerd Dissertation, 2018):

a) Minimizing the risk to harm

b) Obtaining informed consent from participants

c) Protecting the anonymity and confidentiality of participants

d) Avoiding deceptive practices when designing the research

e) Providing participants with the rights to withdraw from the research at any time
Chapter 4. Timeline

4.1 Progress Report

A progress report was prepared monthly for review by the supervisor, course professor, and the company representative. This was done as outlined in the requirements of the SEDV 625 Research project course and shown in Appendix C. A total of four (4) progress reports were submitted from end of March 2018 to end of June 2018.

4.2 Activities

Activities completed for

March 2018

- Submission of Final Research Proposal to Supervisor and Company Representative for approval and signature
- Continued with literature review
- Meeting with CCAL Mentor, Doug Koroluk for advice and connection
- Initiated contact with AER to understand on Directive 60 draft which had not been published yet

April 2018

- Submitted first progress report to Supervisor, Company Representative and SEDV 625 professor
- Interview with Ian Kuwahara, Senior Technical Advisor from AER on Directive 60 changes
- Researched on Draft Directive 60 which is published for public viewing and comment
- Researched on Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector) which is published for public viewing and comment

- Data collection on parameters identified for further researched

May 2018

- Submitted second progress report to Supervisor, Company Representative and SEDV 625 professor

- Interview with industry expert, Roy Meyer, Corporate Measurement Lead from Imperial Oil on the technicality and practicality of measurement functionality

- Meeting with CCAL Mentor, Doug Koroluk

June 2018

- Submitted third progress report to Supervisor, Company Representative and SEDV 625 professor

- Initiated contact with local supplier Spartan Controls that specializes in instrumentation and measuring equipment

- Interviewed Dane Etwaroo, Technical Sales Specialist – Measurement Instrumentation from Spartan Controls

- Attended a one-day Spartan University Seminar on the following courses
  - Overpressure Protection Methods Utilizing Regulators to Reduce Emissions by Denis Goncalves
  - Electronic Flow Measurement by Ravi Rao
Emissions Mitigation Solutions & Methane Reduction Strategies by Dale Smith

Basics of Storage Tank Venting and Protection by Felipe Leibholz

Coriolis Flow Meter Smart Meter Verification Enhancements by Marc Buttler

Open Path Gas Detection Technology for Safety and Environmental Monitoring by Jim Hueston and Kyle MacDonald

Meeting with Supervisor to discuss and conclude on the findings of the research and prepare for the report writing and presentation development

July 2018

Submitted final progress report to Supervisor, Company Representative and SEDV 625 professor

Finalized draft report for submission

Completed oral presentation of research project

4.3 Deliverables

Key deliverables and documents related to this research project include:

- Finalized legal documents;
- Progress report;
- Presentation; and
- Final report.
Chapter 5. Venting Analysis

The research sets out to identify what are the available technologies in the market that can be utilized by the industry to quantify methane emissions through venting process. In order to utilize the right type of technology for quantification, certain parameters are researched to realize its potential and limitations. For both measurement and estimation, the following parameters are researched:

- Processes associated with venting;
- Venting flow, velocity, and pressure; and
- Venting gas composition, if it is a sweet or sour gas.

5.1 Venting Processes

As was shown in Figure 1, venting occurs at the equipment source itself or via tanks containing hydrocarbon. Pneumatic venting occurs typically from natural gas driven pneumatic devices which are used as liquid level controller, pressure regulators, and valve controllers. These pneumatic devices then bleed off the natural gas as part of normal operation to maintain the right pressure (EPA, 2018). This process is similar for the compressor seal where natural gas is used to separate faces when it is rotating thus creating less friction. The venting process is required to maintain reliability, performance, safety, and operation of the gas seal. Glycol dehydrator is used to remove water vapour from natural gas to meet pipeline water specification as wet gas travelling through the pipe may result in clogging and rusting. Glycol or 18ri ethylene glycol (TEG) is used to remove the water vapour from the wet gas via contact column. The TEG is regenerated for reuse and the water is flashed off for disposal which would contain hydrocarbon.
such as methane and other volatile organic compounds (VOC) (Hy-Bon, 2014). Tank venting refers to storage tank used to store hydrocarbon liquid. These tanks are usually atmospheric by design and requires venting to maintain the internal pressure which is caused by evaporation of the liquid hydrocarbon (ProtectoSeal, 2018).

The brief description of the processes associated with venting and its equipment has provided clarity on its venting requirements and limitations. As such, according to Directive 60, a list of limit requirements for each equipment has been established to ensure that re-engineering and retrofitting is applied to reduce methane emissions. Refer to Appendix A for full guideline on each equipment’s venting limit.

5.2 Venting Parameters

From the parameters identified in Section 3.2, the following parameters were further researched:

- Venting mass flow rate;
- Venting pressure; and
- Venting velocity.

The venting gas mass flow rate corresponds directly to the inventory of natural gas within the equipment of process. As such, the maximum mass flow rate of the natural gas that can be vented is calculated based on the maximum inventory as a function of time. Hence, the larger the inventory that is stored within the process or equipment, the higher the maximum mass flow rate that can be achieved. However, the maximum mass flow rate that is discussed is based on a complete blowdown scenario which is not a typical occurrence. On the other end of the spectrum
is the issue of no flow or low flow rate of the vent gas. Each measurement device has its limitation on its ability to detect and measure low mass flow rate.

Most venting processes operate at atmospheric or near atmospheric pressure as it is released directly into the atmosphere and utilizes no further driving force to effect its release. As described above, the vent gas is released only when it has reached certain pressure and a small amount discharged to maintain the pressure within the equipment. This would also result in intermittency in the release and not a continuous flow of vent gas for measurement. The low-pressure parameter is crucial in the selection of the measurement devices that would be available to function accurately.

The vent gas velocity is central in the selection of the type of measurement devices that would be suitable to accurately measure vent gas. As velocity is a function of volumetric flow rate and cross section of the vent pipe, the velocity is directly proportional to the flow rate of the natural gas vented. There are several measurement devices that utilize velocity as a function in its measurement. One of the ways to increase the velocity of the vent gas to improve the measurement accuracy is to reduce the cross section of the pipe.

The various types of measurement devices currently available in the market, its function and limitations on the above-mentioned parameters will be further analyzed in detail in Section 6.2 below.
5.3 Venting Gas Composition

Natural gas has been used synonymously as methane, given its usually high concentration; however, it should not be assumed that natural gas is consists wholly of methane. It composes hydrocarbon-based gases such as methane, ethane, propane, butane, and to a certain extent some of the heavier hydrocarbon in smaller quantities and non-hydrocarbon-based gases such as CO$_2$, nitrogen, water vapour, oxygen, helium, and hydrogen sulphide (H$_2$S) and these are collectively considered as impurities. CO$_2$, nitrogen, and helium are known as diluents as they do not burn and do not provide any heating value (FERC, 2004).

The composition of natural gas in Alberta consists of relatively high H$_2$S concentration. Natural gas containing more than 1% of H$_2$S is termed as sour gas and it accounts for one-third of the total natural gas production in Alberta (Alberta Energy, 2018). This is considered a substantial proportion and Figure 2 below illustrates the area of the sour gas within Alberta and the range of its concentration. The range of sour gas concentration is crucial in the study and research of methane quantification as the corrosive nature of the sour gas can prove to be a limiting factor in choice of quantification types as some measuring devices are not suitably designed to handle sour gas.

Impurities such as water vapour, CO$_2$, and H$_2$S are removed from natural gas during processing to meet the specification of the pipeline standards. Hence, it is typical for the measurement devices used for metering purposes to be in contact with natural gas that has already been treated and cleared of these impurities. However, in this research, for the purpose of venting from equipment, it must be assumed that the vented natural gas may not have been treated and
still retain such impurities. Therefore, this set of assumptions will be analyzed further in Section 6.2 to determine the suitability of the measurement devices.

Figure 2. High Sulphur Areas in Alberta

Source: (Hea, 1991)
Chapter 6. Measurement Quantification

Measurement quantification process is the use of measurement devices to provide an accurate reading of flow rate of vented natural gas from each equipment. This is usually done at the source of the equipment unless there is a header routing to a centralized vent stack. There are several types of measurement devices available in the market with proven track record that are capable of measuring gas flow. Measurement done via the measurement devices are typically considered to be reliable, fairly accurate provided that it is calibrated and verified, real-time recording, and simple to use provided that installation for the measurement devices are done by specialized technicians.

In this chapter, we will evaluate further on the measuring requirements stipulated by AER, learn on the types of measurement devices available in the market that are considered to be suitable for vent gas measurement, and the analysis of the different measurement devices.

6.1 Measuring Requirements

In order to accurately measure and report on the methane emitted from different equipment or sources, AER Directive 60 has quoted AER Directive 17: Measurement Requirements for Oil and Gas Operations when vent gas from a site must be quantified using continuous metering or periodic testing, as well as acceptable testing methods.

Directive 17 provides guidelines on gas measurement and its specific requirements. It defines a gas meter as an equipment or device that is used to indicate gas volume, and to continuously and accurately measure gas with measurement devices. As such, it would be fitting for use to measure vent gas and thus was referred to in Directive 60. Directive 17 focuses on standards of
accuracy in its measurement, measurement uncertainty, and calibration and proving of the measuring devices at different locations and custody transfer. Whilst these may not be relevant to vent gas measurement, the requirements of the measurement device installation as illustrated in Table 1 is relatable for vent gas measurement. For each different type of measurement devices, a certain installation standard from a reputable institution is established and to be adhered to should a measurement device be used to quantify vent gas.

Table 1. Installation standards compliance for flow meters

<table>
<thead>
<tr>
<th>Measurement Device</th>
<th>Installation Standards Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vortex</td>
<td>1985 or later edition of AGA Report 7: Measurement of Gas by Turbine Meters. Correction for static pressure, temperature, and compressibility required</td>
</tr>
<tr>
<td>Coriolis</td>
<td>Latest edition of AGA Report 11: Measurement of Natural Gas by Coriolis Meter. External gas sample analysis and density must be used to determine the gas volume at base conditions of 1 atm and 15°C temperature</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>1998 or later edition of AGA Report 9: Measurement of Gas by Multipath Ultrasonic Meters. Must include instrumentation that allows for continuous pressure, temperature, and compressibility correction</td>
</tr>
<tr>
<td>Differential Pressure</td>
<td>1991 or later edition of ISO 5167: Measurement of fluid flow by means of orifice plates, nozzle, or venturi tubes inserted in circular cross-section conduit running full</td>
</tr>
<tr>
<td>Positive Displacement</td>
<td>1992 or later edition of ANSI B109.1: Diaphragm Type Gas Displacement Meters (up to 500 acf/hr capacity)</td>
</tr>
</tbody>
</table>

Source: Author compiled from Directive 17, 2018.
However, it should be noted that Directive 17 is written with the intention and design of gas production at specific temperature and pressure under continuous flow and may only serve as a guideline to vent gas measurement requirements as they both operate under very different conditions.

6.2 Measurement Devices

There are several measurement devices identified as being suitable for the use measuring the amount of methane vented to the atmosphere. These devices will be discussed further in the section below to have a better understanding on its technical function.

6.2.1 Vortex Flow Meter

Vortex flow meters measure fluid velocity using a principle of operation referred to as the von Kármán effect, which states that when flow passes by a bluff body, a repeating pattern of swirling vortices is generated. In a Vortex flow meter, an obstruction in the flow path, often referred to as a shedder bar, serves as the bluff body. The shedder bar causes process fluid to separate and form areas of alternating differential pressure known as vortices around the back side of the shedder bar (EmersonV, 2018). A diagram of a typical flow meter is shown in Figure 3.

The vortex flow meter is designed to handle low velocity and will only stop measuring and reading when the velocity is approaching almost zero. It is also suited for gas measurement with an accuracy of ±1% and may withstand some contaminants within the gas system, though not recommended. It is suitable for sour gas measurement as the meter is built with stainless steel material.
6.2.2 Coriolis Flow Meter

Coriolis flow meter measures mass flow through the two tubes and is based on the principles of motion mechanics. Fluid moves through the two tubes within the sensors and it forces the tube to oscillate in opposition at the natural resonant frequency. As the tube oscillates, the voltage generated from each pickoff creates a sine wave which indicates that the motion of one tube relative to the other. The time delay between the two sine waves is known as Delta T, which is directly proportional to the mass flow rate. (EmersonC, 2018). Figure 4 shows a coriolis meter with the tubes hidden inside the casing whilst Figure 5 illustrates the principles behind the creation of Delta T.
The coriolis flow meter has outstanding low flow sensitivity and flow rate range of 1-54,000 kg/h. It boasts of a gas mass-flow accuracy of ±0.25% and has the capacity to measure the density as well which can be very useful in the conversion of both mass and volumetric flow rate. It is suitable for sour gas measurement as the meter is built with stainless steel material.

Figure 4. Coriolis Flow Meter

Source: (EmersonC, 2018)
6.2.3 Ultrasonic Flow Meter

Ultrasonic flow meter uses acoustic or sound waves to determine the velocity of a fluid flowing through the pipe. Under no flow condition, the frequencies of an ultrasonic wave transmitted in a pipe and its reflection are the same. When there is fluid moving through the pipe, the frequency of the reflected wave is different due to the Doppler effect. The Doppler effect describes the change in the observed frequency of a wave when there is relative motion between the wave source and the observer. The sensor sends and receives ultrasonic waves between transducers in both the upstream and downstream directions in the pipes. Under no flow conditions, it takes the same time to transmit and receive the ultrasonic wave. However, under flowing condition, the reflected wave will be much slower than the transmitted wave frequency. Therefore, the time difference between the sending and receiving the wave will be used to process and determine the flow rate (Universal Flow Monitors, 2018c).
Figure 6 shows an example of an ultrasonic flow meter. It should be noted that the flow meter consists of only the blue sensor and not the flanged tubing it covers. This is one of the greatest advantages of ultrasonic flow meter as it does not require any retrofitting of piping to insert a flow meter or sensor. It is mounted onto existing piping by bundling the flow meter around the piping, thus reducing downtime and installation costs. Besides measuring mass flow rate, it also has the ability to measure volume, density and viscosity of the fluid and is highly accurate of up to ±0.01%. This is highly suitable for sour gas as it does not require any modification to the flow meter specification as the sour gas is contained within its existing piping (EmersonU, 2018).

Figure 6. Ultrasonic Flow Meter

Source: (EmersonU, 2018)
Figure 7 shows an improvement to the ultrasonic flow meter by Emerson by providing two meters and two transmitters in a single body to increase reliability and efficiency. It has the ability to permit two independent measurements with the installation of just one single flow meter. (EmersonD, 2016)

Figure 7. Improvement to Ultrasonic Flow Meter

6.2.4 Differential Pressure Flow Meter

Differential pressure flow meter utilizes the Bernoulli principle to measure the flow of a fluid in the pipe. It introduces a constriction in the pipe creating pressure drop across the flow meter. As
the fluid flow increases, more pressure drop is created, as stated by the Bernoulli principle that an increase in speed of a fluid occurs simultaneously with a decrease in pressure. Impulse piping route the upstream and downstream pressures of the flowmeter to the transmitter that measures the differential pressure to determine the fluid flow. Different geometries are used for different measurements, with the simplest version of orifice plate to V-cone and venturi tubes (Universal Flow Monitors, 2018a).

Figure 8, Figure 9, and Figure 10 show examples of the types of geometries utilized for the differential pressure flow meters. One of the key advantage of these flow meters is the optimization factor for different fluids and goals. It may not be suitable for non-linear differential pressure signal and its accuracy may be affected through this (Universal Flow Monitors, 2018a).

Figure 8. Structure of a V-Cone Flow Meter

Source: (Tan, 2010)
Figure 9. Orifice Flow Meter

Source: (Emerson, 2018)

Figure 10. Venturi Meter

Source: (Engineers Edge, 2018)
6.2.5 Positive Displacement Diaphragm Flow Meter

Positive displacement diaphragm meter utilizes the flow of the fluid to calculate the volume of gas that passes through it. This is accomplished through the known volume that is displaced for each stroke of the diaphragm which is sealed between the measuring chambers of the device (Thomson, 2018). The gas flow into the meter inlet or chamber, which has an oscillating diaphragm and contains a known capacity of the gas. This section fills and empties the gas and with each cycle the volumetric flow rate can be determined (Steinberg, 2014). Figure 11 shows a diagram of a digitized diaphragm flow meter.

![Figure 11. Digitized Positive Displacement Diaphragm Flow Meter](source)

Source: (Idex, 2018)

The diaphragm flow meter is capable of reading low flow rate up to 0.5 acf/day with accuracy of ±2% and suitable for smaller line sizes (Calscan Solutions, 2018). However, as the diaphragm is made of rubber seal material, it may be limited when dealing with sour gas measurement.
6.3 Comparison of Measurement Devices

Section 6.2 provides a good background briefing on the types of flow meters currently available in the industry that prove to be popular.
Table 2 below shows a summary of the functions of the flow meters including the advantages and disadvantages.

It can be seen that each flow meter has its distinct advantages and disadvantages as a general. When coupled with the information from Section 5, Venting Analysis, it would seem that vortex flow meter and positive displacement flow meter would be a better fit as they are able to read low flow condition, which is fundamental in venting process. However, this is only a general conclusion from the limited information that has been gathered thus far, and further information on the size of the vent pipe, the length of the pipe, pressure drop across the pipe, and the effect of intermittency of reading on the flow meter should be collated and investigated before making the final decision on the type of flow meter to be used to measure vent gas accurately.
Table 2. Analysis of Flow Meters

<table>
<thead>
<tr>
<th></th>
<th>Vortex</th>
<th>Coriolis</th>
<th>Ultrasonic</th>
<th>Differential Pressure</th>
<th>Positive Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept</td>
<td>Von Karman effect</td>
<td>Motion mechanics</td>
<td>Doppler effect</td>
<td>Bernoulli principle</td>
<td>Volume</td>
</tr>
<tr>
<td>Flow Function</td>
<td>Velocity (sheddler bar)</td>
<td>Mass flow (tubes)</td>
<td>Acoustics (sound waves)</td>
<td>Volumetric flow</td>
<td>Volumetric flow</td>
</tr>
<tr>
<td>Contaminants</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±1%</td>
<td>±0.25%</td>
<td>±0.01%</td>
<td>±1%</td>
<td>±2%</td>
</tr>
<tr>
<td>Advantages</td>
<td>- Ability to read low flow - Low maintenance</td>
<td>- High accuracy</td>
<td>- No penetration - High accuracy - Low maintenance</td>
<td>- Optimization availability</td>
<td>- Good for small lines - Ability to read low flow</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>- High cost</td>
<td>- High cost - Unavailability of accuracy in fluctuating conditions and low pressure</td>
<td>- Unavailability of accuracy in fluctuating conditions</td>
<td>- Low rangeability from non-linear differential pressure signal</td>
<td>- High maintenance</td>
</tr>
</tbody>
</table>

Source: Author compiled from various sources. Shin Roey Tan, 2018.
Chapter 7. Estimation Quantification

Estimation quantification relies on information acquired through the processes to project an approximated amount. As such, the more reliable and accurate the information that is fed into the estimation process, the more factual the approximated amount would be. The estimation models to be evaluated further are identified as empirical which address past and observed information, and prediction which focuses on software simulation based on some data criteria.

7.1 Empirical Estimation

To accurately estimate vent gas empirically, previous data is key in providing a trend or pattern. Empirical model denotes that a formula for estimation is derived from data collected previously and based on some guesses and assumptions.

The information on the venting analysis in Chapter 5 would be highly appropriate and relevant for use in the empirical estimation model. This would provide a background basis on the development of the empirical formula.

There are two ways of collating the data set required to formulate the empirical model. It can be done by:

- Industry available data; and
- Site specific data.

Industry available data is a compilation of industry wide data provided by numerous oil and gas producers for each source of emission over years. This data would be representative for that particular source of emission, namely the equipment types of the same specification. This data is
only a generic representation and does not include the efficiency, condition, and wear and tear of the equipment. Site-specific data on the other hand is derived from surveys conducted at the facility directly. Surveys such as the Greenpath 2016 Alberta Fugitive and Vented Emission Inventory Study could provide the producers with such data that is more representative of its facility (Greenpath Energy Ltd, 2016).

The process to develop the empirical formula is as follow:

- Emission source categorization;
- Operating mode sub-categorization;
- Steady-state and unsteady-state determination;
- Measurement techniques; and
- Emissions factor derivation (Kirchgessner et al, 2018).

As discussed in Section 5.1, there are many processes within the facility that vent methane. Emission source from similar equipment or process parameter should be identified and categorized accordingly. Following that, a sub-category would be established for different operating mode such as for start-up and shutdown, normal operating, maintenance, and emergency. This sub-category is critical as the different operating mode would vent different quantity of methane.

A survey would be conducted by specialists at the facility to determine the vent gas rate and amount for each corresponding category, sub-category, and the different states of emissions. There are several measurement techniques available to conduct the survey:

- Component measurement method; and
- Gas tracer method, if applicable.

All data collected through the surveys would be tabulated and computed for the different scenarios in order to derive the corresponding emissions factor coefficient. It is usually done through inductive approach. The emissions factor would be used to predict future venting emission rate.

The emissions factor coefficient derived through empirical data and inductive approach is a simplistic model that makes it easy for use by analysts in the company. However, the coefficient is a static figure that emerged from the survey conducted at that particular time, with certain parameters and assumptions. It does not allow for manipulation of the dynamics of the constant changes in process and venting parameters. Therefore, at a suitable interval, another survey should be conducted to verify that the emissions factor coefficient remains valid for its categories and to update the coefficient if necessary to ensure that it remains relevant and accurate.

As with all modelling, there are numerous assumptions and uncertainties built into its algorithms. These assumptions should be clearly stated in the development of the emissions factor coefficient to lessen uncertainties. This will ensure that the emissions factor coefficient will retain its representativeness of the results that it is modelling.
7.2 Prediction Estimation

Prediction estimation or more commonly known as software simulation modelling tool is fast gaining traction in the oil and gas industry. Traditionally used in the safety department to protect human lives, environment, and asset, this software tool can be expanded to calculate discharge rate from the vent gas source. These software tools are designed with intricate algorithms and fine-tuned with industry data and have become industry trusted and reliable source for analysis of hydrocarbon or toxic gas release consequence modelling.

There are several types of dispersion modelling software tools available and we will be focusing on two types in this research:

- Process Hazard Analysis Software Tool (PHAST™) utilizing 2D model; and
- Computational Fluid Dynamics (CFD) Simulation utilizing 3D model.

7.2.1 Process Hazard Analysis Software Tool (PHAST™) utilizing 2D model

PHAST is an industry proven and recognized tool that is used to calculate potential discharge and dispersion of target gas from a release source. It utilized Unified Dispersion Modelling (UDM) in its simulation modelling. It is capable of simulating two-phase jet flow, heavy and passive dispersion including droplet rainout and pool spreading/evaporation (Wilcox, 2013). For the purpose of this study, we are interested only in single phase flow with a clear focus on discharge and dispersion consequence modelling. The UDM can model a wide range of scenarios with distinctions as tabulated in Table 3.
Table 3. Factors associated with different range of scenario for PHAST™ modelling

<table>
<thead>
<tr>
<th>Factor</th>
<th>Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum</td>
<td>Pressurized or unpressurized</td>
</tr>
<tr>
<td>Time-dependency</td>
<td>Steady-state, finite-duration, instantaneous, or time-varying dispersion</td>
</tr>
<tr>
<td>Buoyancy</td>
<td>Buoyant rising cloud, passive dispersion, or heavy-gas-dispersion</td>
</tr>
<tr>
<td>Thermodynamic Behaviour</td>
<td>Isothermal, or cold or hot plume, vapour or liquid or solid or multiple phase</td>
</tr>
</tbody>
</table>

Source: Author compiled from various PHAST™ literature sources, 2018.

The factors can be customized for vent gas estimation through the discharge rate calculation. In this case, the scenario for vent gas discharge would most probably have the following factors:

- Momentum: slight pressurization, almost atmospheric;
- Time-dependency: mostly steady-state but with variation;
- Buoyancy: buoyant rising cloud as methane is less dense than air; and
- Thermodynamic behaviour: mostly isothermal, unless the gas is highly pressurized and of low temperature, and vapour phase.

Discharge process is defined by PHAST™ as the release of the fluid through a release source, usually a leak or hole, under pressure. It will be able to calculate the release rate or flow rate of the fluid if the following parameters are input through the software:

- Leak or hole size;
- Diameter of the release piping;
- Release pressure; and
- Temperature.

As the release fluid loses its momentum, it transitions from discharge to dispersion modelling where the flow of the fluid is driven by external parameter rather than by its internal potential energy. For the dispersion calculation, the following parameters are required in addition to those mentioned in the discharge modelling:

- Wind speed;
- Pasquill stability class;
- Ambient temperature, particularly in Alberta as the range between winter and summer is huge;
- Release height from ground; and
- Surface roughness.

Figure 12 shows the simulation of a fluid release into the atmosphere and the distinction between discharge and dispersion modelling. It should be noted though, that the illustration focuses on two-phase fluid and is extended to rainout and pool collection, which is not part of our study.
Most modelling scenarios have their own uncertainties built into the system due to the rigidness of the software tool. As these uncertainties are capable of skewing the results, it is paramount that the uncertainty errors are reduced as much as possible. A sensitivity can be performed to reduce the magnitude of uncertainties by modifying certain parameters that are uncertain into the modelling scenario. Another method is to conduct the Monte Carlo method which is designed into most modelling software tools. The Monte Carlo method is a computerized mathematical technique that perform risk analysis by building models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty. Through numerous iterations – sometimes more than tens of thousand – this method produces distributions of possible outcome value of the consequence modelling (Palisade, 2018).
7.2.2 Computational Fluid Dynamics (CFD) Simulation utilizing 3D model

Conventional fluid flow is governed by partial differential equation (PDE) which is representative of the conservation law for mass, momentum, and energy. CFD is considered as a replacement for the conventional PDE system with a set of algebraic equations which can be solved using digital computers. It provides qualitative and quantitative prediction of fluid flow with:

- Mathematical modelling (PDE);
- Numerical methods (discretization and solution techniques); and
- Software tools (solvers, pre and post processing utilities) (Kuzmin, 2018).

Figure 13. Schematic comparison between experiment and CFD simulation

Source: (Kuzmin, 2018)

Figure 13 provides a visualization on how CFD simulation mimics the fluid flow in real life demonstrated through experimental value. Though it may not be fully identical, this is sufficient for engineers to conduct numerical study to understand and predict how fluid flow may develop. There are many applications for CFD; however, we will only be focusing on fluid flow for vent gas dispersion with the aim of quantifying its release amount.
Figure 14 illustrates further on how CFD simulation is able to duplicate the smoke plume as seen in the aerial view. The difference between a CFD and consequence modelling provided by PHAST™ is that CFD allows for the integration of the facility’s 3D image to be superimposed into the software. This is essential as the assumption made in PHAST™ is that the discharge is released directly to open spaces with no congestion or disturbance. Most CFD software are capable of simulating the discharge and dispersion modelling to integrate the congestion area of equipment, piping, vessels, and other barriers which is instrumental in the study of fluid flow (DNV GL, 2018).

The CFD analysis process typically follows this flow:

a) Defining the problem statement. What is required to be quantified or simulated;
b) Choose the relevant mathematical model. Which flow model and reference frame would be most suitable;

c) Discretization process. A set of algebraic equations will be set up with:
   - Mesh generation through the decomposition of elements and cells;
   - Space discretization through spatial derivatives;
   - Time discretization through temporal derivatives;

d) Iterative solver for the non-linear equations with outer and inner iterations;

e) CFD simulation. The quality of the simulation is determined by the mathematical model and its underlying assumption;

f) Post-processing and analysis to extract the desired information from the computed field;

and

g) Verification of the CFD codes on all the input data (Kuzmin, 2018).

As with all predictive modelling, the CFD simulation is prone to uncertainty and error stemming from the assumptions and representativeness of the data input. Sensitivity analysis and Monte Carlo method analysis can be performed to reduce the uncertainties and determine the most probabilistic outcome from the simulation.

It should be noted that due to the extreme number of input data required and the complexity of the underlying principles to simulate the CFD, this modelling must be performed by SME in this field and not just any random designers or analysts.
7.3 Hybrid Quantification

There is an innovation in the market that was discovered recently and categorized as a hybrid personally because it encompasses both measurement and estimation model. This is known as the GasFinder3-Op Portable Open Path Tunable Diode Laser (TDL) Analyzer (Boreal Laser Inc., 2018).

Historically, gas detectors are deployed in the oil and gas industry for safety purposes, to raise alarm on high concentration of flammable cloud or toxic gas. An open path detector is a set of detectors mounted on structure with a clear line of sight between the transceiver and the reflector to communicate between each other and detect any of the target gas, such as methane or H₂S. The GasFinder3-Op is designed in such a way that it is able to detect every target gas molecule and calculate the concentration across the length of the detectors in measured in meter (m), to generate a concentration in ppm-m (Boreal Laser Inc., 2018). Figure 15 illustrates on how the GasFinder3-Op is deployed in the field.

Figure 15. GasFinder3-Op Schematic

Source: (Boreal Laser Inc., 2018)
As the GasFinder3-Op is capable of operating continuously, it will provide real-time continuous monitoring on the methane emission from source with response time or scan rate at one sample per second. This will provide extremely accurate measurement of the vent gas emission, even for exceptionally low flow rate or concentration. It also has a huge range for the path length of up to 750m (Boreal Laser Inc., 2018).

It can now be combined with weather data and simulated in a dispersion model to predict an emission rate of the vent gas. Figure 16 depicts how this hybrid model of measurement and prediction can be applied.

Figure 16. GasFinder3- Op Estimation Schematic

Source: (Boreal Laser Inc., 2018)
Chapter 8. Analysis of both Quantification Types

An analysis was done on both quantification types to comprehend their pros and cons. Table 4 shows a high-level comparison of the quantification types. Each factor will be further analyzed in the following sections. This will provide further guidelines on the selection and implementation of the quantification type in the facility.

Table 4. Comparison between quantification types

<table>
<thead>
<tr>
<th></th>
<th>Measurement</th>
<th>Estimation</th>
<th>Prediction</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Suitability</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Complexity</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>


Legend: 1 being most and 4 being least

8.1 Cost

Cost is one of the most important factor associated to the selection and implementation of the type of quantification type to be used. High cost may be a deterrent to the producers, especially in the current economic climate. As shown in Table 4, measurement quantification has the highest cost associated through the purchase of the measurement devices. As there is no header routing to a centralized vent stack, numerous devices are required to be installed at the emission source in order to measure the release rate. Furthermore, as with all operational devices, there is added cost to maintenance of the devices that needs to be factored into the total cost. Hybrid
quantification ranks second as there is still cost associated with the purchase of measurement devices. It is not required to be installed at each emission source as it has a wider range of coverage, hence reducing the upfront cost of procurement. Empirical quantification ranks third as it still requires survey to be performed by specialists at interval. Prediction quantification ranks as the lowest cost as it only requires the purchase or subscription of the software tool to be utilized for the simulation.

8.2 Accuracy

Accuracy is defined as the ability to produce results that matches most closely with the highest precision. As discussed earlier in Section 6 and Section 7, much as each quantification type is capable of its performance, there is limitation to its accuracy. Measurement quantification is considered to be the most accurate of all quantification types listed as it provides real-time data that is coupled with calibration and verification system. Hence, the only limitation to its accuracy would be in the measurement device’s internal accuracy. The hybrid quantification is the next most accurate quantification type as it is able to provide real-time data to be simulated in the prediction model. The only limitation to accuracy would be in the range that the measurement device would cover. Next is the empirical quantification. Its accuracy is similar to the prediction quantification with the caveat that the data utilized is provided directly from the facility, making it more relevant compared to prediction quantification which utilizes generic industry data. The limitation to accuracy for empirical quantification is that the data utilization is not real-time data. This is because the survey is only conducted in interval resulting in time-lapse inaccuracy as there is no approach available to update the emissions factor coefficient otherwise. The prediction quantification is the least accurate of all quantification types mentioned as it is not focused on
one facility and its data. The data used in the software simulation is a culmination of industry’s data with different parameters. However, it should not be assumed that it is not functional. The prediction quantification provides a fairly accurate guidance with guestimate results that can be verified at field, if necessary.

8.3 Suitability

Although it is shown through the cost and accuracy factors that the measurement quantification is the most preferred type to be implemented, it must be balanced with the suitability factor. In order for any quantification type to be adequately deployed, it must meet the specification of the measuring parameters. In this section, rather than being specific in meeting the function, it would be better to have a larger range of specifications it is able to accommodate. Using this criterion, the hybrid quantification ranks first as it has a wide range of coverage with the least amount of measurement devices required. It is also capable of taking reading of extremely low concentration. This makes it extremely suitable for situations where the flow is too low to be read by standard measurement devices. The second rank on the list is the prediction quantification. It has the ability to perform numerous simulations under different scenarios of varying parameters. This makes it suitable to be deployed at the facility without requiring much modification as it is mostly a table top approach. Following that is the empirical quantification which utilizes survey as an input factor. Surveys can be easily conducted at site and this increases the suitability of this quantification type as there is no limitation on the parameters of the source of emissions. Last on the list is the measurement quantification. It is suitable for quantification only if the measurement device is designed to meet the specifications and parameters of the vent source.
8.4 Complexity

Complexity is defined as how easy or complex it might be to deploy the quantification type and what other factors are required to ensure the successful implementation of the quantification. The prediction quantification is ranked as the most complex quantification type in the list. As this is considered a table top approach, most of the simulation is undertaken using the software tools. The software tool is a highly complex software with multiple assumptions and algorithms behind it and would require a specialist who is well-verse in this subject to perfectly execute the simulation and not just any designer or analyst. The next on the list is the hybrid quantification as it also requires simulation utilizing software tool for the same reasons. Following that is the empirical quantification. The survey data would provide the necessary information for inferential results but would require an engineer or scientist to determine the emissions factor coefficient. Last on the list would be the measurement quantification. It is simple, straightforward, and can be operated by the field technicians that are already working in the facility as it is the same measuring devices that are part of the plant operation. There would be no further expertise required to utilize this quantification type.
Chapter 9. Venting Technologies

To meet the ACLP objectives and targets, besides the quantification of the methane emissions, it is also important for producers to target on the optimization of venting. In this chapter, we will discuss briefly on several new technologies available in the market that focus of venting optimization utilizing the following concept

a) Venting elimination;
b) Venting reduction; and
c) Venting capture.

9.1 Venting Elimination

Two new technologies on venting elimination are identified in this topic for further discussion, but it is to note that this is a non-exhaustive list and there may be many other technologies or innovation available in the market. The venting elimination technologies are:

- Electrification configuration for pneumatic equipment; and
- Instrument air substitution for pneumatic equipment.

Pneumatic operation is defined as the utilization of compressed air or gas in science and industry in order to perform mechanical work and control (Hafner Pneumatik, 2018). In the oil and gas industry, pneumatic is the preferred choice for the operation of pumps and instruments and the medium of choice is natural gas as it is readily available and usually under pressure. This natural gas is vented to the atmosphere once it has run through a series of instruments or pumps and this constitutes a high amount of vented methane gas. This is considered not only an
environmental concern but also monetary waste as the natural gas has monetary value as a product for sale.

This venting source can be fully eliminated through the electrification of all pneumatic equipment; i.e. the substitution of electrical pumps and controller from pneumatics. This will eliminate the need for pressurized natural gas to be fed into these pneumatic equipment as it can perform its mechanical work without pressurized gas. It must be noted that pneumatic chemical injection pumps continue to be used given its simplicity, reliability and low capital cost of pneumatic controllers (PTAC, 2017). The adoption of this technology is highly costly as it involves the complete changeout of huge number of equipment from pneumatic to electric. It is identified that due to its high upfront cost, it is mostly preferred for greenfield deployments

Another mitigation technique that might be less costly then the electrification configuration would be the substitution of instrument air instead of natural gas as the medium for pneumatic operation. Instrument air is atmospheric air pressurized through an electric air compressor. Through the adoption of this technology, venting of natural gas from pneumatic sources can be fully eliminated as it is now only atmospheric air being vented instead (PTAC, 2017). This would be considered least costly than the electrification configuration technology as the amount of retrofitting required is noticeably less. The piping to these equipment would remain the same with the only addition of an instrument air system package.
9.2 Venting Reduction

Two new technologies on venting reduction are identified in this topic for further discussion, but it is to note that this is a non-exhaustive list and there may be many other technologies or innovation available in the market. The venting reduction technologies are:

- Replacement of high bleed devices to low bleed ones; and
- Installation of low bleed retrofit kits on existing devices.

As discussed earlier in Section 9.1, pneumatic equipment vents natural gas to the atmosphere as part of its operation. This is categorized into high bleed (vent) and low bleed. High bleed is defined as venting of gas of more than 6 scf/hr and low bleed is anything below that threshold. Generally, there are three basic designs of pneumatic instrumentation devices, namely;

- Continuous bleed devices which are used to modulate flow, liquid level, or pressure, and will generally vent gas at a steady rate. They are used for throttling control and in situation where rapid responses are required, such as flow or pressure control.
- Intermittent or actuating bleed devices which perform snap-acting or on/off-type control, and vent gas only when they stroke a valve open or closed, or when they throttle gas flows. Examples include certain liquid-level controllers or controllers used for emergency shut down valve (ESDV).
- No-bleed devices which are non-emitting devices such as self-contained devices that vent into the downstream pipeline or driven by compressed air.

Figure 17 shows an example of a schematic of a gas pneumatic control system. This device regulates the pressure of the natural gas stream together with the process condition. In order to
close the valve, the pneumatic gas is directed to the actuator and pushes the diaphragm against the spring which effectively pushed the valve plug closed. When the pneumatic gas is vented off the actuator, the spring pushes the valve back open. The weak pneumatic signal to the pneumatic controller causes continuous bleed (vent) of natural gas to the atmosphere (Natural Gas STAR Partners, 2018). The amount of natural gas vented is based on the pressure, the higher the pressure, the more natural gas is vented.

Figure 17. Pneumatic Device Schematic

Source: (Natural Gas STAR Partners, 2018)

This process can be improved through the replacement of the device from a high bleed to low bleed that have similar performance capabilities. This is the preferred method to be adopted
should the high bleed device not be instrumental in maintaining the function required, i.e. quick response time (PTAC, 2017). The adoption of this method is high in cost and should be weighed in on the amount of methane emission reduction. Another method is to retrofit the current device with a low-bleed kit. This method is much easier to deploy as it does not involve the change out of existing devices. The retrofit kit may include having a high capacity internal relief, thus negating the need to vent to atmosphere or in a smaller quantity.

9.3 Venting Capture

An innovative technology developed by Spartan Controls named Slip Stream© which is a proprietary, patented technology that captures vented hydrocarbon gas, which would otherwise be lost to the atmosphere, and supplemented as fuel source for natural gas engines and process burners or auxiliary burners. Figure 18 illustrates on how this technology is deployed on an auxiliary burner for the glycol reboiler. The illustration is similar for engines and other burners. Slip Stream© is designed to capture low pressure, highly variable vented hydrocarbon gas and condensate and re-route it into the combustion chamber. It can be easily integrated into existing installations resulting in fuel savings and GHG reduction (Spartan Controls, 2018).
Figure 18. Slip Stream Technology

Source: (Spartan Controls, 2018)
Chapter 10. Limitations and Future Research

As with all research, there is limited time and resource to complete study to our satisfaction. With the research concluding at this level, there are several unfinished scopes that could be explored further should the opportunity arises in the future. The remaining of the chapter focuses on the limitation and future research for this project.

10.1 Scope of Quantification Model

Out of all the parameters listed for research in Section 3.1, there are several parameters that remain, namely:

- Volume of vent gas;
- Continuous vs intermittent venting;
- New vs old facilities;
- Measurement devices’ threshold; and
- Calibration and verification of measurement devices.

The volume of vent gas parameter was a difficult one to identify and collate data as this information was never required to be measured and reported. This parameter is crucial in the continuation of the research as it is a key factor in the identification of the right measurement device that could be utilized. A study of methane emission inventory by Greenpath Energy Ltd focused instead on the location emission in Alberta rather than the source of emission (Greenpath Energy Ltd, 2016). This report can be further assessed to breakdown on its inventory to specific source.
Venting process occurs under two conditions, either continuous or intermittent. The intermittent venting requires to be researched further as it is not within the conventional process in the oil and gas industry. Most of the measurement devices in the market are designed and geared towards production which is on a continuous basis, and hence the study into how the intermittency may have an effect on the reliability and accuracy of the measurement devices.

Older facilities in Alberta have long been around and its design are focused more towards production and operation performances. It is unlikely for an old facility to have a venting header routed to a single vent stack. As such, this research focuses on source emission and direct measurement or estimation. The research can be expanded to investigate on how quantification may be performed for a vent header to a direct vent stack, and if this design retrofit may be plausible.

Types of measurement devices were discussed extensively in Section 6.2. However, the limitation and threshold of these measurement devices were not delved deeper into due to the limited time available for this research. I understand from the Spartan Control representative that there are numerous parameters at stake in the identification of the measurement devices’ threshold, which includes the pipe size, pressure, temperature, density, turndown required, and accuracy required. Furthermore, the research did not go into details on the calibration and verification capacity for each of the measurement devices. As the calibration and verification is part of the requirements under Directive 17, it would be essential to expand the research to discern on the best available measurement device for utilization.
10.2 Technical Issues

As discussed earlier in Section 8.2, it has shown that the measurement quantification is far more accurate than the estimation quantification. However, much as it is the most accurate model available, it is not without its challenges. Due to the threshold and other parameters listed above, there are challenges to the accuracy to both quantification types, and thus, this serves as the most crucial limitation to the completion of the research. More investigation and analysis are required to fully comprehend the nature of the limitation to its accuracy under these circumstances.

One other technical issue facing this research is the insufficient or incomplete information or data on venting process available for public access. Unlike typical oil and gas production which is recorded and reported internally and externally to regulators, and collated for public access, venting process and its associated parameters have never been required to be measured, collated, and reported. Thus, this information, should it be available, has been kept within each producer internally, with no public access to these data. It is hoped that in the future, as this information becomes much more available to public, the research can be improved by having a better data set that is representative of the industry.

10.3 Future Research

This research has limited its scope to the intentional release of methane emission due to the time and resource constraints. Future research for this study can be expanded on this methodology to include:

- Indirect or unintentional methane emission i.e. fugitive emissions;
- Complete GHG inventory; and
- Verification scheme for the reporting

Directive 60’s requirements on methane emission quantification include both intentional and unintentional release of methane. It is only practical that the research should continue with the expansion of the scope to include fugitive emission. As such, the research will have a new set of parameters based on the nature of fugitive emission as its processes are different from venting.

This quantification methodology on methane emission can be amalgamated with CO$_2$ reporting to complete the GHG inventory. Out of the known GHG, CO$_2$ and methane are the most prevalent ones in the oil and gas industry. Hence, the amalgamation to produce a total of CO$_2$e would be a synergistic solution in the determination of total carbon footprint of a company. This would also come in handy for a company that reports on Carbon Disclosure Project (CDP).

As the quantified amount of methane emitted is required to be reported to the regulator at a specified interval, it is highly important that the methodology and equipment or software utilized to derive the figures are within the requirements specification. Hence, a verification scheme can be developed into Directive 60 for the quantification reporting to ensure that the measurement and estimation have been done to the acceptable procedure or standards and is verifiable and auditable. Currently, Alberta levies carbon tax on consumption of hydrocarbon and it does not extend to emission of un-combusted methane. This might change in the future considering the potency of methane as a GHG. The verification system might come in handy in the future if these figures were to be used as part of the carbon tax calculation given that the carbon tax in Alberta is currently levied at CAD30/tonne (Government of Alberta, 2018).
Chapter 11. Conclusions and Recommendations

11.1 Impact

The main impact from the new requirement in Directive 60 in quantifying and reducing methane emission is on the environment and potential effect in GHG reduction in the oil and gas industry. Besides being a key tool for the producers to demonstrate regulatory compliance, it can also be used to quantify and relate to cost savings from methane emission from carbon offset, given that carbon tax is priced at CAD30 per tonne. The research results in providing high level guideline in the quantification of methane emission would be beneficial to producers as they begin the task of developing the Methane Reduction Retrofit Compliance Plan. Lastly, the research also highlights on the feasibility and challenges each quantification model carries as the producers weigh in on the most suitable model to be utilized at the facility.

11.2 Audience

The audience that would be interested in the results of this research includes the oil and gas producers who are required to comply with the new requirements and how the quantification and reduction of methane emissions would influence their future development plans. Project management teams are considered an audience for this research as they would better understand the requirements and how it could be utilized during design phase to eliminate, optimize, reduce, and manage methane emissions. Policy makers and regulators could use the opportunity to review and update the regulations to include more descriptive requirements given the technologies available in the market in the future.
11.3 Outcome

The potential outcome of this research is for the incorporation of its result as an initial framework in the development of the estimation manual as listed in Directive 60. Future regulatory evaluation by the regulators can be expanded to include verification scheme on the quantification methodology to provide a more transparent, accountable, and auditable trail. The future work as a continuation of this research can be expanded to include fugitive emission and complete GHG inventory to include other GHG such as carbon dioxide to meet the objectives of ACLP and Paris Accord.

11.4 Recommendations

The research concluded with several recommendations that can be implemented to improve not only the quantification methodology but also to streamline in meeting the objectives of ACLP. One of the recommendations is to develop an online reporting tool for producers to submit its methane emissions for ease of collation and publishing by the regulators. This will provide the necessary transparency and information to the public on how the oil and gas industry is engaged in reducing methane emissions and achieving the set targets of ACLP. This may be incorporated into the currently utilized platform in AER, Petrinex, if it is possible.

Another recommendation would be the creation of a common platform through a non-governmental organization (NGO) to share innovation and new technology on methane elimination, reduction, management, and quantification. This would contribute significantly to the sharing and exchange of ideas and technology within the industry to realize the current best available technology that may be implemented. Besides the market in Alberta, the NGOs tasked
to the creation of the common platform may look globally in search of the most suitable technology that may be deployed within the Alberta oil and gas industry.
References

   Calgary: Alberta Energy Regulator.

   Edmonton: Alberta Energy Regulator.


   https://www.energy.alberta.ca/NG/ANG/Pages/SG.aspx

   https://www.alberta.ca/climate-leadership-plan.aspx#p8419s1


https://www.researchgate.net/figure/Structure-of-a-V-cone-flow-meter_fig1_231094827


http://unfccc.int/paris_agreement/items/9485.php


Appendix A – Directive 60 Summary of Vent Gas Limits and Fugitive Emission Survey Requirements

Summary of vent gas limits and fugitive emission survey requirements; ‘existing’ means before 1st Jan 2020, ‘new’ means on or after 1st Jan 2020 (AER60, 2018)

Figure 19. Summary of Vent Gas Limits and Fugitive Emission Survey Requirements

<table>
<thead>
<tr>
<th>Source</th>
<th>Category (effective date)</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>All venting sources</td>
<td>Overall vent gas limit (Effective release date of finalized directive, with exemptions until 2023)</td>
<td>$15.0 \times 10^3 \text{ m}^3/\text{month}$ or $9.0 \times 10^3 \text{ kg}$ of methane/ month</td>
</tr>
<tr>
<td>Venting</td>
<td>Defined vent gas limit for existing sites</td>
<td>Subject to overall vent limit</td>
</tr>
<tr>
<td></td>
<td>Defined vent gas limit for new sites (Effective release date of finalized directive)</td>
<td>$3.0 \times 10^3 \text{ m}^3/\text{month}$ or $1.8 \times 10^3 \text{ kg}$ of methane/ month</td>
</tr>
<tr>
<td></td>
<td>Vent gas limits for new and existing crude bitumen batteries (Effective January 1, 2022)</td>
<td>Crude bitumen fleet average of $3.0 \times 10^3 \text{ m}^3/\text{month}$</td>
</tr>
<tr>
<td>Pneumatic devices</td>
<td>Vent gas limits for existing pneumatic devices (Effective January 1, 2023)</td>
<td>Replace, retrofit, or modify instruments with a low-vent alternative</td>
</tr>
<tr>
<td></td>
<td>Vent gas limits for new pneumatic devices (Effective January 1, 2022)</td>
<td>Control vent gas</td>
</tr>
<tr>
<td>Compressors/seals</td>
<td>Vent gas limits for existing centrifugal compressors (Effective January 1, 2023)</td>
<td>$&lt;10.2 \text{ m}^3/\text{hr/compressor}$</td>
</tr>
<tr>
<td></td>
<td>Vent gas limits for new centrifugal compressors (Effective January 1, 2022)</td>
<td>$&lt;3.4 \text{ m}^3/\text{hr/compressor}$</td>
</tr>
<tr>
<td></td>
<td>Vent gas limits for existing reciprocating compressors (Effective January 1, 2023)</td>
<td>Fleet average vent rate of $&lt;0.83 \text{ m}^3/\text{hr/throw}$, with no compressor venting gas over $5 \text{ m}^3/\text{hr/throw}$</td>
</tr>
<tr>
<td></td>
<td>Vent gas limits for new reciprocating compressor seals (Effective January 1, 2022)</td>
<td>Units with $\geq 4$ throws, control vent gas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Units with $&lt;4$ throws, fleet average vent rate of $&lt;0.83 \text{ m}^3/\text{hr/throw}$, with no compressor venting gas over $5 \text{ m}^3/\text{hr/throw}$</td>
</tr>
<tr>
<td>Source</td>
<td>Category</td>
<td>Requirement</td>
</tr>
<tr>
<td>------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Glycol dehydrators</td>
<td>Vent gas limits for existing glycol dehydrators</td>
<td>Fleet average methane emissions rate of &lt;136 kg of methane/day/operating dehydrator</td>
</tr>
<tr>
<td></td>
<td>(Effective January 1, 2023)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vent gas limits for new glycol dehydrators</td>
<td>&lt;88 kg of methane/day</td>
</tr>
<tr>
<td></td>
<td>(Effective January 1, 2022)</td>
<td></td>
</tr>
<tr>
<td>Fugitive Emissions</td>
<td>Facility or equipment type:</td>
<td>Triannual fugitive emission surveys</td>
</tr>
<tr>
<td></td>
<td>Gas plants (&lt;0.01 mol/kmol H2S)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compressor stations (&lt;0.01 mol/kmol H2S)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Controlled liquid hydrocarbon tanks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Controlled produced water storage tanks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Effective January 1, 2020)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Facility or equipment type:</td>
<td>Annual fugitive emission surveys</td>
</tr>
<tr>
<td></td>
<td>Gas plants (≥0.01 mol/kmol H2S)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compressor stations (≥0.01 mol/kmol H2S)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Batteries</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Custom treating facilities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injection/disposal facilities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Effective January 1, 2020)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Facility or equipment type:</td>
<td>Annual screenings</td>
</tr>
<tr>
<td></td>
<td>Well sites</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Effective January 1, 2020)</td>
<td></td>
</tr>
</tbody>
</table>

Appendix B – Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector)

Table 5. Requirements on Methane Emissions by Regulating Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector)

<table>
<thead>
<tr>
<th>Emissions Source</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fugitive (leaks)</td>
<td>- Implementation of a leak detection and repair (LDAR) program to stop natural gas leaks</td>
</tr>
<tr>
<td></td>
<td>- Inspections for leaks three times per year</td>
</tr>
<tr>
<td></td>
<td>- Corrective action when leaks are found</td>
</tr>
<tr>
<td></td>
<td>- Data of implementation: January 1, 2020</td>
</tr>
<tr>
<td>General facility production venting</td>
<td>- Venting limit of 1,250 m$^3$ of natural gas per month (15,000 m$^3$ per year)</td>
</tr>
<tr>
<td></td>
<td>- Conservation of natural gas for re-use on site or for sale, or flaring/clean incineration of natural gas</td>
</tr>
<tr>
<td></td>
<td>- Data of implementation: January 1, 2020</td>
</tr>
<tr>
<td>Venting from pneumatic devices</td>
<td>- Venting limit of 0.17 m$^3$ of natural gas per hour for pneumatic controllers</td>
</tr>
<tr>
<td></td>
<td>- Conservation of natural gas for re-use on site or for sale, or replacement with non-emitting or low-bleed pneumatic device</td>
</tr>
<tr>
<td></td>
<td>- Data of implementation: January 1, 2020</td>
</tr>
<tr>
<td>Venting from compressors</td>
<td>- Annual measurements of emissions of natural gas from compressor vents</td>
</tr>
<tr>
<td></td>
<td>- Corrective action when emissions are higher than the applicable limit</td>
</tr>
<tr>
<td></td>
<td>- Data of implementation: January 1, 2020</td>
</tr>
<tr>
<td>Venting from well completions involving hydraulic fracturing</td>
<td>- No venting</td>
</tr>
<tr>
<td></td>
<td>- Conservation of natural gas for re-use on site or for sale, or flaring/clean incineration of natural gas</td>
</tr>
<tr>
<td></td>
<td>- Data of implementation: January 1, 2020</td>
</tr>
</tbody>
</table>

Source: Author compiled from Ministry of Justice, 2018.
### Appendix C – Timeline for Research

#### Table 6. Timeline

<table>
<thead>
<tr>
<th>Task</th>
<th>Start Date</th>
<th>End Date</th>
<th>Duration</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Draft Proposal</td>
<td>11/01/17</td>
<td>12/20/17</td>
<td>36d</td>
<td>100%</td>
</tr>
<tr>
<td>2 3 Mins Presentation</td>
<td>02/02/18</td>
<td>02/02/18</td>
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<tr>
<td>3 Final Proposal</td>
<td>01/15/18</td>
<td>03/01/18</td>
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<tr>
<td>- Introduction</td>
<td>01/15/18</td>
<td>03/01/18</td>
<td>34d</td>
<td>100%</td>
</tr>
<tr>
<td>- Literature Review</td>
<td>01/22/18</td>
<td>03/01/18</td>
<td>29d</td>
<td>100%</td>
</tr>
<tr>
<td>- Methodology</td>
<td>01/29/18</td>
<td>03/01/18</td>
<td>24d</td>
<td>100%</td>
</tr>
<tr>
<td>- Timeline</td>
<td>02/05/18</td>
<td>02/05/18</td>
<td>1d</td>
<td>100%</td>
</tr>
<tr>
<td>- References</td>
<td>01/15/18</td>
<td>03/01/18</td>
<td>34d</td>
<td>100%</td>
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<tr>
<td>4 Research &amp; Data Collection</td>
<td>03/01/18</td>
<td>05/31/18</td>
<td>66d</td>
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</tr>
<tr>
<td>- Survey</td>
<td>03/01/18</td>
<td>03/30/18</td>
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<tr>
<td>- Interview</td>
<td>03/05/18</td>
<td>04/30/18</td>
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<td>- Industry input</td>
<td>04/01/18</td>
<td>05/31/18</td>
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<td>100%</td>
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<tr>
<td>- Assumptions</td>
<td>03/01/18</td>
<td>05/31/18</td>
<td>66d</td>
<td>100%</td>
</tr>
<tr>
<td>- Data Collection</td>
<td>04/01/18</td>
<td>05/31/18</td>
<td>45d</td>
<td>100%</td>
</tr>
<tr>
<td>5 Progress Report 1</td>
<td>04/01/18</td>
<td>04/01/18</td>
<td>1d</td>
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</tr>
<tr>
<td>6 Progress Report 2</td>
<td>05/01/18</td>
<td>05/01/18</td>
<td>1d</td>
<td>100%</td>
</tr>
<tr>
<td>7 Progress Report 3</td>
<td>06/01/18</td>
<td>06/01/18</td>
<td>1d</td>
<td>100%</td>
</tr>
<tr>
<td>8 Analysis, Findings, Interpretation &amp; Discussions of Findings</td>
<td>06/01/18</td>
<td>06/29/18</td>
<td>21d</td>
<td>100%</td>
</tr>
<tr>
<td>Task</td>
<td>Start Date</td>
<td>End Date</td>
<td>Duration</td>
<td>Completion</td>
</tr>
<tr>
<td>------------------------------</td>
<td>------------</td>
<td>----------</td>
<td>----------</td>
<td>------------</td>
</tr>
<tr>
<td>9 Limitation, Conclusions &amp; Future Research</td>
<td>06/15/18</td>
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